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STATIC LOAD TESTS ON
THE YELLOWKNIFE ICE SHEET

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by

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I. INTRODUCTION

During the 1971-72 winter at Yellowknife, Canada, a SUNOCO E&P test program was conducted to determine the dynamic response of an air cushion vehicle as it traversed through and over an ice sheet. As part of the overall program, static load tests were run to obtain data on the response of an ice sheet to heavy loads distributed on the ice with a large load area.

The goal for the static load tests was to cause the ice to fail under a known load and load area. At specified time intervals the deflection profile of the ice sheet around the load was monitored and recorded. One of the objectives of these tests was to extend present knowledge for loads on small load areas such as track vehicles to loads on large load areas such as an air cushion platform for an arctic drilling rig. Another objective was to evaluate the potential use of a static load test as a method for measuring engineering ice properties.

II INFINITE ICE SHEET MODEL

Nevel (1) has developed mathematical models for a semi-infinite plate on an elastic foundation and for an infinite strip on an elastic foundation. The infinite strip model has been programmed on a computer and used to study problems of loading an ice sheet covering a river. One can extend Nevel's computer program to study loadings on an infinite ice sheet by simply putting into the program an extremely large value for the width of the river relative to the dimensions of the load area(2).

Since the derivation of the mathematical model is formidable, it will not be presented in this report. Reference 1 contains the derivation in sufficient details for those readers who are interested. The resulting equations used to develop the computer program are presented in Appendix A.

For the static load tests we are interested in the theoretical deflection factors at each survey stake. This factor is

$$W = \frac{wkL^2}{P} \qquad (1)$$

where

W = theoretical deflection factor, dimensionless
w = deflection, ft.
k = foundation modulus (water density), lb/cu ft.
P = load, lb
$L = \left[\frac{Eh^3}{12k(1-\rho^2)}\right]^{1/4}$, characteristic length, ft.
E = modulus of elasticity, psi
h = ice thickness, ft.
ρ = Poisson's ratio, dimensionless

Equation (1) can be used to solve for the ice deflection at each survey stake. The calculated deflection profile will be compared to the measured deflection profile.

III. TEST CONDUCT AND RESULTS

Four static load tests were conducted on the ice sheet covering the Back Bay area near Yelloknife, Canada. In the first three tests the load was applied rapidly by pumping lake water into either a swimming pool or a large plywood tank. These three tests took place in the designated test area as shown in Figure 1. For the fourth test the unloaded air cushion vehicle was positioned on the ice at 500 feet beyond the end of Test Course No.8 (see Figure 1).

The deflection of the ice sheet was measured using a surveyor's level and survey stakes. The stakes were placed at measured intervals along each of the two major axes of the load. Before the load was applied, the elevation data were obtained for the stakes at time zero and thereafter at a preselected time interval. The reports containing the original field data were placed in the permanent data file.

The elastic deflection at each rod position was calculated using the theoretical deflection factors. The measured deflections at selected times were plotted as a function of distance from the load. These times were chosen so as to present the changes of the deflection profiles with time.

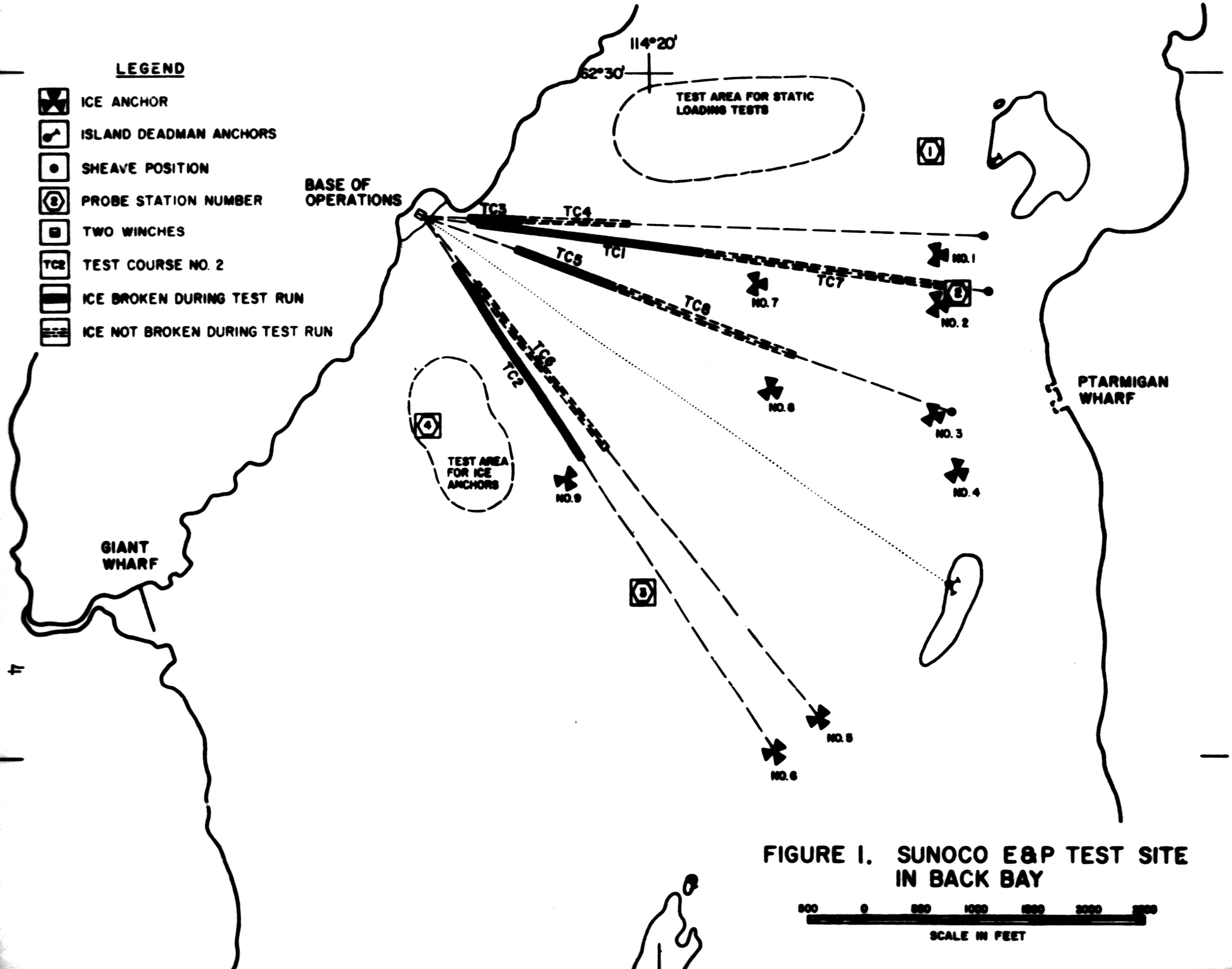


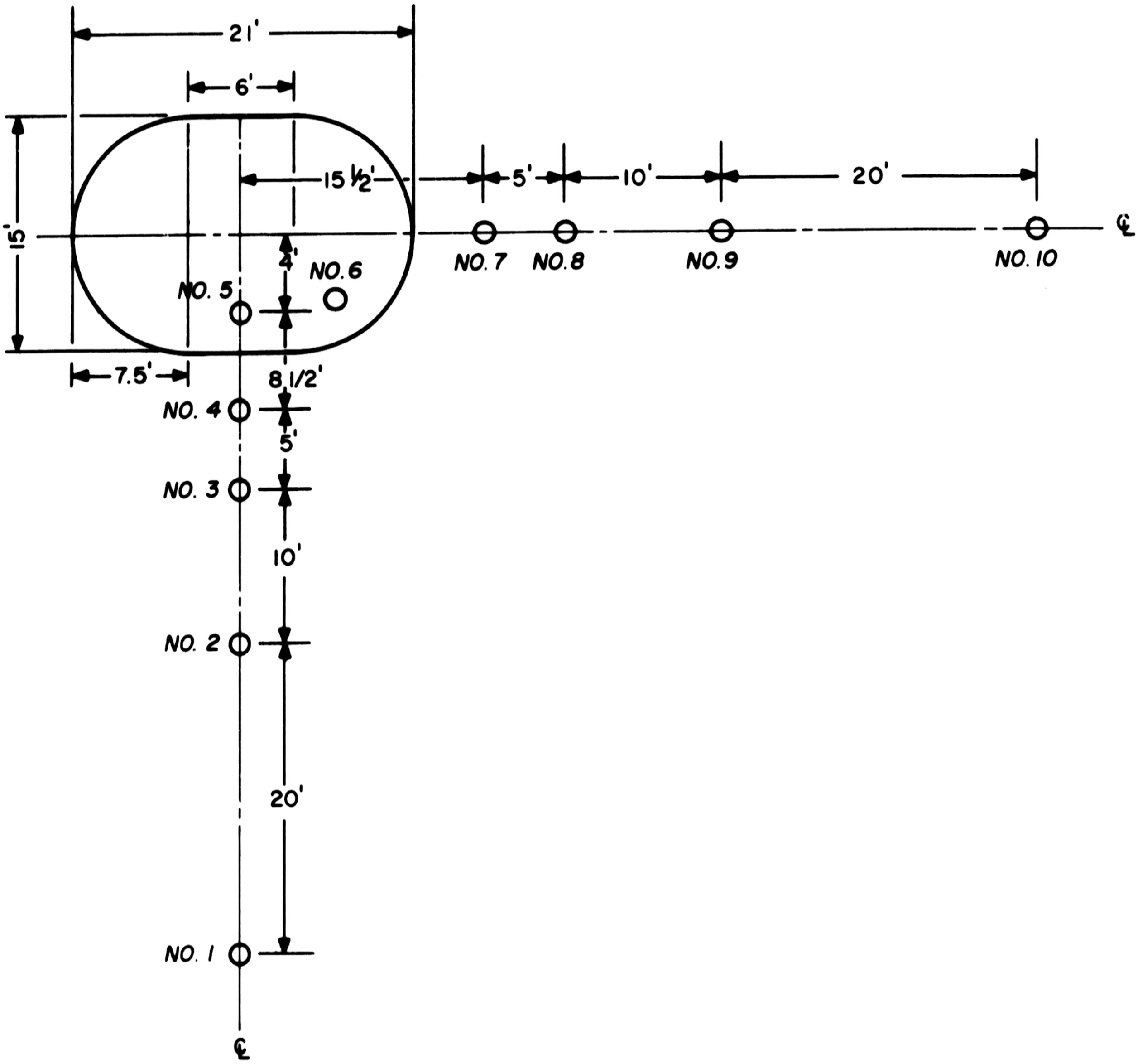
FIGURE I. SUNOCO E&P TEST SITE IN BACK BAY

A. STATIC LOAD TEST NO.1

On November 20, 1971, a swimming pool with dimensions of 21' x 15' x 4' was assembled and positioned on the ice sheet. The ice thickness was 13 inches and the water depth was 15 feet. Nine survey stakes were placed along the two major axes of the swimming pool as shown in Figure 2. At rod position No.6 the survey stake was on a float so that the water level could be measured at the same time the ice deflection readings were being taken. Table I presents the incremental deflection at each rod position and the cumulative water level. The theoretical deflection factor for each rod position is also given. In Figures 3 and 4 the deflection profiles are illustrated for the longitudinal and the traverse direction.

The rate of loading initially averaged 52 pounds per minute for the first third of the time and then dropped to 30 pounds per minute as an overall average. This rate was lower than the 4500 pounds per minute we were striving to obtain.

The vinyl plastic pulled away from the frame when the pool was half full. No cracks in the ice adjacent to the pool were observed.



LAYOUT DIAGRAM FOR
STATIC LOAD TEST NO. 1

FIGURE 2

TABLE I

Data Summary for Static Load Test No.1

Incremental Deflections (Feet)

TIME	TRANSVERSE DIRECTION					LONGITUDINAL DIRECTION				LOAD WATER	
min.	Rod 1	Rod 2	Rod 3	Rod 4	Rod 5	Rod 7	Rod 8	Rod 9	Rod 10	Level(ft)	Weight(lbs)
170	-0.02	0.0	-0.06	-0.04	-0.06	-0.04	-0.02	-0.02	-0.0	0.41	6,823
250										0.71	11,816
300	-0.00	-0.04	-0.04	-0.09	-0.10	-0.06	-0.04	-0.02	-0.0	0.88	14,645
350										1.03	17,141
420	0.02	-0.04	-0.06	-0.10	-0.14	-0.06	-0.04	-0.02	0.04	1.31	21,801
605										1.51	25,129
1,110	0.02	-0.04	-0.06	-0.12	-0.20	-0.10	-0.06	-0.04	-0.02	1.73	28,791
1,170										1.93	32,119
1,220	0.00	-0.04	-0.12	-0.16	-0.26	-0.14	-0.10	-0.04	-0.0	2.09	32,782
1,280	0.00		-0.16	-0.18	-0.28	-0.16	-0.12	-0.04	-0.0	2.27	37,777
1,335	0.00	-0.04	-0.18	-0.20	-0.32	-0.18	-0.12	-0.04	-0.0	2.41	40,107
1,395	0.00	-0.04	-0.18	-0.22	-0.34	-0.20	-0.14	-0.04	-0.0	2.59	43,103

Theoretical Deflection Factors (Dimensionless)

0.0131 0.0620 0.0867 0.0987 0.1130 0.0904 0.0779 0.0541 0.0200

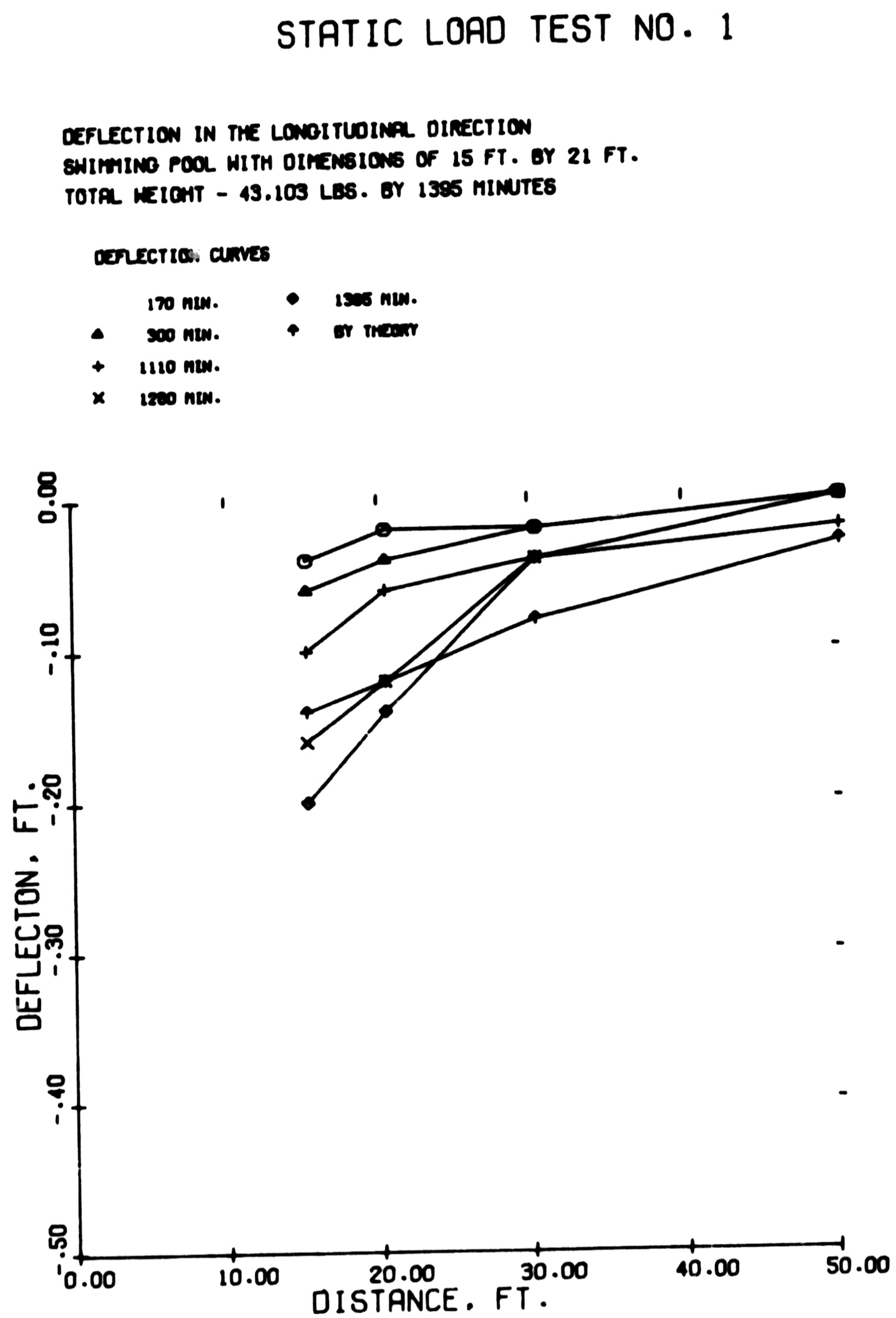


Figure 3. Static Load Test No.1: Deflection in the Longitudinal Direction

MILL.OFFSHORE AND ARCTIC DRILLING GRP.

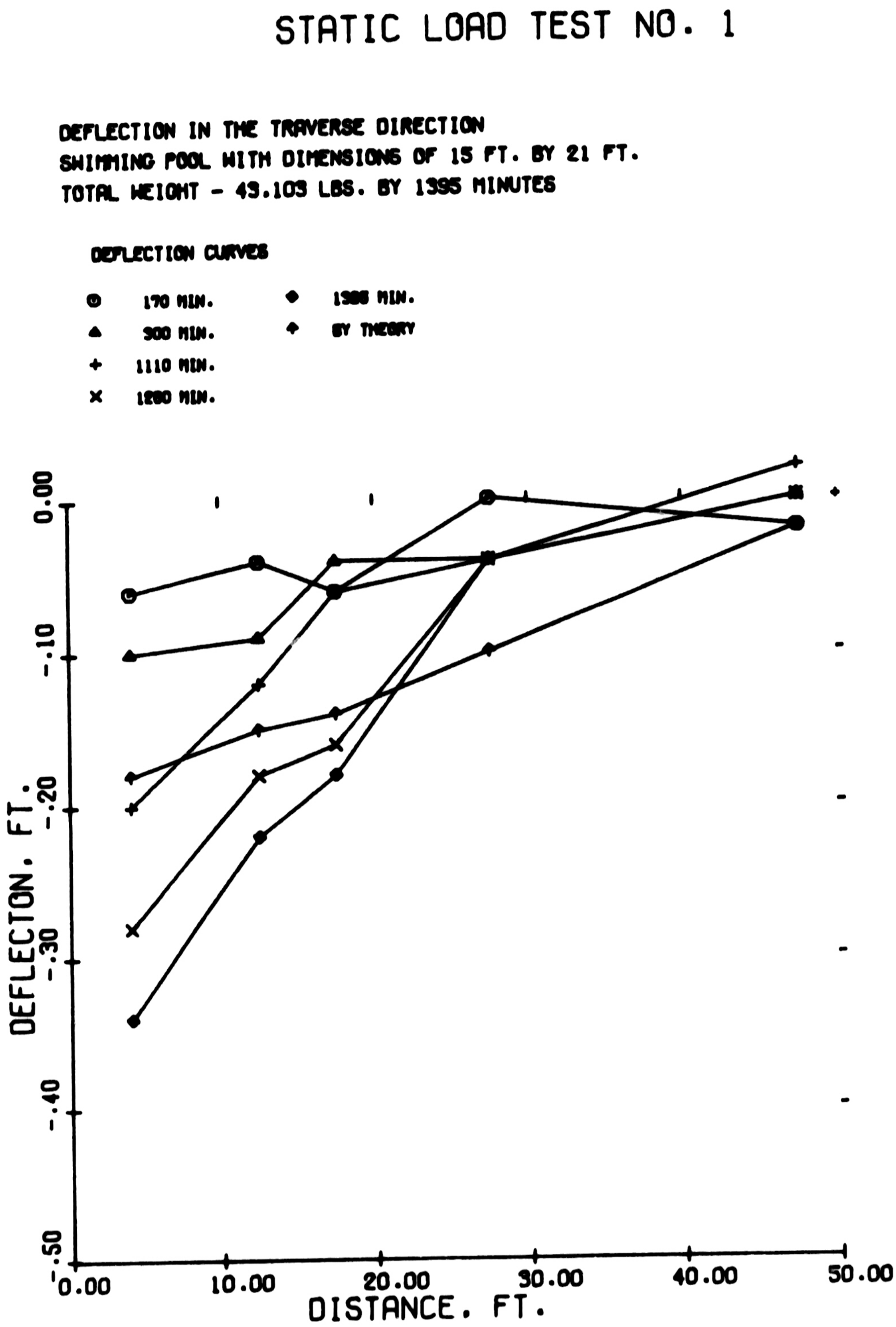
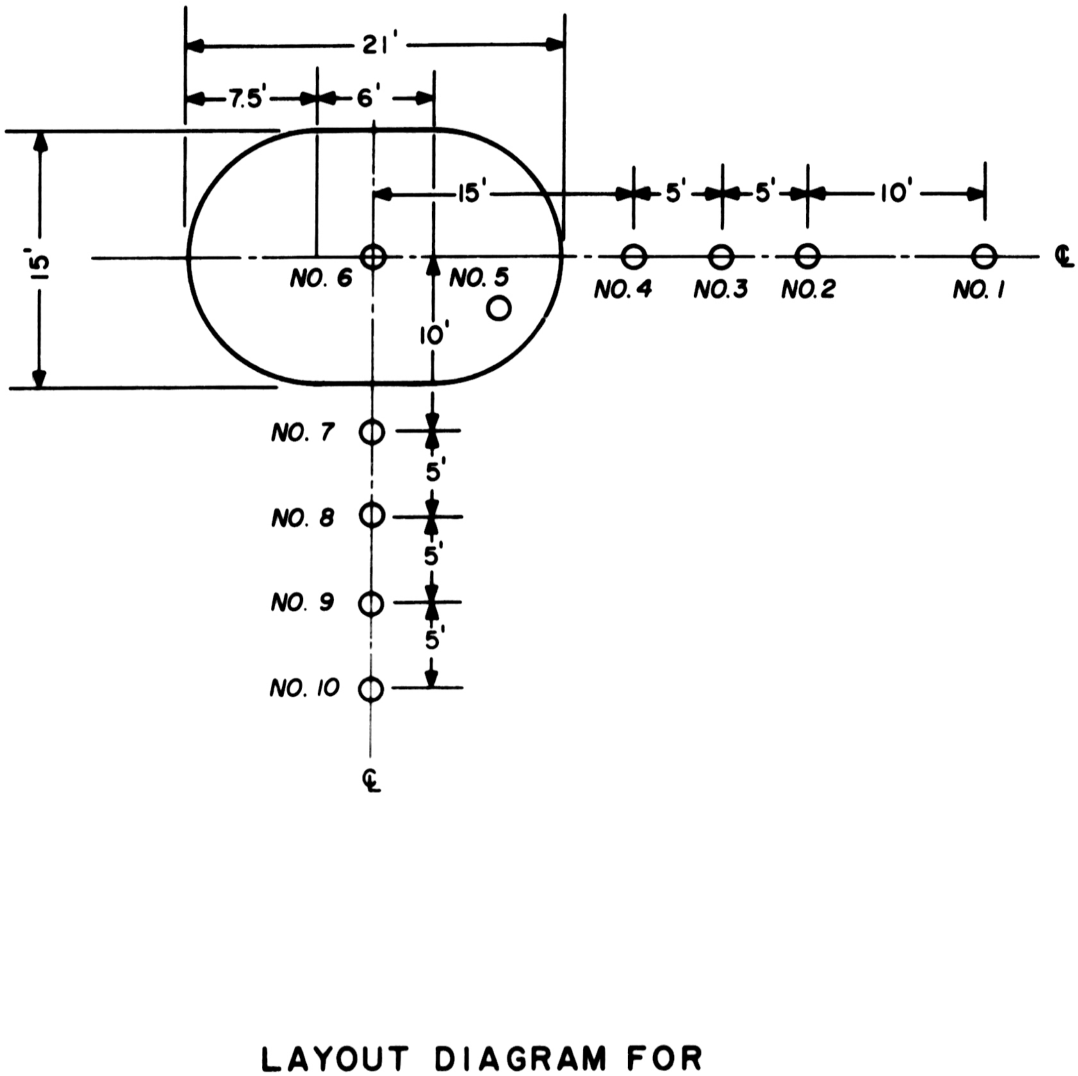


Figure 4. Static Load Test No.1: Deflection in the Traverse Direction

B. STATIC LOAD TEST NO.2

A reinforced plywood pool was used on November 27, 1971. The dimensions of the pool was 21' x 15' x 4'. The ice thickness was recorded as 15.5 inches at a point 10 feet from the pool. As the pool was being filled, lake water came up through this hole and began filling the depressed area surrounding the pool. The rate of loading averaged 3240 pounds per minute. The deflection of the ice sheet was monitored for 46 hours. The positions of the survey stakes are shown in Figure 5. The incremental deflections and the cumulative water level are presented in Table II. The deflection profiles for this test are shown in Figures 6 and 7.



LAYOUT DIAGRAM FOR
STATIC LOAD TEST NO. 2

FIGURE 5

TABLE II

Data Summary for Static Load Test No.2

Incremental Deflections (Feet)

TIME	LONGITUDINAL DIRECTION				TRANSVERSE DIRECTION					LOAD WATER	
min.	Rod 1	Rod 2	Rod 3	Rod 4	Rod 6	Rod 7	Rod 8	Rod 9	Rod 10	Level(ft)	Weight(lbs)
5	0.0	-0.02	-0.02	-0.04	-0.07	-0.06	-0.05	-0.04	-0.04	1.38	22,966
8	0.0	-0.05	-0.06	-0.08	-0.11	-0.10	-0.09	-0.06	-0.04	1.93	32,119
11	0.0	-0.07	-0.08	-0.10	-0.14	-0.12	-0.12	-0.08	-0.05	2.29	38,110
16	0.0	-0.13	-0.15	-0.18	-0.26	-0.23	-0.19	-0.16	-0.11	3.14	52,256
19	0.0	-0.15	-0.19	-0.22	-0.34	-0.29	-0.25	-0.20	-0.12	3.70	61,575
23	0.0	-0.17	-0.22	-0.24	-0.38	-0.31	-0.26	-0.21	-0.14		
30	0.0	-0.17	-0.22	-0.28	-0.43	-0.35	-0.28	-0.24	-0.18		
50	0.0	-0.23	-0.30	-0.38	-0.54	-0.42	-0.34	-0.27	-0.20		
70	0.0	-0.29	-0.34	-0.40	-0.57	-0.44	-0.35	-0.27	-0.20		
100	0.0	-0.33	-0.40	-0.48	-0.72	-0.54	-0.42	-0.32	-0.22		
190	0.0	-0.37	-0.47	-0.58	-0.93	-0.67	-0.52	-0.38	-0.28		
250	0.0	-0.42	-0.55	-0.71	-1.13	-0.84	-0.63	-0.53	-0.39		
340	0.0	-0.55	-0.72	-0.88	-1.42	-1.04	-0.76	-0.69	-0.52		
1,300	0.0	-0.71	-0.99	-1.29	-3.57	-1.39	-0.86	-0.87	-0.61		
2,740	0.0	-0.71	-1.00	-1.28	-3.98	-1.39	-0.86	-0.88	-0.62		

Theoretical Deflection Factors (Dimensionless)

0.0549	0.0759	0.08600	0.0980	0.1167	0.1064	0.0970	0.0861	0.0750

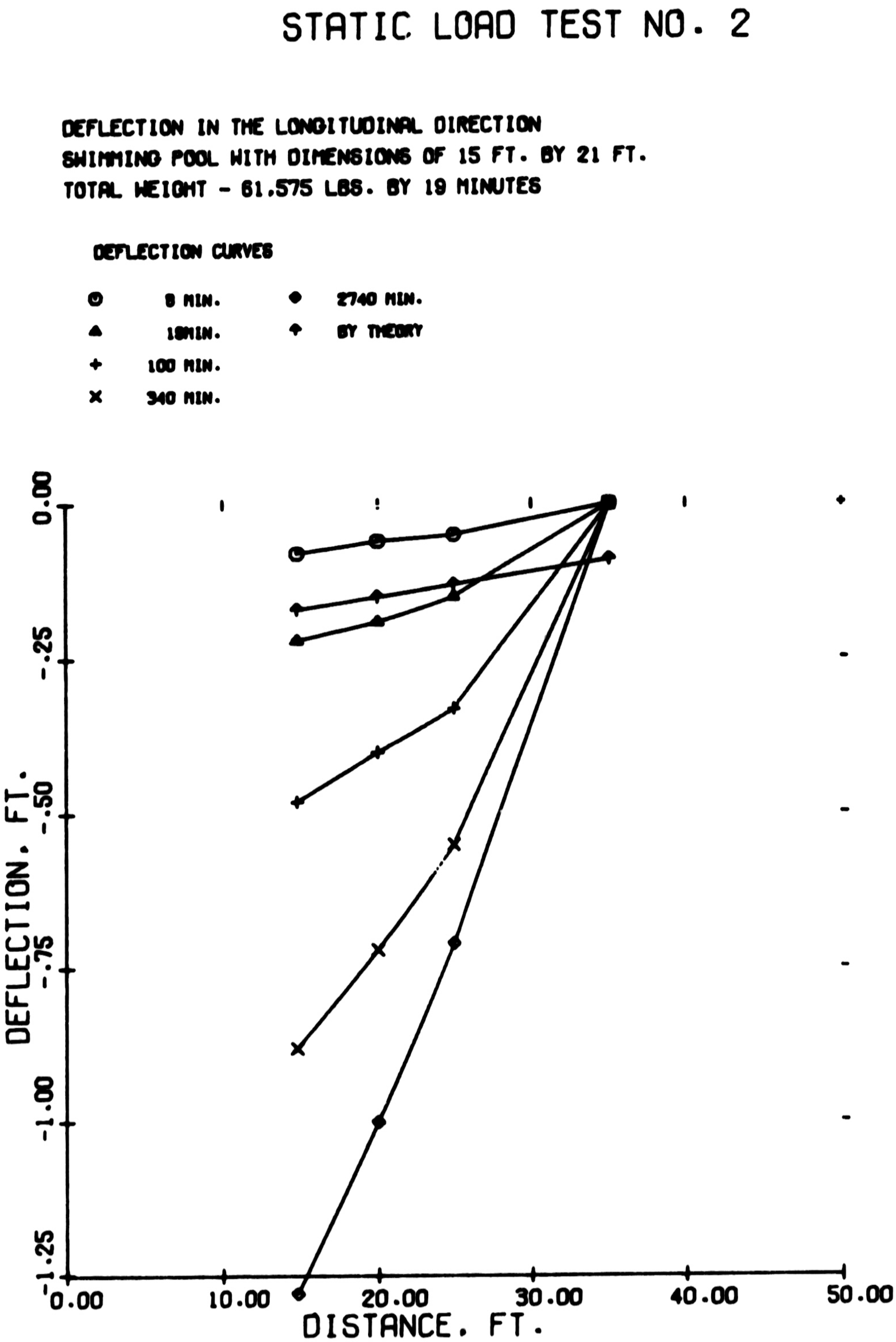


Figure 6. Static Load Test No.2: Deflection in the Longitudinal Direction

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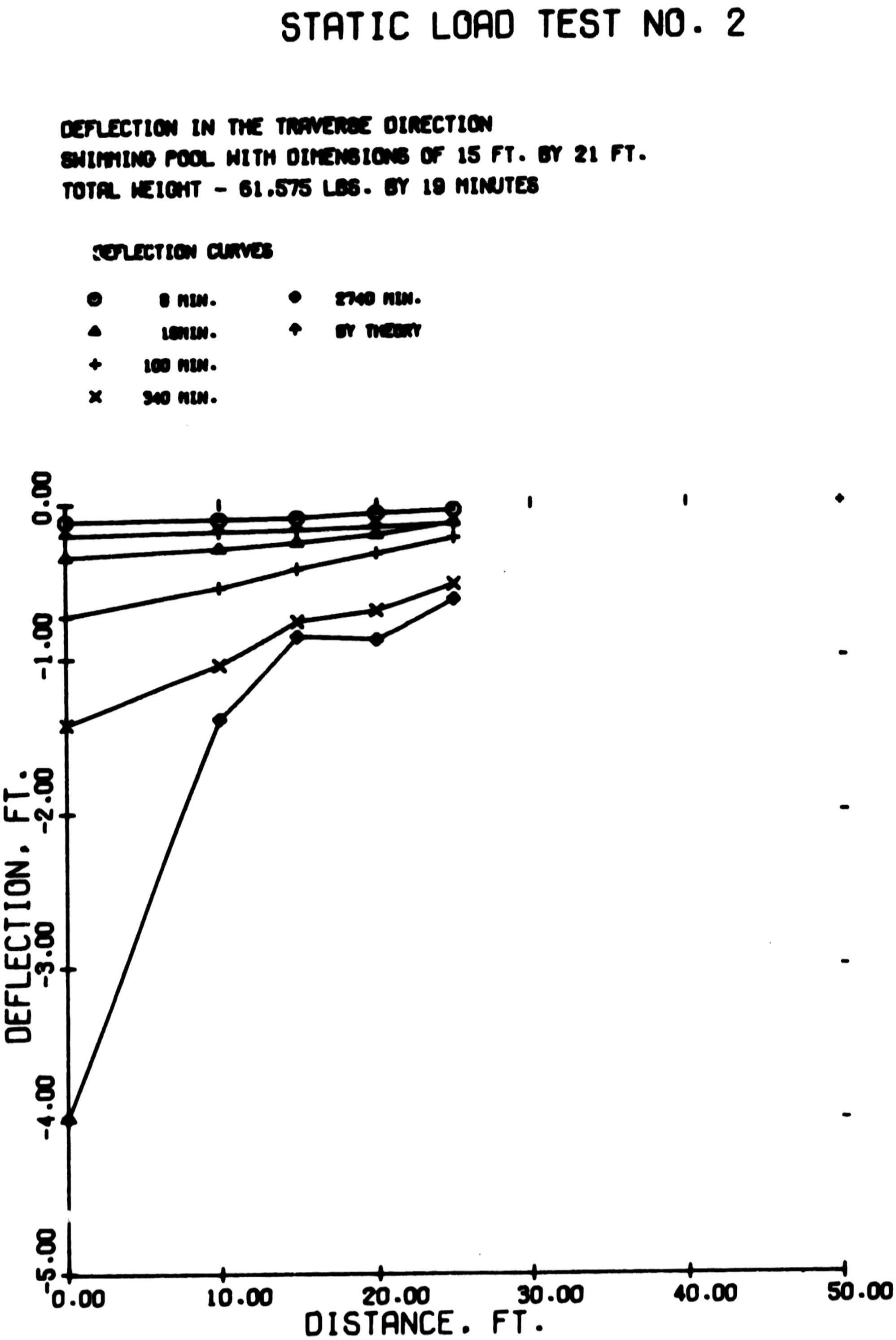
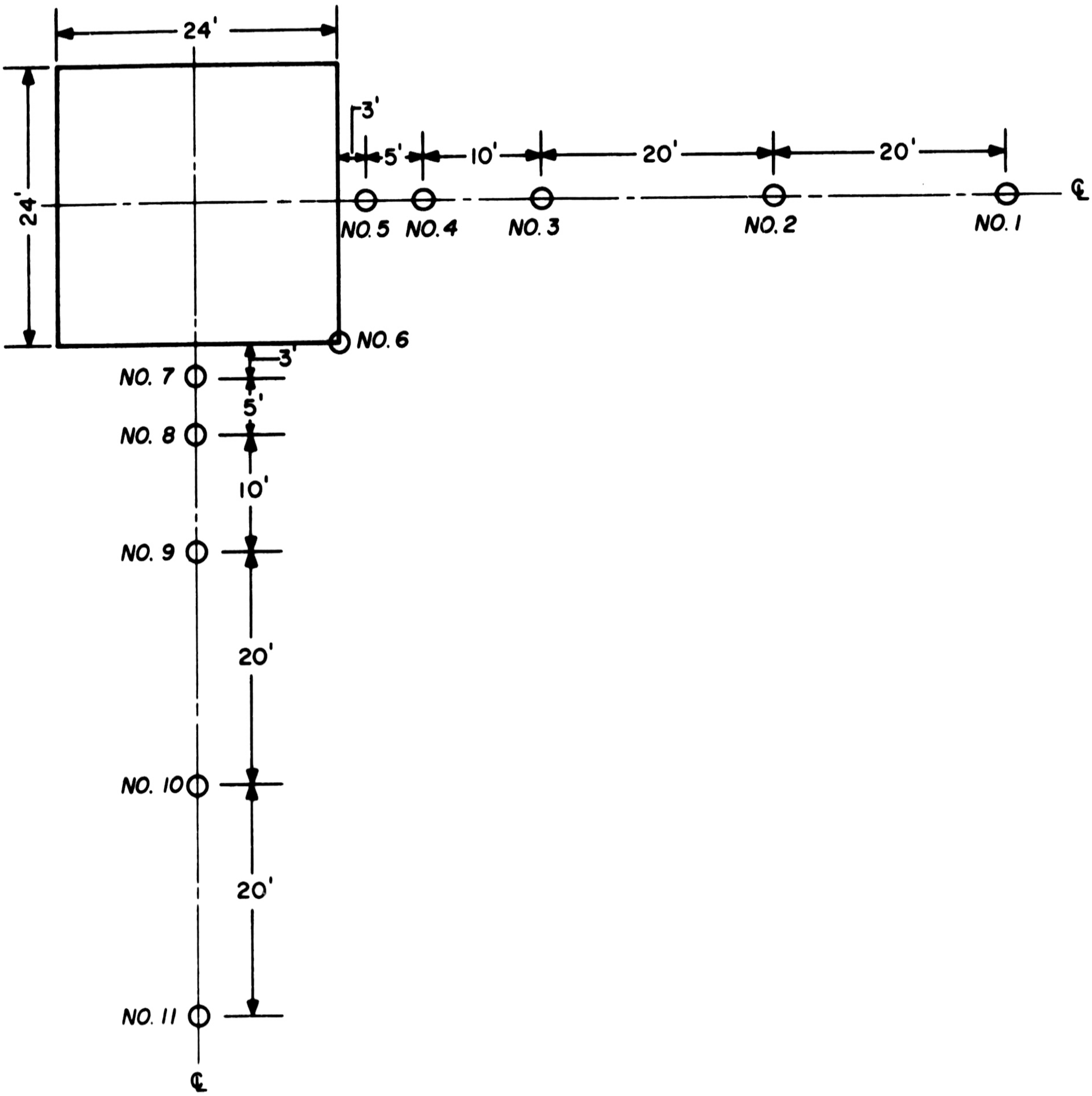


Figure 7. Static Load Test No.2: Deflection in the Traverse Direction

C. STATIC LOAD TEST NO.3

For the third test a large plywood tank reinforced with wire, was built with the dimensions of 24' x 24' x 8'. On December 16,1971, the survey stakes were positioned as shown in Figure 8. The ice thickness at the pump (100 feet away) was 19 inches. The averaged rate of loading was 2345 pounds per minute. Fifty minutes into the test, the on-site observers reported that several of the existing thermal cracks in the surrounding ice had begun to widen. After 60 minutes, a crack had formed around the tank at a radius of 30 feet. The bottom of the tank separated from the sides at 69 minutes into the test. The incremental deflections and the cumulative water level are given in Table III. Figures 9 and 10 illustrate the deflection profiles in the longitudinal and the traverse direction.



LAYOUT DIAGRAM FOR
STATIC LOAD TEST NO. 3

FIGURE 8

TABLE III

Data Summary For Static Load Test No.3

Incremental Deflections (Feet)

TIME	LONGITUDINAL DIRECTION					CORNER	TRANSVERSE DIRECTION					LOAD WATER	
min.	Rod 1	Rod 2	Rod 3	Rod 4	Rod 5	Rod 6	Rod 7	Rod 8	Rod 9	Rod 10	Rod 11	Level(ft)	Weight(lbs)
3	-0.02	-0.02	-0.04	-0.06	-0.06	-0.07	-0.08	-0.06	-0.02	-0.01	-0.02	0.23	8,267
10	-0.02	-0.01	-0.08	-0.11	-0.10	-0.17	-0.14	-0.08	-0.07	-0.02	0.00	0.62	22,280
17	-0.02	-0.01	-0.10	-0.14	-0.16	-0.22	-0.18	-0.14	-0.12	-0.05	0.00	0.87	31,270
22	-0.02	-0.03	-0.13	-0.18	-0.20	-0.26	-0.22	-0.18	-0.14	-0.05	-0.01	1.56	56,070
27	-0.02	-0.03	-0.16	-0.22	-0.24	-0.32	-0.27	-0.22	-0.16	-0.07	-0.01	1.88	67,570
35	-0.02	-0.02	-0.20	-0.28	-0.32	-0.38	-0.34	-0.28	-0.20	-0.07	-0.01	2.37	85,180
40	-0.02	-0.03	-0.12	-0.34	-0.38	-0.44	-0.40	-0.30	-0.22	-0.05	-0.01	2.70	97,040
45	-0.02	-0.06	-0.27	-0.40	-0.44	-0.50	-0.46	-0.37	-0.25	-0.03	-0.00	3.10	111,400
50	-0.02	-0.07	-0.32	-0.46	-0.54	-0.60	-0.54	-0.44	-0.30	-0.04	-0.00	3.42	122,900
55	-0.01	-0.06	-0.34	-0.52	-0.60	-0.64	-0.60	-0.50	-0.32	-0.04	-0.00	3.70	133,000
60	-0.01	-0.07	-0.38	-0.55	-0.65	-0.71	-0.66	-0.54	-0.34	-0.03	-0.00	3.91	140,500
65	-0.00	-0.05	-0.40	-0.64	-0.74	-0.80	-0.74	-0.60	-0.38	-0.05	-0.00	4.24	152,400

Theoretical Deflection Factors (Dimensionless)

0.0177	0.0401	0.0734	0.0922	0.1009	0.0977	0.1009	0.0922	0.0734	0.0401	0.0177

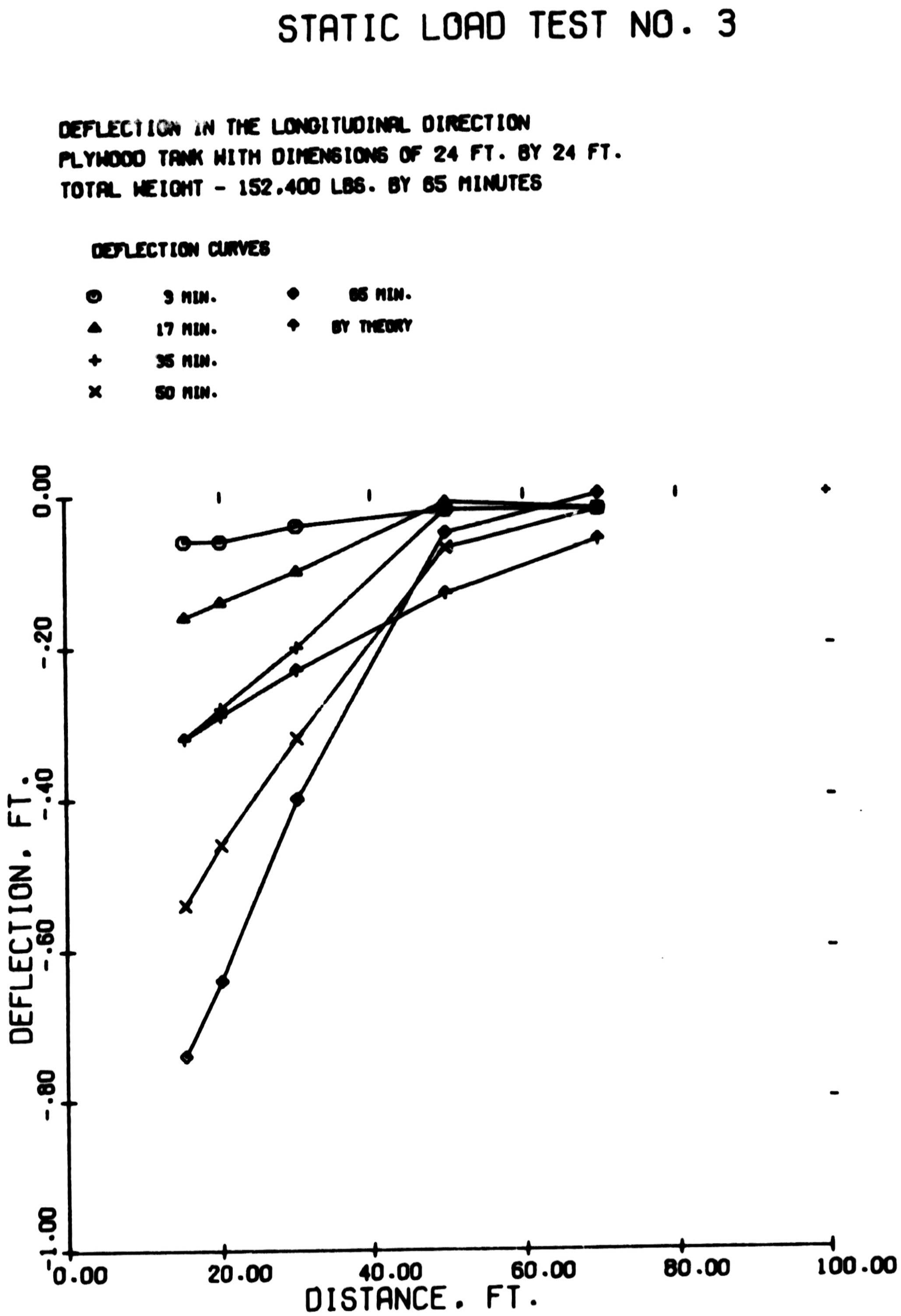


Figure 9. Static Load Test No.3: Deflection in the Longitudinal Direction

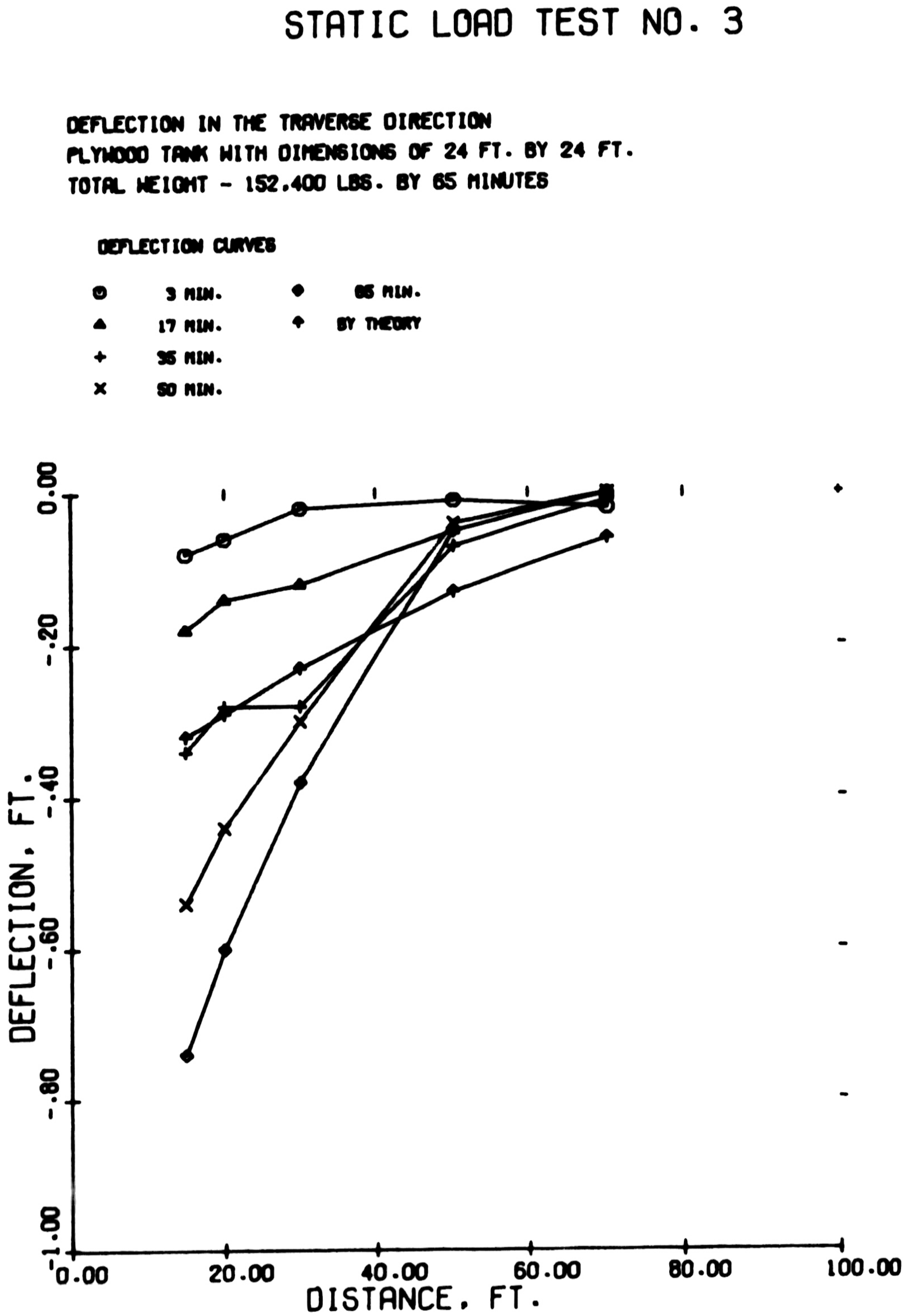


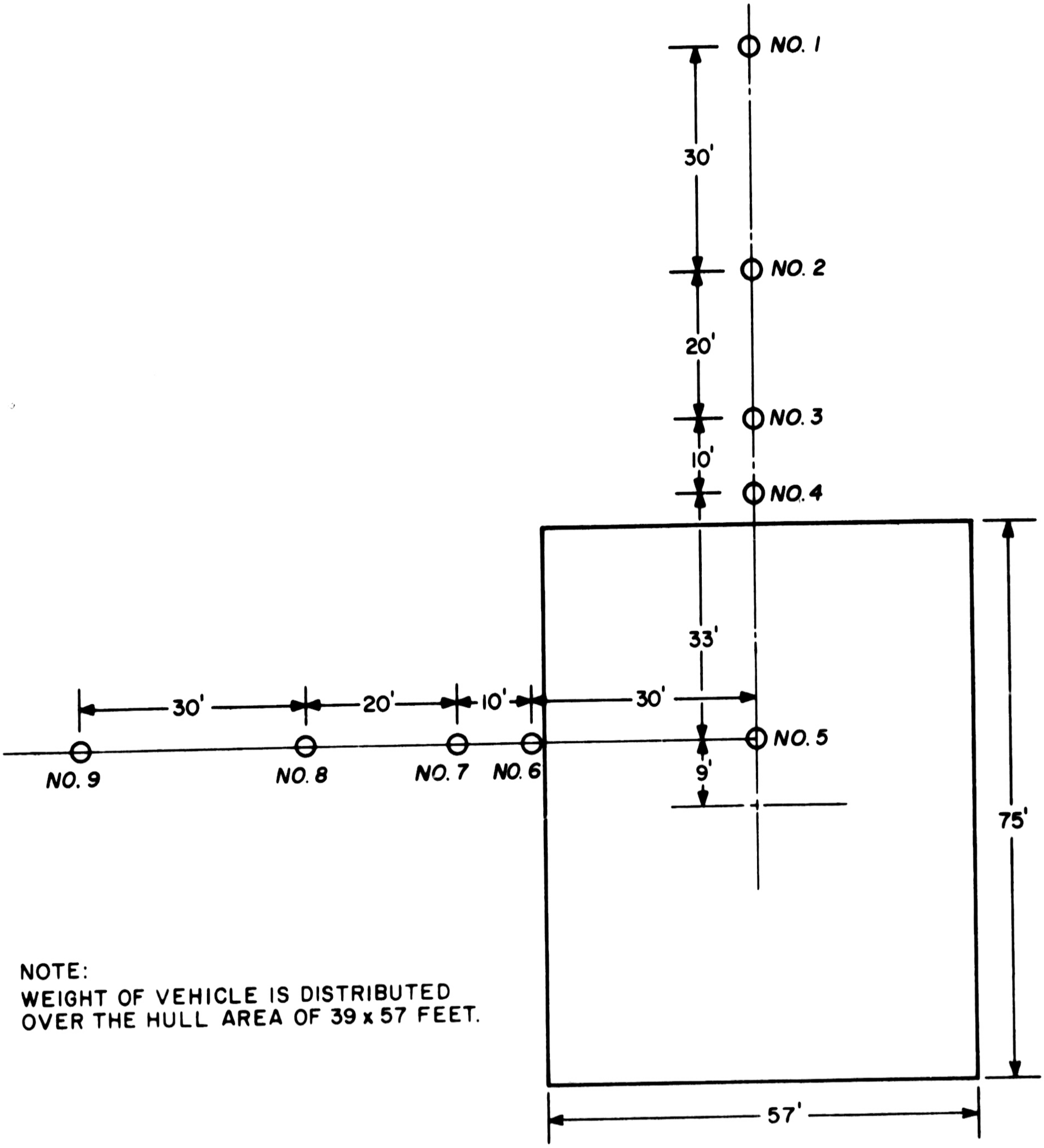
Figure 10. Static Load Test No.3: Deflection in the Traverse Direction

D. STATIC LOAD TEST NO.4

For this test the air cushion vehicle having an unloaded gross weight of 187 tons was positioned on the ice at 500 feet beyond the end of test course No.8. The weight on the ice was distributed over the hull area which was 57' x 39'. After positioning the vehicle, the survey stakes were placed as shown in Figure 11. The ice thickness in the general area of the vehicle was 30 inches.

The test began on February 11, 1972 and was terminated after a period of 49 hours. Between nine and twenty hours into the test, five peripheral cracks occurred 20 to 40 feet out from the vehicle. Since this time period was at night, no one could estimate the approximate time the cracks began to appear. Table IV summarizes the data for this test. Deflection profiles are given in Figure 12 and 13.

The positioning of the vehicle caused an initial deflection which was not measured nor was the field data adjusted for it. The reference elevations were taken within twenty minutes after the vehicle was positioned on the ice.



LAYOUT DIAGRAM FOR
STATIC LOAD TEST NO. 4

FIGURE 11

TABLE IV

Data Summary for Static Load Test No.4

Incremental Deflections (Feet)

TIME	LONGITUDINAL DIRECTION					TRANSVERSE DIRECTION			
min.	Rod 1	Rod 2	Rod 3	Rod 4	Rod 5	Rod 6	Rod 7	Rod 8	Rod 9
30	-0.06	-0.20	-0.27	-0.30	-0.75	-0.38	-0.33	-0.22	-0.09
90	-0.09	-0.21	-0.30	-0.38	-1.20	-0.44	-0.39	-0.26	-0.13
210	-0.06	-0.19	-0.29	-0.36	-1.07	-0.42	-0.37	-0.24	-0.12
510	-0.06	-0.19	-0.28	-0.40	-1.10	-0.43	-0.37	-0.25	-0.12
1,230	0.00	-0.11	-0.27	-0.37	-1.10	-0.47	-0.36	-0.19	-0.10
2,970	0.02	-0.07	-0.25	-0.39	-1.20	-0.47	-0.33	-0.18	-0.03

Theoretical Deflection Factors (Dimensionless)

0.0200	0.0528	0.0727	0.0832	0.1109	0.0957	0.0860	0.0654	0.0384

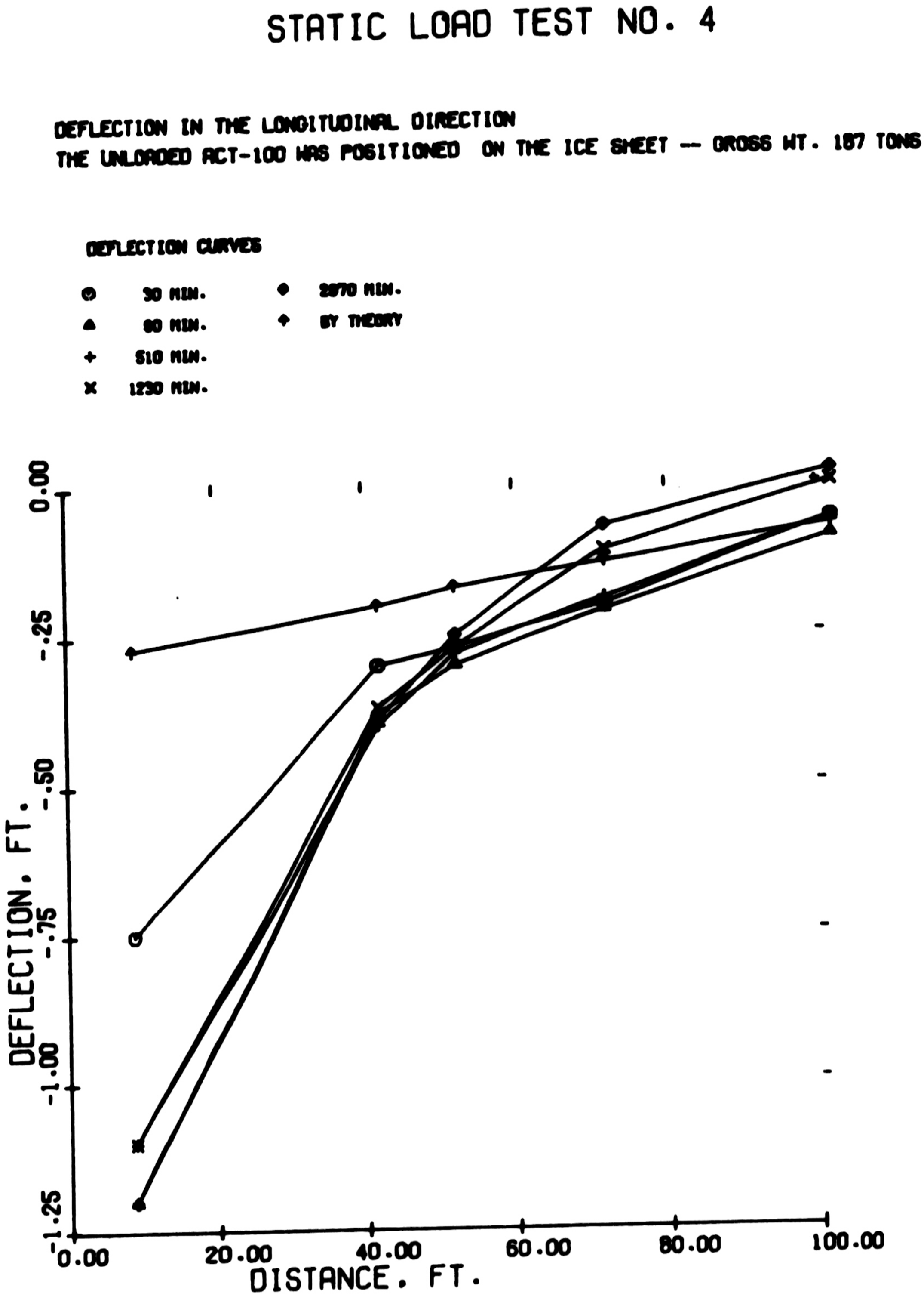


Figure 12. Static Load Test No.4: Deflection in the Longitudinal Direction

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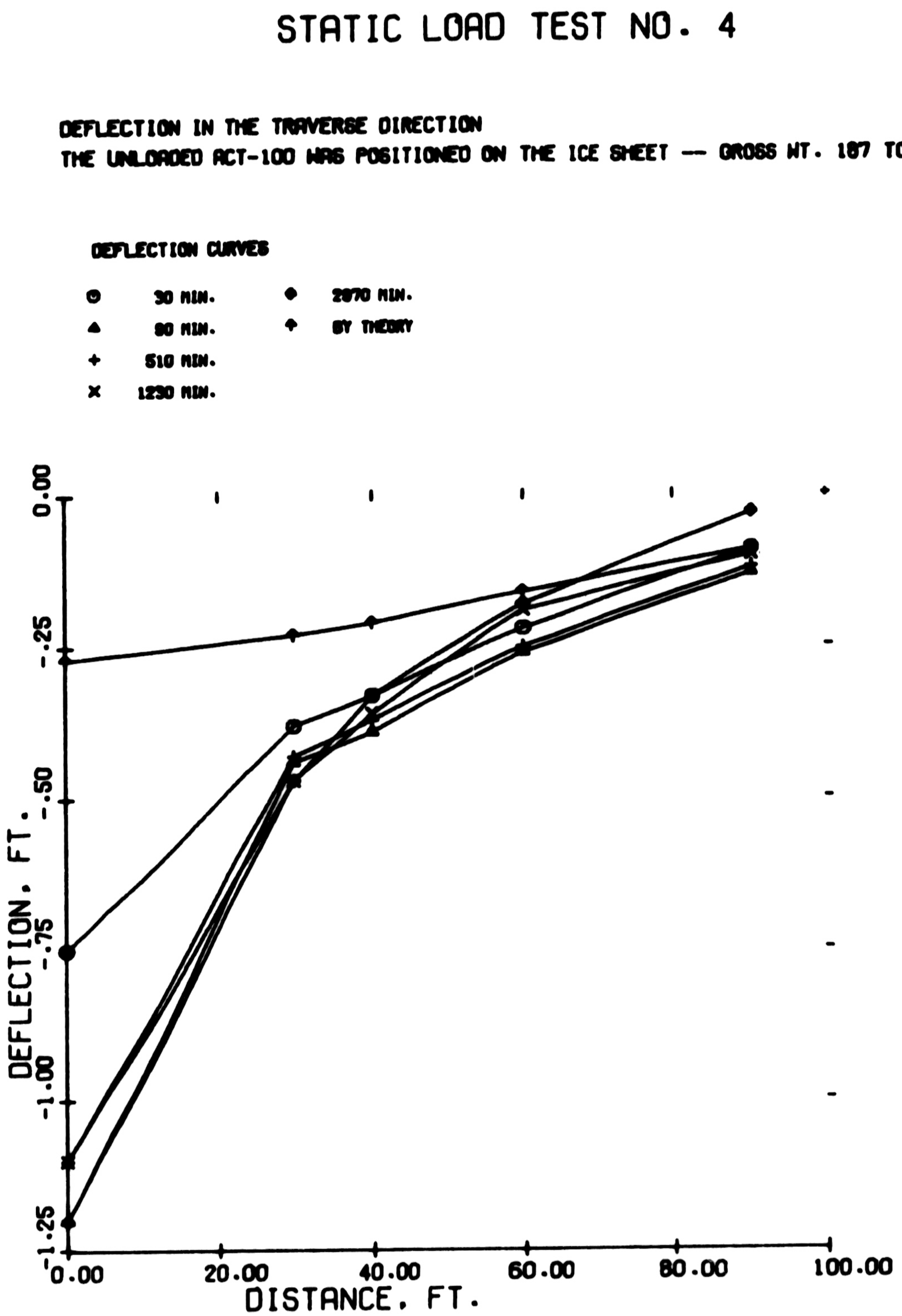


Figure 13. Static Load Test No.4: Deflection in the Traverse Direction

IV DISCUSSION OF RESULTS

The measured deflection profiles were compared to the elastic deflection profiles in Figures 3,4,6,7,9,10,12, and 13. In every case the measured deflections were larger near the load than the elastic deflections. The maximum deflection under the load was considerably greater than the deflection predicted by elastic theory.

The classical upward deflection at the rim of the depressed area was not detected in the data nor observed at the test site. Creation and propagation of cracks in the interior of the ice sheet was not observed because of the snow cover. Major cracks of separation were seen only in Test Numbers 3 and 4, but complete failure of the ice sheet did not occur in any of the tests.

The viscoelastic behavior of the ice sheet was more pronounced than was anticipated. These deflection profiles cannot be used to valuate engineering ice properties because the proper equations have not been developed at this time. The set of equations for an infinite strip on an elastic foundation are inadequate for estimating the deflection profile of the ice sheet.

Since an ice sheet exhibits viscoelastic properties, we need to extend our elastic model by incorporationg viscous effects. Some effort (3,4) has been done along these lines but the derived equations are only valid for deflections directly under the load and for relative small load areas.

V CONCLUSIONS

1. Deflection profiles cannot be used to evaluate engineering ice properties because the proper equations have not been developed.

2. Maximum deflection under the load was considerably greater than the deflection predicted by the elastic theory.

3. The viscoelastic behavior of the ice sheet was more pronounced than was anticipated.

4. The set of equations for an infinite strip on an elastic foundation was inadequate for estimating the deflection profile of the ice sheet.

5. Loading rates less than 4500 pounds per minute were too slow and usually allowed creep conditions to occur several minutes before the tanks were completely filled.

VI RECOMMENDATIONS

1. Production Research Department should direct an effort toward the development of equations for predicting the viscoelastic response of an infinite ice sheet on an elastic foundation. This set of equations should predict the time dependent deflection profiles when the ice sheet is subjected to large distributed loads.

2. The potential for using deflection profiles to determine engineering ice properties should be evaluated.

3. Static load tests should be performed on fresh water ice to establish the reliability of the equations.

VII REFERENCES

1. Nevel, D.E.: "A Semi-Infinite Plate On An Elastic Foundation", CRREL Research Report No. 136, March, 1965

2. ______________: Personal communication.

3. ______________: "Time Dependent Deflection Of A Floating Ice Sheet", CRREL Research Report No. 196, July, 1966.

4. Frankenstein, G.E.: "Strength Of Ice Sheets", Proceedings of Conference on Ice Pressures Against Structures, Laval University, Quebec, Canada, November 1966, pp. 79-87

APPENDIX A

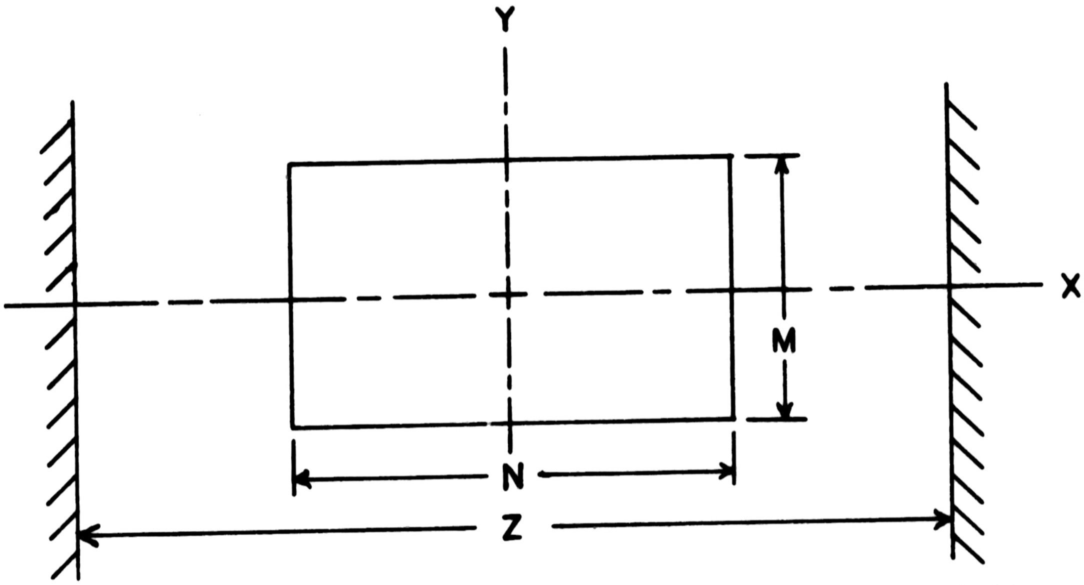
NEVEL'S MATHEMATICAL MODEL FOR AN INFINITE ICE SHEET

NEVEL'S MATHEMATICAL MODEL

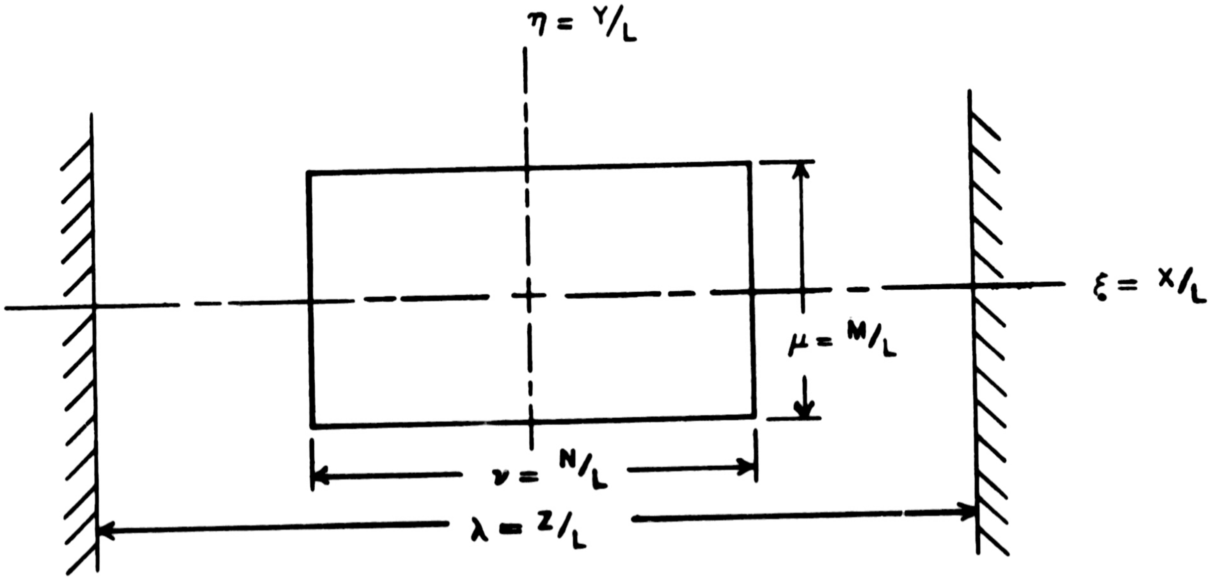
FOR AN INFINITE ICE SHEET

Nevel(1) developed the mathematical equations for an infinite strip on an elastic foundation. A computer program based on these equations has been prepared. This program can be used to simulate an infinite plate by assigning an extremely large value to the width of the river.

The program considers an ice sheet over a river with a rectangular load placed at the center.



Using the characteristic length of ice, L, we convert to a dimensionless system.



We can approximate an infinite ice sheet by assigning a large value to the width of the river.

The input variables to the computer program are:

Z = width of river, ft.
M = y-axis dimension of load, ft.
N = x-axis dimension of load, ft.
L = characteristic length of ice, ft.
X = x-axis dimension for point(s) of interest, ft.
Y = y-axis dimension for point(s) of interest, ft.
TF = maximum terms in series (500), dimensionless
ρ = Poisson's ratio for ice, dimensionless

The computer program will then calculate the value of each of the following output items which are all dimensionless:

$\frac{WkL^2}{P}$ = deflection factor

$\frac{W_x kL^3}{P}$ = slope factor in x direction

$\frac{W_y kL^3}{P}$ = slope factor in y direction

$\frac{\sigma_x h^2}{P}$ = moment factor in x direction

$\frac{\sigma_y h^2}{P}$ = moment factor in y direction

$\frac{\sigma_{xy} h^2}{P}$ = shear moment factor

W = deflection, ft.
k = foundation modulus (water density), lbs/cu.ft.
P = load, lbs
L = characteristic length of ice, ft.
w_x = slope in x direction, ft./ft.
w_y = slope in y direction, ft./ft.
h = ice thickness, ft.
σ_x = stress in x direction, psi
σ_y = stress in y direction, psi
σ_{xy} = shear, psi

Since we usually know k,h,L, and P, we can calculate w, w_x, w_y, σ_x, σ_y, and σ_{xy}.

The computer program is based on the following equations:

$$\frac{wkL^2}{P} = \frac{1}{\pi\lambda}\sum \frac{Y}{\mu}\left[\frac{2}{\phi\nu}\sin\frac{\phi\nu}{2}\right]\cos\phi\xi \qquad (1)$$

$$\frac{W_x k L^3}{P} = \frac{1}{\pi\lambda}\sum \frac{Y}{\mu}\left[\frac{2}{\phi\nu}\sin\frac{\phi\nu}{2}\right](-\phi)\sin\phi\xi \qquad (2)$$

$$\frac{W_y k L^3}{P} = \frac{1}{\pi\lambda}\sum \frac{Y'}{\mu}\left[\frac{2}{\phi\nu}\sin\frac{\phi\nu}{2}\right]\cos\phi\xi \qquad (3)$$

$$\frac{\sigma_y h^2}{P} = -\frac{6}{\pi\lambda}\sum \frac{[Y'' - \sigma\phi Y]}{\mu}\left[\frac{2}{\phi\nu}\sin\frac{\phi\nu}{2}\right]\cos\phi\xi \qquad (4)$$

$$\frac{\sigma_x h^2}{P} = -\frac{6}{\pi\lambda}\sum \frac{[-\phi Y + \sigma Y'']}{\mu}\left[\frac{2}{\phi\nu}\sin\frac{\phi\nu}{2}\right]\cos\phi\xi \qquad (5)$$

$$\frac{\sigma_{xy} h^2}{P} = -\frac{6(1-\rho)}{\pi\lambda}\sum \frac{Y'}{\mu}\left[\frac{2}{\phi\nu}\sin\frac{\phi\nu}{2}\right](-\phi)\sin\phi\xi \qquad (6)$$

FOR $\eta > \mu$

θ = dummy variable, i.e., $\sin\theta\Big]_b^a = \sin a - \sin b$

$$Y = \frac{1}{\epsilon^4}\left\{\left[e^{-\beta\theta}\cos\theta\right]_{\eta+\frac{\mu}{2}}^{\eta-\frac{\mu}{2}} + \phi^2 Y''\right\} \qquad (7)$$

$$Y' = \frac{1}{\epsilon^2}\left[e^{-\beta\theta}(\beta\sin\theta + \gamma\cos\theta)\right]_{n-\frac{\mu}{2}}^{n+\frac{\mu}{2}} \qquad (8)$$

$$Y'' = \left[e^{-\beta|\theta|}\sin\theta\right]_{n+\mu/2}^{n-\mu/2} \qquad (9)$$

FOR $\eta < \mu$

$$Y = \epsilon^{-4}\left\{\left(1-e^{-\beta(\eta-\frac{\mu}{2})}\cos(\eta+\tfrac{\mu}{2})\right)+\left(1-e^{-\beta(\mu-\frac{\eta}{2})}\cos(\mu-\tfrac{\eta}{2})\right) + \phi^2 Y''\right\} \qquad (10)$$

$$Y' = \epsilon^2\left[e^{-\beta\theta}(\beta\sin\theta + \gamma\cos\theta)\right]_{\frac{\mu}{2}-\eta}^{\frac{\mu}{2}+\eta} \qquad (11)$$

$$Y'' = \left[e^{-\beta|\theta|}\sin\theta\right]_{n+\mu/2}^{\eta-\mu/2} \qquad (12)$$

FOR $\mu = 0$

$$\frac{Y}{\mu} = \epsilon^{-2}e^{-\beta\eta}(\beta\sin\eta + \gamma\cos\eta) \qquad (13)$$

$$\frac{Y'}{\mu} = -e^{-\beta\eta}\sin\eta \qquad (14)$$

$$\frac{Y''}{\mu} = e^{-\beta\eta}(\beta\sin\eta - \gamma\cos\eta) \qquad (15)$$

where:

$$\phi = \pi T / 2$$

T = series count number, i.e., for $\sum_{1}^{N} \theta_i$, $i = 1, 2, 3, \ldots N$ then T has same value as i.

$$\epsilon = \sqrt[4]{1 + \phi^4}$$

$$\beta = \sqrt{\frac{\epsilon^2 + \phi^2}{2}}$$

$$\gamma = \sqrt{\frac{\epsilon^2 - \phi^2}{2}}$$