An Investigation of Water Surface Temperature by an Airborne Infrared Radiometer: Lake Hefner, Oklahoma

by
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ABSTRACT

The effect of a monomolecular film of cetyl alcohol (hexadecanol) on the surface temperature of Lake Hefner, Oklahoma, was investigated using an airborne infrared radiometer. It was found that in three of six cases studied, the monomolecular film produced a temperature rise at the water surface. The temperature rise seems to be caused by an interaction of latent heat flux and sensible heat flux from the subsurface water. The grid pattern flown by the aircraft over the lake must be chosen carefully to delineate the monolayer. In three cases for which significant warming was found, two showed good agreement of the isotherm pattern with the film boundary. Comparisons of aircraft and boat radiation surface temperature indicate that the intervening atmosphere causes the aircraft reading to be about 1.0°C lower than the boat reading. Comparison of the aircraft monitored surface radiation temperature with subsurface temperature determined with a thermistor demonstrated the existence of a thermal gradient in the surface layer of water. The effect of the hexadecanol on this gradient was to reverse it, producing a "warm skin" emperature. A study of the energy budget at the air-water interface, using supporting micrometeorological data, indicates that sensible heat

transfer from subsurface water may be responsible for maintaining a relatively constant surface temperature. The diurnal variation, in one case study, was found to have a range of 1.0°C arising from variations of latent heat transfer, sensible heat transfer from the air, and solar radiation. Theoretical considerations indicate that surface cooling caused by variation of evaporation with fetch is in excess of that observed. A model is presented for further research which balances cooling of surface water by fetch variation of evaporation with fetch variation of sensible heat transfer from the subsurface water.

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The 1966 Evaporation Reduction Experiment at Lake Hefner was a joint effort by many different groups and the spirit of cooperation was very rewarding to the experimenters. They would like to acknowledge the following groups which aided substantially in this research: ESSA (ITSA) Boulder Laboratories; the Department of Agricultural Engineering, Oklahoma State University; the National Severe Storms Laboratory, Norman, Oklahoma; the Computing Center, University of Oklahoma; and the Sea-Air Interaction Laboratory - ESSA.

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CHAPTER I

INTRODUCTION

History of Surface Temperature Measurements During Hexadecanol Applications to Lake Surfaces.

The use of a hexadecanol monolayer to reduce evaporation has been thoroughly investigated in the laboratory (Rideal, 1925; Langmuir and Langmuir, 1927; Langmuir and Schaefer, 1943; La Mer, 1960). In the early 1950's the Bureau of Reclamation, USDI, began field experiments to determine the effect of monomolecular films on evaporation reduction. After several preliminary studies, a prototype field experiment was conducted at Lake Hefner, Oklahoma City, Oklahoma. In a report of this field experiment, Harbeck (1959) argued that a reduction of evaporation by a monomolecular film would alter the energy budget at the air-water interface in such a manner as to cause a water surface temperature rise.

The results from the Lake Hefner evaporation reduction study of 1958 show a 9% reduction of evaporation over an 88 day period with a corresponding rise in water temperature* of 1.0°C (Harbeck, op. cit.). In evaporation pan

*In this report, surface temperature will be taken to mean the first 20 microns of water; subsurface temperature: 20 microns to 1 centimeter; and water temperature: any depth below 1 centimeter.

experiments, Crow (1961) showed an increase in water temperature of 3.0°C after covering the water surface with hexadecanol. A 14% reduction of evaporation was computed over a 17 day period in a field experiment at Lake Sahuro, California during which a 1.1°C rise in subsurface temperature was noted (Korberg, 1961).

Objectives of the Study.

There were five objectives of the research reported herein. The principal objective was to determine by airborne infrared techniques if hexadecanol altered the water surface temperature of a lake during a mesoscale field experiment. A wind tunnel investigation (Grossman and Marlatt, 1966) showed a rise in surface temperature concurrent with the application of hexadecanol to an evaporating water surface. No detailed observations in the field, however, had been made to determine the effect of the monolayer on water surface temperature over a time period shorter than a few weeks.

The second objective was to determine the ability to map the monolayer boundary by an analysis of the lake surface temperature field. The motivation for this part of the investigation was a need to rapidly and accurately assess the amount of film on the lake at any given time, day or night.

The third objective was to compare observation of water surface temperature taken from an aircraft at 300 meters with simultaneous observation of surface and subsurface temperatures taken from a boat. Such a comparison would allow an examination of the effect of the intervening atmosphere on the aircraft observations of surface temperature and the existence of a temperature gradient in the upper few millimeters of the water surface.

A fourth objective of this investigation was to study the diurnal variation of water surface temperature, without the interference of the monolayer, placing particular emphasis upon the interaction of energy fluxes at the interface.

The final objective of this study was to investigate, in the field, the effect of evaporation on water surface temperature. In an earlier study, Ewing and McAlister (1960) found that surface temperature measured by an infrared radiometer dropped rapidly when evaporation was taking place from water in an open pan. The same result was obtained by Grossman and Marlatt (op. cit.) in wind tunnel studies.

CHAPTER II

BACKGROUND OF AIRBORNE INFRARED INVESTIGATIONS OF WATER SURFACE TEMPERATURE

Stommel (1953) was probably the first to measure water surface temperature with an airborne infrared radiometer (a Golay detector). The primary purpose of his investigation was to observe horizontal temperature gradients rather than absolute surface temperatures. Ewing (1952) obtained similar measurements in the Caribbean Sea.

Richardson and Wilkins (1957) were the first to fly a radiometer similar to the one used in the study reported here. Their radiometer employed a chopper (see Appendix I) to modulate the target signal. A blimp was used as their instrument platform. A three-inch diameter mirror with a 1.5 inch focal length was used to collect the infrared signal. This instrument, though bulky, had a sensitivity of $\pm 0.02^{\circ}C$.

Since the early work of Stommel, Ewing, and Richardson, much work has gone into perfecting an airborne system. Compromises of accuracy, size, weight, and expense, however, had to be made. A good general discussion of the problems encountered with such airborne measurements can be found in Techniques for Infrared Survey of Sea Temperature (Clarke, 1964).

Lenschow (1962) was one of the first to study lake surface temperatures using an airborne radiometer over several lakes in Wisconsin at different times of the year. Similar measurements are reported by Peterson (1965) for central Canada. Ragotzkie and Bratnik (1965) were able to infer dynamic features of Lake Superior from such airborne surveys. Richards and Massey (1966) proposed that the Great Lakes be regularly surveyed by airborne infrared. Such surveys are presently being carried out on the East and West Coasts of the U.S.A. (Ewing, 1965; Clarke, op. cit.) Marlatt's study (1966) was probably the first detailed investigation of the surface temperature of a small lake from the air.

CHAPTER III

DESCRIPTION OF INSTRUMENTATION

The principal instrument used in this investigation was an infrared radiometer which utilizes the emitted radiation of an object to measure its temperature. In the case of water, it measures the mean temperature of the first 20 microns of water (McAlister, 1964). One radiometer was located on board the aircraft and another was on board a small boat. Both radiometers detected radiation only in the interval 7.5 to 16.0 microns, employing a modulating device to measure the target signal which was then detected, amplified and displayed by the electronics package. The radiometers were carefully calibrated against a known, stable black body source.

The subsurface temperature was measured by a floating thermistor device (Marlatt, 1967) monitored from a boat, and its data were read directly from a modified Wheatstone bridge.

A detailed discussion of the instruments, power supplies, problems associated with the use of the instruments and inherent instrumental errors may be found in Appendix I.

CHAPTER IV

EXPERIMENTAL PROCEDURE

Description of the Lake Environment.

Lake Hefner (Fig. 1) is located in Oklahoma City, Oklahoma, approximately 5 miles northwest of the downtown area and is part of the domestic water supply. It is approximately 2.4 miles long and 2.1 miles wide with a surface area of 3.9 square miles. Residential areas border the lake on the east and south; to the west is a golf course; a dam with open fields below is the northern border. There are extensive shallow portions of the lake on the west and south, with deeper areas to the north (Fig. 2).

A sprinkler system for applying the hexadecanol film to the lake is located along the southern edges of the lake (Fig. 1). Good coverage of the lake by the monolayer therefore was achieved only during periods of southerly wind flow. Figure 3 shows a view of the monolayer on the lake from 300 meters.

Aircraft Procedures.

The monitoring of the surface temperature from the air was a relatively simple operation. The radiometer was shock

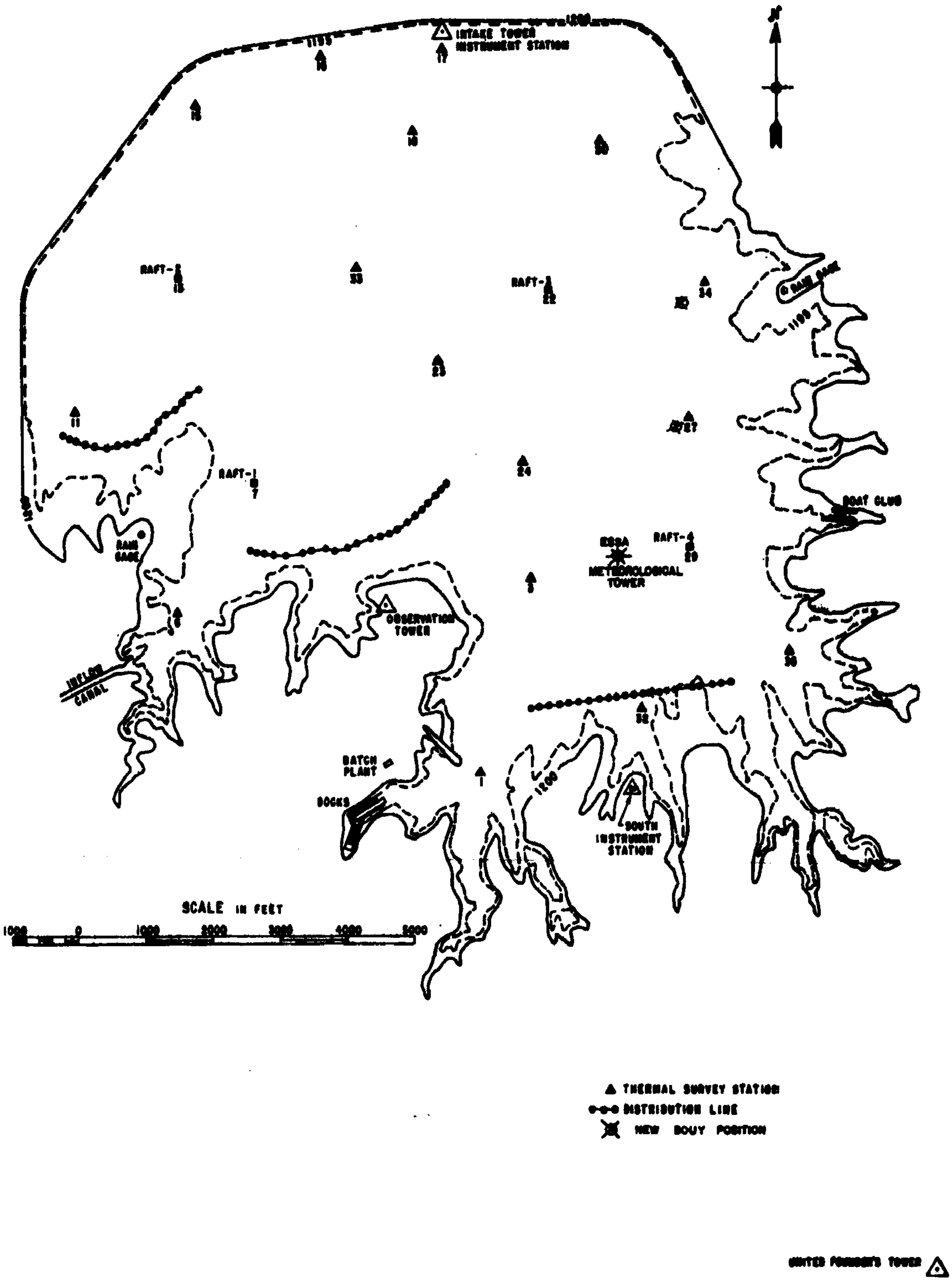

Figure 1.-- Map of Lake Hefner (Instrument Placement and Application Sites)

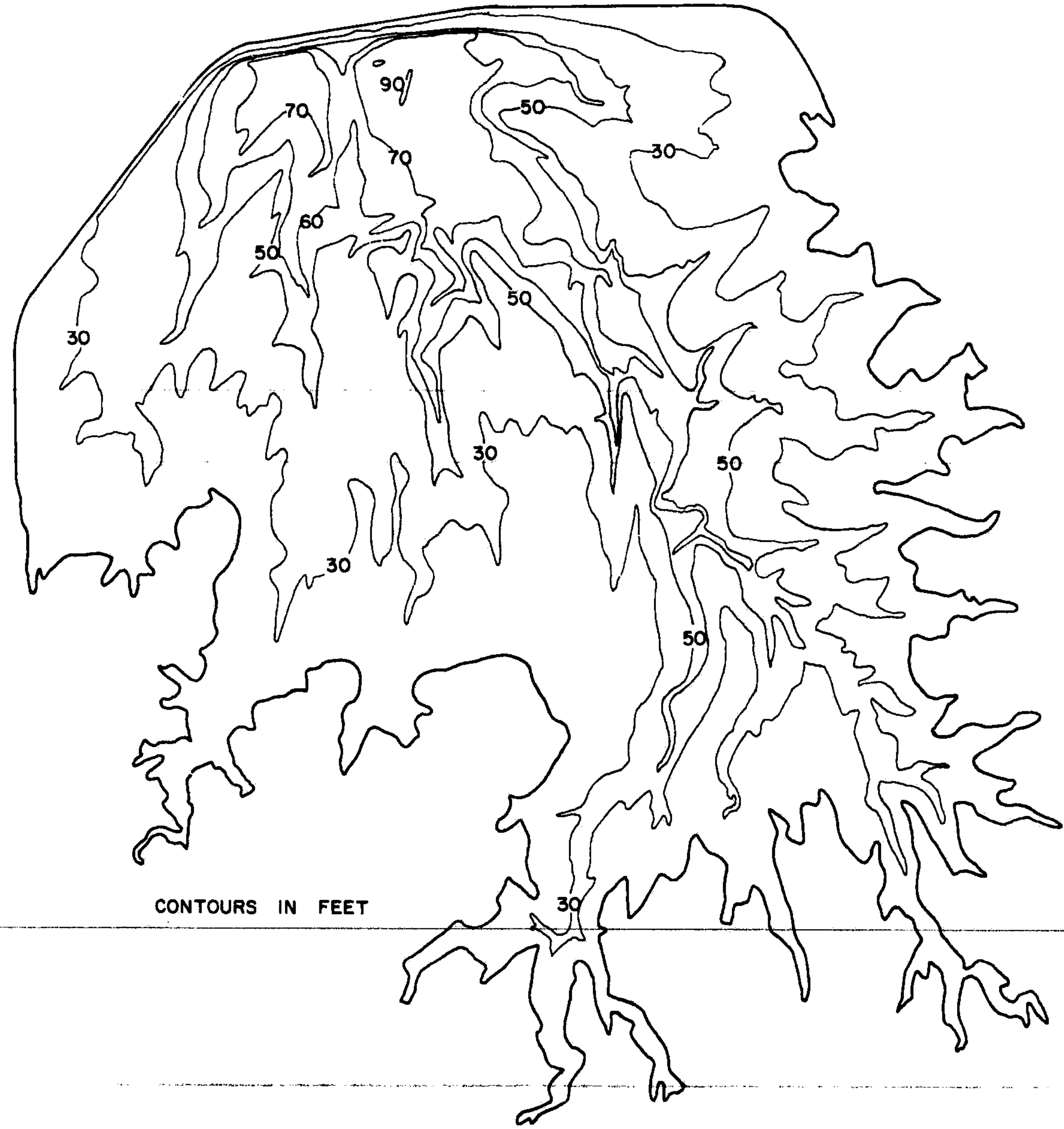

Figure 2.-- Map of Lake Hefner
(Depth Contours)

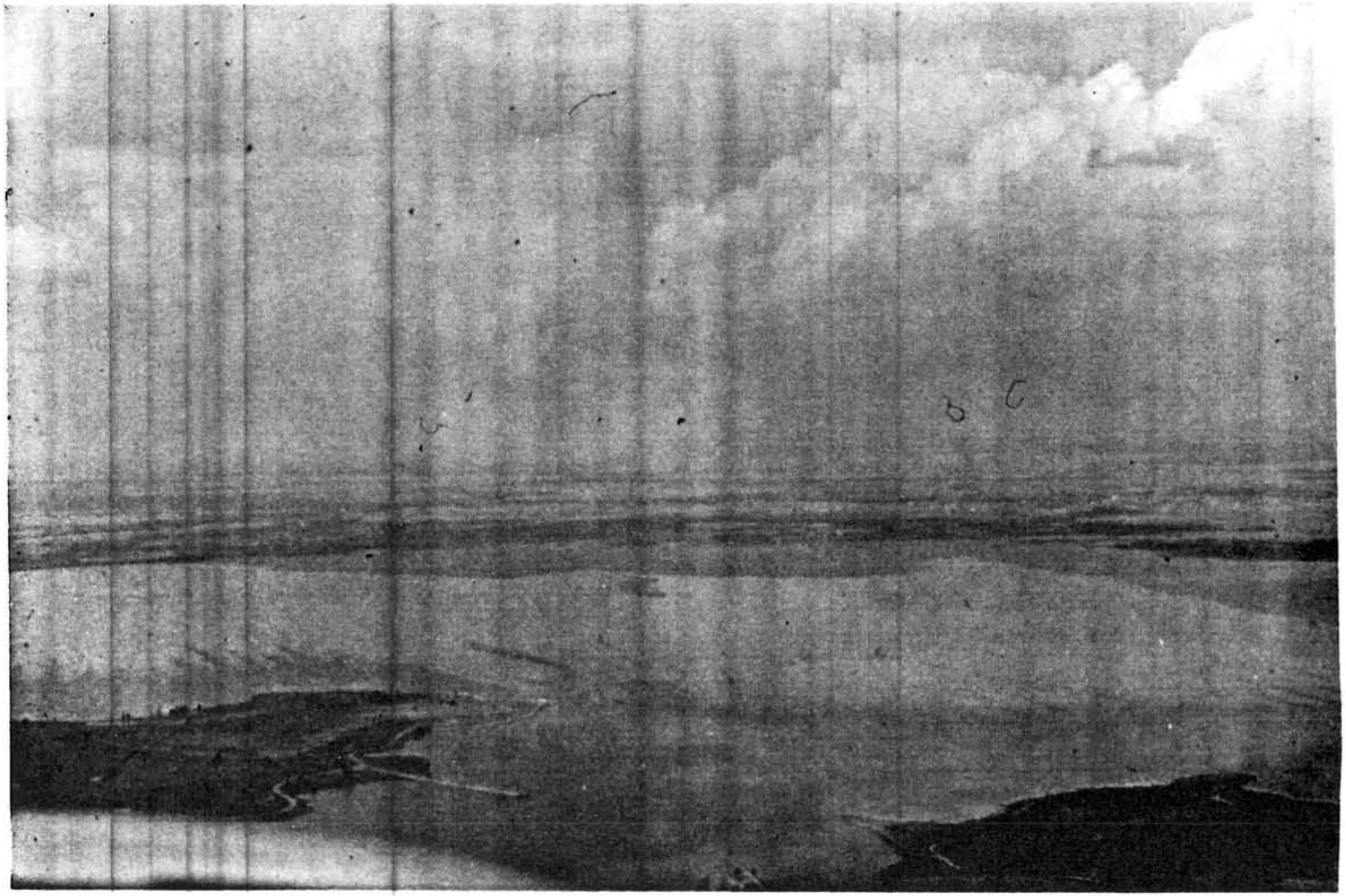

Figure 3.-- Photo of Monolayer on Lake

mounted into a plexiglass portion of the fuselage of a Piper Twin Comanche aircraft (Fig. 4) well away from the main slipstream. The plane was flown over a prescribed course at a constant height. Flights were generally made every four hours in a given study period, however, weather and film conditions altered this schedule at times. The proximity of a heavily populated area required a minimum flight altitude of 300 meters. Figure 5 shows a map of the flight path. Each leg of the flight was flown parallel to a road (actually 100 to 200 meters to the east or west) in order that the pilot could visually keep the aircraft on course. These roads were one-half mile apart. From these considerations, the experimenters concluded that an east-west accuracy of ± 100 meters was obtainable in plotting temperatures on maps of the lake surface.* The "criss-cross" legs were flown in order to fill in data and provide a repeatibility check on the radiometer output. A typical leg took 2 to 3 minutes to complete and an entire flight took approximately 40 minutes.

At night, navigation was more difficult, especially in the early morning hours. Generally, the streets and roads were well lighted, but little guidance was available

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*In cases where the plane was definitely off course, the temperatures were "fitted" to the lake. In general this was to fit the temperatures on the map and have the temperatures lakeshore boundary match the map lakeshore boundary.

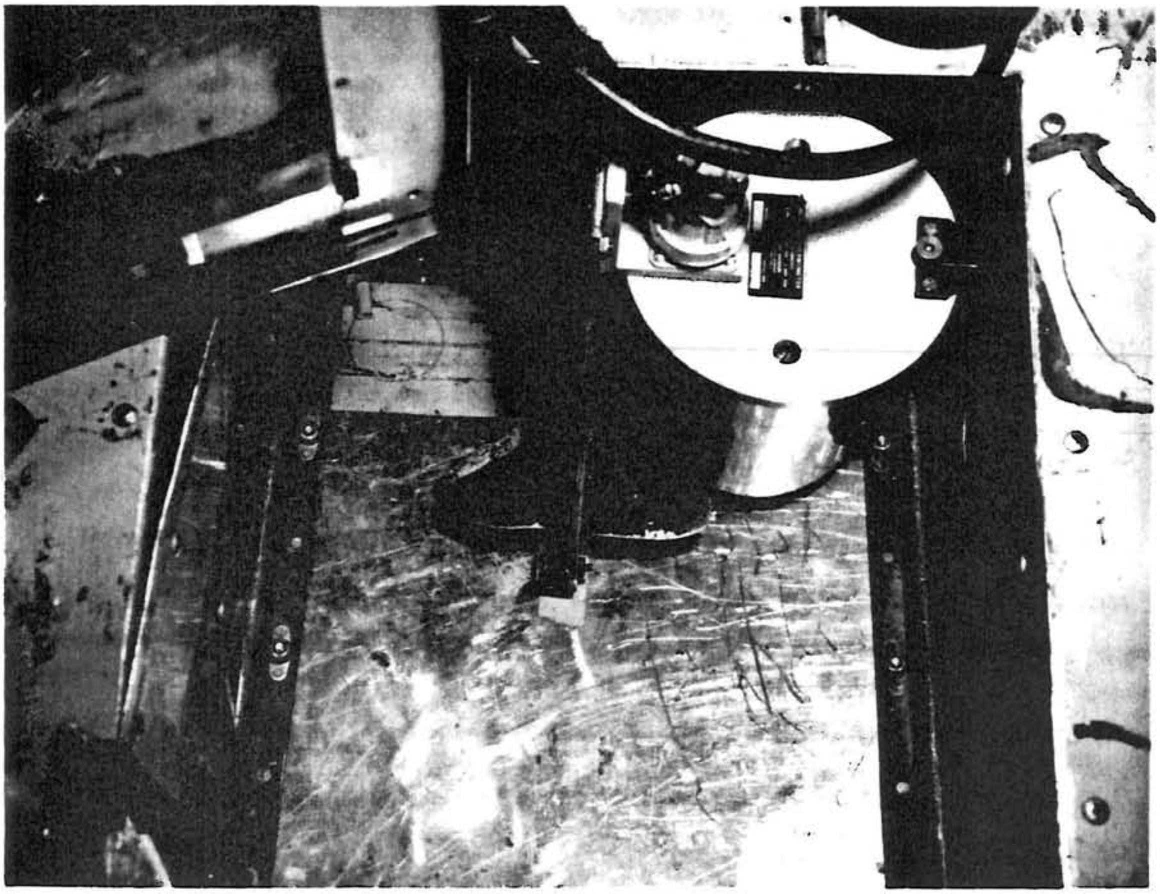

Figure 4.-- Photo of Radiometer in Aircraft

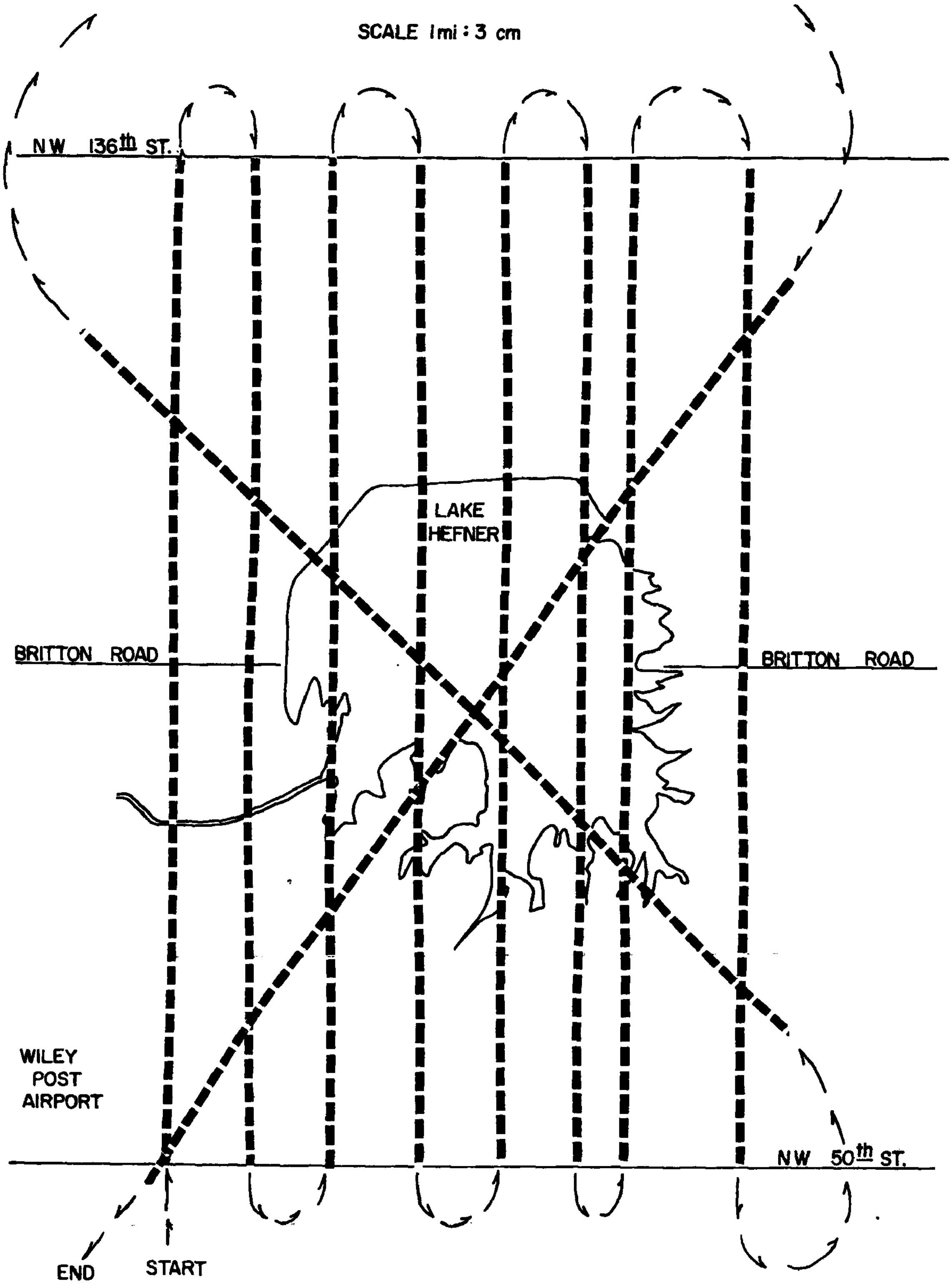

Figure 5.-- Map of Aircraft Flight Path

on the "criss-cross" legs. However, very little adjustment of the data on the lake surface had to be made during analysis.

Accurate placement of the data on the north-south line of flight required an accurate knowledge of the ground speed of the aircraft. This adjustment for ground speed was made during the data reduction. Two roads running east-west were selected as beginning and termination points of each run (Fig. 5). As the plane crossed the roads, they were sighted through the plexiglass window fitted into the bottom of the fuselage. At the time of crossing, a mark was placed on the strip chart by an event marker. When the strip chart data were being reduced on an analog-to-digital device, data were taken between the two marks denoting the beginning and end of a particular run. (Accuracy of data points north-south is $\pm$ 50 meters.) Figure 6 shows that the spacing between data points differs from leg to leg due to a shift in ground speed.

Boat Procedure.

A boat was used on the lake to make infrared temperature measurements as well as conventional surface temperature measurements with the floating thermistor described above (see Fig. 7) simultaneously with the aircraft measurements. Even on a small lake such as Lake Hefner, the ability to accurately locate a position on the

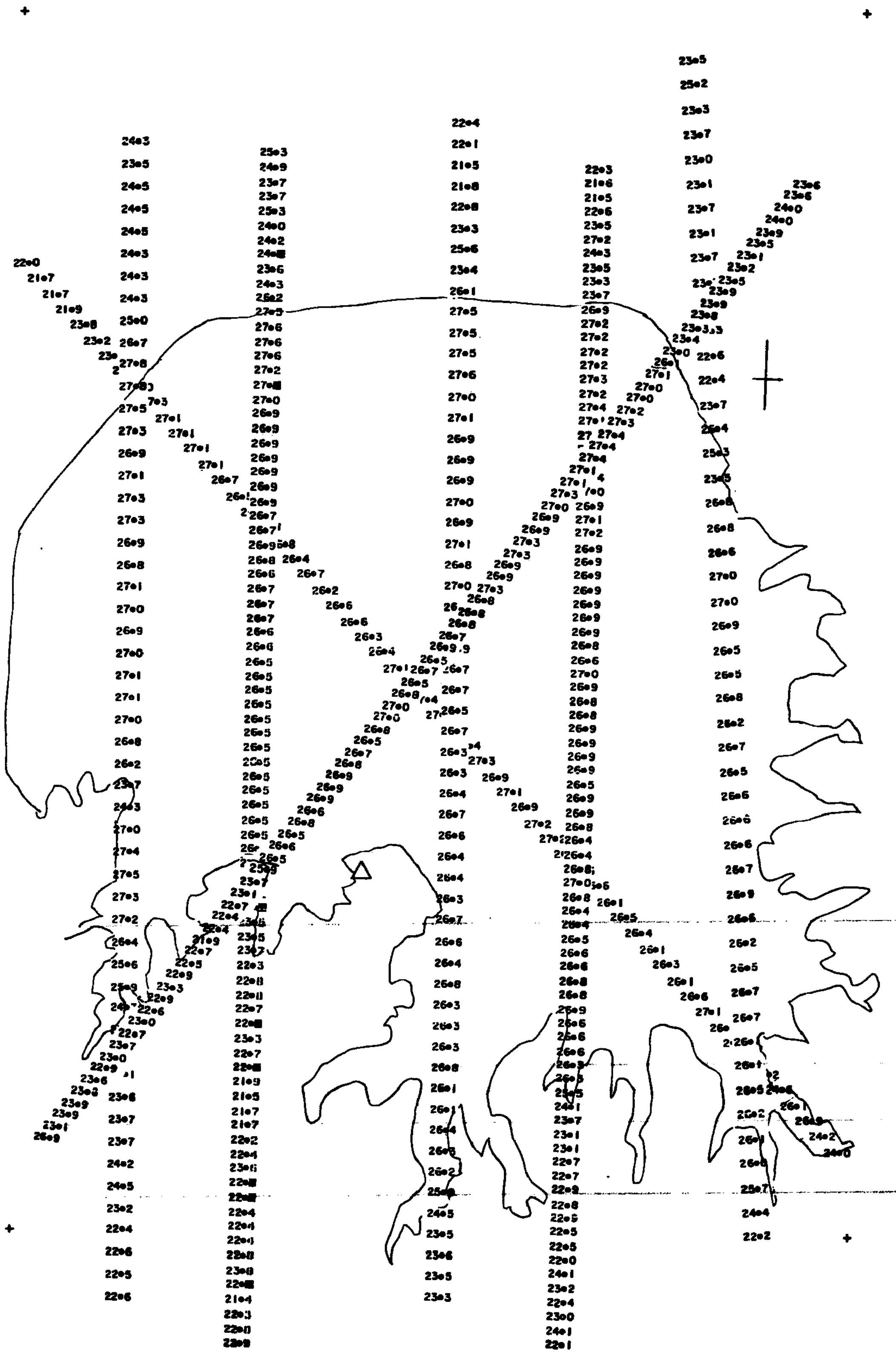

Figure 6.-- Data Sample Plotted
on Map of Lake

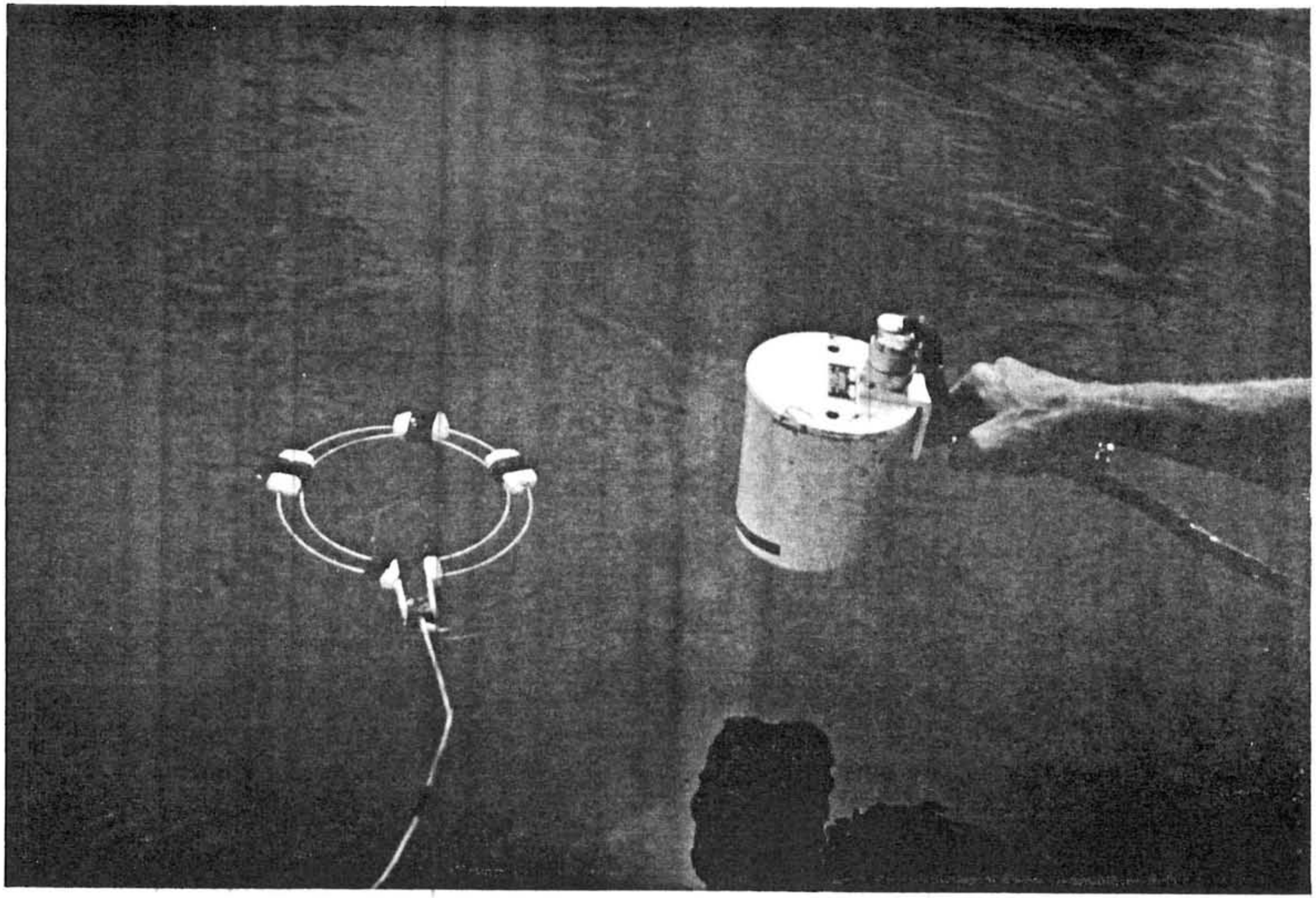

Figure 7.-- Photo of Measurements
Being Taken from Boat

lake is difficult. This was done by using the styrofoam buoys placed in the lake by a group from the Department of Agricultural Engineering, Oklahoma State University. These buoys were then located on a map (Fig. 1) by sighting them with a transit. The buoys were sighted in again at a later date and positions adjusted. Few of the buoys had drifted from their initial positions (Fig. 1). Accuracy of placement of the buoys on the map was about ± 50 meters.

On a typical measurement run, the boat would stop by a buoy and observations would be taken. When a special feature was investigated away from a buoy, its position was estimated by eye. In the daylight hours, this operation was relatively simple and straightforward. However, at night, finding the buoys proved difficult. On the average, therefore, the number of observations at night was less than the number taken during a daylight run.

CHAPTER V

ERROR ANALYSIS

Maximum Instrument Errors

A complete error analysis is necessary for two reasons. First, a change of surface temperature of a few tenths of a degree Celsius can be indicative of an alteration of energy budget at the air-water interface. Such an accuracy is necessary, therefore, to detect the presence of the film. Second, several physical processes at the lake surface and in the atmosphere had to be investigated since the amount of error they would introduce was unknown.

Table 1 summarizes the maximum instrument error and also gives errors due to data processing. Other error sources will be discussed later.

Other Forms of Error.

One of the most difficult problems in remote sensing is the distinction of the signal desired from noise which accompanies the measured phenomenon. In this case, the signal desired was a change in water surface temperature caused by an alteration of the energy budget at the air-water interface. In this study, such a temperature change

TABLE 1

ERROR ANALYSIS SUMMARY

	Boat Radiometer (°C)	Boat Thermistor (°C)	Aircraft Radiometer (°C)
Sensor Error	±1.0	±0.3	±0.5
Recorder Error*	0.0	0.0	±0.1
Data Reduction Error*	0.0	0.0	±0.1
Total Maximum Error	±1.0	±0.3	±0.7

*These errors also add to the aircraft radiometer resolution error of ±0.2°C to give a maximum resolution error of ±0.4°C.

due to application of a hexadecanol monolayer is of primary importance. Also of interest is a temperature change due to variation of the energy budget with time and with fetch. Therefore, in this investigation all other temperature variations must be regarded as noise.

These "noise" signals will be briefly discussed below. A more detailed discussion of the entire error analysis problem may be found in Appendix II.

There were four major error sources which came to bear upon the objectives of this study. An error due to the effect of the intervening atmosphere upon the aircraft measurement of water surface temperature was corrected by a computer program.* The alteration of the infrared emissivity of the water surface by the monolayer was found to be negligible. Temperature advection and upwelling effects were assumed small during the time period of a particular aircraft flight. While there was a limit to film boundary resolution due to the motion of the aircraft, it was superseded by the resolution limit set by the data sampling time. This resolution limit was such that a film strip less than 67 meters wide would go undetected at an aircraft speed of 45 meters per second.

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*All airborne radiation surface temperatures discussed in this report include this correction.

CHAPTER VI

PRESENTATION OF DATA

In order to create some basis for use of the absolute error, resolution error, and resolving power in the analysis of the lake surface temperature, the mean surface temperature of the entire lake was chosen as the most natural datum level.

It will be shown that in some cases the film seems to cause slight warming of the skin temperature and sub-surface temperature underneath it. This would cause the indicated radiation surface temperature to be increased by a factor related to the amount of time the aircraft spent over the film cover during a complete run. This is related to the amount of film on the lake.

Of the eighteen cases presented, six had a film cover. The percentage of film covering the lake during the flight is presented in Table 2. In most of the cases, the percentages do not show an inordinate bias toward the amount of data taken in or out of the film, so one would find it difficult to detect the effect of so slight a bias. Furthermore, there is no way of finding an explicit quantitative relationship to correct for this bias in placing the isotherms.

TABLE 2

PERCENT FILM COVER, AUGUST, 1966
LAKE HEFNER, OKLAHOMA

Date/Local Time	% CVR
17/12	19
17/16	33
28/14	43.2
28/20	50.0*
29/13	38.8
30/14	53.6

*Estimated figure.

The lake isotherms derived from the aircraft measurements are presented in Appendix III. The isotherms are deviations from the average lake temperature with an interval of 0.5°C. In the analysis, smoothing was by eye. At times, even though the difference between two values was less than the required maximum of ±0.4°C, an isotherm was drawn between them to permit a continuity of data to one side or other of the isotherm. Such a decision is justified upon noting that the r.m.s. resolution error of the aircraft radiometer was ±0.2°C (see Appendix II).

Figure 8 shows a partitioning of the lake into four areas approximately equal in size. Average temperatures were determined for each of these areas, which were sufficiently separated from one another and from the shore to reduce interaction between areas and the shore. The lake was divided into such areas to investigate the possibility of persistently warm or cool areas. Figure 9 shows a plot of the deviations from the overall average lake surface temperature for each of the areas.

Mean airborne radiation temperatures and their standard deviations for the four areas are presented in Table 3. Flights were made from 17 August, 1966, to 30 August, 1966. The data are presented in chronological order. Table 4 gives the average airborne radiation temperature, the average boat radiometer temperature, and the average boat thermistor temperature for the entire lake surface.

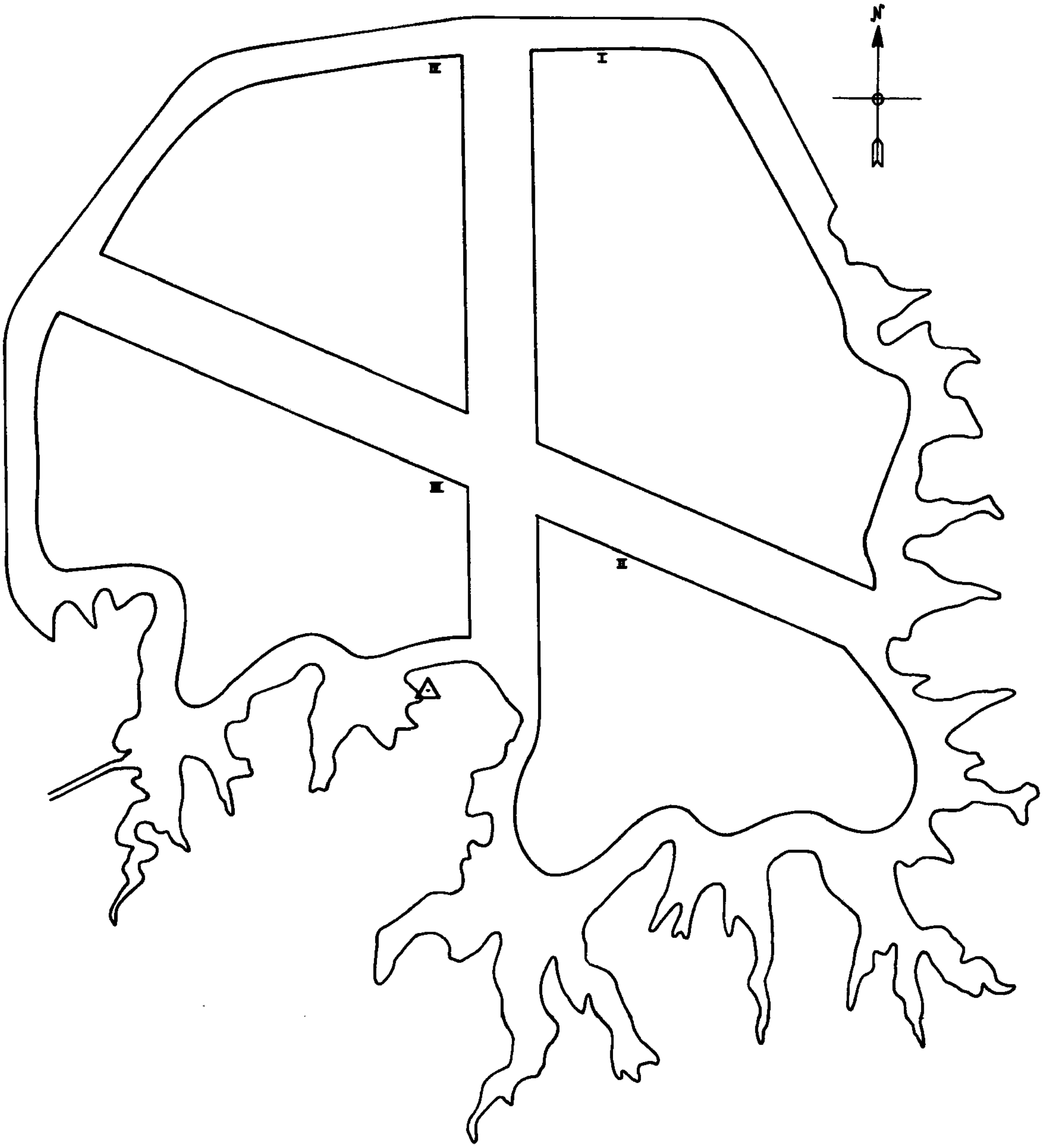

Figure 8.-- Map of Lake Partitioned into Four Areas

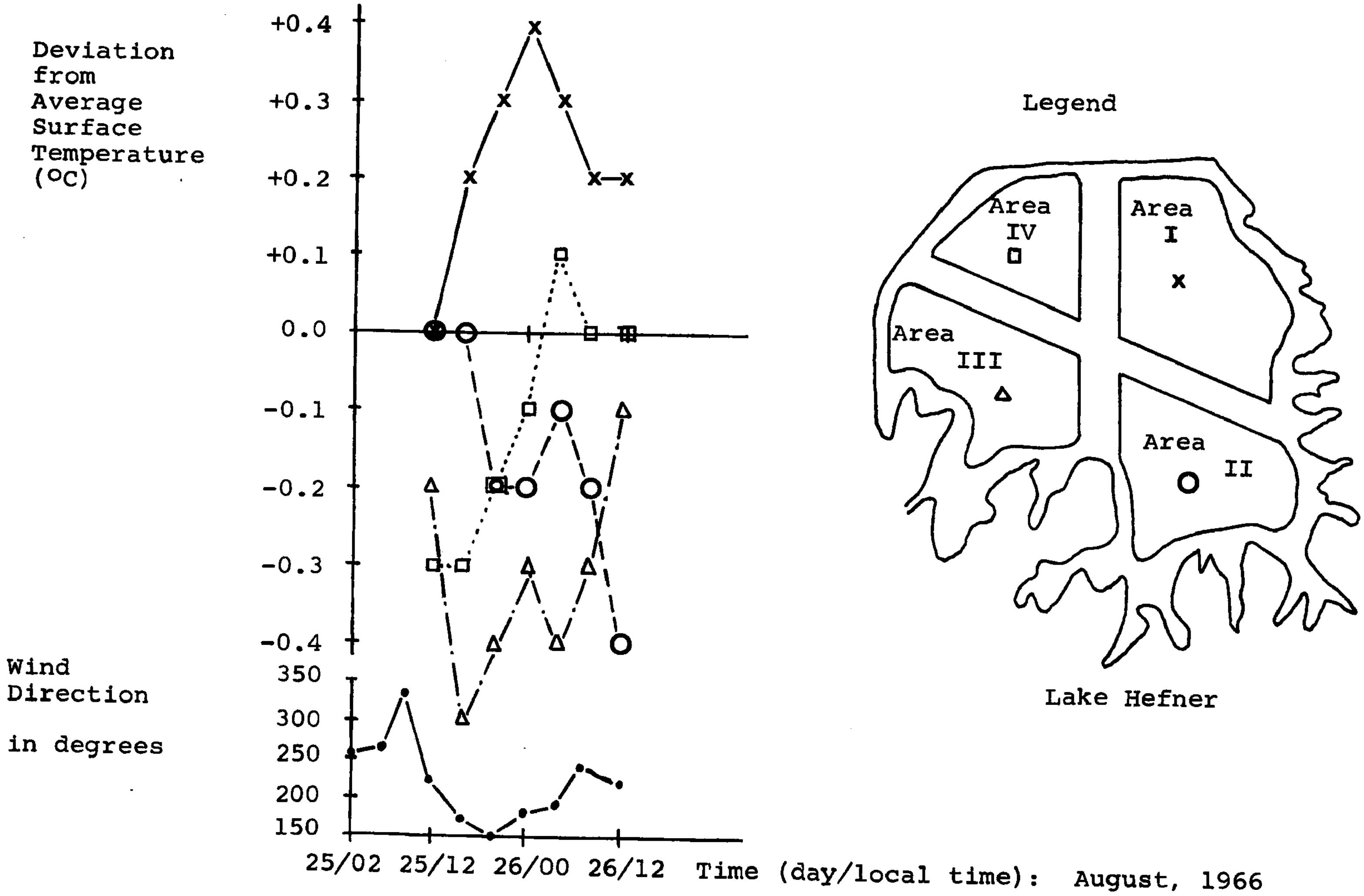

Figure 9.-- Deviation From Area Average Surface Temperature-vs-Time

TABLE 3

AREA AVERAGES OF AIRCRAFT MONITORED SURFACE TEMPERATURE (°C)
LAKE HEFNER, AUGUST 1966

August 1966 Date/Time	Area I	I	Area II	II	Area III	III	Area IV	IV
17/12	27.9	±.29	27.9	±.30	28.1	±.40	28.1	±.22
17/16	28.5	±.27	28.5	±.19	28.7	±.28	28.7	±.19
19/08	26.6	±.19	26.4	±.20	--------Data Rejected--------			
19/12	28.1	±.21	27.4	±.25	27.7	±.23	27.4	±.29
19/16	28.7	±.24	28.6	±.19	28.9	±.20	28.7	±.25
19/20	28.1	±.27	27.6	±.24	27.7	±.27	28.0	±.21
25/12	25.9	±.28	25.9	±.37	25.7	±.28	25.6	±.27
25/16	26.1	±.25	25.9	±.30	25.4	±.23	25.6	±.23
25/20	25.3	±.31	24.8	±.33	24.6	±.18	24.8	±.26
26/00	25.2	±.18	24.6	±.26	24.5	±.17	24.7	±.19
26/04	25.1	±.27	24.7	±.19	24.4	±.25	24.9	±.25
26/08	25.2	±.19	24.9	±.21	24.8	±.24	25.1	±.25
26/12	25.7	±.21	25.2	±.21	25.5	±.19	25.6	±.18
28/01	25.1	±.20	24.9	±.20	25.1	±.29	25.3	±.19
28/14	25.8	±.19	25.4	±.16	26.0	±.18	26.3	±.28
28/20	25.8	±.36	25.6	±.29	25.4	±.10	25.7	±.23
29/13	25.8	±.16	25.5	±.21	25.6	±.17	25.8	±.16
30/14	25.5	±.27	25.5	±.25	25.5	±.29	25.8	±.24

TABLE 4

MEAN SURFACE TEMPERATURE (°C) AND FIRST STANDARD DEVIATION OVER ENTIRE LAKE

Aircraft and Boat Measurements

Date/Time	Aircraft Radiometer	σ A/C	Boat Radiometer	σ Br	Boat Thermistor	σ Bt
17/12	28.0	±.32				
17/16	28.6	±.28				
19/08	26.6	±.55				
19/12	27.6	±.27		No Data Available		
19/16	28.7	±.27				
19/20	27.8	±.32				
25/12	25.9	±.33	26.0	±.27	26.5	±.16
25/16	25.9	±.39	26.8	±.41	26.3	±.34
25/20	25.0	±.45	No Data:	Boat Failure		
26/00	24.8	±.38	25.7	±.71	25.9	±.41
26/04	24.8	±.36	25.7	±.68	25.5	±.34
26/08	25.1	±.29	25.6	±.50	25.5	±.29
26/12	25.6	±.33	25.5	±.38	25.6	±.20
28/01	25.1	±.27	24.7	±.29	25.0	±.45
28/14	25.8	±.34	25.8	±.78	25.3	±.74
28/20	25.6	±.38	25.0	±.24	24.8	±.18
29/13	25.7	±.24	25.3	±.37	25.3	±.27
30/14	25.5	±.29	25.1	±.24	25.2	±.31

No reliable boat data for the period 17 August, 1966, to 20 August, 1966, were obtained.

Table 5 presents a summary of average aircraft surface temperatures located within the film as well as corresponding averages taken outside the film cover. A summary of results of a student's "t" test on the hypothesis that the average temperature within the film is equal to that outside the film is also included in Table 5.

TABLE 5

MEAN SURFACE TEMPERATURE (°C) (AIRCRAFT) AND FIRST STANDARD DEVIATION
IN AND OUT OF FILM COVER AND RESULTS OF
STUDENT "t" TEST ON THE MEANS
LAKE HEFNER, AUGUST 1966

Date/Time	Average Temperature In	σ_{In}	Average Temperature Out	σ_{Out}	%Film Cover	"t"	Accept $\bar{T}_{IN}=\bar{T}_{OUT}$ @ 10% Level
17/12	28.1	±.46	28.0	±.32	19.0	-	yes
17/16	28.5	±.30	28.5	±.28	33.0	-	yes
28/14	26.0	±.32	25.7	±.28	43.2	5.769	no
28/20	25.6	±.21	25.3	±.26	50.0	1.470	no
29/13	24.9	±.21	24.9	±.24	38.8	-	yes
30/14	24.7	±.29	24.4	±.24	53.6	1.250	no

CHAPTER VII

DISCUSSION OF RESULTS

Detection of the Monolayer.

One of the major objectives of this study was the determination of the effect of a hexadecanol monolayer on water surface temperature. There were six aerial observations of water surface temperature during which a monolayer covered portions of the lake. From statistical analysis of these six water surface temperature patterns, it was found that a significant rise of surface temperature occured within the film boundary in three of the cases.

The ability to detect the monolayer must involve the interaction of instrument accuracy, airborne radiometer resolving power, amount of film on the lake, and the length of time that the film had covered the water surface.

First, the instrument must sufficiently accurate to detect a temperature difference caused by the film. Laboratory investigations showed that the radiometer used had this accuracy. The airborne resolving power*, amount of

*The ability of the radiometer to detect a temperature change while in flight (see Gaevskiy, et.al., 1965).

film on the lake, and the grid pattern flown by the aircraft are also intimately connected to the detection of the effect of the monolayer. This is emphasized by the fact that detection of warming by the monolayer was found only in those cases where 40% or more of the lake was covered by the film. The relationship between the amount of time over which the hexadecanol acted on the water surface and the detection of its effect on surface temperature is not known quantitatively. However, if meteorological parameters can be considered as representative of energy budget adjustments, then detection of the film's effect should be noticeable within an hour after its application to the lake surface. In all cases which were evaluated, the film had been applied at least two hours before the flight.

The method of computing the averages for comparison of the surface temperature within the film boundary with the open water surface temperature was as follows: A map of film coverage nearest flight time was overlaid on the lake surface temperature field. Temperature inside and outside the film cover boundary were then arithmetically averaged.

The averaging technique had to assume the film cover was motionless, which was not strictly true. However, the main body of the film was quasi-stationary during a given flight period. Slight movements of the film boundaries could have caused a decrease in detection ability and also may have produced higher variances of the sample of temperatures taken both in and out of the film.

Only the aircraft radiometer temperatures provided a sample sufficiently large enough to be used in statistical analysis. The distribution of temperatures within each sample was Gaussian to a close degree of approximation. An "F" test was performed on each pair of temperature samples (in and out of the film) to determine whether the variances of the samples could be considered equal or unequal.*

According to the result of the "F" test, a Student's "t" test was then performed to test the hypothesis that the average temperature within the film differed significantly from the mean temperature outside of the film. In all cases tested, this hypothesis was rejected at the 10% level on a one-tailed test. The hypothesis was rejected for observations taken on 28 August 1400L, 28 August 2000L, and 30 August 1400L.

As an example, consider the 30 August 1400L case. The average temperature within the film boundary was 0.3°C higher than the average of the temperatures taken outside of the film. The value of "t" was 1.25 with 72 degrees of freedom; therefore, the hypothesis that the means were equal was rejected at the 10% level.

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*The variance used in this discussion is not the instrument error. It is a measure of the spread of temperature values taken in or out of the film boundaries. The comparison in this case is not between instruments but between measurements taken with the same instrument over different areas of the lake.

Theoretical Support of Monolayer Detection.

The radiation surface temperatures are representative of a thin layer of water which should be very sensitive to the energy fluxes which enter and leave it. One might suppose that these fluxes are in equilibrium for very short periods of time due to the many thermal and dynamic phenomena which may influence this surface layer. The major energy fluxes which act upon the surface layer are schematically represented in Fig. 10). They are: the flux of latent heat (evaporation), the flux of sensible heat, the solar input, and the long wave radiational cooling. The sensible heat flux acts on both sides of the air-water interface.

The immediate effect of the film on the water is to reduce the flux of latent heat. This would cause a net influx of energy into the surface layer in the form of solar insolation and sensible heat, thus causing a surface temperature rise.

Saunders (1967) considers another effect of a monolayer on the energy budget of the surface layer. He feels a surface film increases the vertical dimension of the viscous boundary layer within the water.* This thickening of the viscous layer is caused by the inhibition of

*The dimension of the viscous boundary layer is smaller than the surface layer representative of the radiation temperature.

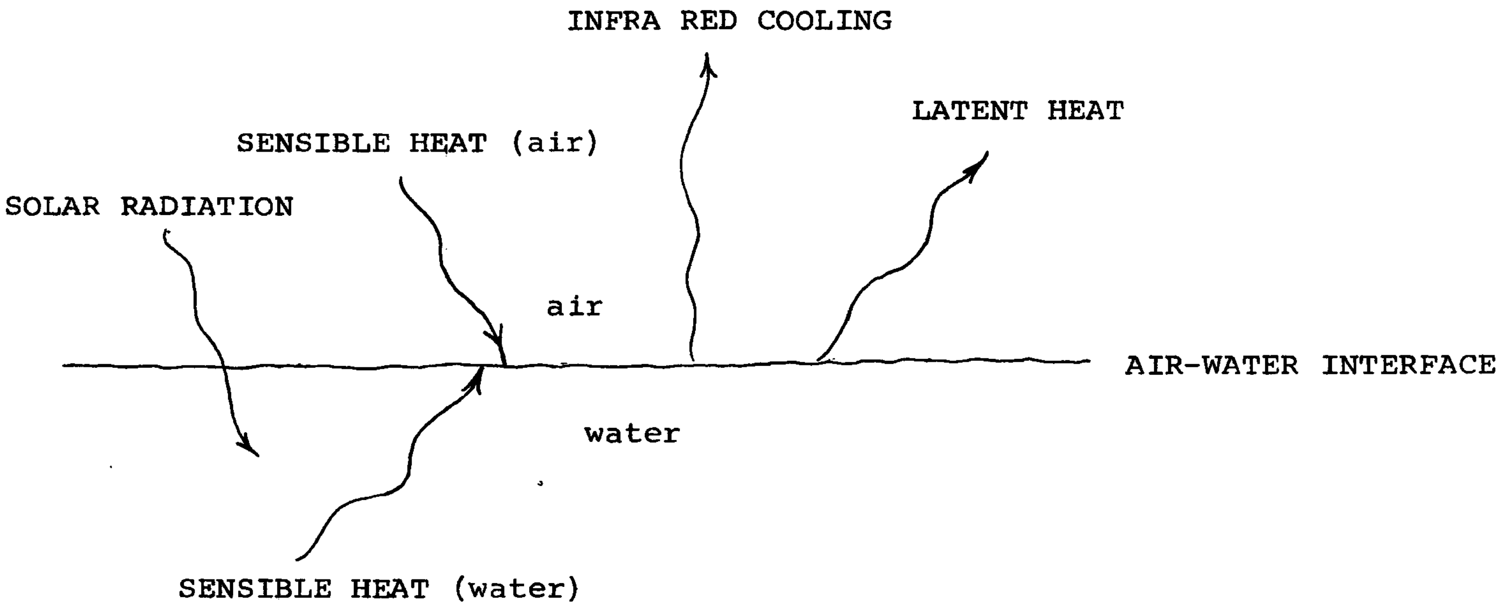

Figure 10.-- Major Energy Fluxes Acting at an Air-Water Interface

horizontal motion near the water surface by the film. An increase of the viscous boundary layer would cause the transfer of sensible heat from the water into the surface layer to be less effective under the film. Figure 11 shows that for the cases reported here the subsurface water was, on the average, cooler than the surface water. Thus the cooling effect of sensible heat transfer within the water was less effective under the film than in open water, adding to the temperature difference between film covered water and open water. If the subsurface water had been warmer than the surface water, then the observed temperature difference between open and film covered water might have been less.

It appears from the preceding discussion that the primary fluxes causing a temperature difference between open and film covered water are latent heat flux and sensible heat flux transferred within the water. The relative contributions of these two fluxes are, at present, unknown.

The above discussion also points to the fact that other fluxes which act at the water surface must be negligible in producing a temperature difference between open and film covered water. In the daytime, the albedo of the film covered water was the same as that for open water (Beard and Wibelt, 1966); therefore the film did not affect the flux of solar radiation. The damping of capillary waves by the film would lower the boundary layer in

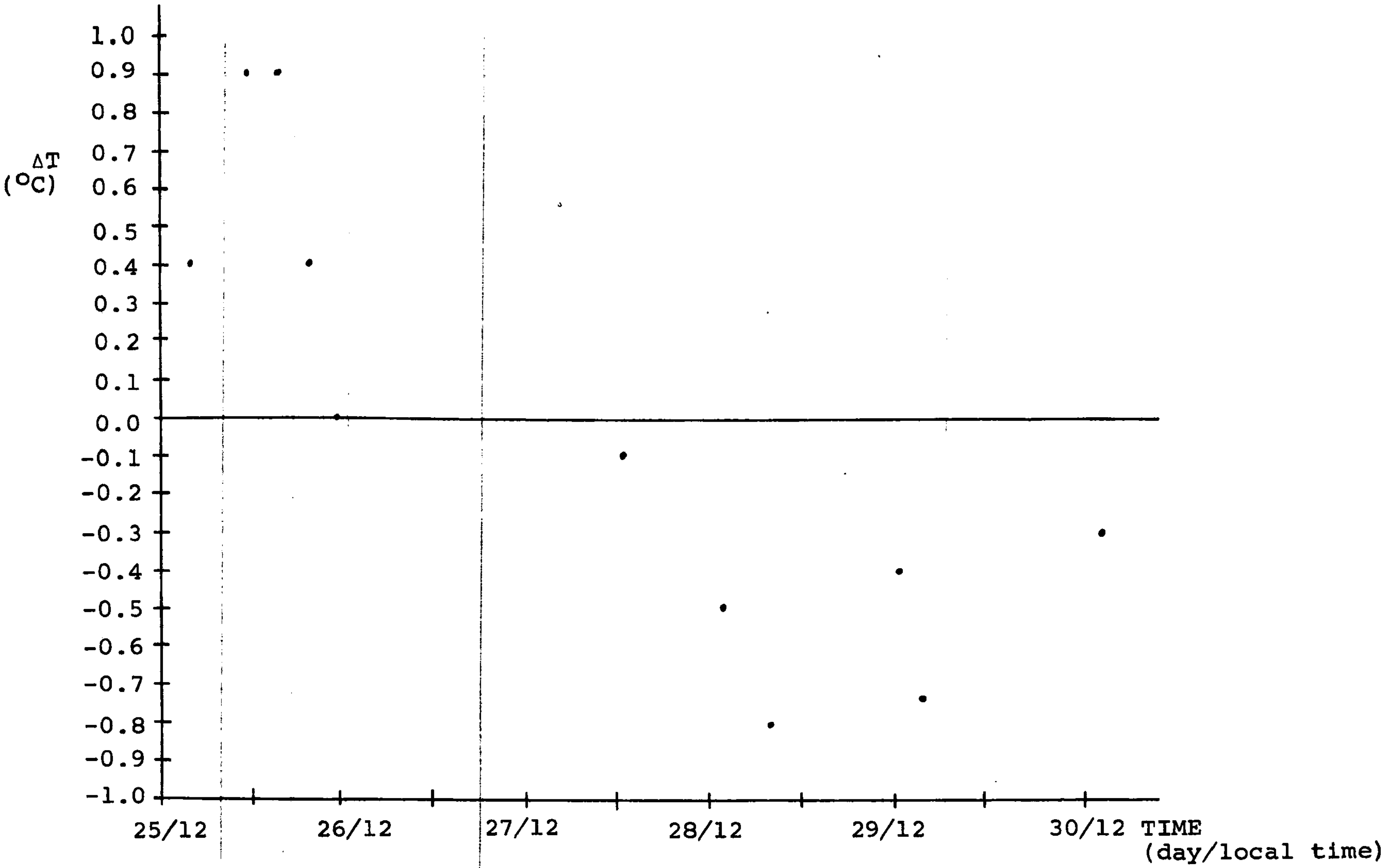

Figure 11.-- Floating Thermistor Temperatures
Minus Aircraft Temperatures-Vs-Time

the air over the film and probably cause heat transfer into film covered portions of the lake to occur at a faster rate. The effect is similar to the warming theory of Saunders, i.e., film covered areas would appear warmer relative to open water. The experimenters feel that, though this difference in heat transfer may occur, it is small compared to the other mechanisms causing temperature differences between film covered and open water. At night the radiational cooling would be the same over both film covered water and open water, since the film had no effect on emissivity in the infrared (see Appendix II).

Surface Temperature Isotherms and the Film Cover.

The essence of the second objective of this investigation was to locate the monolayer cover by an analysis of the lake surface temperature field. Three cases showed warming under the film cover. In each case, the percent film cover on the lake was between 43.7% and 53.6%. Therefore, the mean surface temperature isotherm should correspond well with the film boundary, since approximately half the temperatures were within the boundary and half were outside the film boundary.*

Of the three cases, two show an overall correspondence between the mean surface temperature isotherm and the film

*This statement assumes: 1) negligible advection of temperature on the lake surface; 2) negligible upwelling; 3) that the temperature difference between open and film covered water is not large. All three assumptions are valid for this study.

boundary. Figures 32 to 36 show the boundary temperature field of the lake and the film boundary. (See Appendix III).

The first case, 28 August 1400L, (Fig. 32) shows poor correlation between the mean isotherm and the monolayer boundary. This could be due to the fact that the monolayer application was halted at 1400L and the film started to drift northward. The film coverage map used for comparison with the surface isotherms was completed at 1425L. Thus there was movement of the main film body during the aircraft flight. This would result in decay of imaging ability (i.e., the image would be "blurred" beyond recognition). Figure 33 is the same isotherm analysis with the film boundary for 1500L included. The correlation, though again poor, is somewhat better due to the fact that the map was plotted during the latter part of the aircraft flight.

For the 28 August 2000L study the correlation between the mean surface isotherm and the film boundary is improved (see Fig. 34). The southern boundary of the film corresponds to the approximate position of the mean surface isotherm. Also, a break in the film cover oriented north-south near the northwest corner of the lake is well represented by the mean surface isotherm. Note that warmer temperatures, relative to the mean, fall within the film border.

The analysis of the 30 August 1400L flight (Fig. 36) produced favorable results. The mean surface isotherm compares well with the monolayer boundary. Again, a break in the film occuring in the northern sector of the lake appears in the analysis of the temperature field.

In reviewing these three cases, it might be said that the mean surface isotherm correlates well with the edge of the main body of the monolayer. However, the choice of the mean isotherm was dependent upon the percentage of film cover on the lake. Optimum detection seemed to occur when the film covered 50% of the lake surface. Detection may be just as negative at 70% coverage (rare at Lake Hefner) as it was at 30% coverage. Therefore, the flight pattern seems to have a "detection filter" inherent in it. Widening the "filter" to include other amounts of film coverages would necessitate a higher resolution flight grid. Under the circumstances, such a pattern would have been very difficult to fly. It was also observed that small scale features of the film cover, whose dimensions were set by the data sampling time (see ERROR ANALYSIS, p. 18), were not detected. This could have been a result of degradation of the data during the analog to digital conversion and/or another effect of the flight pattern.

Comparison of Surface Temperature Monitored from Boat and Aircraft.

In his early work on airborne infrared sea surface temperature, Stommel (op.cit.) stated that, at 300 meters, one can neglect the effect of an intervening atmosphere on radiation measurements. Lenshow (op.cit.) supported a similar statement with computations which assumed a warm spring or cool summer day in Wisconsin. However, the atmospheric effect on airborne infrared measurements under a moist air mass may be appreciable. For example, Shaw (1966) shows a difference of 1.0°C between infrared temperature measured at 130 meters and those measured at 300 meters over Lake Ontario. Saunders (1966) also states that at 300 meters over the ocean the "apparent" infrared temperature can differ from the actual surface temperature by ±0.5°C.

In this particular study, the effect of the intervening atmosphere on the infrared data collected in the aircraft was not negligible. The methods by which this effect may be corrected and a description of the method finally selected appear in Appendix II. Table 6 shows that, at Lake Hefner, a correction on the order of 1.0°C with a range of ±0.2°C had to be applied to the aircraft infrared measurements (see footnote, p. 20).

This environmental error was generally computed from radiosonde sounding at Tinker Air Force Base or Will Rogers International Airport. In one case, however, a kitoon sounding taken near the midlake meteorological tower was used for the temperature-humidity profile of the lower 60 meters. From 60 meters to flight level, the sounding was taken from the Will Rogers radiosonde. Correction using the Will Rogers sounding alone was lower by 0.1°C than that

TABLE 6

COMPUTED ENVIRONMENTAL ERROR ($^{\circ}C$) DUE TO WATER VAPOR
LAKE HEFNER, AUGUST 1966
(T computed - T measured)

Date/Time	Error	Date/Time	Error
17/12	1.1	26/00	1.0
17/16	0.8	26/04	1.3
19/08	1.0	26/08	1.2
19/12	1.1	26/12	1.1
19/16	0.9	28/01	1.1
19/20	1.0	28/14	1.3
25/12	1.2	29/10	1.0
*25/16	0.9	29/13	0.8
25/20	1.0	30/14	1.0

*Kitoon sounding; all others used radiosonde at Tinker AFB or Will Roger's International Airport.

Note: The error computed for 25/16 using just the Tinker radiosonde was 0.8$^{\circ}C$.

using the kitoon-Will Rogers combination. This is understandable, since Will Rogers was upstream from the lake in this case, and more water vapor can be expected over the lake at lower levels than upstream of it. From this observation, one may expect all environmental corrections to be low, on the order of 0.1°C.

Since the aircraft and boat measurements were simultaneous, a comparison of the respective surface temperatures was possible. A check on the influence of the intervening atmosphere between the aircraft and the surface can be made by comparing the boat radiometer surface temperature with the corrected aircraft temperatures. If the intervening atmosphere correction is valid, the two temperatures should be equal within the limits of instrument accuracy. Table 7 shows the aircraft radiometer temperatures are equal to the boat radiometer temperature within the framework of the statistical analysis.

When comparing aircraft measurements of water surface temperature with those monitored from a boat, one must recognize the effect of the respective methods of data acquisition. The airborne radiation measurement is the average temperature of a fairly large swath of water, while the boat radiation and thermistor measurements are essentially made at a point. Both measurements include a weighting factor (a result of the instrument optics) which is difficult to evaluate but which may effect the comparison (Dutton, 1964; Marlatt, 1964). Averaging the data was

TABLE 7

SUMMARY OF STATISTICAL TESTS OF HYPOTHESIS:
$\bar{T}$ Aircraft Radiometer = $\bar{T}$ Boat Radiometer
LAKE HEFNER, AUGUST 1966

Date Local Time	$\bar{T}$ Boat Rad - $\bar{T}_{a/c}$ Rad (^{o}C)	"t" Using σ= Absolute Error of Boat Rad and $\sigma T_{br} \neq \sigma T_{a/c}$	Reject $\bar{T}_{br} = \bar{T}_{a/c}$ @ 10% Level
25/12	+0.1	0.1	No
25/16	+0.9	0.9	No
25/20	-	-	-
26/00	+1.1	1.1	No
26/04	+0.7	0.7	No
26/08	+0.5	0.5	No
26/12	-0.1	0.1	No
28/01	-0.4	0.4	No
28/14	0.0	0.0	No
28/20	-0.6	0.6	No
29/13	-0.4	0.4	No
30/14	-0.4	0.4	No

performed in an attempt to minimize this effect in the comparisons. However, the influence of sample size and the method of measurement on the comparison of aircraft and boat radiometric measurements is observed in a comparison of their standard deviations. The boat radiometer standard deviation is consistently larger than those accompanying the aircraft measurements (see Table 4).

Although the possibility of a gradient of temperature in the upper few millimeters of the sea surface was discussed briefly by Montgomery (1940) and Woodcock (1941), Ball (1954) showed conclusively that a gradient was possible. Ball used an infrared radiometer to substantiate his argument, arguing that the radiation measured by the radiometer was indicative of the temperature in the upper millimeter of the water surface. In his experiment, Ball found the radiometer surface temperature to average 0.3°C cooler than the water temperature measured by the standard bucket technique. Ball also estimated that the region through which this gradient acted was 0.15 centimeters. It may be noted that a "cool" surface temperature reflects what seems to be an unstable temperature stratification. Applying certain ideas of Rayliegh, Ball computed that a temperature difference of 13°C could be maintained in this thermal boundary without overturning.

Further work on this thermal boundary layer was carried out by Ewing and McAlister (op.cit.) with a more sophisticated radiometer than that used by Ball. They proposed the infrared radiation temperature corresponded to the mean temperature of the first 100 microns of water. Using infrared radiation measurements made at night, which were corrected for reflected sky radiation, Ewing and McAlister found the difference between bucket temperature and radiation temperature to be 0.6°C. Again a "cool" radiation temperature was noted. Their experiments also revealed that the thermal boundary maintained itself under upwelling until the surface of the water was ruptured. Later work by McAlister (op.cit.) states that water is opaque in the infrared band 7.5 microns to 15 microns at depths greater than 20 microns. He uses this fact in proposing a dual waveband radiometer to measure sensible heat flow in the water surface.

The relationship between the radiation temperature and the subsurface (i.e. bucket, intake, or floating thermistor in this case) temperature is complex and depends upon the air-water interface radiation balance, turbulent transfer of sensible heat from the air and within the water, and the transfer of latent heat from the surface. Boudreau (1966) related radiation temperatures obtained on board an oceanographic research vessel to bucket temperatures by employing a regression analysis. He believed the observed "cool" surface temperature was due to latent heat transfer.

Many workers have compared airborne infrared measurements of water surface with those taken from a boat. In general, the comparison has been with bucket or intake temperatures (Ragotzkie, 1964; Pickett, 1966; Saunders, op.cit.; Lenschow, op.cit.; Gaevskiy et. al., op.cit.). However, some investigators have had the opportunity to compare aircraft observations of surface temperature with a boat-mounted radiometer (Richards and Massey, op.cit.; Shaw, op.cit.; Pauls, 1966; Richards, 1966; Marlatt, op. cit.; Oshiver and Berberian, 1965).

In this study, evidence of a thermal gradient in the surface layer should appear in the comparison of the aircraft radiation temperature with the subsurface temperature obtained by the floating thermistor. These two temperatures should differ. Furthermore, the hexadecanol monolayer may be expected to alter the thermal gradient. One possible result of monolayer application would be to reverse the thermal gradient due to the reduction of latent heat transfer from the water surface.

Table 8 shows the result of "t" tests on the hypothesis that the average of the floating thermistor measurements was equal to the average of the airborne radiometer measurements. In general, the "t" tests showed the aircraft radiometer temperatures were not equal to the floating thermistor measurements. This affirms the existence of a thermal gradient in Lake Hefner.

Beginning with the film application on 28 August, the surface layer gradient was reversed (see Fig.11). In other words, a "cool" surface temperature was observed without

TABLE 8

SUMMARY OF STATISTICAL TESTS OF HYPOTHESIS:
$\overline{T}$ Boat Thermistor = $\overline{T}$ Aircraft Radiometer
LAKE HEFNER, AUGUST 1966

Date/ Local Time	$\overline{T}_{Boat\ Therm} - \overline{T}_{a/c}$ (°C)	"t" Using σ = Abs. Max. Error of Thermistor & $\sigma_{therm} \neq \sigma_{a/c}$	Reject Hypothesis $\overline{T}_{therm} = \overline{T}_{a/c}$ @ 10% Level
25/12	+0.6	2.000	yes
25/16	+0.4	1.333	yes
25/20	No Data Available:	Boat Failure	
26/00	+0.9	3.000	yes
26/04	+0.9	3.000	yes
26/08	+0.4	1.333	yes
26/12	0.0	0.0	no
28/01	-0.1	.333	no
28/14	-0.5	1.666	yes
28/20	-0.8	2.666	yes
29/13	-0.4	1.333	yes
30/14	-0.3	1.000	no

the film while a "warm" surface temperature was observed concurrent with film application.

The observed gradient reversal is supported by theory. Without the hexadecanol monolayer, one would expect "cool" skin due to the transfer of latent heat from the water surface. Field investigations have shown that hexadecanol reduces local evaporation by approximately 60% (Bean and Florey, 1967). The percent reduction of evaporation over the entire lake is probably much lower since there are open evaporating areas of water on the lake as well as film covered areas. However, with a good film cover, it would seem plausible that the overall reduction of latent heat transfer would cause a net energy influx into the surface layer by solar radiation and sensible heat from the air (also for a short period of time by sensible heat transfer from the water). This net energy influx would warm the surface layer. From Fig. 11, it is estimated that the overall warming of the surface layer by the film is on the order of 0.4°C to 0.8°C. This is in general agreement with the values given by Harbeck (op.cit.) and those found in laboratory experiments (Grossman and Marlatt, op.cit.).

<u>Case Study of Diurnal Variation of Surface Temperature</u>.

The infrared radiometer measures the temperature of a very thin layer of water near the surface. It is plausible to assume that any surface temperature change with time is due to net energy gain or loss in this surface layer.

Therefore,

1) net energy into surface layer per unit time = flux of sensible heat from the air + flux of sensible heat from the water + latent heat flux + solar insolation into surface layer + radiational cooling from surface.

This model assumes that there is no net horizontal advection of temperature into or out of the region of interest. Furthermore, a local thermal equilibrium condition exists in the surface layer only when the fluxes balance exactly.

If a cylindrical volume of water whose area is subtended by the normal viewing angle of a stationary radiometer is considered, then,

$$2)\quad \rho_w C_{p_w} \frac{\partial T_s}{\partial t} = -C_{p_A} \rho_A K_H \frac{\partial \Theta_A}{\partial z} - C_{p_w} \rho_w K_{HW} \frac{\partial \Theta_w}{\partial z} - \rho_A L K_q \frac{\partial q}{\partial z} + \tau W + \beta \sigma T_s^4 .$$

This equation assumes that the transferred properties such as Θ_A, Θ_W and q have no horizontal divergence and that they are in local equilibrium (i.e., $\frac{\partial q}{\partial t} = 0$).

Now, $q = \epsilon \frac{e}{p}$, so substituting into (2) and assuming $\frac{\partial(\frac{1}{p})}{\partial z} \doteq 0$ for the vertical distances of interest to this problem gives,

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*See Appendix IV, p.112 for glossary of terms used in equations.

$$3)\quad \rho_W C_{PW}\frac{\partial T_s}{\partial t} = -C_{PA}\rho_A K_H\frac{\partial \theta_A}{\partial z} - C_{PW}\rho_W K_{HW}\frac{\partial \theta_W}{\partial z} - \rho_v L K_q p\epsilon\frac{\partial e}{\partial z} + \tau W + \beta\sigma T_s^4 .$$

If z = 0 is the water surface, and assuming all gradients to be linear over the small distances concerned, then by finite differencing,

$$4)\quad \rho_W C_{PW}\frac{\partial T_s}{\partial t} = \frac{C_{PA}\rho_A K_H}{z_1}[\theta_s-\theta_{Az_1}] + \frac{C_{PW}\rho_W K_{HW}}{z_2}[\theta_s-\theta_{Wz_2}] + \rho\frac{L K_q p\epsilon}{z_3}[e_s-e_{z_3}] + \tau W + \beta\sigma T_s^4 .$$

From Hasse (1963) it is shown that $\theta_s = T_s$ and in water $\theta_W \doteq T_W$, so

$$5)\quad \rho_W C_{PW}\frac{\partial T_s}{\partial t} = \frac{C_{PA}\rho_A K_H}{z_1}[T_s-\theta_{Az_1}] + \frac{C_{PW}\rho_W K_{HW}}{z_2}[T_s-T_{Wz_2}] - \frac{\rho L K_q p\epsilon}{z_3}[e_s-e_{z_3}] + \tau W + \beta\sigma T_s^4 .$$

Using the Clausius-Clapeyron equation gives

$$6)\quad \frac{\partial T_s}{\partial t} = \frac{1}{\rho_W C_{PW}}\left\{\frac{C_{PA}\rho_A K_H}{z_1}[T_s-\theta_{Az_1}] + \frac{C_{PW}\rho_W K_{HW}}{z_2}[T_s-T_{Wz_2}] + \rho\frac{L K_q p\epsilon}{z_3}\,\mathrm{EXP}\left(-\frac{L}{R_v T_s}+K\right) + \rho_v\frac{L K_q p\epsilon}{z_3}e_{z_3} + \tau W + \beta\sigma T_s^4\right\}.$$

Solution of the time dependent differential equation expressed in (6) would give a functional relationship between surface temperature, T_s, and time and could be compared to numerical values of $T_s = T_s\ (t)$ found from curves of the diurnal variation of surface temperature. Once the validity of the equation was checked in this manner, it would be possible to use (6) for an investigation of energy flux interaction at an air-water interface.

Several problems, however, are immediately apparent. As it stands, the equation is nonlinear in T_s. There are methods of linearizing which may be attempted in the solution of (6) if it were not for a more crippling deterrent to its solution. This problem lies mainly in present knowledge of K_H and K_{HW}, the eddy transfer coefficients in air and water. Very little is known about K_{HW} near the air-water interface. In the air above the interface, the assumption generally made in turbulence studies, i.e., $K_H/K_M = 1$, does not hold. As for the expression of K_{HW} as a function of time, nothing is known; while $K_H = K_H\ (t)$ seems to be related to time through stability, the exact relationship is still being sought. Due to this obvious complexity, only a quasi-mathematical discussion of the diurnal variation can be submitted.

The magnitudes of energy fluxes measured at the mid-lake meteorological tower at midday on 26 August are presented in Table 9 to give some idea of relative importance. The sensible heat transfer in the water was not measured. Normally, the latent heat flux would tend to dampen the combined fluxes of sensible heat from the air and solar energy. A non-linearity in the flux interaction is the dependence of the vapor pressure gradient on surface temperature. As an example, suppose the water surface temperature increased. Such an increase would necessarily cause an increase in vapor pressure gradient producing a

TABLE 9

MEASURED FLUXES AT AIR WATER INTERFACE, LAKE HEFNER, OKLAHOMA
26 AUGUST 1966 1200L

Sensible Heat From Air-Water*	Latent Heat	Radiation Infra-red	Solar Input
($ergs/cm^2$ sec)	($ergs/cm^2$ sec)	($ergs/cm^2$ sec)	($ergs/cm^2$ sec)
$.5x10^4$	$1.5x10^4$	$40x10^4$	$2x10^4$

*The flux of sensible heat in this case was away from the water surface. However, the temperature gradient and wind shear above the interface were similar to the more common case of heat transfer into the surface. Therefore, the order of magnitude here presented should be similar to heat transfer into the surface. Stability effects, however, should make heat transfer into the water surface slightly less, if the wind profiles were similar in both cases.

cooling effect due to a greater latent heat transfer. Assuming air and subsurface temperature were warmer than the surface temperature (at the surface) would be checked by a reduction of sensible heat transfer above and below the air-water boundary.

Upon investigating the flux magnitudes, however, one finds that, even at midday, infrared cooling of surface temperature is quite large.

This would cause a drastic cooling of the lake surface, if there were no flux other than that of sensible heat from air and solar radiation to transport heat into the surface layer. It is suggested that the flux of sensible heat from subsurface water into the surface layer is extremely important in maintaining the relatively constant surface temperature observed at Lake Hefner.* This flux would probably vary slightly due to the high heat capacity of water.

If the sensible heat transfer from the subsurface water tends to balance the radiational cooling, then the energy fluxes responsible for a diurnal variation of surface temperature are the fluxes of latent heat, sensible heat from the air above the water, and solar radiation. Figure 12 shows the diurnal variation of surface temperature during the period 25 August 1200L to 26 August

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*While this report was in manuscript, measurements by McAlister (1967) were made known to the author to support this hypothesis.

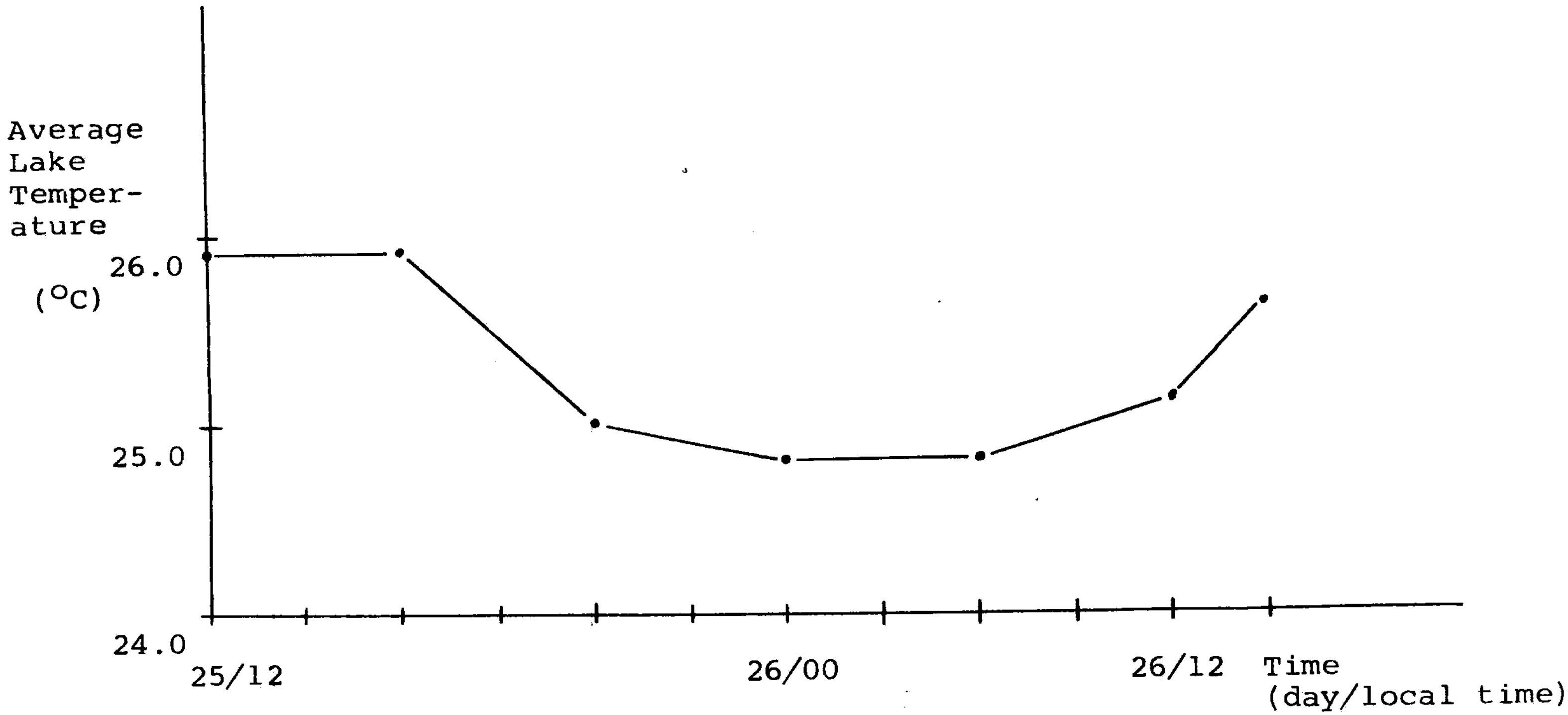

Figure 12.-- Aircraft Radiometer average Lake Surface Temperature -vs-Time, Lake Hefner, August 1966

Eq. (6) which becomes

$$13)\quad \frac{dT_s}{dt} = \frac{1}{\rho_w C_{P_w}} \left\{ \frac{C_{P_w}\rho_w K_{HW}}{z_2}\left[T_s - T_{wz_2}\right] - \frac{\rho L K_q p \epsilon}{z_3} \mathrm{EXP}\left[-\frac{L}{R_v T_s} + K\right] + \frac{\rho L K_q p \epsilon e_{z_3}}{z_3} \right\}.$$

Upon differentiating along fetch one obtains,

$$14)\quad \frac{d}{dt}\left[\frac{dT_s}{dx}\right] = \frac{1}{\rho_w C_{P_w}} \frac{d}{dx} \left\{ \frac{C_{P_w}\rho_w K_{HW}}{z_2}\left[T_s - T_{wz_2}\right] - \frac{\rho L K_q p \epsilon}{z_3} \mathrm{EXP}\left[-\frac{L}{R_v T_s} + K\right] + \frac{\rho L K_q p \epsilon e_{z_3}}{z_3} \right\}$$

Now, integrating with respect to time gives

$$15)\quad \left.\frac{dT_s}{dx}\right|_{t_1}^{t_2} = \frac{1}{\rho_w C_{P_w}} \int_{t_1}^{t_2} \frac{d}{dx} \left\{ \frac{C_{P_w}\rho_w K_{HW}}{z_2}\left[T_s - T_{wz_2}\right] - \frac{\rho L K_q p \epsilon}{z_3} \mathrm{EXP}\left[-\frac{L}{R_v T_s} + K\right] + \frac{\rho L K_q p \epsilon e_{z_3}}{z_3} \right\} dt .$$

The solution of Eq. (15) is prohibitive without further research of the air-water interface. It is, however, one of the logical models to test in the future.

From Fig. 9, it is seen that Area IV was nearly always cool relative to the average lake surface temperature. However, for several hours previous to the aircraft measurements of the surface temperature the wind had a definite westerly component. Therefore, Area IV would be expected to be cool if an evaporation process is important in the alteration of surface temperature. Returning to Fig. 9, it should be noted that as the wind shifted into the south, Area IV began to warm rapidly, finally becoming warmer than the average surface temperature. It would not seem possible that upwelling effects could produce such rapid warming.

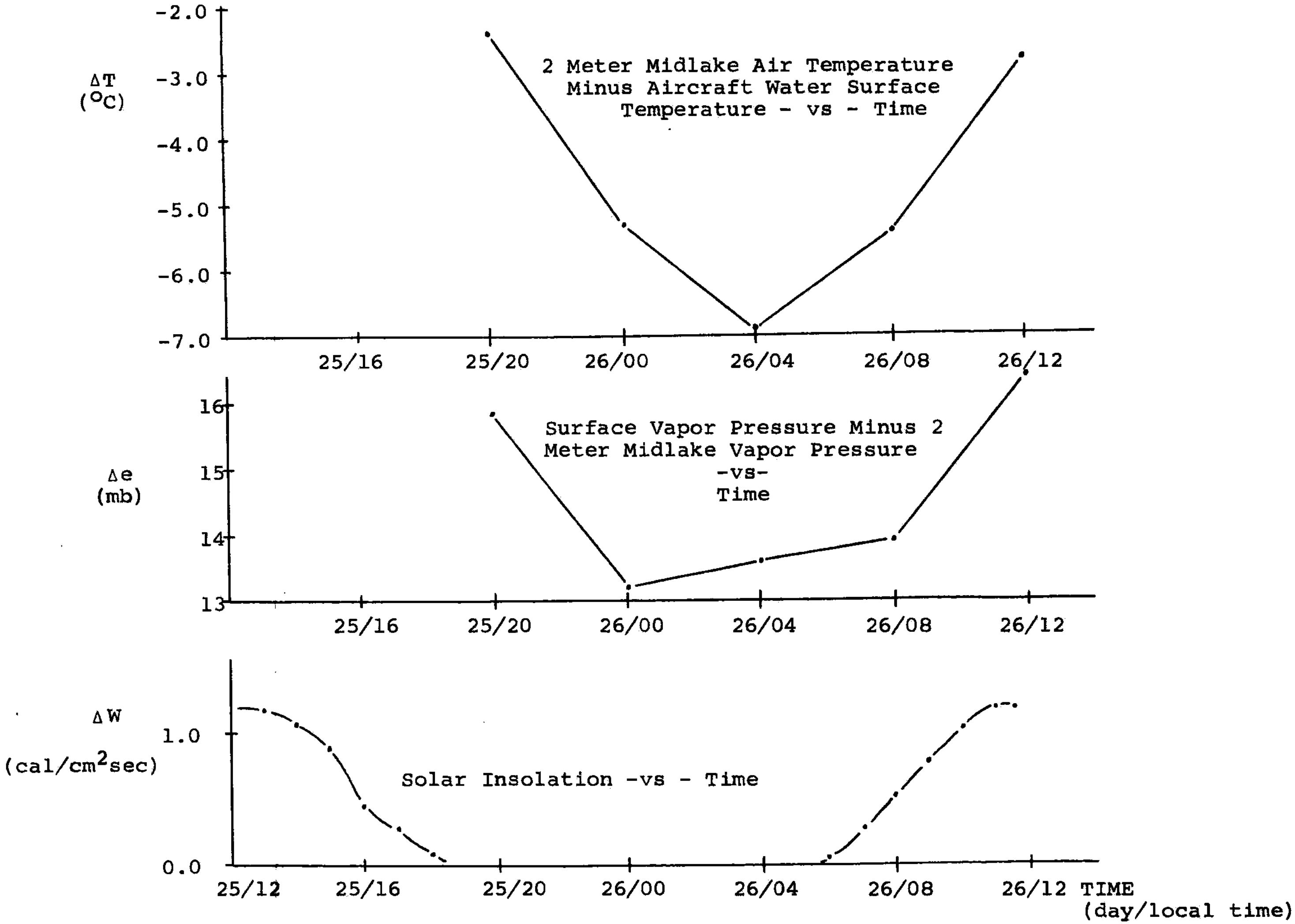

Figure 13. -- Energy Flux Indicators-Vs-Time, 25-26 August 1966

sensible heat transfer during this period was from the water surface to the air and was probably the major cause of the overall decrease in surface temperature.

<u>The Structure of the Lake Surface Temperature Field and Its Relation to the Variation of Evaporation with Fetch</u>.

Millar (1939) hypothesized a water vapor blanket to form over a lake similar to a boundary layer of air over a flat plate. Considering this ideal case, there would be a noticeable variation of evaporation with fetch at Lake Hefner due to the decrease in vapor gradient with fetch and increase of wind speed with fetch. It would follow that such a variation in evaporation would cause a variation in surface temperature with fetch.

From the mass transfer equation for evaporation used at Lake Hefner,*

7) $$E = k U_2 [e_s - e_2] \quad , \text{ where } \quad = 1.5 \times 10^{-3}.$$

Differentiating with respect to the direction along the mean wind, x, gives

8) $$\frac{dE}{dx} = k\left\{[e_s - e_2]\frac{dU_2}{dx} + U_2\frac{de_s}{dx} - U_2\frac{de_2}{dx}\right\} .$$

From the Clausius-Clapeyron equation

9) $$\frac{de_s}{dx} = \frac{L e_s}{R_v T_s^2}\frac{dT_s}{dx}$$ and substituting (9) into (8) results in

10) $$\frac{dE}{dx} = k\left\{[e_s - e_2]\frac{dU_2}{dx} - U_2\left[\frac{L e_s}{R_v}\frac{d\left(\frac{1}{T_s}\right)}{dx}\right] - U_2\frac{de_2}{dx}\right\} .$$

---

*The assumptions inherent in the use of this equation can be found in Anderson (1950).

Solving for $\frac{d(\frac{1}{T_s})}{dx}$

11) $$\frac{d(\frac{1}{T_s})}{dx} = -\frac{R_v}{Le_s U_2}\left\{[e_s - e_2]\frac{dU_2}{dx} - U_2\frac{de_2}{dx}\right\} + \frac{R_v}{kU_2Le_s}\frac{dE}{dx} .$$

Now,

$$\left|\frac{R_v}{kLU_2e_s}\frac{dE}{dx}\right| \gg \left|\frac{R_v}{LU_2e_s}\left\{U_2\frac{de_2}{dx} - [e_s - e_2]\frac{dU_2}{dx}\right\}\right| .$$

So

12) $$\frac{d(\frac{1}{T_s})}{dx} \doteq \frac{R_v}{kL}\left(\frac{1}{U_2e_s}\right)\frac{dE}{dx} = \frac{.12}{U_2e_s}\frac{dE}{dx} .$$

This equation shows that a change in surface temperature with fetch is effected mainly by a change in evaporation rate with fetch. As evaporation increases with fetch, Eq. (12) requires that the surface temperature decrease with fetch.

Anderson (op.cit.) gives a schematic diagram of evaporation rate as a function of fetch over an open body of water which shows a maximum of evaporation near the windward shore. Therefore, considering such an idealized situation as described by Anderson, one may expect cooler surface temperatures in this area relative to surface temperatures downstream. Using Eq. (12) and evaporation data taken at two meters for 26 August 0000L, it was calculated that the surface temperature should decrease by 3.0°C along the mean wind path from the south meteorological station to the midlake tower. Such extreme cooling was not seen in the surface temperature pattern on the lake (Fig. 30). The southern area (Area II) was

0.6°C cooler than the northern area (Area I) at this time. Calculation of the overall cooling from south site to intake tower shows the southern area to be 0.2°C cooler than the northern area.

This particular flight was the only one in which evaporation data fitted Anderson's model. Other periods show evaporation increasing all across the lake, though there is more variation with fetch in the southern areas than in the northern areas (with a south wind). Figure 14 shows the departure from the average lake surface temperature for each of the areas as a function of wind direction. Almost always, when a south wind is blowing, temperatures are cooler in the southern areas than in the northern areas.

From the calculations given above it must be concluded that evaporation alone accounts for an excessive surface cooling with fetch. From an examination of variation of surface temperature with fetch during periods when the flux of sensible heat from the air is reversed (i.e. from cooling to warming the lake surface layer), sensible heat transfer from the air appears unimportant in the change of surface temperature with fetch. This leaves only the flux of sensible heat from the water to account for the fact that cooling was not as extreme as computed using evaporation alone.* Under these conditions, again consider

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*Note that variation of solar insolation and radiational cooling with fetch are considered unimportant in this development.

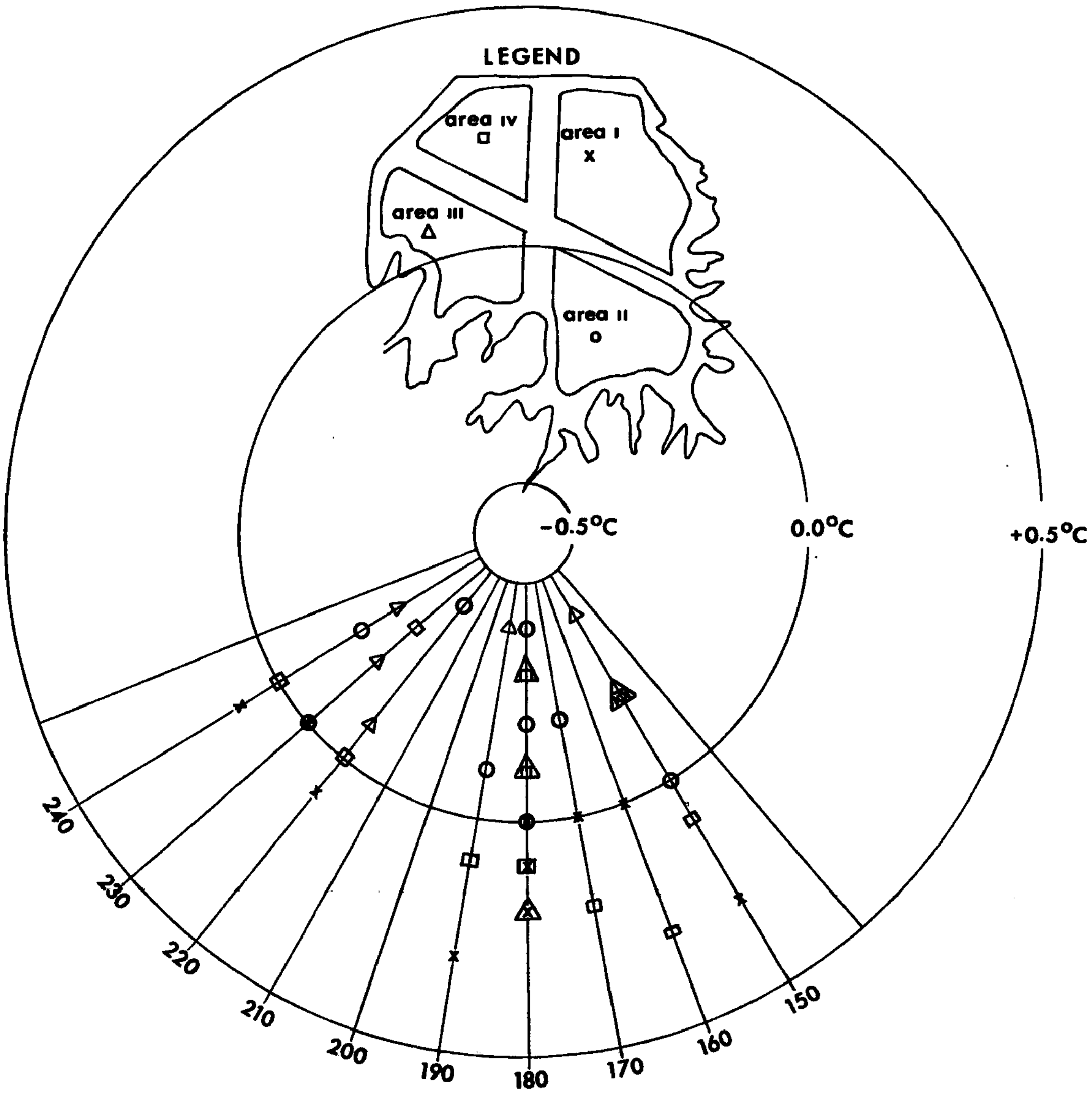

Figure 14. Deviation From Area Average Surface Temperature-vs-Wind Direction

Eq. (6) which becomes

$$13) \quad \frac{dT_s}{dt} = \frac{1}{\rho_w C_{P_w}} \left\{ \frac{C_{P_w}\rho_w K_{HW}}{z_2}[T_s - T_{wz_2}] - \frac{\rho L K_q p \epsilon}{z_3} EXP\left[-\frac{L}{R_v T_s} + K\right] + \frac{\rho L K_q p \epsilon e_{z_3}}{z_3} \right\}.$$

Upon differentiating along fetch one obtains,

$$14) \quad \frac{d}{dt}\left[\frac{dT_s}{dx}\right] = \frac{1}{\rho_w C_{P_w}} \frac{d}{dx} \left\{ \frac{C_{P_w}\rho_w K_{HW}}{z_2}[T_s - T_{wz_2}] - \frac{\rho L K_q p \epsilon}{z_3} EXP\left[-\frac{L}{R_v T_s} + K\right] + \frac{\rho L K_q p \epsilon e_{z_3}}{z_3} \right\}$$

Now, integrating with respect to time gives

$$15) \quad \frac{dT_s}{dx}\Big|_{t_1}^{t_2} = \frac{1}{\rho_w C_{P_w}} \int_{t_1}^{t_2} \frac{d}{dx} \left\{ \frac{C_{P_w}\rho_w K_{HW}}{z_2}[T_s - T_{wz_2}] - \frac{\rho L K_q p \epsilon}{z_3} EXP\left[-\frac{L}{R_v T_s} + K\right] + \frac{\rho L K_q p \epsilon e_{z_3}}{z_3} \right\} dt .$$

The solution of Eq. (15) is prohibitive without further research of the air-water interface. It is, however, one of the logical models to test in the future.

From Fig. 9, it is seen that Area IV was nearly always cool relative to the average lake surface temperature. However, for several hours previous to the aircraft measurements of the surface temperature the wind had a definite westerly component. Therefore, Area IV would be expected to be cool if an evaporation process is important in the alteration of surface temperature. Returning to Fig. 9, it should be noted that as the wind shifted into the south, Area IV began to warm rapidly, finally becoming warmer than the average surface temperature. It would not seem possible that upwelling effects could produce such rapid warming.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

The results of a statistical analysis of airborne water surface temperature obtained with a hexadecanol monolayer on Lake Hefner show that the surface temperatures in the film were warmer than the overall lake average. The amount of relative warming was on the order of 0.3°C. This warming was primarily caused by a reduction of sensible heat transfer from cooler subsurface water. The warming was detected for films which covered from 43.2% to 53.6% of the lake area. Warming was not detected for film coverages less than 40%.

Three cases in which a temperature difference between film covered and open water were examined in detail. In two of these cases, significant correlation was found between the monolayer boundary and the mean surface temperature isotherm. Since these cases had a film coverage of approximately 50% on the lake surface, the mean surface isotherm would naturally follow the film boundary. This points to the fact that the isotherm chosen to "map" the film cover is dependent upon the percent coverage of film on the lake.

When a correction for the radiative properties of the atmosphere between the aircraft and lake was applied to the airborne radiometer measurements, there was a general agreement of these measurements with radiometric measurements made at the same time in a boat. This confirmed the fact that the environmental error cannot be neglected under the conditions encountered. The environmental correction was on the order of 1.0°C with a range of ±0.2°C. The environmental error computations indicated that attenuation of the target radiation was the most important feature in the correction.

Comparison of aircraft and boat thermistor monitored surface temperatures revealed the existence of a thermal gradient in the upper layer of water. Without the monolayer, a "cool" skin prevailed. However, upon application of the monolayer, the gradient was reversed, and a "warm" skin was apparent. From an examination of the magnitude of the gradient reversal, it was estimated that the monolayer caused a net surface temperature warming on the order of 0.8°C over a period of several days.

A theoretical expression for the variation of surface temperature with time was developed to model the diurnal variation of surface temperature. The expression, however, was not solvable in the present state of turbulence study. The main problem in its solution was that very little is known quantitatively about adjustment of the various energy fluxes with time. It was shown by comparing relative values of fluxes measured at midday over the lake that sensible heat from the water played an important role in maintaining a relatively constant surface temperature. This left sensible heat from the air, latent heat and solar radiation to be the major fluxes determining the diurnal variation of surface temperature. One case study of diurnal variation of surface temperature at Lake Hefner was performed. The range of variation was 1.0°C with a maximum of surface temperature occurring near 1400L. It was found that an important cooling mechanism in evening may be sensible heat transfer from the air. Sensible heat transfer from the air with solar insolation provides the major warming mechanism during the day. The lake cooled during the period by 0.3°C. This cooling was attributed to a transfer of sensible heat from the lake surface.

A theoretical relationship between variation of evaporation with fetch and variation of surface temperature with fetch was explored. In an example presented using this relationship the computed variation of surface temperature was far more than that which was observed. A model was proposed which accounted for the lower observed values by a balance of evaporation and sensible heat transfer from the water. The model could not be tested, since adequate descriptions of the time variation of many parameters appearing in the model equation are, at present, unknown.

CHAPTER IX

RECOMMENDATIONS

It has been shown that in some cases the film can be detected through aircraft-infrared survey of water surface temperature. It is obvious that further work in the detection of monolayers by infrared techniques is necessary. It is recommended, therefore, that further experiments of this nature include high resolution infrared photography* in the 8-12 micron region of the spectrum.

Several problems are immediately eliminated with infrared photography. The flight time can be shortened considerably, since the grid pattern flown in this study (see Fig. 7) can be substantially reduced. The film cover can be directly compared to the infrared photograph without extensive data reduction. If further correlations compare with those presented in Figure 37 and Figure 39, then the percent film cover can probably be directly taken from the infrared photograph. Absolute values of surface temperature can be extracted from the infrared photograph by means of a grey scale calibration.

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*An infrared camera is a scanning infrared radiometer. These instruments can be purchased or leased.

The method of infrared measurement of lake surface temperature, as reported herein, has some advantages. Even though monolayer detection is somewhat involved and low percent film cover escapes detection, a quantitative estimate of average surface temperature over portions of the lake and the entire lake can be obtained. The main problem in this case is one of instrument accuracy. To increase the accuracy of the radiometer, the scale width of the strip chart must be increased. As a result of the Lake Hefner study here reported, a simple method of increasing radiometer accuracy is presented and recommended for further studies of water surface temperature.

In this study, a 50 mv full scale recorder was used for the average output from the radiometer while over the lake was 27-32 mv. A lower scale, say 10 mv, would have greatly increased the resolving power of the instrument however, such a scale setting was not compatible with the output of the radiometer. It is therefore proposed that in future studies a small DC power supply be installed in series with the in-flight data acquisition system so that the voltage from the power supply subtracts from the radiometer output (see Fig. 15). This scheme will allow the use of more sensitive recorder scales. One such system, constructed since this study was completed and now in use at Colorado State University, has a resolution accuracy of $\pm 0.1^{\circ}C$. Field tests of the system have proven very successful.

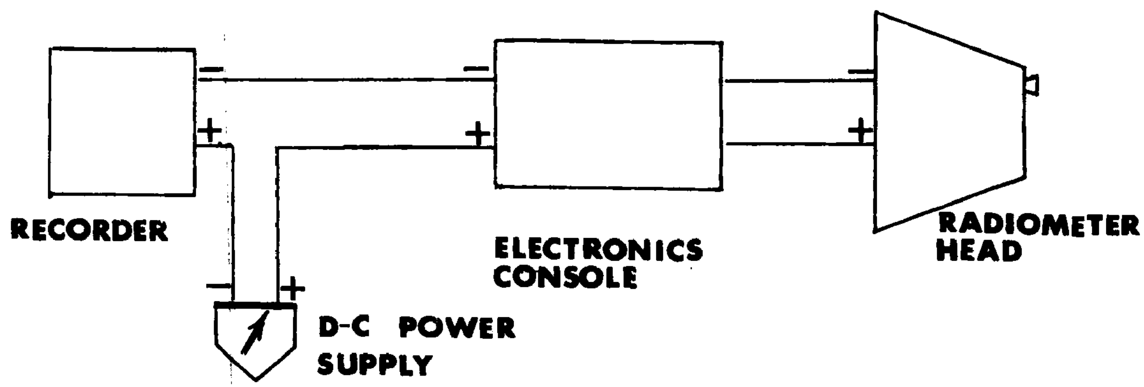

Figure 15.-- Schematic Diagram of D.C.
Bucking of Radiometer Output

In such a system, high frequency noise becomes a problem. This can be countered somewhat by placing a capacitor across the recorder leads in parallel with the radiometer output. The addition of a capacitor in such a manner will increase the radiometer time constant. Therefore, each experimenter will have to determine an acceptable ratio of noise to time constant.

The discussion of the diurnal cycle in the report pointed out the complexity of the interacting fluxes of energy at the air-water interface. At the present time, it is difficult to relate variations of water surface temperature, under natural conditions, to any particular flux of energy (for instance, evaporation). Further study, however, on the relative magnitude of energy fluxes at the interface, especially that of the sensible heat from the water, may be able to sufficiently define the problem so that surface temperature combined with easily measured physical quantities can be an indicator of a particular energy flux as well as the net energy flux.

From the comments on the cooling of certain areas of the lake, one can see that, on the meso and micro scale, knowledge of the energy flux variation with fetch is far from complete. Aerial surveys of water surface temperature of lakes in conjunction with studies of the structure of the atmosphere over the lake and its environment are necessary to further understanding of the three dimensional character of the turbulent boundary layer.

This study must be considered as a pilot study. Much more work is necessary before the mechanisms of energy balance at the lake surface are fully known. Aerial surveys such as the one here reported should prove a valuable companion to further studies in physical limnology and air-sea interaction.

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APPENDIX I

APPENDIX I

DESCRIPTION OF INSTRUMENTATION

In this investigation, two infrared radiometers were used. A Barnes Engineering Radiation Thermometer model IT-2 was used in a boat, and a model IT-3 was used in the aircraft.

The operation of the Barnes Model IT-2 is well described elsewhere (Frank, J.L., 1964; Lenschow, op.cit.; Shaw, op.cit.). It is a thermistor bolometer in which incoming radiation is filtered by an indium-antimonide/ Kodak Itran-2 filter system and focused on a compensated thermistor flake. A highly reflective surface, known as the chopper, interrupts the incoming signal at 90 cps and allows radiation from a stable black body cavity, known as the reference or heater, to be collected by the thermistor. The result is a 90 cps wave, amplitude modulated according to the difference between the temperature of the target and that of the reference. This signal is then detected and amplified. Calibration curves relate the output voltage to target temperature. Both instruments used by Colorado State University in this study were accurately calibrated by a more sophisticated system resembling that described by Salomonson (1964). The calibration data were statistically analyzed.

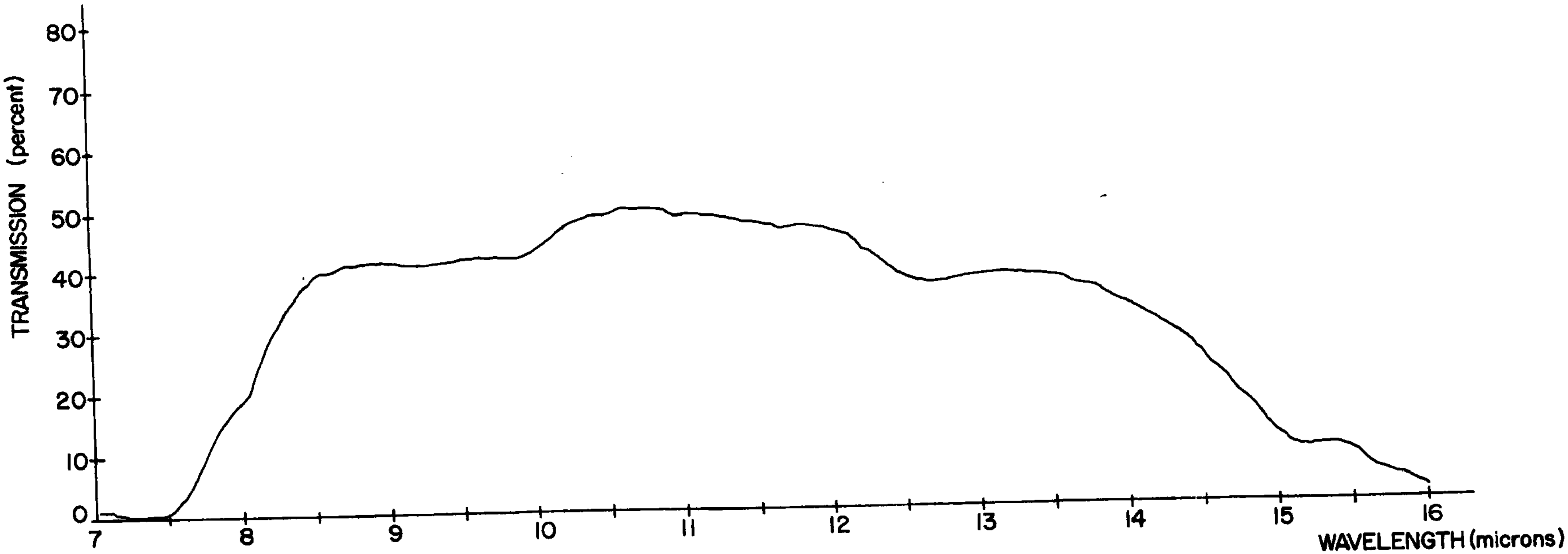

Figure 16.-- Filter Transmissivity Curve for Indium Antinomide-Kodak Intran 12 Filter

The IT-2 radiometer used had a bandpass from 7.5 μ to 16 μ (see Fig . 16) with approximate half power points at 8 μ and 12 μ. The field of view was 3^{o} and the time constant was .5 seconds. The absolute accuracy was determined to be $\pm 0.7^{o}C$ from the standard error of estimate on the linear regression of the calibration data. However, in the boat, this accuracy degenerated somewhat and the experimenters believe $\pm 1.0^{o}C$ is a fair estimate of the absolute accuracy of the IT-2 in the field.

There are several inherent instrumental errors in the IT-2. Some of these are discussed by Clarke (op.cit.). The IT-2 radiometer reference temperature has a tendency to shift, requiring frequent calibrations. The electronics are not high precision components, with most resistons accurate only to ±10%. However, this should not cause a noticeable output error once in flight, since this error would be masked by larger errors. Lenschow (op.cit.) mentions problems with the preamplifier circuit; these were not encountered in this study. As stated in the Operating Manual, the IT-2 has a very limited range of input power voltage and frequency. The input power voltage must be controlled between 105 volts and 125 volts. The input frequency must be controlled between 59.5 cps and 60.5 cps. It is in this respect that the IT-2 and IT-3 differ. The IT-3 radiometer has a wider range of input power voltage and frequency, making it more suitable for field experiments. Another annoying characteristic of the model IT-2 radiometer is its response to an external radio source; this has been encountered by other groups (see Clarke, op.cit. page 89). The model IT-2 used in this investigation has been found to be very sensitive to radio interference. This resulted in the rejection of some data taken at the lake in the vicinity of a microwave phase system experiment being carried out by ESSA-Boulder Laboratories.

The IT-2 was driven by a portable power supply and was in use approximately an hour for each run. The power supply was recharged after each run. Due to the strict requirements of input voltage and frequency, a time test was made on the output voltage and frequency of the power supply under an IT-2 load (see Fig. 17). It was noted that the output voltage of the portable power supply was too high and the frequency too low. Over the first one and a half hours, however, negligible change was seen in both. To solve this problem, the IT-2 was calibrated using this power source rather than a conventional power source.

The basic optics and operations of the Barnes Model IT-3 radiometer are the same as that of the Barnes Model IT-2. Many of the electronic components, however, have been improved. The heater circuit seems to be more stable and slight shifts in the calibration of the IT-3 over long periods have been noted. The filter used in the IT-3 was

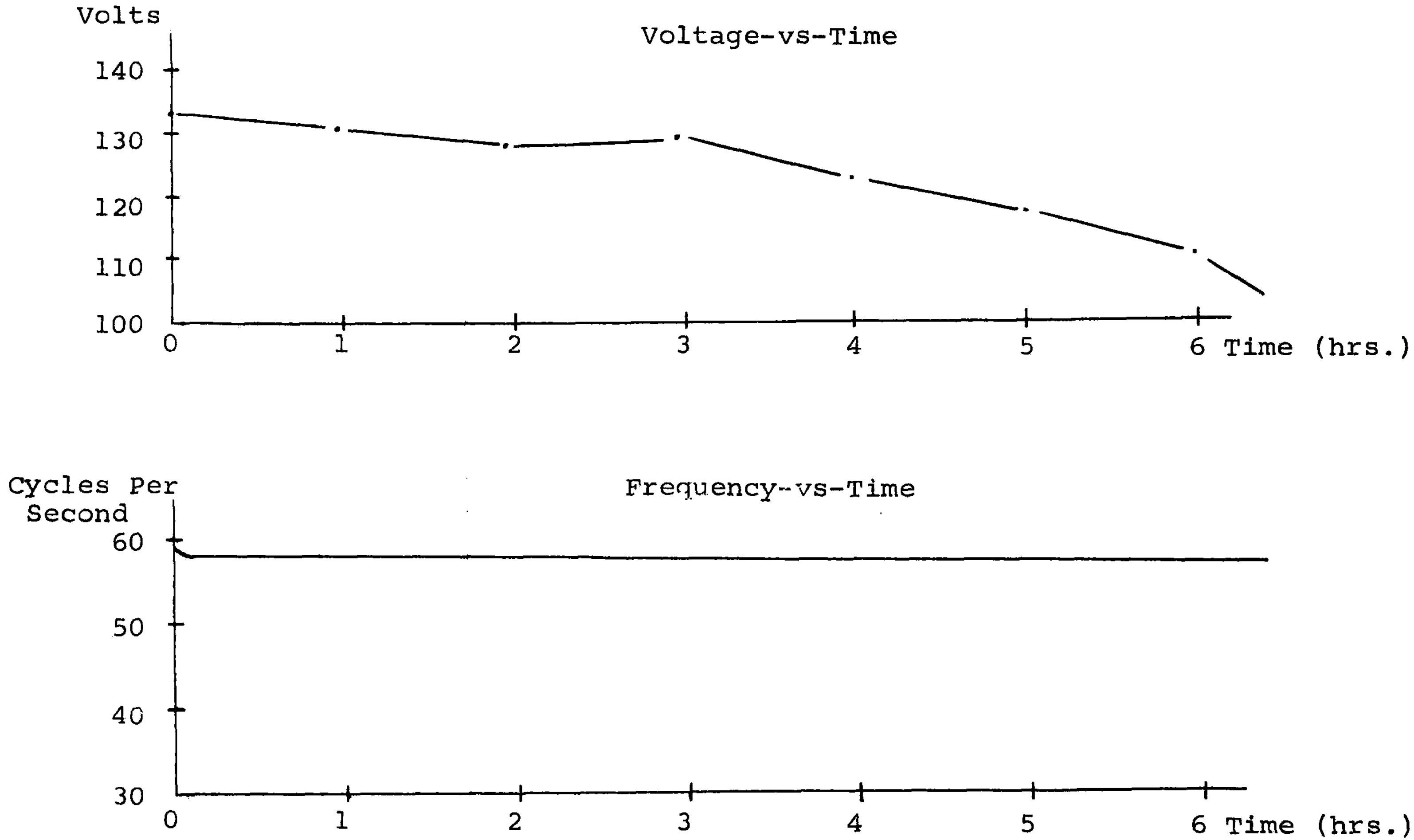

Figure 17.-- Voltage-Vs-Time: Portable Power Supply for Boat Radiometer and Frequency-Vs-Time: Portable Power Supply for Boat Radiometer

identical to that used in the IT-2. The field of view was also 3°. The IT-3 has two response times, 50 milliseconds and 500 milliseconds. The 500 millisecond response was chosen to be used in flight due to an obvious reduction in high frequency noise when operating in this mode. Another main difference between the IT-3 and IT-2 is the low response of the IT-3 to external radio noise due to improved shielding in the electronics package. The only radio noise which seemed to affect the IT-3 in flight was the keying of the aircraft microphone. The input frequency range is wider for the model IT-3 which allows a range from 58.7 to 61.3 cps. This was well within the capability of the aircraft power supply which was monitored in flight by a voltmeter and frequency meter. Calibration of the IT-3 shows it has a laboratory accuracy of $\pm.5^{\circ}C$ on a 50 millivolt full scale recorder and at the 500 millivolt time response, a laboratory resolution of .1 - .2°C would not be unusual.

The output of both the model IT-2 and IT-3 is a DC voltage. The output of the Model IT-2 was read from a temperature scale (ammeter) on the face of the electronics package. Readings from this temperature scale were reduced from a calibration of the instrument.* In flight,

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*The Barnes Engineering Company quotes accuracies of the IT-2 to be $\pm 2.0^{\circ}C$ absolute and $\pm 5^{\circ}C$ resolution. C.S.U. calibrations show these specifications to be very conservative; accurate, careful calibrations have shown the Barnes instruments to be consistently better than the manufacturers specifications.

the output of the model IT-3 was recorded on a strip chart recorder with a 50 millivolt full scale response. The IT-3 was calibrated to the recorder used in this study. The rated error on the recorder is .2% of full scale which resulted in a recorder error of approximately .1°C. A repeatability check of the IT-3 was performed over Horsetooth Reservoir, Colorado. The water temperature at the north end of the reservoir was measured ten times in approximately twelve minutes. The standard deviation of the ten measurements was $\pm$.1°C.

There were two methods of measuring water surface temperature in this study: radiometric and floating thermistor. The floating thermistor system consisted of a bead thermistor suspended in the center of a styrofoam and wire ring, which reduced the capillary wave action, allowing the thermistor to be slightly covered with water. The average depth of the thermistor was on the order of 0.2 - 0.5 cm below the water surface. The output of the thermistor was read on a wheatstone bridge. The thermistor system was calibrated to a precision thermometer over the range of temperatures 15.0 - 35.0°C and an absolute error of $\pm$.3°C was computed from the calibration data.

APPENDIX II

APPENDIX II

ERROR ANALYSIS

The following section deals with errors inherent in the data reduction and errors affecting data analysis. The prime importance of this discussion will be the delineation of the limits from which conclusions can be drawn from the data.

Data Reduction Errors.

Though quite simple, the least straightforward part of the data reduction was reduction of the airborne radiometric data. At collection time, the data were stored in analog form on strip charts. A digital voltmeter was used to convert the data into a form compatible with computer input. This system has an error of $\pm$.01 millivolt which is approximately $\pm$.01°C and therefore can be neglected as an error source.

A subjective error source must be considered due to the method of presenting the analog data to the digital voltmeter. The analog to digital system used in this study was essentially a DC power supply connected in parallel to the strip chart recorder and the digital voltmeter. The output of the digital voltmeter was connected to a card punch. A particular strip chart was "rerun" on the strip chart recorder. The power supply voltage was then manually varied so that the needle of the strip chart recorder always followed the line previously recorded in the actual run. The sampling time of the digital voltmeter was constant and thus "picked off" the voltages as the chart was rerun. The sampling time was 1.5 bits per second real time. The sampling time was adjusted so that the strip chart was running at one half the original speed thus improving the accuracy of the reduced data.

The magnitude of the error introduced by the operator of the DC power supply would have been complicated beyond the scope of this presentation had it not been for the relatively light variation of lake surface temperature on each aircraft traverse. Fluctuations of the lake surface temperature were generally low frequency fluctuations and therefore were easily followed. While an objective measurement of this error was not possible, the experimenters felt that an error of $\pm 0.1^{\circ}C$ was inherent in the system. This error applies to both absolute error and resolution error.

The effect of this subjective error may be reduced by using tape recorded data coupled with a sophisticated analog to digital system.

Since there were relatively few data points taken in the boat, reduction was by hand. The collected data were a visually integrated average taken over a period of about a minute. Therefore, the reduction of the boat data consisted of applying these values to the calibration curve. The slope of the calibration curve was very close to one, and no "subjective" error was inherent in this data reduction scheme.

The errors presented in Table 1 of the text were the maximum errors. These errors were used in the statistical analysis of the comparison between temperatures monitored from the boat and aircraft. The resolution error was important in confirming the detection of the monolayer. The maximum errors were used to provide the experimenters with an extra measure of confidence in drawing their conclusions.

Another popular approach to the error problem is the use of a root mean square error. Consider the total data presentation error to be made up of instrument, recorder, and data reduction error so $\mathcal{E}_T = \mathcal{E}_i + \mathcal{E}_r + \mathcal{E}_{Dr}$. The r.m.s. error is defined as

$$\mathcal{E}_{r.m.s} = \sqrt{\overline{\mathcal{E}_T^2}} = \sqrt{\overline{\mathcal{E}_i^2} + \overline{\mathcal{E}_r^2} + \overline{\mathcal{E}_{Dr}^2} + 2\overline{\mathcal{E}_i\mathcal{E}_r} + 2\overline{\mathcal{E}_i\mathcal{E}_{Dr}} + \cdots}$$

where $\overline{\mathcal{E}_i\mathcal{E}_r} = 0$ if $\mathcal{E}_i$ is an error independent of $\mathcal{E}_r$. Now $\mathcal{E}_i, \mathcal{E}_r$ and $\mathcal{E}_{Dr}$ are all independent of one another so

$$\mathcal{E}_{r.m.s} = \sqrt{\overline{\mathcal{E}_i^2} + \overline{\mathcal{E}_r^2} + \overline{\mathcal{E}_{Dr}^2}}$$

Thus the aircraft r.m.s. absolute error is

$$\mathcal{E}_{A/c\ r.m.s} = \sqrt{(0.5)^2 + (0.1)^2 + (0.1)^2} = \sqrt{0.27} \doteq 0.5\,^\circ C$$

and the resolution error for the aircraft is

$$\varepsilon_{res, r.m.s} = \sqrt{(0.2)^2 + (0.1)^2 + (0.1)^2} = \sqrt{0.6} \doteq 0.2^\circ C$$

The use of these errors instead of the maximum errors would only strengthen the conclusions drawn in this report.

Environmental Errors.

Environmental errors can be considered extraneous infrared radiation sources and sinks other than that of the target. Principally, these are atmospheric attenuation, atmospheric re-radiation, reflected atmospheric radiation and reflected cloud radiation. The magnitude of the errors introduced by the environment is highly variable but for the most part can be corrected.

Figures 18 and 19 show schematically the environmental sources of infrared radiation. The theoretical investigation of these sources has been thorough. Bouguer (1760) experimentally investigated monochromatic absorption by a nonscattering medium with an invariant transmission spectrum. This approach was reintroduced by Lambert many years later. However, except for certain gases and short optical paths, this method does not effectively describe radiative transfer in the infrared. Simpson (1928) improved upon the Lambert approach by recognizing in his model the band structure of the

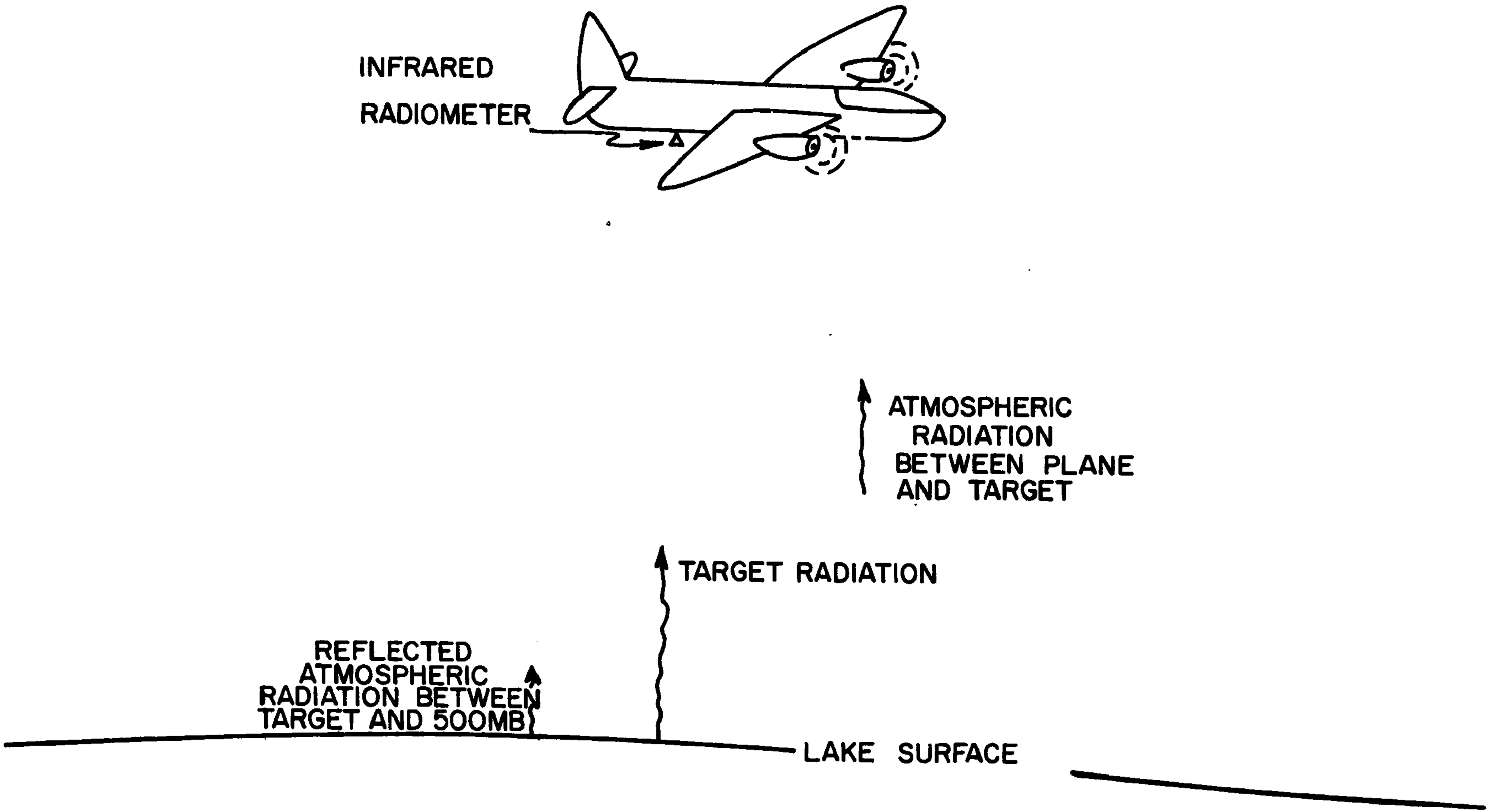

Figure 18.-- Schematic Diagram of Environmental
Radiation Errors: No Cloud

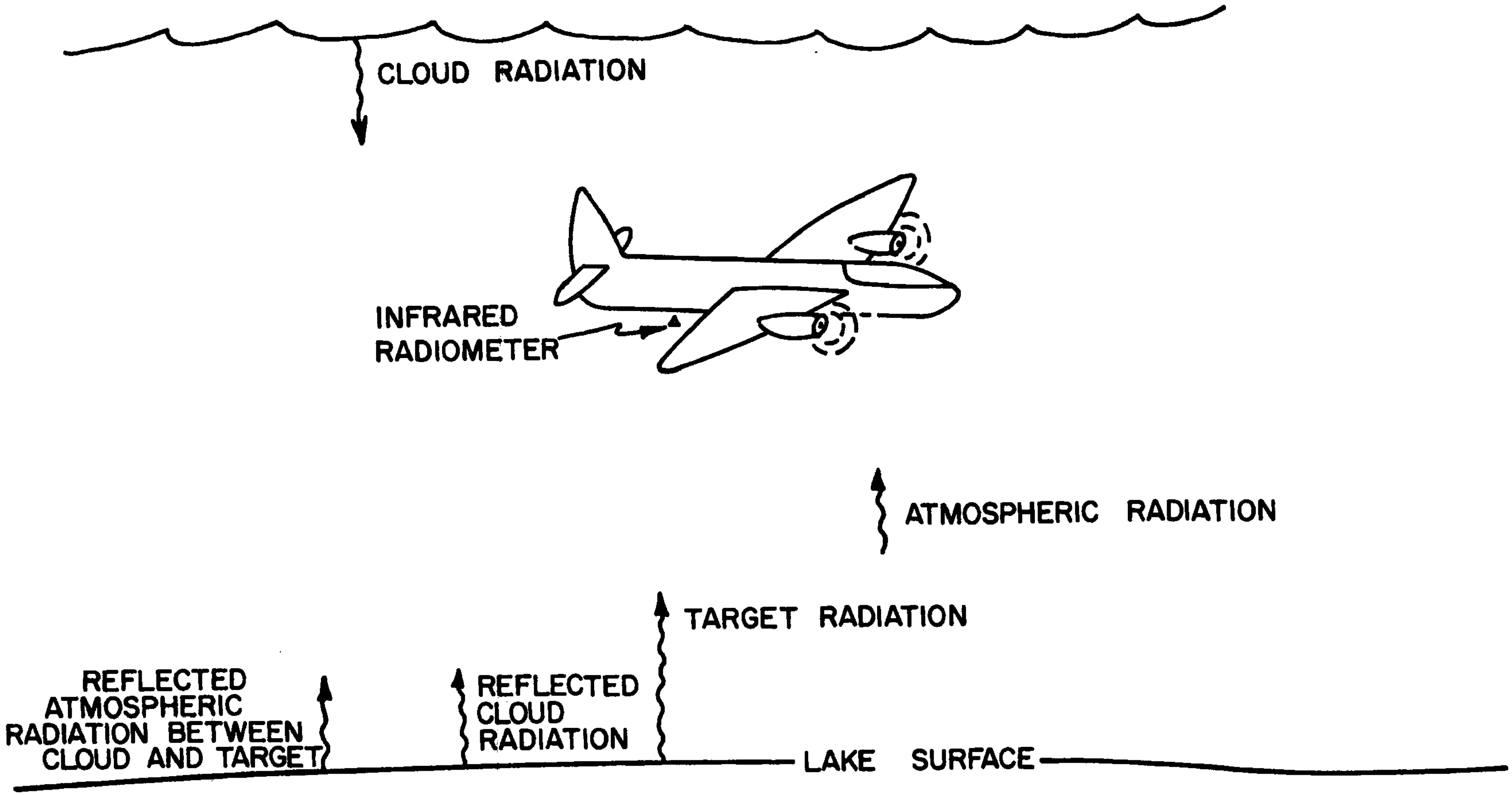

Figure 19.-- Schematic Diagram of Environmental Radiation Errors: Overcast Cloud

transmission spectrum of atmospheric gases (in the infrared this is mainly the vibration-rotation bands of water vapor and carbon dioxide). This band structure is very complex and Simpson's model, while it offered a basis for further theoretical work, was not accurate enough to give sufficient agreement with experimental results. Elsasser (1942, 1962) improved Simpson's model considerably by a closer approximation of the band structure. By averaging over a finite wave length interval, Elsasser was able to smooth the transmission curves so that they could be represented by a mathematical expression. He was then able to apply this to a given infrared radiation transfer problem. His results agreed favorably with experimental data. Goody (1964) improved the Elsasser model by considering a random distribution of the band structure and averaging over a finite band width. The Goody and Elsasser models form the basis of most of the subsequent theoretical solutions of terrestrial infrared radiative transfer problems.

In the present study, a computer program written by Shaw (op.cit.) was used to correct for the environmental error sources. This program, written in Fortran IV, is slightly restrictive, for the equations used for transmission values of water vapor are valid to approximately 500 mb. It is, however, capable of accounting for attenuation of target radiation, direct atmospheric radiation coming from the layer of air between the aircraft and the target, reflected atmospheric radiation (from 500 mb to the surface), and reflected cloud radiation. More complex and more complete computer programs for non-scattered radiative transfer have been based on models constructed by Wark et al. (1962), Davis (1965), and Kunde (1967).

Other methods of correcting for the environmental errors have been proposed. Lorenz (1966) provides a scheme for estimating the specular and diffuse reflection of sky radiation by applying actual measurements made of sky radiation spectra to the integral,

$$\int_{\lambda_1}^{\lambda_2} \Theta_\lambda \gamma_\lambda \beta_\lambda \, d\lambda$$

where Θ_λ is the filter transmissivity of a Barnes PRT-4 (essentially the same as the radiometer filters used in this study), γ_λ is the reflection spectrum for water and β_λ the spectrum of sky radiation for a given location and time. From this the contribution of reflected sky radiation which makes up the total signal measured by the radiometer is obtained. It is then possible to compute the adjustment necessary to correct the indicated surface temperature measurement from the aircraft. He assumes direct atmospheric radiation between the plane and target to be negligible. Over an evaporating body of water, this may not be the case, especially if it is a large body of water (see Shaw, op.cit., pp. 38ff).

Saunders (op.cit.) proposes a novel method of correcting the environmental errors. Essentially his procedure involves doubling the atmospheric path length from the target to the radiometer. This can be done by rotating the radiometer 60 degrees from the vertical while flying over a water surface which he assumes to have negligible horizontal temperature gradient. Saunders considers the variability of emissivity with viewing angle when discussing the contribution of reflected atmospheric radiation to the error. The angle at which this contribution doubles is close to, but not exactly 60 degrees from the vertical. Therefore, the amount of deviation from the 60 degree angle must be considered as an error source in his scheme; however, it is slight. Furthermore, this "doubling" angle varies seasonally since the reflected atmospheric radiation is a function of the vertical distribution of temperature and water vapor as well as the viewing angle.

Saunders' procedure is more applicable to ocean surfaces and large lake surfaces than small lake surfaces. The size of Lake Hefner prohibited the use of this relatively accurate and easy method of applying corrections to the environmental errors. Furthermore, as it will be seen in a later section, horizontal gradients of 0.5 to 1.0^{o}C were not unusual on the lake surface. Therefore, one of Saunder's principal assumptions was compromised in this case.

Taking all arguments into account, Shaw's correction for environmental error was found to be more applicable to the measurements made at Lake Hefner than the correction procedures proposed by Lorenz and Saunders.

Errors Due to Circulations Within the Lake.

Another error source which may affect the detection of the film is the upwelling of cooler bottom water. This could introduce a temperature gradient in the lake similar to that encountered when the hexadecanol film was applied. Also, advection of temperature could occur as a result of horizontal motions.

With a persistent wind from the south at Lake Hefner, one would expect a piling up of water on the north side of the lake. The resulting pressure gradient in the water should be compensated by a circulation as in Fig. 20, assuming an equilibrium condition is reached. The resulting vertical motions, however, should be small due to the short fetch of the lake, which determines the pressure gradient at a given wind speed. Furthermore, the lake, during the period of study, was almost isothermal to a depth approaching 30 feet. Due to the stable temperature stratification below that level, one would hardly expect the cold, dense bottom water to be mixed upward to any great extent. Therefore, the transfer of heat as a result of vertical motions within the lake caused by surface stress will be neglected as small.

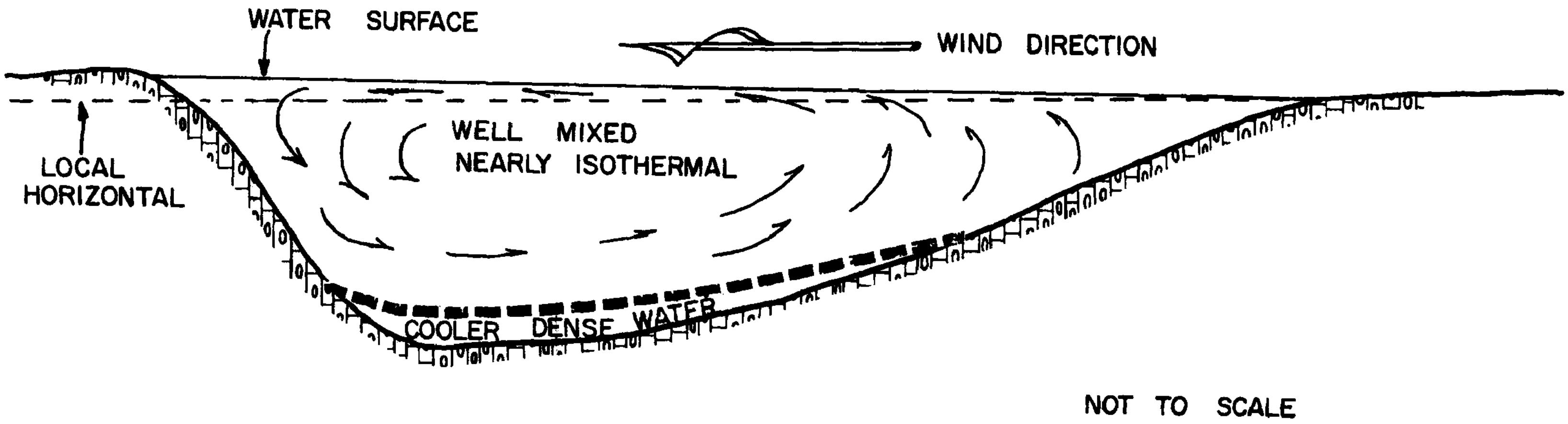

Figure 20.-- Model of Vertical Motions
in Lake Hefner

Very little work on horizontal circulation systems in small lakes has been done. T. Laevastu (1962) reports on an investigation performed on two medium-sized lakes in Central Sweden in 1951. From these studies a qualitative model of horizontal circulation in a small- to medium-sized lake is developed. Figure 21 shows this model applied to Lake Hefner. The current shown can flow in either direction along the leeward shore. The direction it takes depends upon the interaction of the lake configuration and wind direction.

A study of Lake Hefner currents would be a valuable addition to the intense study of the lake which has already been carried out in the past decade. About the only concept of currents on the lake would be given by the motions of the film. However, the film is primarily spread by wind stress on the lake surface and the spreading speed seems greater than the surface water speed, thus the use of the film as an indicator of surface currents would probably be doubtful. At the wind speeds which spread the film (not greater than 13 knots) one might expect these surface currents to be small.

The aircraft radiometer could detect a temperature difference, in flight, of $\pm 0.4^{\circ}C$.* However, the fact that the measurements are being made while in motion puts

*Maximum resolution error.

Figure 21.-- Model of Horizontal Cirulations
in Lake Hefner: South Wind

definite spatial limitations on the detection of a temperature difference (and consequently a film layer). Gaevskiy (op.cit.) mentions that this resolving power (as opposed to resolution) depends upon the altitude of the aircraft, the ground speed of the aircraft, the time constant of the measuring device and the field of view of the measuring device.

As a result of data reduction requirements, a sampling time of 1 bit per 1.5 seconds was chosen. Therefore, the effect of the time constant on detection of a temperature difference can be neglected at the expense of increasing the minimum width of the strip. Thus, for the reduced data, the minimum widths of detectable film strips are 67 meters and 107 meters respectively for ground speeds of 45 meters/second and 71.6 meters/second.

Emissivity Error.

Recall that the effect of the intervening atmosphere can be removed from the aircraft radiation measurements of the water surface temperature. However, one effect on the radiation measurements which may affect the resulting water surface temperatures is the possible shift of emissivity in the infrared due to the hexadecanol film.

At Lake Hefner the effect of an emissivity difference between open water and that covered with the monolayer was neglected for two reasons. First, Saunders (op.cit.) has stated that, unless an interference pattern is seen on a water surface as a result of a surface film, classical electro-magnetic theory predicts no change in emissivity. From the air the film is readily seen (see Fig however, no interference patterns are present. The mechanism which accounts for the film's easy definition when viewed from the air is the damping of capillary waves. This changes the pattern of light reflection but not the amount of reflection (Dirmhirn, 1968). Furthermore, tests on the emissivity of water covered with hexadecanol carried out in an emissivity box (Buettner and Kern, 1964) at the University of Washington* showed no effect of the film in the 8-12 micron region of the electro-magnetic spectrum. Ragotzkie and Menon (1966) mention that monomolecular surface films should have an effect on the emissivity of a water surface but do not substantiate their argument with measurement. Furthermore, they mention films whose thickness is on the order of 10^{-5} cm as the minimum thickness for an effect to be observed. Conservatively, the thickness of hexadecanol is on the order of 10^{-6} cm.

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*Katsoros, K. Personal communication, 1966.

APPENDIX III

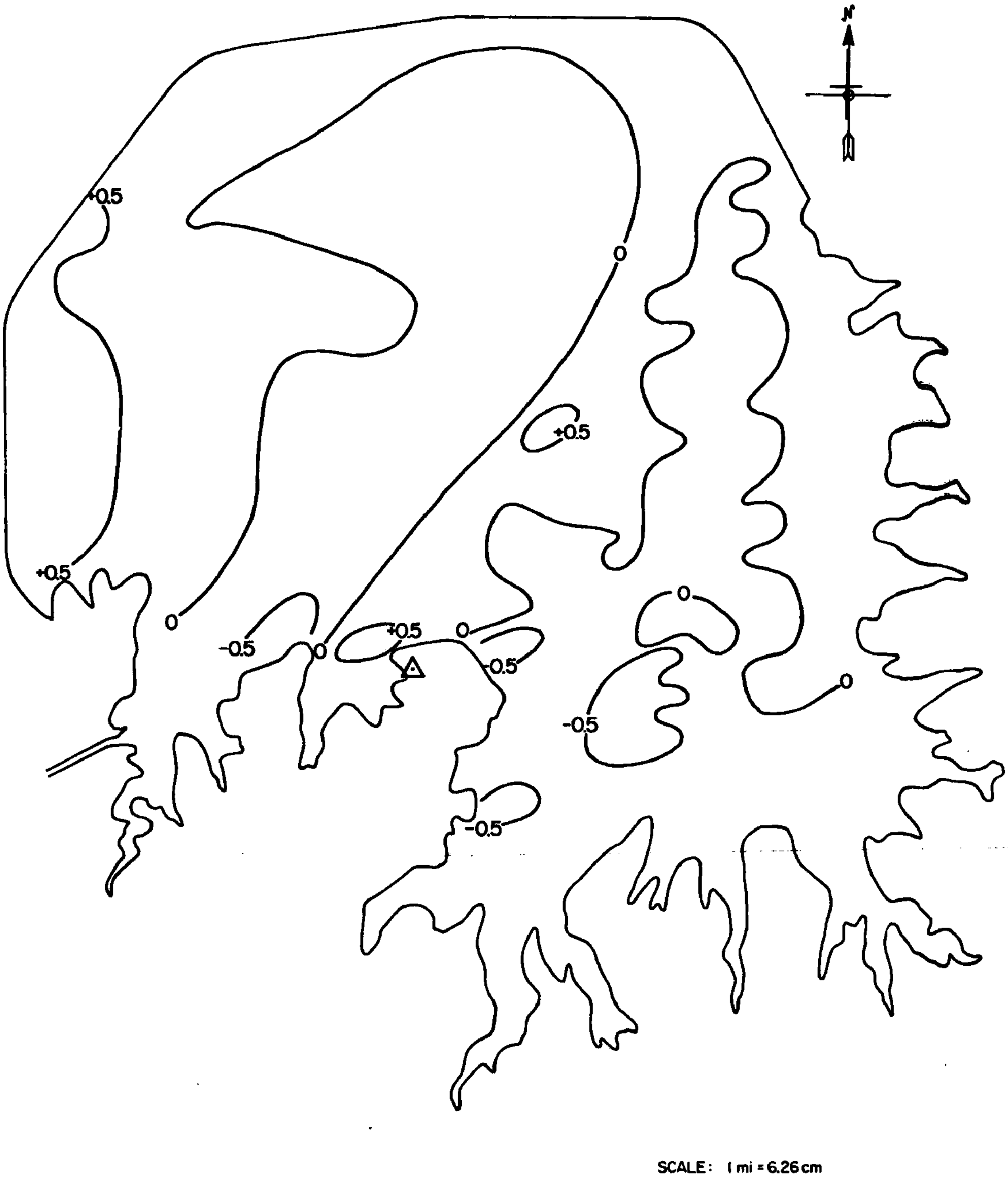

Figure 22.-- Surface Temperature Isotherms (Airborne) for 17 August 1966/1200L

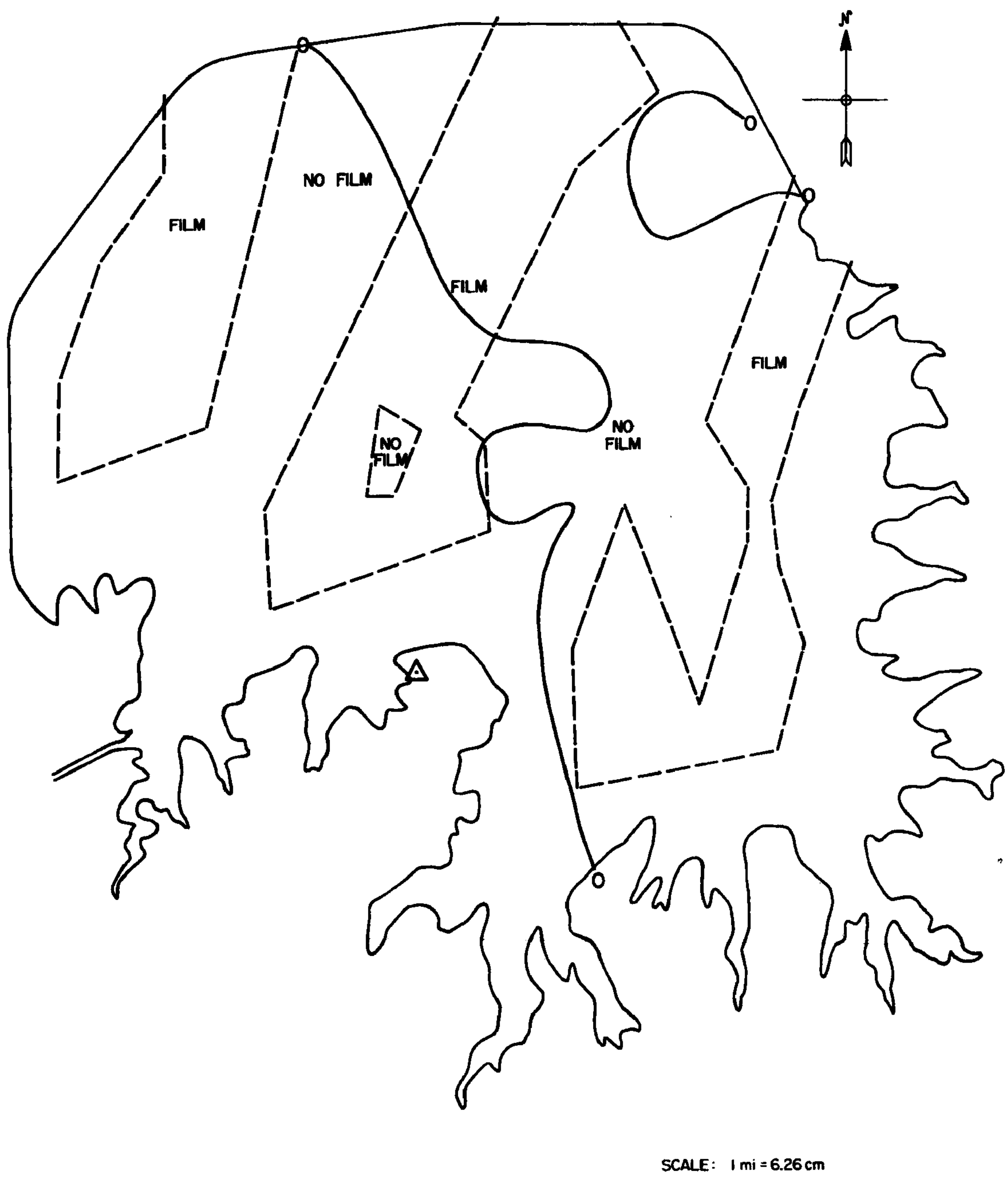

Figure 23.-- Surface Temperature Isotherms (Airborne) for 17 August 1966/1600L

Figure 24.-- Surface Temperature Isotherms (Airborne) for 25 August 1966/1200L

Figure 25.-- Surface Temperature Isotherms (Airborne) for 25 August 1966/1600L

Figure 26.-- Surface Temperature Isotherms
(Airborne) for 25 August 1966/2000L

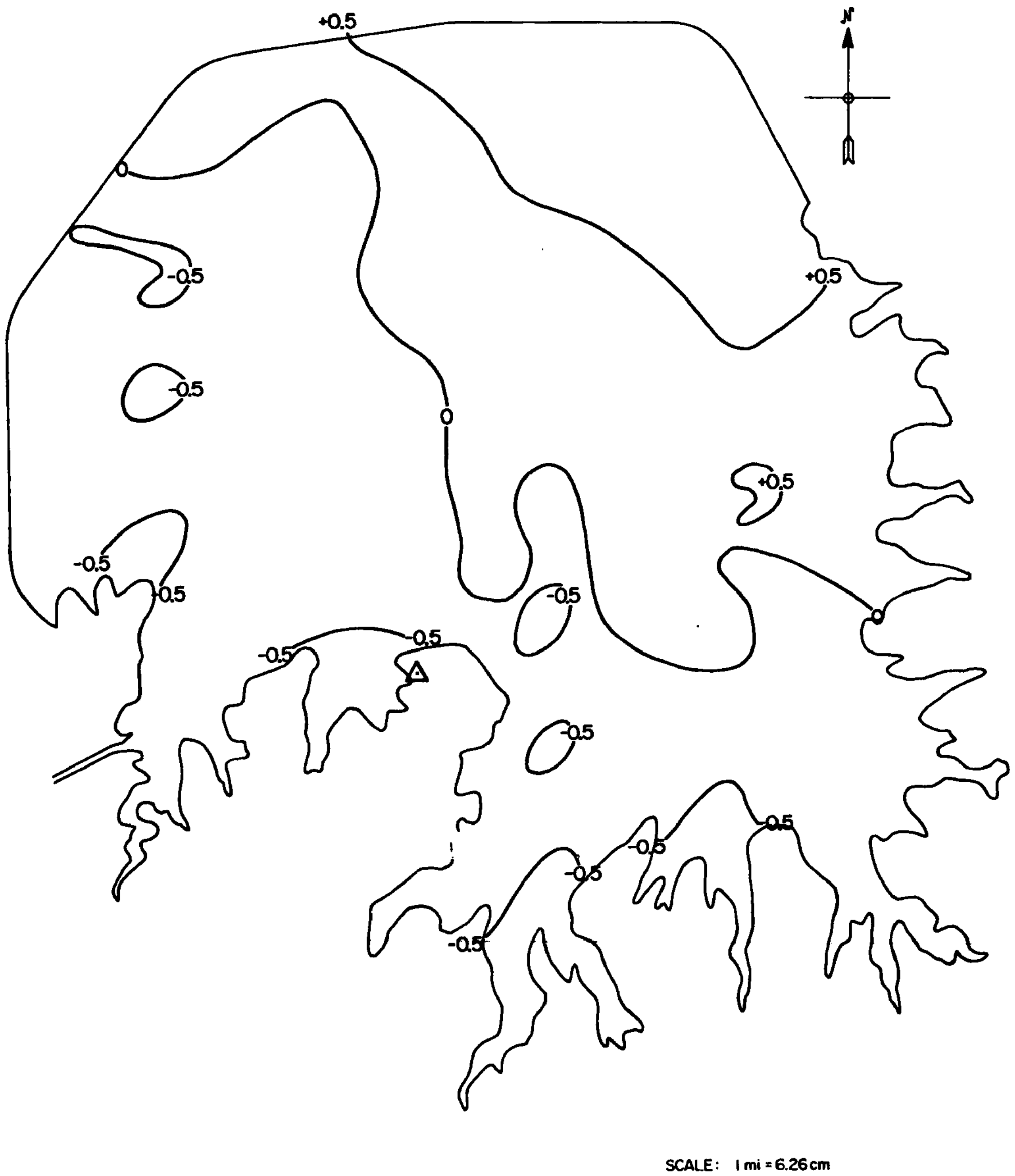

Figure 27.-- Surface Temperature Isotherms (Airborne) for 26 August 1966/0000L

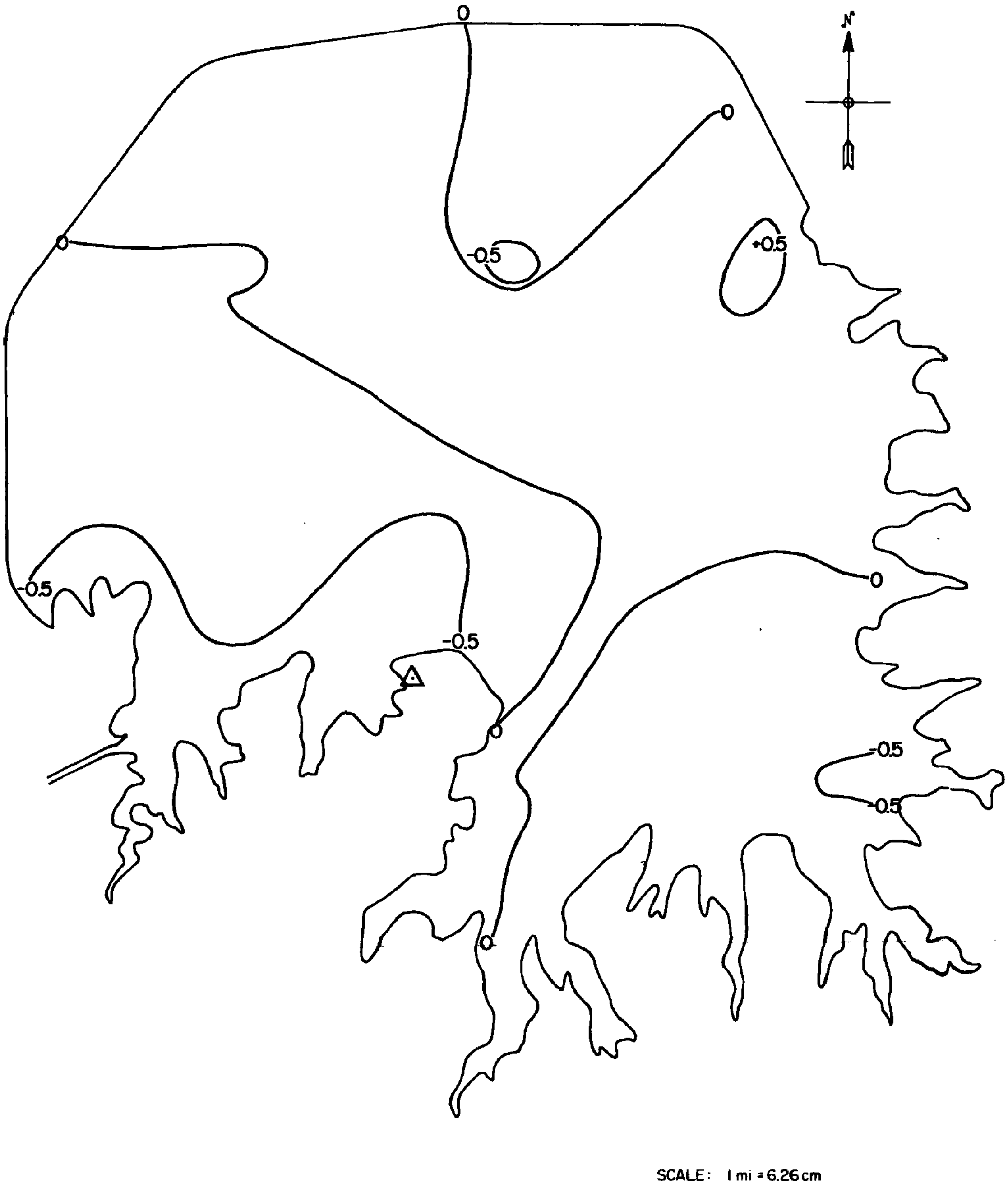

Figure 28.-- Surface Temperature Isotherms (Airborne) for 26 August 1966/0400L

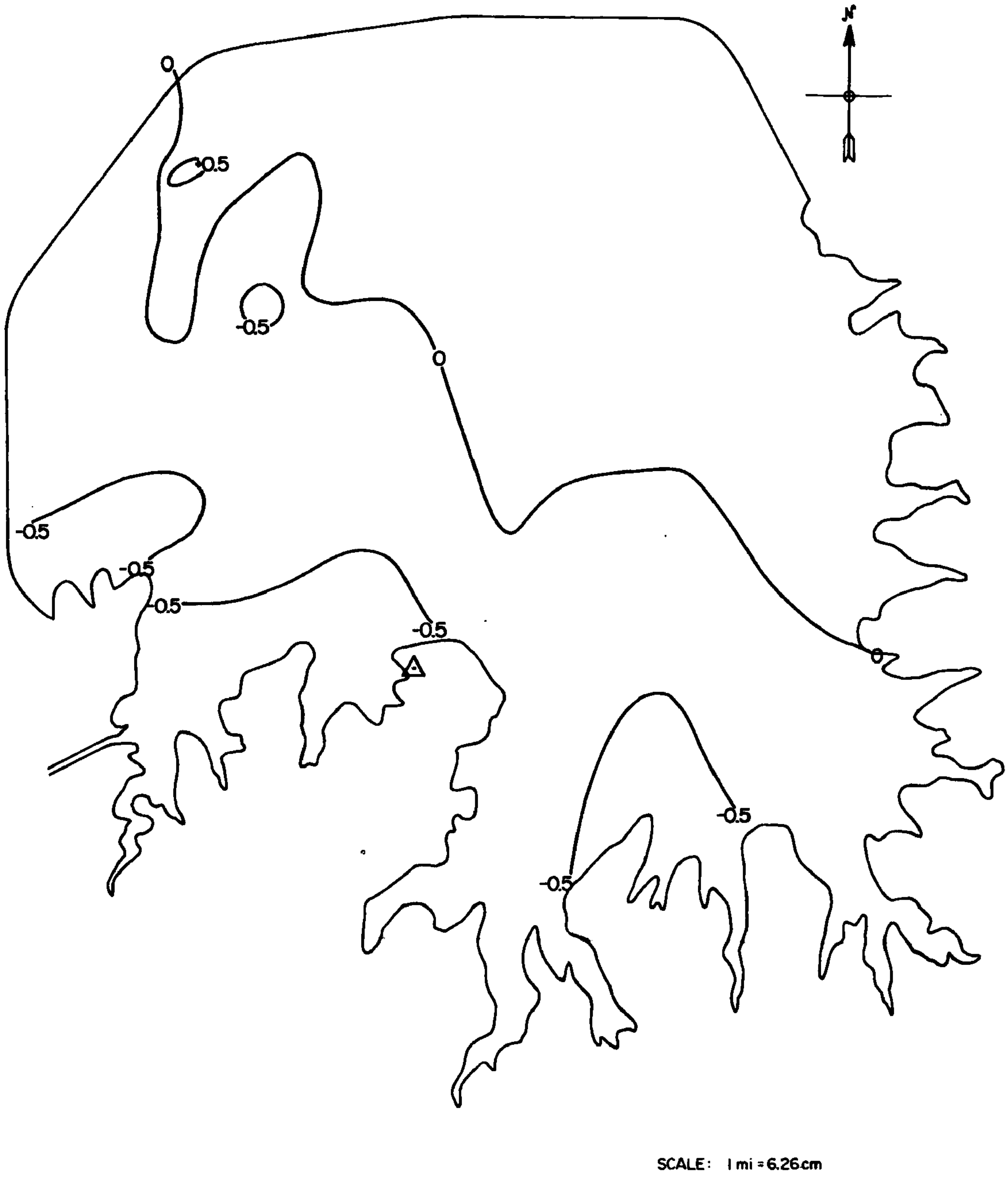

Figure 29.-- Surface Temperature Isotherms (Airborne) for 26 August 1966/0800L

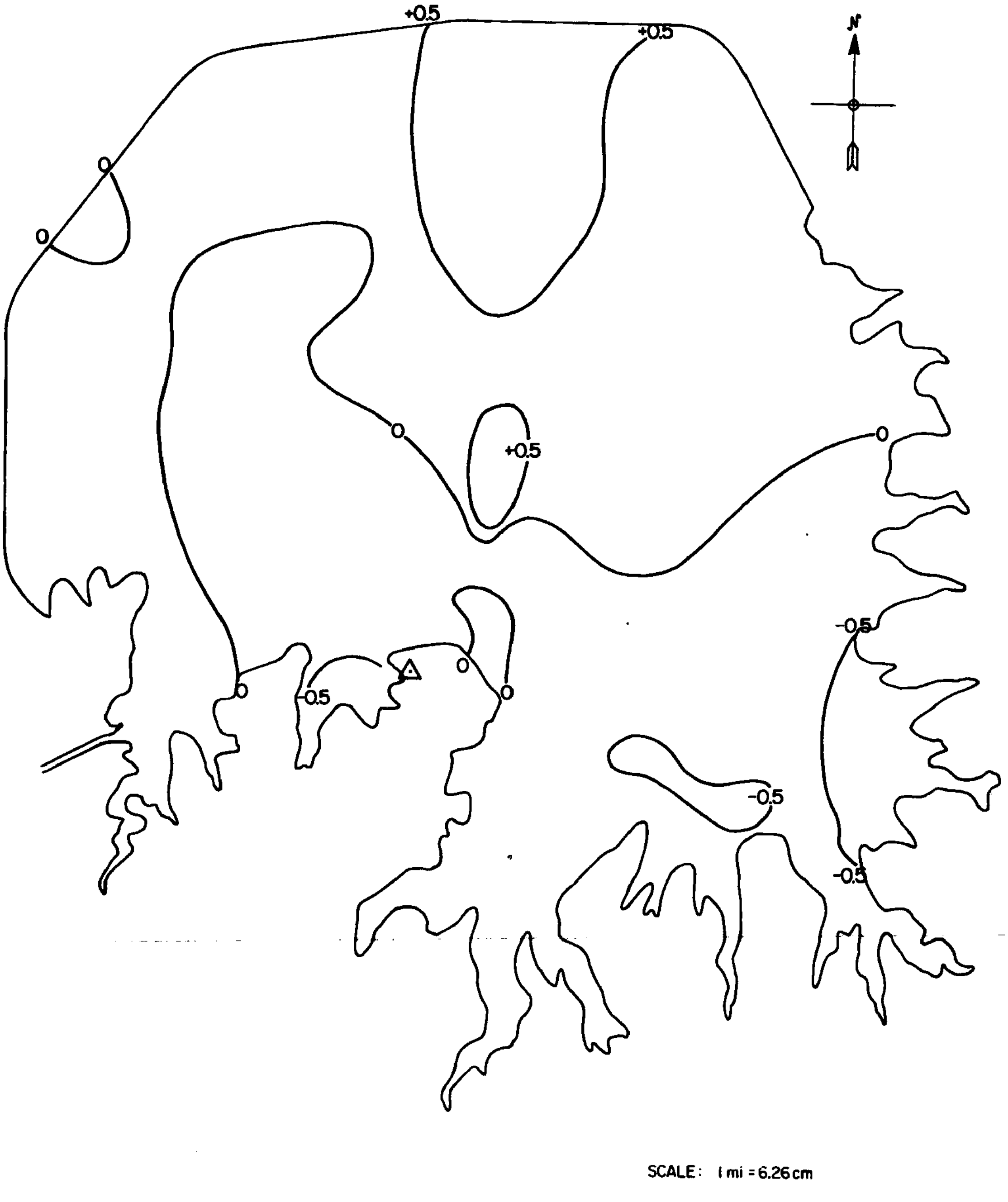

Figure 30.-- Surface Temperature Isotherms (Airborne) for 26 August 1966/1200L

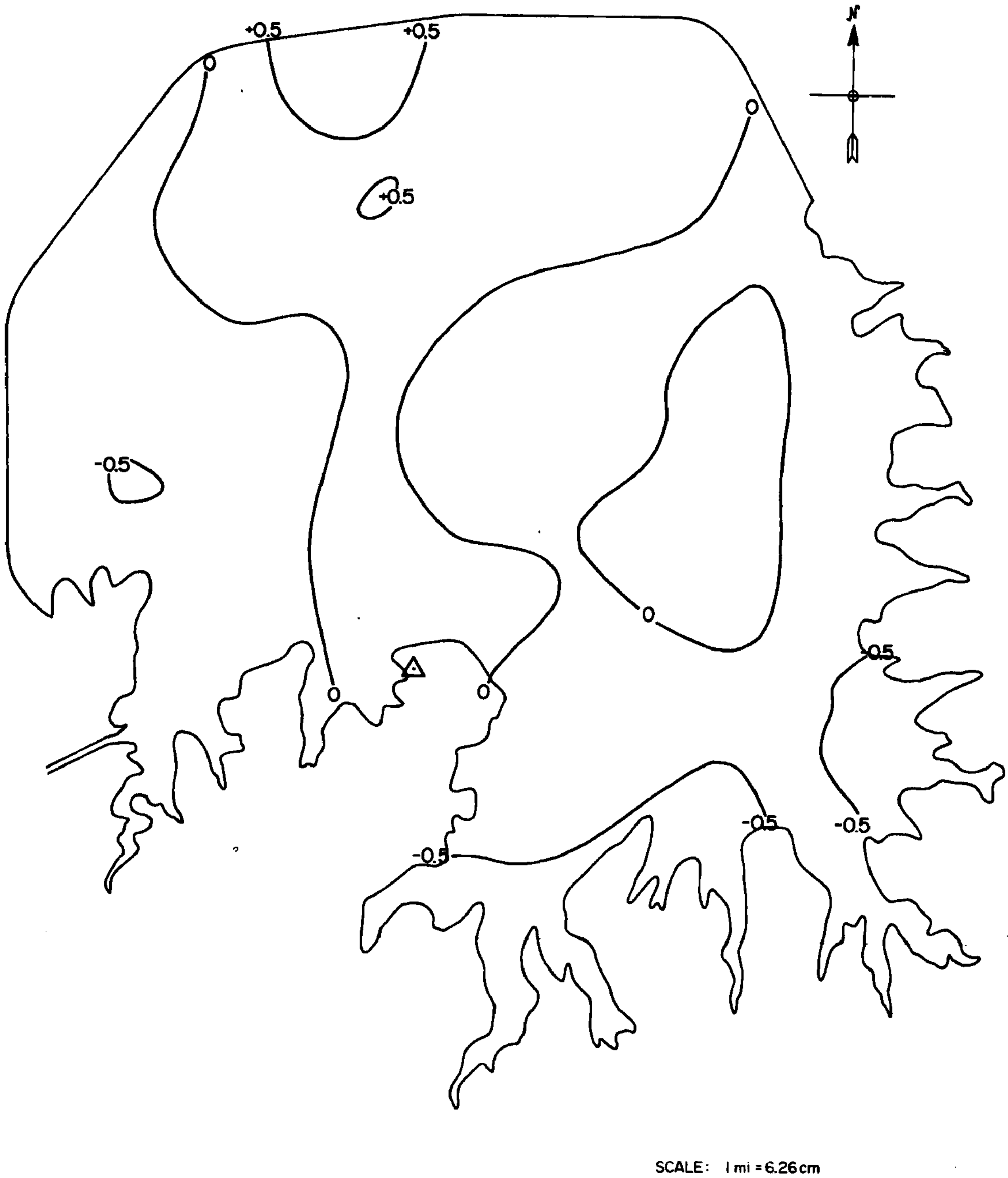

Figure 31.-- Surface Temperature Isotherms
(Airborne) for 28 August 1966/0100L

Figure 32. -- Surface Temperature Isotherms (Airborne) for 28 August 1966/1400L with 1400L Map of Hexadecanol Cover

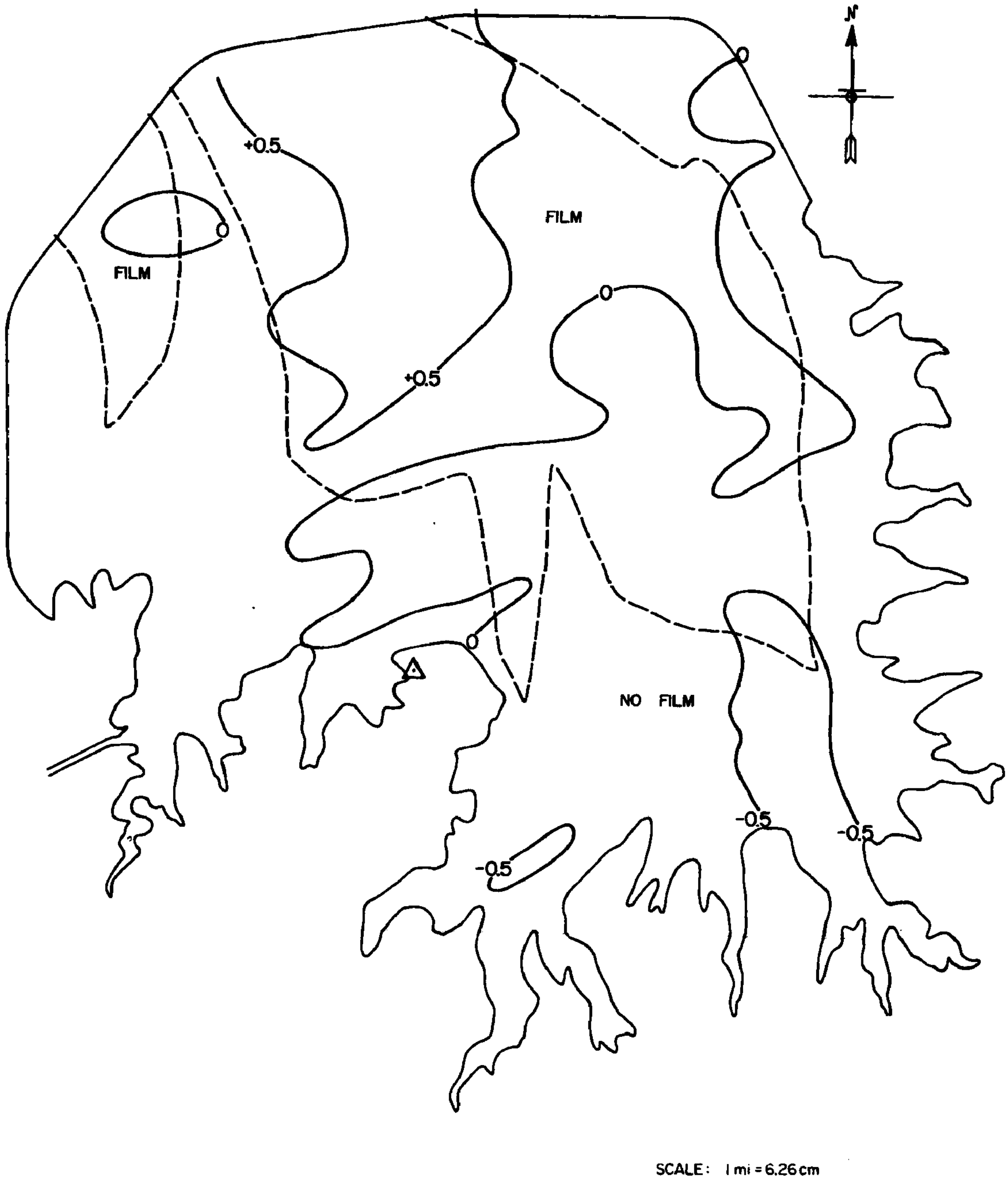

Figure 33.-- Surface Temperature Isotherms (Airborne) for 28 August 1966/1400L with 1500L Map of Hexadecanol Cover

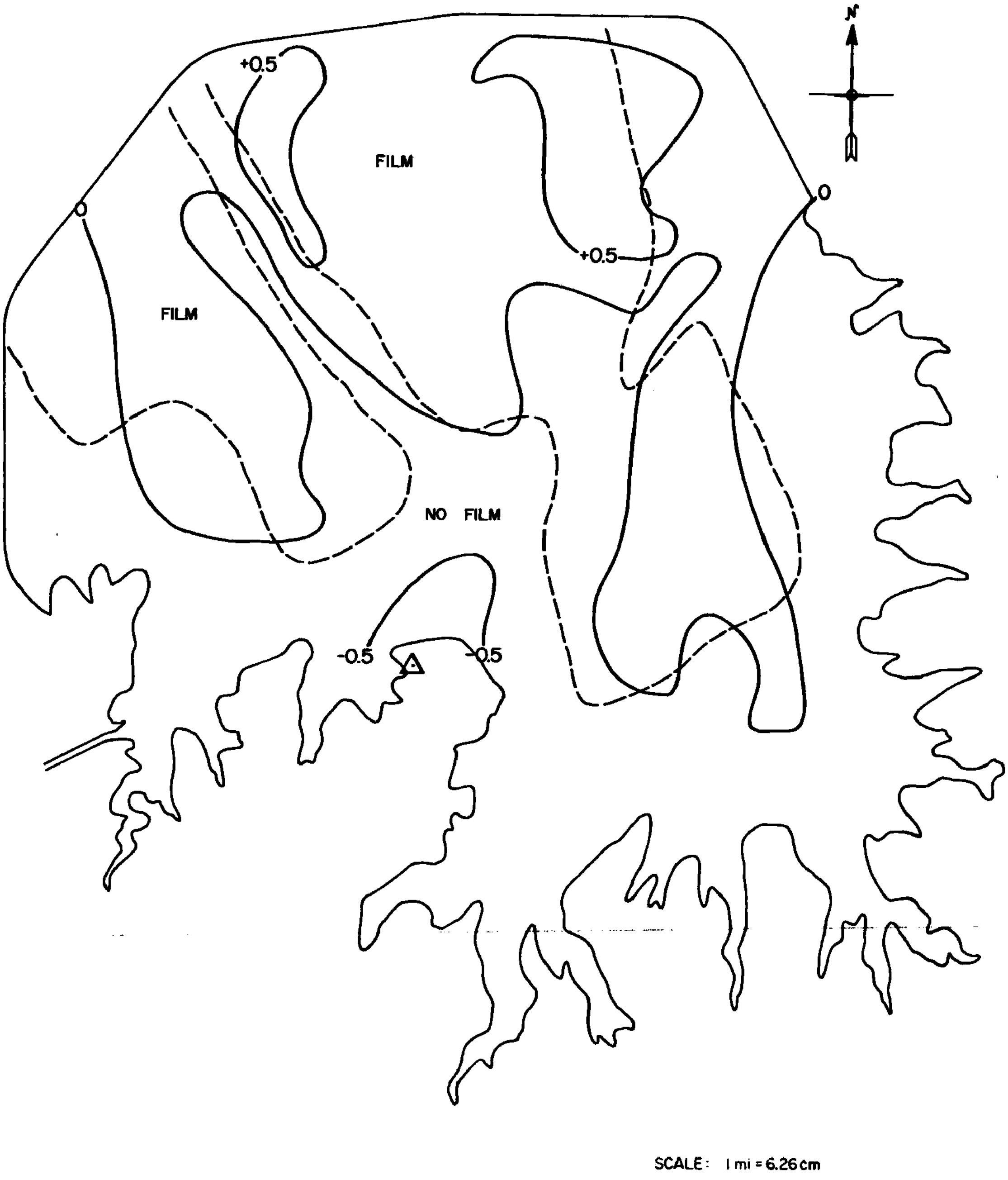

Figure 34.-- Surface Temperature Isotherms (Airborne) for 28 August 1966/2000L with 2000L Map of Hexadecanol Cover

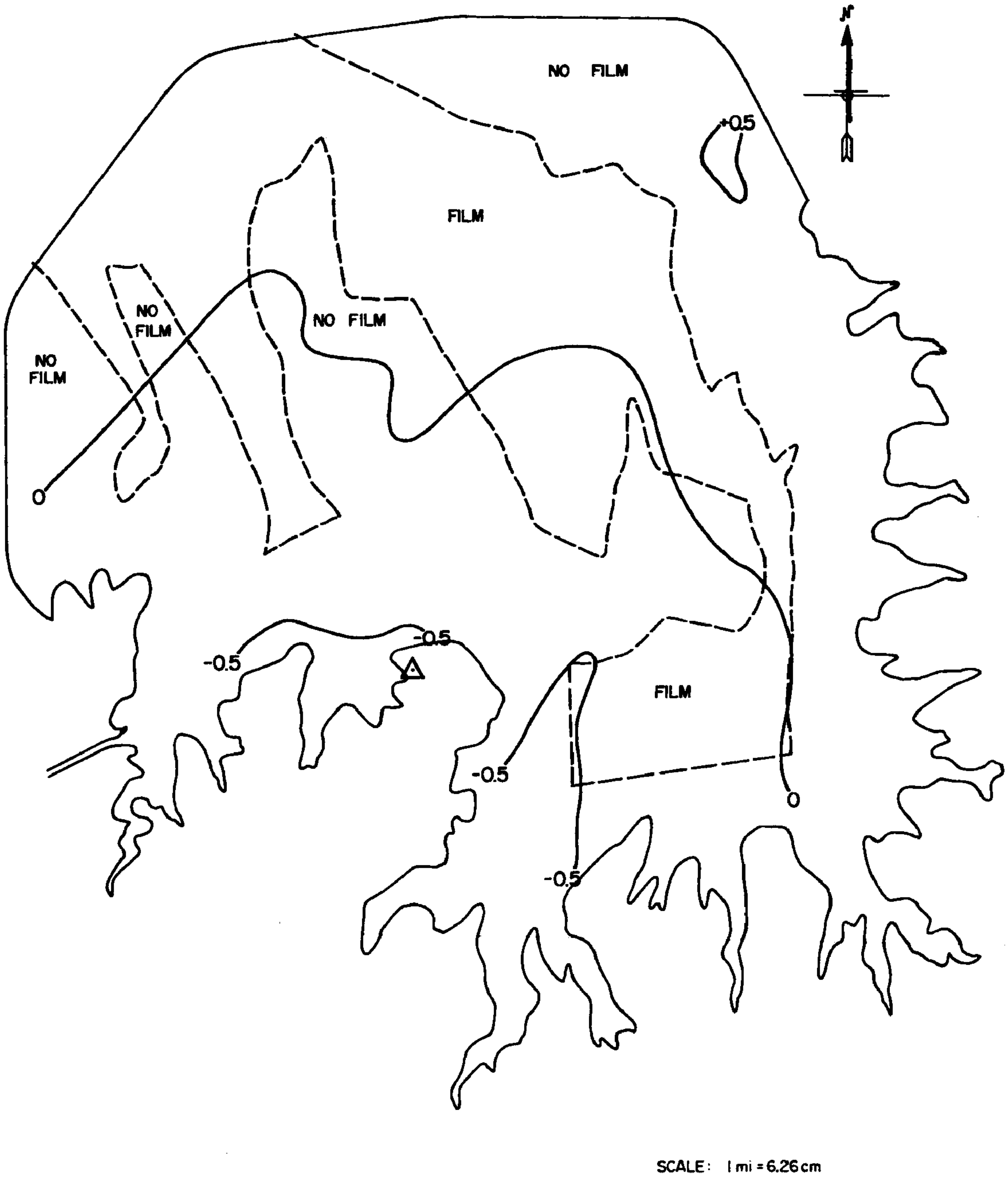

Figure 35.-- Surface Temperature Isotherms (Airborne) for 29 August 1966/1300L with 1300L Map of Hexadecanol Cover

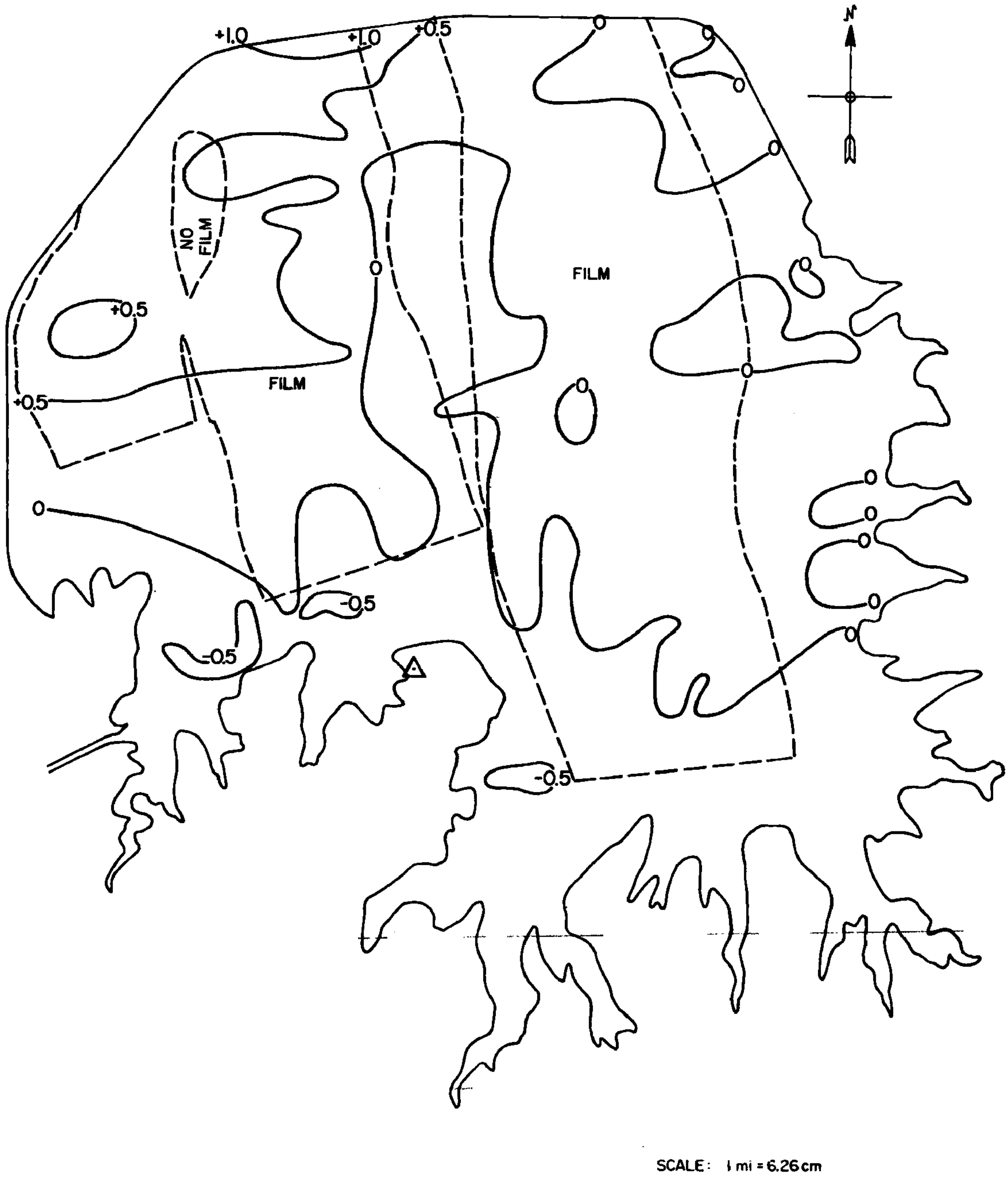

Figure 36.-- Surface Temperature Isotherms (Airborne) for 30 August 1966/1400L with 1400L Map of Hexadecanol Cover

APPENDIX IV

APPENDIX IV

GLOSSARY OF TERMS USED IN EQUATIONS

C_{pw} - specific heat of water

C_{pA} - specific heat of air

ρ_w - density of water

ρ_A - density of air

ρ_v - density of water vapor

θ_z - potential temperature at height z

T_s - water surface temperature

K_H - eddy diffusivity of heat in air

K_{HW} - eddy diffusivity of heat in water

K_q - eddy diffusivity of water vapor

τ - percent of solar insolation intercepted by surface layer

W - flux of solar energy

q - specific humidity

L - latent heat of evaporation

R_v - gas constant for water vapor

z - height coordinate (positive upward) in meters

t - time

x - distance down mean wind direction

U_z - wind speed at height z

k - coefficient in Lake Hefner mas transfer evaporation equation

β - emissivity of water

ϵ - 0·622

$\mathbb{K}$ - a known constant of integration