DESIGN OF A FREE WATER SURFACE TABLE TO BE USED AS AN ANALOGY TO TWO-DIMENSIONAL COMPRESSIBLE GAS FLOW

By

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Report Approved:

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Report Adviser

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Dean of the Graduate School

PREFACE

The purpose of this report is to present the design and construction details necessary for the construction of a free water surface table. A consideration was given to incorporate the desired features but to also maintain the cost to a minimum.

A short introduction to the analogy is given with a table correlating the properties and characteristics of two-dimensional compressible gas flow with those of liquid flow.

The author wishes to acknowledge his appreciation to Dr. G. W. Zumwalt for his excellent guidance throughout the period of the design.

To my wife Agnes and my two children, Harry and Effie, I can only say that I must spend a lifetime making up for the sacrifices that they have made the last 27 months that I might be free to take advantage of a wonderful opportunity.

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LIST OF SYMBOLS

Symbol	Meaning
a	Speed of sound
D	Diameter
d	Water Depth
E	Modulus of Elasticity
Fr	Froude Number
f	Friction Factor
g	Acceleration of Gravity
h_f	Head Loss
I	Moment of Inertia
M	Mach Number
P	Pressure
R	Reynolds Number
T	Absolute Temperature
V	Velocity
W	Weight
ϵ	Roughness Height
γ	Ratio of Specific Heats
ν	Kinematic Viscosity
ρ	Density

Subscripts

o	Value of Stagnation
s	Value in Undisturbed Stream

CHAPTER I

INTRODUCTION

An anology exists between pressure waves in a two-dimensional compressible gas flow and the gravity waves on the free surface of a liquid. The mathematics of this analogy has been known for a long time and the application of this analogy by means of experiments with rectangular water channels appears to have been first suggested by Jouguet (1). The application of this experimental method was implemented by Riabouchinsky (2), Von Karan (3) and Preiswerk (4). Additional investigations (5, 6, 7, 8, 9, 10) were stimulated by the high cost of supersonic wind tunnels which were required for the development of supersonic airplanes and vehicles.

The construction and operation of a water table is a very inexpensive way of studying two-dimensional compressible gas flow. Particularly, phenomena occuring in air at speeds too high for visual observations could be observed at very low speeds (1 to 3 fps) in a water channel. Constructing the bottom and sides of the channel with plate glass, not only provides the smooth surface required, but also lends itself to a wide variety of photographic techniques.

In order to stimulate thinking in the application of a water table, the summary to the analogy is given in table 1, where $\gamma = 2$ is the equivalent value of γ peculiar to a rectangular cross-sectional shape of the water channel.

TABLE I

ANALOGOUS QUANTITIES IN COMPRESSIBLE GAS FLOW AND LIQUID FLOW

Significant quantities and characteristics of two-dimensional gas flow $\gamma = 2$	Corresponding values in analogous liquid flow
Temperature ratio $\frac{T}{T_o}$	Water-depth ratio $\frac{d}{d_o}$
Density ratio $\frac{\rho}{\rho_o}$	Water-depth ratio $\frac{d}{d_o}$
Pressure ratio $\frac{P}{P_o}$	Square of water depth ratio $(\frac{d}{d_o})^2$
Velocity of sound $a = \sqrt{\frac{\gamma P}{\rho}}$	Wave velocity, $c = \sqrt{gd}$
Mach Number $M = \frac{V}{a}$	Froude Number $Fr = \frac{V}{c} = \frac{V}{\sqrt{gd}}$
Shock wave	Hydraulic jump
Subsonic flow	Streaming water
Supersonic flow	Shooting water

Streaming water - velocity of the liquid is less than $\sqrt{gd}$, $(M<1)$

Shooting water - velocity of the liquid is greater than $\sqrt{gd}$, $(M>1)$

The Mach number or Froude number in the liquid can be easily computed from

$$Fr = \left[\frac{2(d_o-d_s)}{d_s}\right]^{\frac{1}{2}}$$

from which it can be seen that the $Fr = 1$ at points where the depth is two-thirds of the total head.

Although it appears that the free surface water table will not generally yield quantitative information that may be used directly in design, it has been successful in reproducing most qualitative aspects of high-speed flows. It gives the operator the opportunity to view various flow patterns which can result in the development of original ideas. Its other advantages are its low cost, simplicity and rapid operation.

CHAPTER II

EXPERIMENTAL METHODS

Nozzle and Test Section

The desire to produce supersonic flow in the analogy suggests the use of a converging-diverging nozzle. Since a uniform flow, free of vertical motion, is desired, the use of the converging-diverging nozzle is possible. This nozzle is quite long, however, and tends to produce small oblique disturbance waves. The method devised to overcome the unwanted waves is the use of a sluice-type nozzle. Tests have shown that a very smooth surface is produced when a well-rounded sluice nozzle is used. In addition, the sluice nozzle permits the Mach number to be varied by merely controlling the head upstream of the sluice gate. Also, the flow depth can be varied by adjusting the sluice gate opening. The Laval nozzle not only creates vertical waves, but is also restricted to a single Mach number.

Photographic Methods

The use of plate glass in the construction of the table permits a wide variety of photographic and group observation techniques. Figures 1a, b, and c are some suggested methods for photography (11).

The glass bottom and sides also present a smooth finish to the water, thereby creating a minimum of flow friction. The slight friction that is present can be approximately cancelled by tilting the table a small amount. This allows the forces of gravity to somewhat compensate for the friction

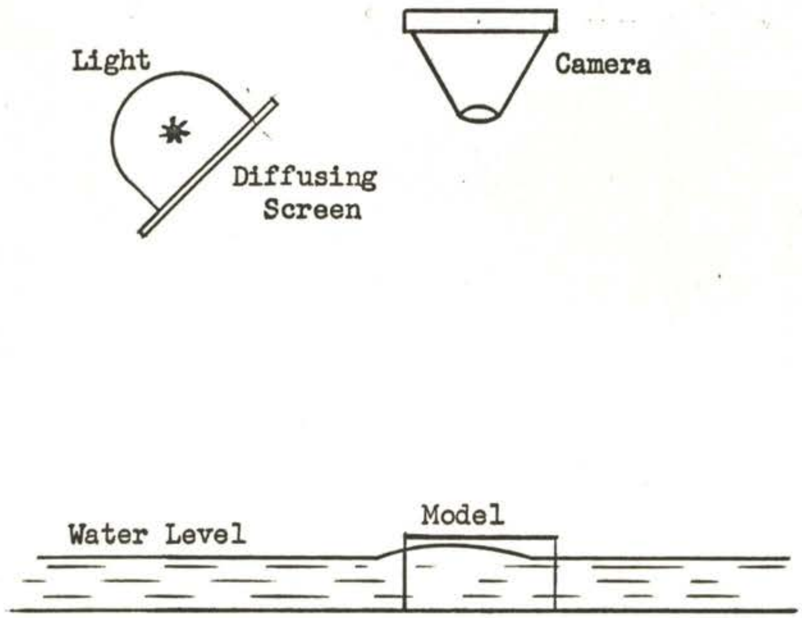


Fig. 1a. Reflection of Diffuse Light From Water Surface

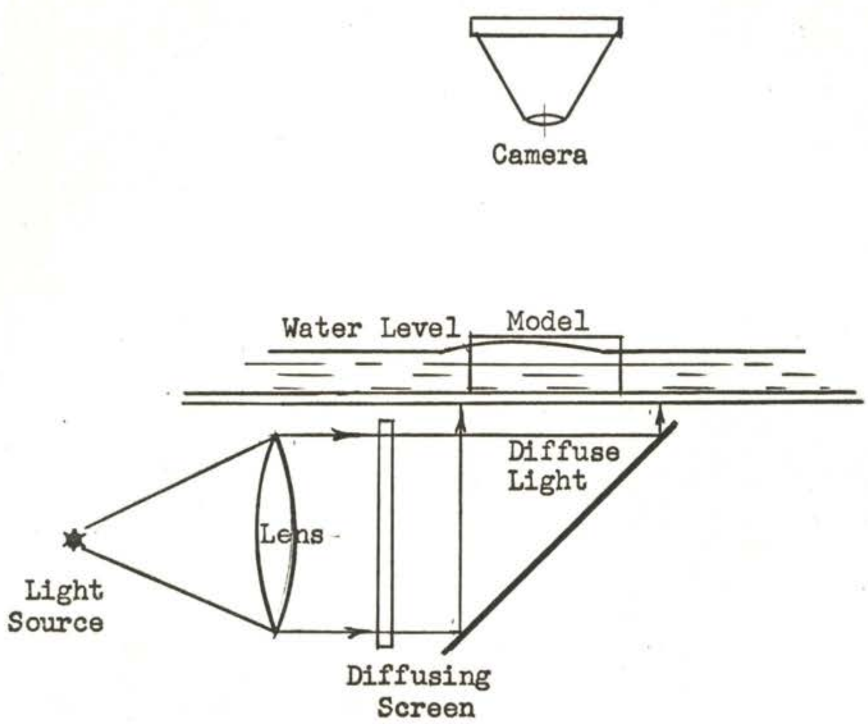


Fig. 1b. Transmission of Diffuse Light Through Water Surface

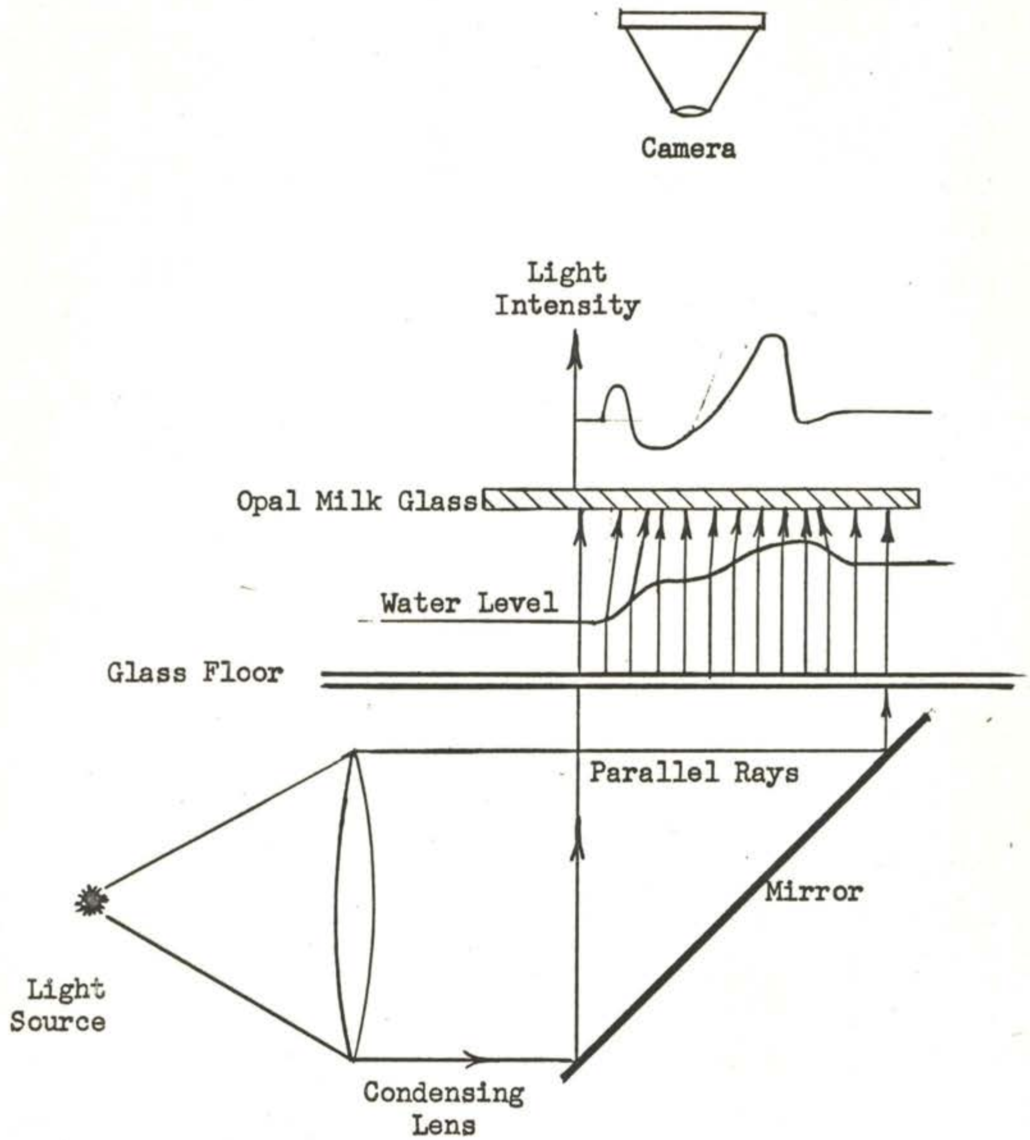


Fig. 1c. Transmission of Light Through Water Surface With Image Thrown On Screen

present. The proper tilt is probably best attained through trial and error.

Measurement of Water Depths

The simplest and most convenient method for determining the depth seems to be a needle probe that is mounted on a transverse mechanism capable of being moved in any of three rectangular coordinate directions. The tip of the probe should be constructed of platinum or other non-corrosive metal. The depth is determined from a vernier scale that should be capable of .001 inches readability. The moment the tip of the probe makes contact with the water, a capillary wave will be clearly seen and the water depth can be read.

Choice of Water Height

The water height selected must be such that the effects of capillary waves will be minimized and also the radius of curvature of the free surface is large compared with the water depth so that vertical motion can be made negligible except in the vicinity of a hydraulic jump.

The effects of capillary waves can be minimized by either using a small flow depth of about 0.25 inches which will result in the capillary waves behaving like gravity waves, or by using flow depths in excess of one foot. The large flow depths will give capillary waves so large that the effects become secondary.

CHAPTER III

VALIDITY OF THE ANALOGY

Some assumptions of the analogy will be reviewed to help evaluate the significance of data obtained from a water table.

Vertical Motions

The basis of the analogue is that water flow is two-dimensional. This assumption may immediately create the impression that the analogue has no validity when vertical motions exist. Although two-dimentional flow rules out any vertical motion, the analogy refers to a limiting case where the vertical components of velocity and acceleration are negligibly small. To maintain the validity, the slope of the water surface must be very small. This suggests the use of large models compared with water depth. In the case of shocks where there are rapid changes in water depth, the vertical motions may effect the analogy considerably. It is believed that the descrepancies that exist between wind tunnel and water table tests are largely due to ignoring of vertical motions in the analogy. In order to maintain the vertical motion to a minimum, a flow of about one-fourth inch in the "supersonic region" is recommended for best results.

Surface Tension

The effects of capillary waves impose a problem on shadowgraph observation and photography. The capillary waves are in many instances more prominent than the phenomena that is attempted to be studied. Attempts have been made to reduce the capillary effects by the adding of wetting agents to the water. This is an effective way of reducing them; but it introduced such unstable shocks, similar to those found in the mixed flow region, that its disadvantages exceeded its benefits. The choice of the water height is a suggested method of overcoming capillary waves.

Shock Wave

The hydraulic jump and shock wave are considered analogous but unfortunately this analogy is not quantitatively exact. The error that exists varies directly with the Mach number, but when the Mach number is not much greater than one, the error is quite small.

The analogy is summarized in the introduction. The entire theory of the water-gas analogy is given in much greater detail in reference (4).

CHAPTER IV

DESIGN CONSIDERATIONS

Table Bottom and Sides

Plate glass will be used for the bottom and sides of the water table to allow for a wide variety of photographic techniques.

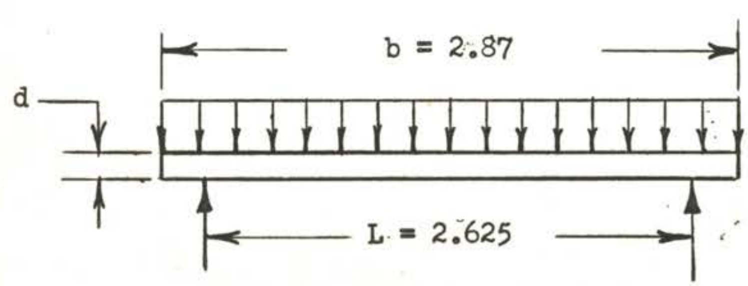
In the selection of the glass, the thickness must be considered so that it will not sag. If the glass sags, it would vary the depth of the water at different locations resulting in a different flow pattern. The variation of the depth would not be known to the operator from the method that is available for depth measurement and the results would be unreliable and the analogy invalid.

In determining the glass thickness, the weight of the water, the weight of the nozzle, and the weight of the model were considered for a maximum depth of one inch.

From the following calculations, the minimum thickness of the glass to be used was determined:

Maximum deflection $D = \frac{5WL^3}{384\ EI}$ $\qquad I = \frac{bd^3}{12}$

E for plate glass = 10×10^6 psi



Wt. of water = (2.87 x1x 1/12)(62.4)	=	15
Assumed Nozzle wt.	=	10
Assumed wt. of Model	=	10
Wt. of 3/8 inch plate glass (3 x1x 1/48) (160)	=	10
		45 #/ft

Design for .01 in. deflection, considering the total weight to be uniforly distributed:

$$D = \frac{5\ WL^3}{384\ E\ \frac{bd^3}{12}} = \frac{5\ WL^3}{32\ E\ bd^3}$$

$$d^3 = \frac{5\ WL^3}{32\ E\ b\ D} = \frac{5(45)(2.625)^3}{32(10 \times 10^6)\ 144(2.87)\frac{.01}{12}}$$

$$d^3 = 3.68 \times 10^{-5}$$

$$d = .033 \text{ ft.} = .366 \text{ inches}$$

A three-eights inch plate glass will suffice for a deflection of .01 inches with one inch water flow, but to decrease the deflection and also allow additional weight for the model and nozzle, one-half inch plate glass should be used. This is readily available commercially.

Table sides: The sides of the table will not be subjected to any significant weight, but they should be thick enough to withstand accidental taps. A one-fourth inch plate glass will be used.

Sluice-Type Nozzle

A sluice-type nozzle will be used primarily to produce a test section flow with a smooth surface.

The sluice nozzle will be constructed of one-half inch plexiglass and can be moved upward at a 45° angle to increase the water flow depth. Refer to Plate 3, sheet 2.

Frame Assembly

The frame assembly will be constructed of 2 X 2 X $\frac{1}{4}$ inch steel angles. This will have sufficient strength to support the table, sluice tank, sump tank, piping, motor and other auxiliary equipment. The floor of the frame will consist of white pine and will be bolted to the bottom of the frame. Refer to Plate 1, sheet 2. Attached to the bottom of the frame will be four casters, swivel type, with rubber wheels. The casters will allow the table to be mobile which will increase its usefullness by locating the table in class meeting areas or wherever else desired. Adjacent to each wheel on the ends of the frame is an adjustable "floor truck lock" to use in leveling the table. When the table is moved to the desired location, the locks will be adjusted to lift the table off the wheels and give the needed slope to the table to overcome the friction of the water on the table, thereby giving constant flow in the test section.

Sump Tank, Sluice Tank and Piping

The tanks and the piping will be constructed of material that will resist corrosion or hold corrosion to a minimum. Galvanized iron, aluminum, copper, brass and rubber were considered. It was decided to use galvanized iron for constructing the tanks rather than aluminum, since it would be easier to work with and may be easily soldered. Piping will be galvanized iron, with rubber hosing used for facilitating connections. The rubber hosing will also decrease sump noise and dampen pump vibrations as well as to facilitate the installation of piping.

An angle valve will be located downstream of the pump to regulate the water flow to the sluice tank, which will determine the head. The regulation of the head in the sluice tank will determine the rate of water flow on the table which, in turn, determines the Mach number in the analogy.

A hose drain and valve will be installed below the sluice tank in order to drain the water from the system when it is not in use.

Carriage Assembly

The assembly for the overhead carriage will be constructed of aluminum with fiber wheels which will be machined to fit snugly over tracks made of one-inch aluminum rod, Plate 5.

Longitudinal one-inch rods will function as tracks so supported as to prevent any deflection. Since the ability to determine the water depth very accurately is a prime factor, care was taken to prevent any sag in the tracks as well as the glass bottom.

Attached to the carriage will be a mount in which the depth gage or an impact tube may be placed. The mount will ride on transverse seven-eighths inch rods and can be moved by the cable and pulley arrangement, shown on Plate 5, across the width of the table. The depth gage (Starrett #445B) and probe will be capable of vertical movement. The combination of the carriage, mount and gage movement will result in the ability to survey the table in all three rectangular coordinate directions.

Water Depth Gage and Pitot Tube

A needle probe with platinum tip mounted on the carriage assembly which may be moved in any of three rectangular coordinate directions will be used for surveying the water depth.

A pitot tube can be used to measure the "stagnation pressure" or total head. The total head is composed of two parts, the static head, h_o, and the dynamic head, Δh, expressed in length of a column of the flowing fluid (Figure 2)

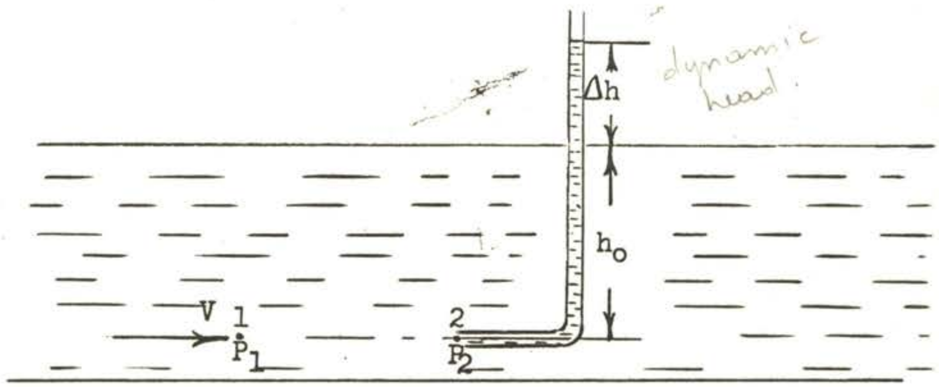


Fig. 2. Pitot tube

Bernoulli's equation written between points 1 and 2 is

$$\frac{v^2}{2g} + \frac{p_1}{\gamma} = \frac{p_2}{\gamma} = h_o + \Delta h$$

since both points are at the same elevation. As $\frac{p_1}{\gamma} = h_o$ the equation reduces to

$$\frac{v^2}{2g} = \Delta h \qquad \text{or} \qquad v = \sqrt{2g\,\Delta h}$$

which gives the velocity of the fluid.

Pump Selection

As previously mentioned in Chapter III, the analogy is more valid when the flow depth is limited so that vertical influence would be negligible.

About a one-fourth inch depth gives the most accurate results, and the depth should be held to a maximum of one inch even at low speeds. Since the analogy loses its validity in depths exceeding one inch, the pump calculations were based on a Froude number of one at a one-inch flow depth. After arriving at the minimum required horse power, the pump was selected from the Deming Company catalog using the total head and the flow rate.

The minimum pump size was determined from the following calculations:

Using two-inch piping

$$Fr = \frac{V}{\sqrt{gd}} \qquad V = 1\,(\sqrt{gd}) = 1\sqrt{32.2(1/12)}$$

$$V = 1.637 \approx 1.64 \text{ fps}$$

Flow = (1/12 X 3 X 1.64) = .41 cu ft/sec

= .41 (448.8) = 184 gal/min

$$V = \frac{Q}{A} = \frac{.41}{\frac{\pi(1/6)^2}{4}} = 18.76 \text{ fps}$$

$$\nu = 1 \times 10^{-5} \text{ @ 70 degrees}$$

$$R = \frac{VD}{\nu} = \frac{18.76\ (1/6)}{1 \times 10^{-5}} = 3.13 \times 10^5$$

$$\epsilon = .0005 \text{ ft (galv. iron)}$$

$$\frac{\epsilon}{D} = \frac{.0005}{\frac{1}{6}} = .003$$

From the Moody Diagram f = .03 (Ref. 14)

Equivalent length of pipe

Three two-inch standard elbows = 3(5.2) = 15.6

One two-inch angle valve = 6.3

Three foot length of straight pipe = 3

24.9

$$h_f = f\frac{L}{D}\frac{V^2}{2g} = .03\ \frac{24.9}{\frac{1}{6}}\ \frac{(18.76)^2}{64.4} = 24.5$$

head loss = 24.5

Elevation head = 1.5

$$h_f = 24.5 + 1.5 = 26 \text{ feet}$$

$$BHP = \frac{Q\ h_f}{3960 \text{ eff}} = \frac{184\ (26)}{3960(.70)} = 1.73 \text{ BHP}$$

The motor pump unit selected is a Deming Unit No. 31 S, 3hp, at 1750 rpm. It will be mounted as shown on Plate 1, sheet 1, with a flex mount to reduce transmission of motor vibrations.

OR

Peerless - PE 808 $20

or Aurora - T26 17

[illegible]

CHAPTER V

SUMMARY AND CONCLUSIONS

The primary objective of this report was to design an apparatus to be used for class demonstration and experiments utilizing the water analogy to two-dimensional compressible gas flow.

The unit was so designed to be self-contained, mobile, inexpensive to construct and operate, yet contain all the features desired in such an apparatus.

Care was taken to allow for adjustments of all parts whose position is critical. This would eliminate the necessity of construction to extreme tolerances.

During the construction of the water table, care should be taken to isolate motor vibrations. In the event that vibration effects cannot be isolated, the present pump mount can be easily removed and a portable mount with its base on the room floor be substituted or provision made for lifting the presently located motor free from the support frame.

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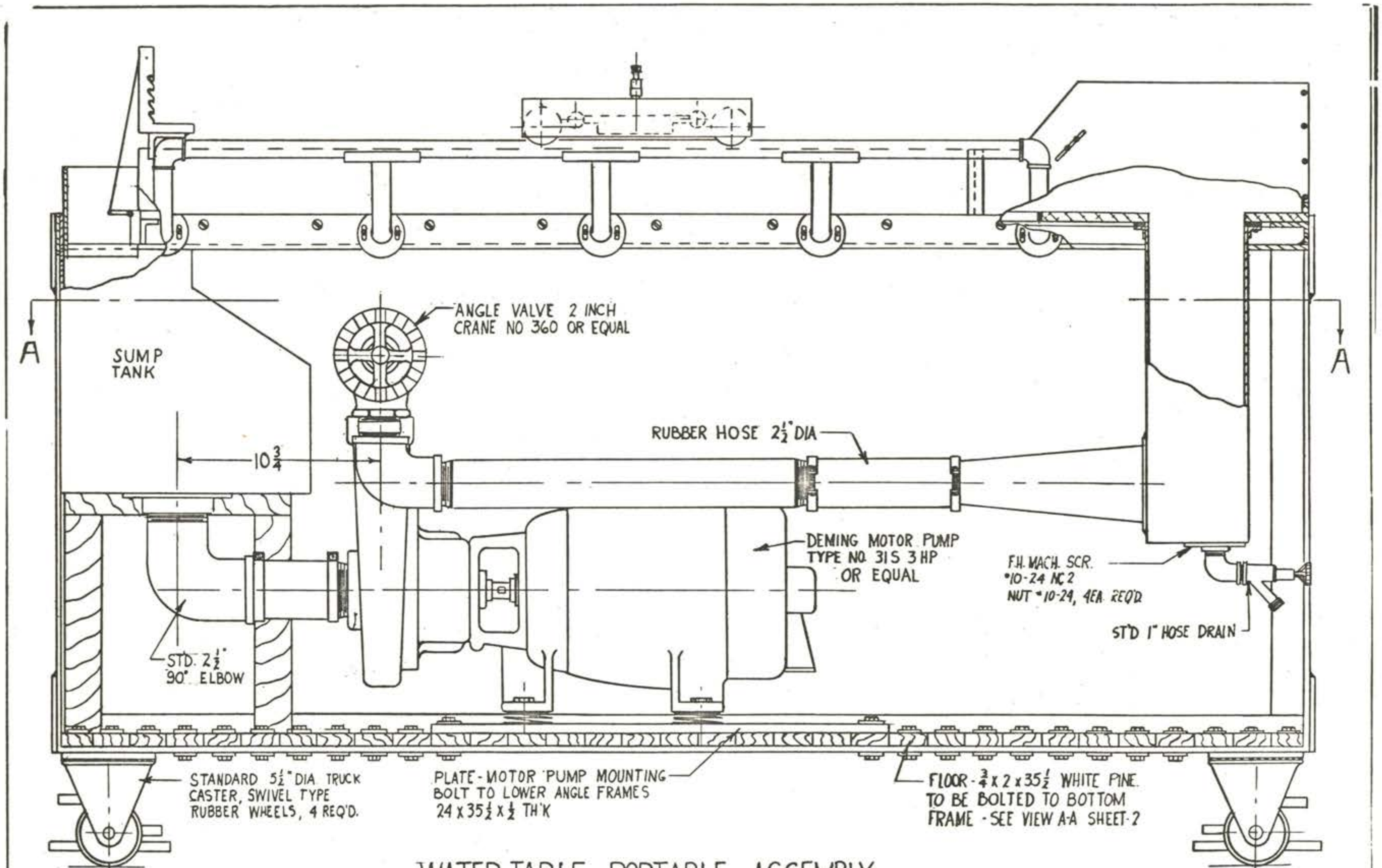
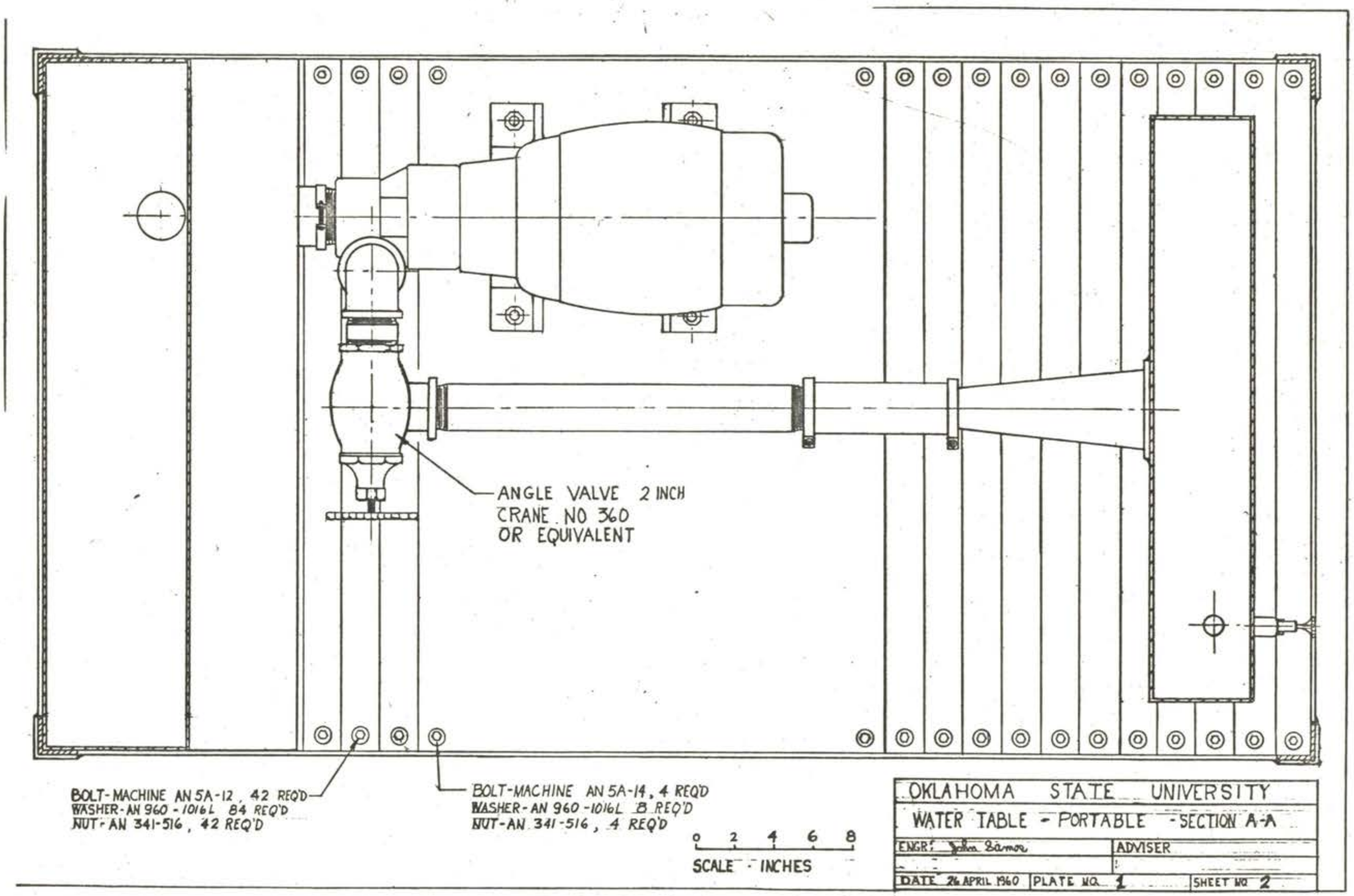
APPENDIX

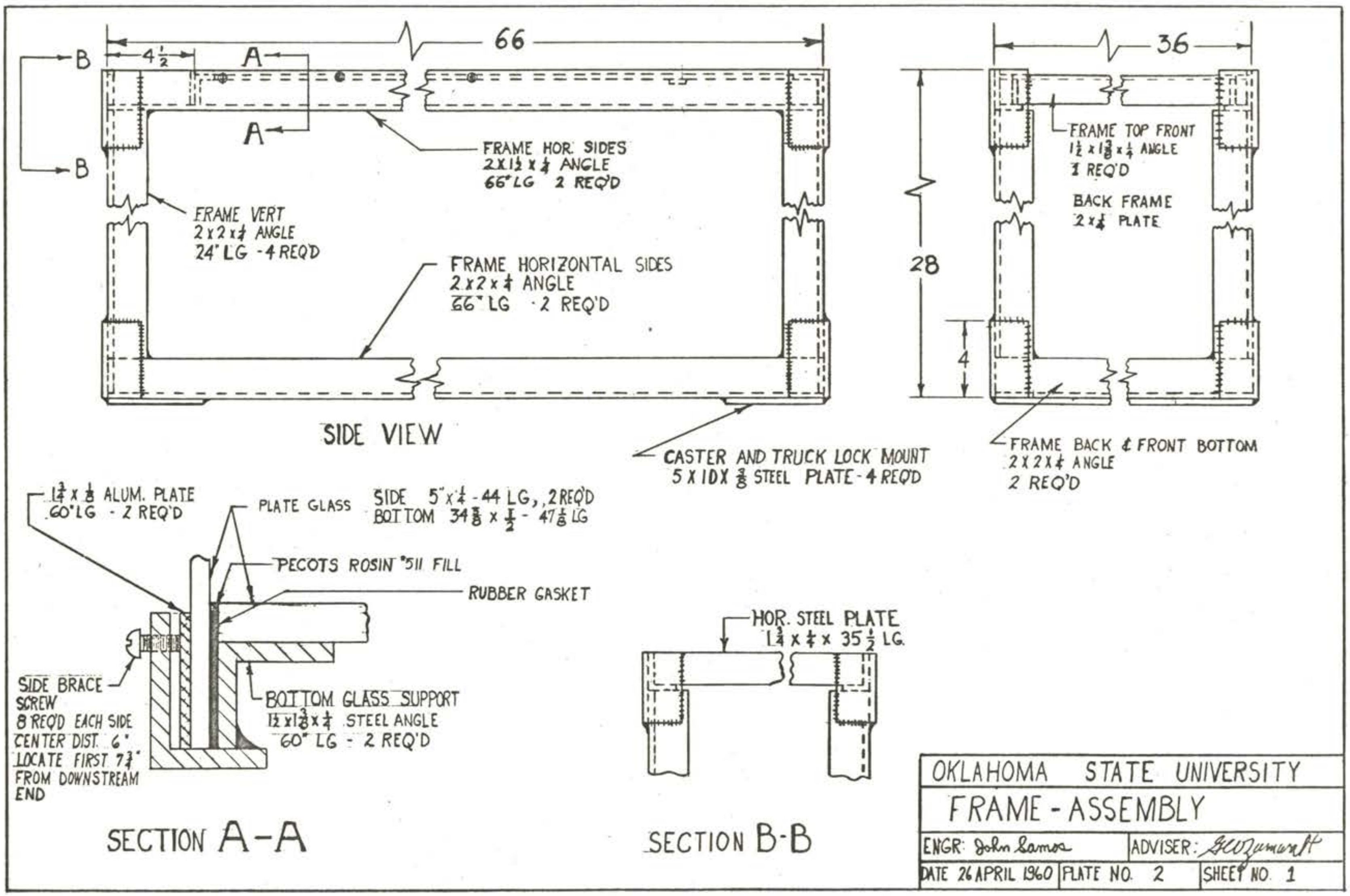
Design Plates

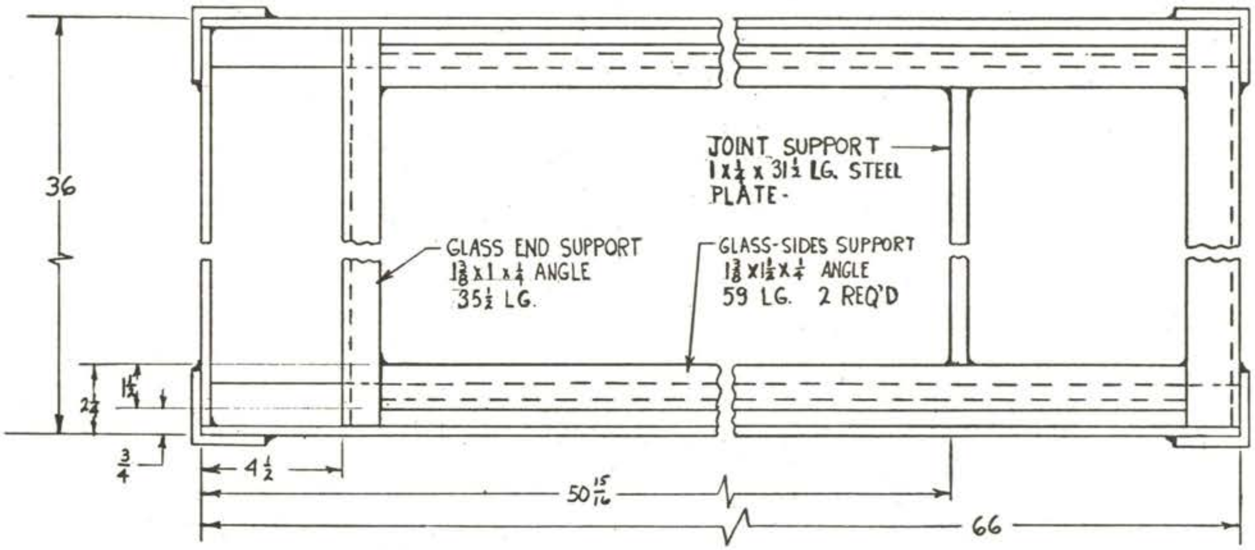


WATER TABLE - PORTABLE - ASSEMBLY

PLATE 1 SHEET 1

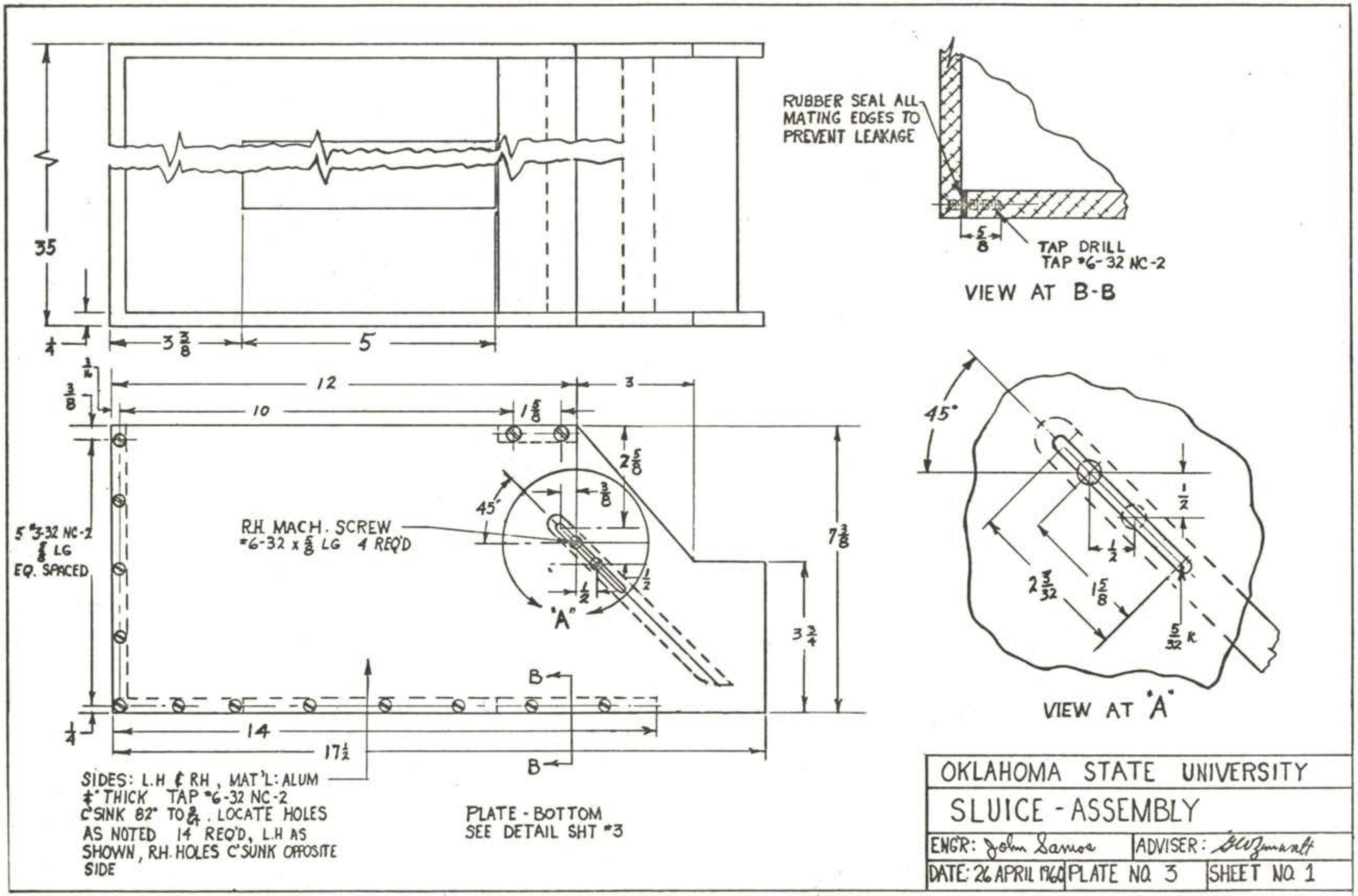

ANGLE VALVE 2 INCH
CRANE NO 360
OR EQUIVALENT
BOLT-MACHINE AN 5A-12, 42 REQ'D
WASHER-AN 960-1016L 84 REQ'D
NUT-AN 341-516, 42 REQ'D
BOLT-MACHINE AN 5A-14, 4 REQ'D
WASHER-AN 960-1016L 8 REQ'D
NUT-AN 341-516, 4 REQ'D
0 2 4 6 8
SCALE - INCHES
OKLAHOMA STATE UNIVERSITY
WATER TABLE - PORTABLE - SECTION A-A
ENGR:
ADVISER
DATE 26 APRIL 1960
PLATE NO. 1
SHEET NO 2

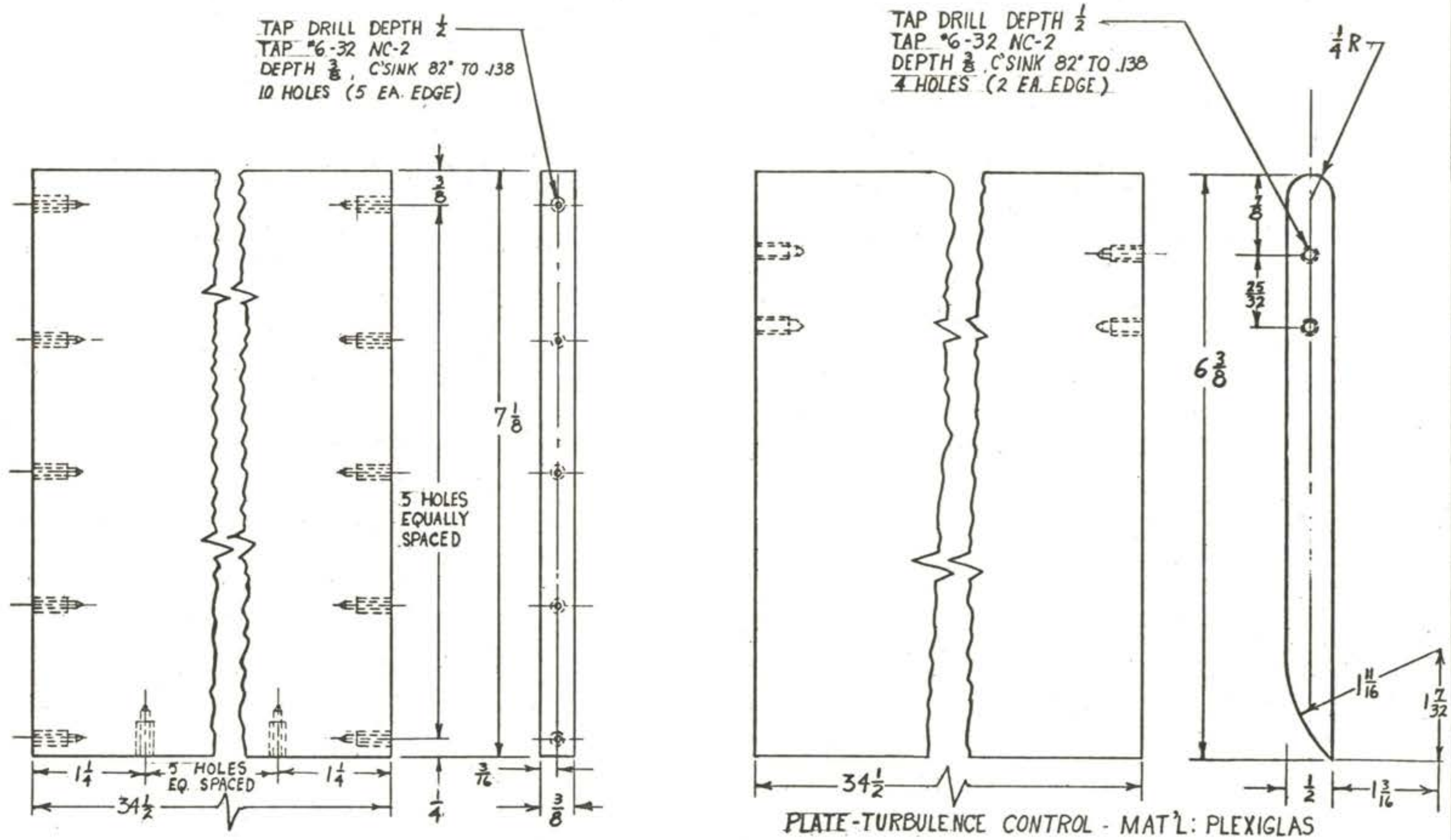

66
36
4 1/2
A
B
FRAME HOR. SIDES
2 X 1 1/2 X 1/4 ANGLE
66" LG 2 REQ'D
FRAME VERT
2 x 2 x 1/4 ANGLE
24" LG - 4 REQ'D
FRAME HORIZONTAL SIDES
2 x 2 x 1/4 ANGLE
66" LG - 2 REQ'D
FRAME TOP FRONT
1 1/2 x 1 3/8 x 1/4 ANGLE
1 REQ'D
BACK FRAME
2 x 1/4 PLATE
28
4
SIDE VIEW
CASTER AND TRUCK LOCK MOUNT
5 X 10 X 3/8 STEEL PLATE - 4 REQ'D
FRAME BACK & FRONT BOTTOM
2 X 2 X 1/4 ANGLE
2 REQ'D
1 3/4 x 1/8 ALUM. PLATE
60" LG - 2 REQ'D
PLATE GLASS
SIDE 5" x 1/4 - 44 LG., 2 REQ'D
BOTTOM 34 3/8 x 1/2 - 47 1/8 LG
PECOTS ROSIN #511 FILL
RUBBER GASKET
SIDE BRACE SCREW
8 REQ'D EACH SIDE
CENTER DIST. 6"
LOCATE FIRST 7 3/4"
FROM DOWNSTREAM END
BOTTOM GLASS SUPPORT
1 1/2 x 1 3/8 x 1/4 STEEL ANGLE
60" LG - 2 REQ'D
HOR. STEEL PLATE
1 3/4 x 1/4 x 35 1/2 LG.
SECTION A-A
SECTION B-B
OKLAHOMA STATE UNIVERSITY
FRAME - ASSEMBLY
ENGR: John Samos
ADVISER:
DATE 26 APRIL 1960
PLATE NO. 2
SHEET NO. 1



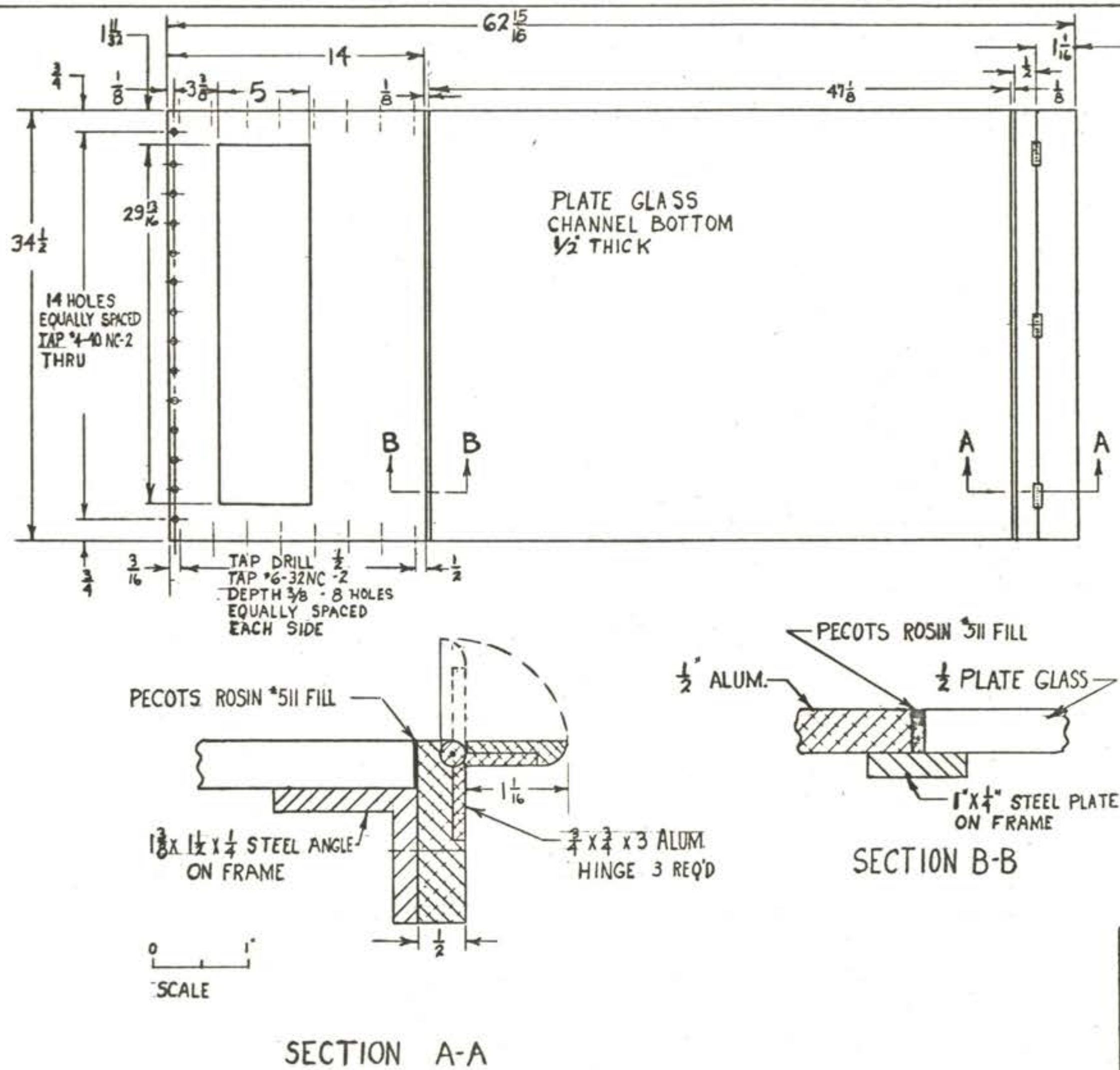
TOP VIEW - UPPER STRUCTURE

OKLAHOMA STATE UNIVERSITY		
FRAME ASSEMBLY-		
ENG'R: John Samos	ADVISER:	
DATE 30 APRIL 1960	PLATE NO. 2	SHEET NO. 2

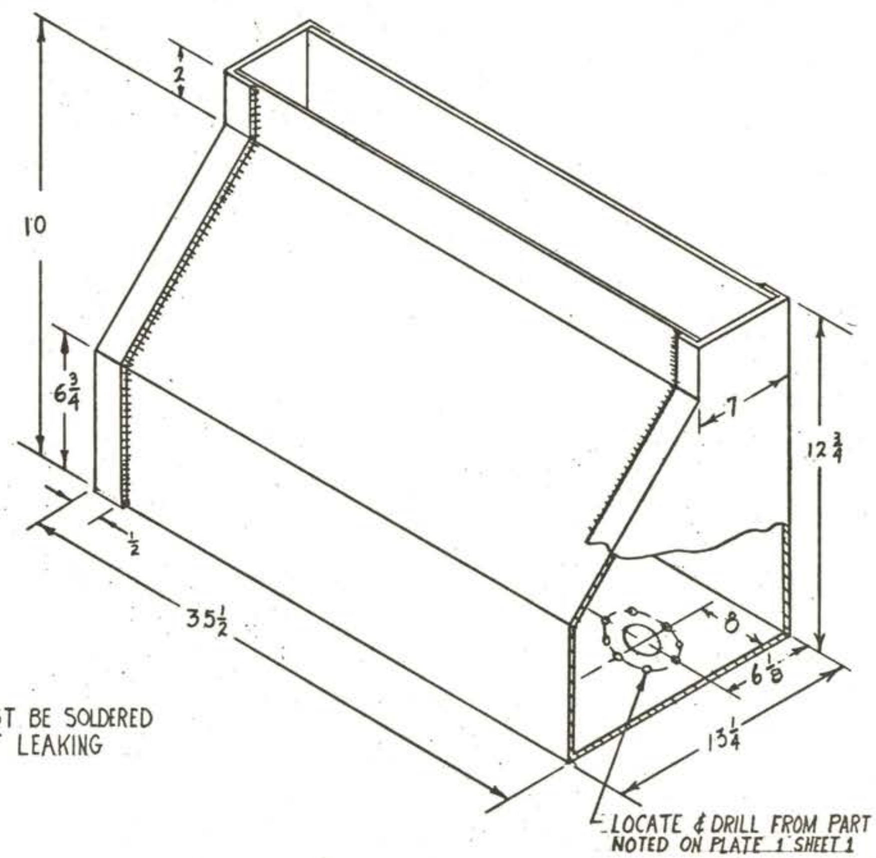

RUBBER SEAL ALL MATING EDGES TO PREVENT LEAKAGE
TAP DRILL TAP #6-32 NC-2
VIEW AT B-B
RH MACH. SCREW #6-32 x 5/8 LG 4 REQ'D
5 #3-32 NC-2 5/8 LG EQ. SPACED
SIDES: L.H & RH, MAT'L: ALUM 1/4" THICK TAP #6-32 NC-2 C'SINK 82° TO 3/8. LOCATE HOLES AS NOTED 14 REQ'D, L.H AS SHOWN, RH. HOLES C'SUNK OPPOSITE SIDE
PLATE - BOTTOM SEE DETAIL SHT #3
VIEW AT "A"
OKLAHOMA STATE UNIVERSITY
SLUICE - ASSEMBLY
ENG'R: John Samos
ADVISER: G.W. Zumwalt
DATE: 26 APRIL 1960
PLATE NO. 3
SHEET NO. 1

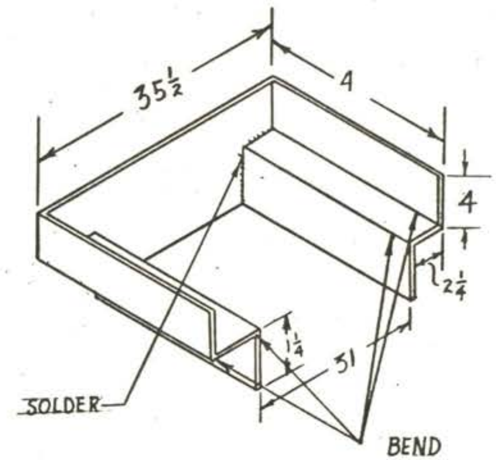


OKLAHOMA STATE UNIVERSITY		
SLUICE - DETAILS		
ENGR: John Samos	ADVISER: G. W. Zumwalt	
DATE 28 APRIL 1960	PLATE NO. 3	SHEET NO. 2



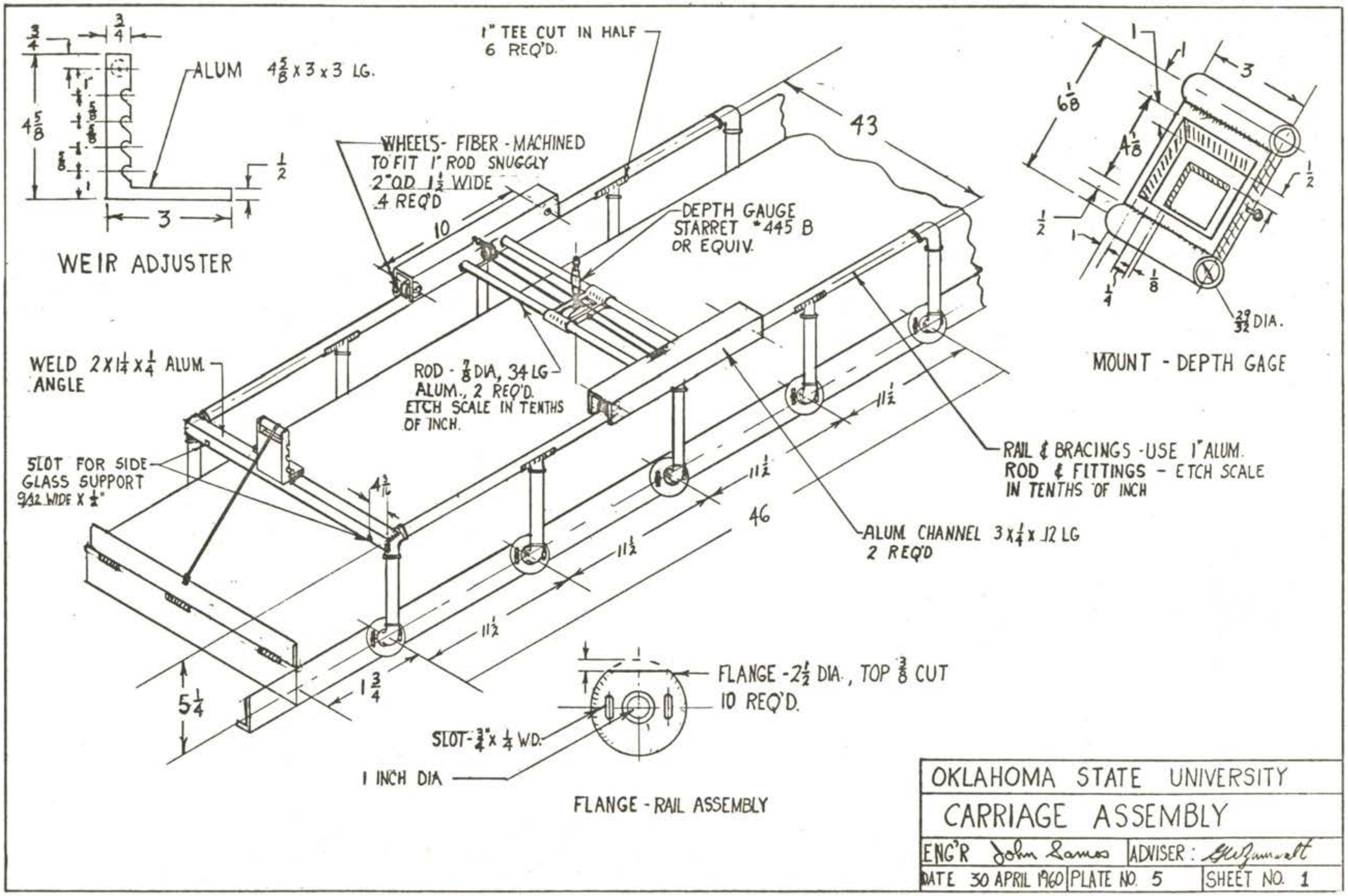
OKLAHOMA STATE UNIVERSITY	
CHANNEL BOTTOM - DETAILS	
ENGR John Samos	ADVISER: [illegible signature]
DATE 29 APRIL 1960	PLATE NO. 3	SHEET NO. 3



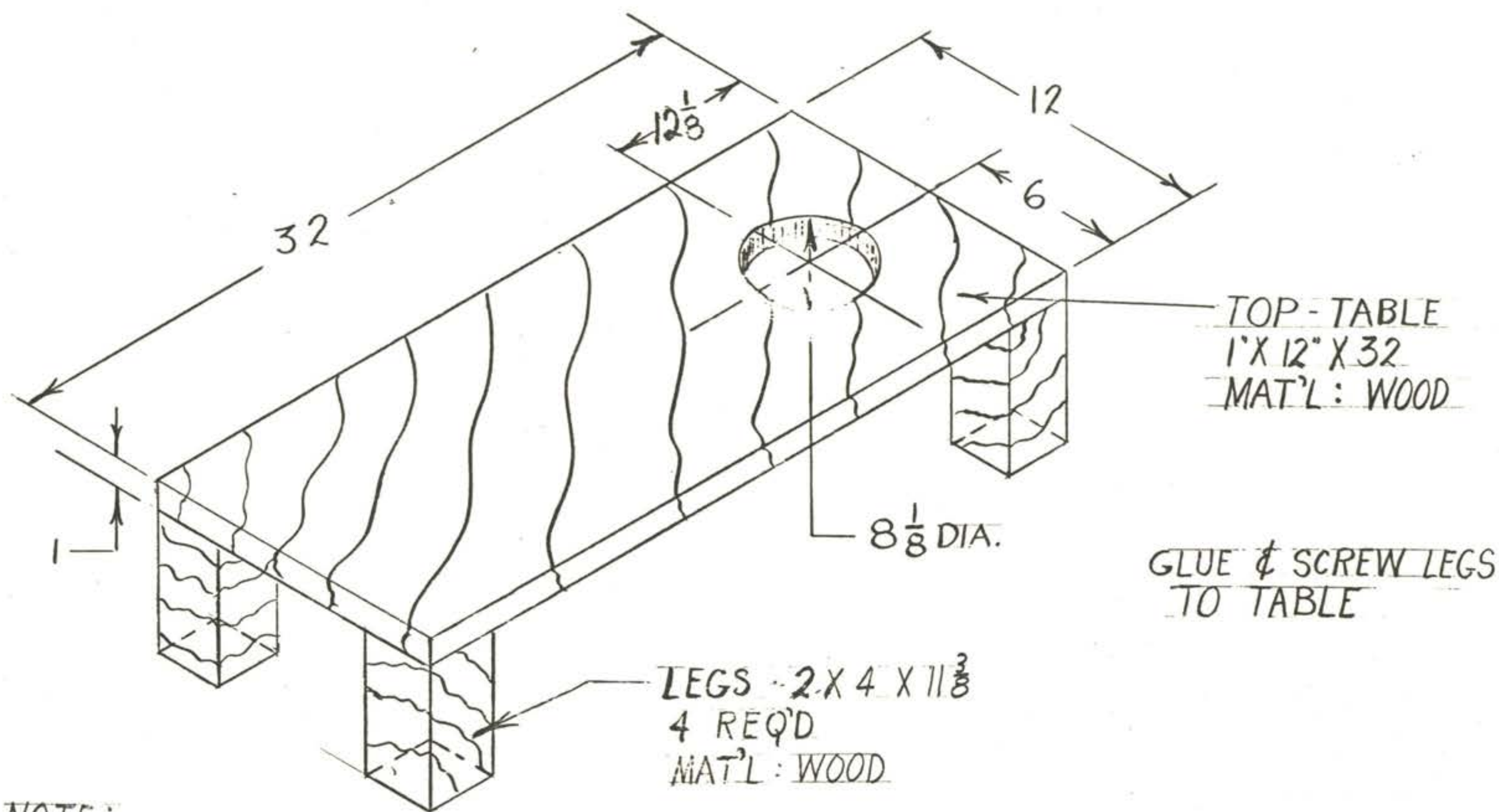


NOTE:
EDGES MUST BE SOLDERED
TO PREVENT LEAKING

OKLAHOMA STATE UNIVERSITY		
TANK - SUMP		
ENG'R John Samos	ADVISER: Guzmanlt	
DATE 26 APRIL 1960	PLATE NO. 4	SHEET NO. 1



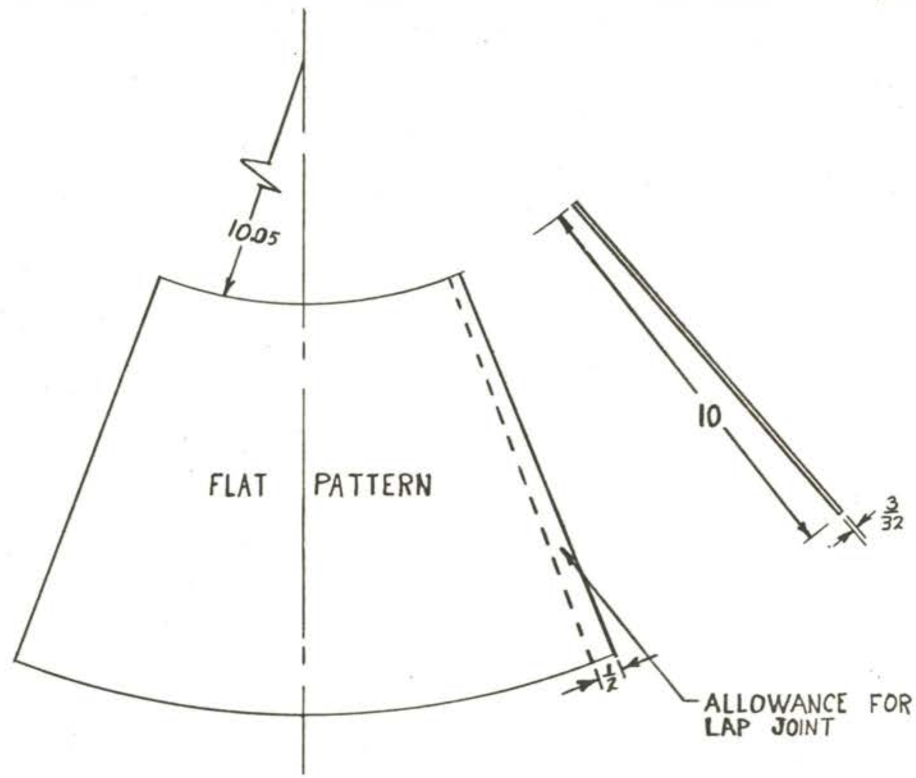
WEIR ADJUSTER
ALUM 4⅝ x 3 x 3 LG.
1" TEE CUT IN HALF
6 REQ'D.
WHEELS - FIBER - MACHINED
TO FIT 1" ROD SNUGGLY
2" O.D. 1½ WIDE
4 REQ'D
43
DEPTH GAUGE
STARRET #445 B
OR EQUIV.
MOUNT - DEPTH GAGE
29/32 DIA.
WELD 2 X 1¼ X ¼ ALUM. ANGLE
ROD - ⅞ DIA, 34 LG -
ALUM., 2 REQ'D.
ETCH SCALE IN TENTHS
OF INCH.
SLOT FOR SIDE GLASS SUPPORT
9/32 WIDE X ½"
RAIL & BRACINGS - USE 1" ALUM.
ROD & FITTINGS - ETCH SCALE
IN TENTHS OF INCH
ALUM. CHANNEL 3 X ¼ X 12 LG
2 REQ'D
46
FLANGE - 2½ DIA., TOP ⅜ CUT
10 REQ'D.
SLOT - ¾" X ¼ WD.
1 INCH DIA
FLANGE - RAIL ASSEMBLY
OKLAHOMA STATE UNIVERSITY
CARRIAGE ASSEMBLY
ENG'R John Samos
ADVISER:
DATE 30 APRIL 1960
PLATE NO. 5
SHEET NO. 1



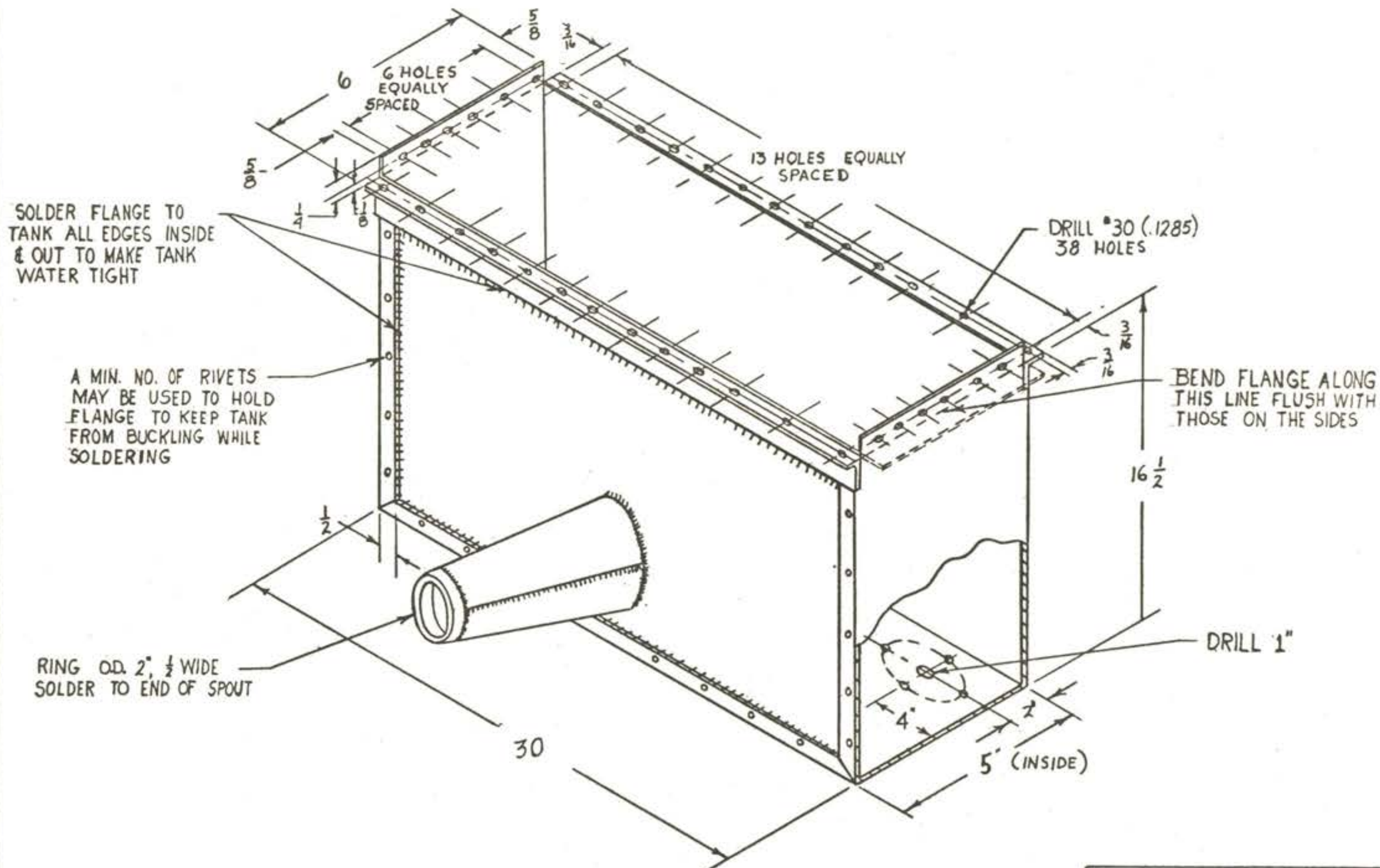
NOTE:

TABLE TO BE SECURE & MOUNTED TO FLOOR DIRECTLY BELOW SUMP TANK TO ALLOW FLANGE TO PROTRUDE THROUGH HOLE PROVIDED

OKLAHOMA STATE UNIVERSITY		
SUMP-TABLE		
ENG'R: John Samos	ADVISOR: Glen W. Zumwalt	
DATE 24 APRIL 1960	PLATE NO. 6	SHEET NO. 1



OKLAHOMA STATE UNIVERSITY		
SPOUT - SLUICE TANK		
ENGR: John Samos	ADVISER: G.L. Zumwalt	
DATE 27 APRIL 1960	PLATE NO. 7	SHEET NO. 1



OKLAHOMA STATE UNIVERSITY		
TANK - SLUICE		
ENG'R: John Samos	ADVISER: [illegible]	
DATE 25 APRIL 1960	PLATE NO. 8	SHEET NO. 1

VITA

John Samos

Candidate for the Degree of

Master of Science

Report: DESIGN OF A FREE WATER SURFACE TABLE TO BE USED AS AN ANALOGY TO TWO-DIMENSIONAL COMPRESSIBLE GAS FLOW

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born in New York City, New York, August 27, 1923, the son of Frank and Effie Samos.

Education: Attended grade school in New York, New York, graduated from the High School of Commerce in New York, New York in 1942. Attended for varying periods, Academy of Aeronautics, New York, Pennsylvania State College, Sacramento State College and the University of Houston. Received the Bachelor of Science Degree from Oklahoma State University, with a major in Mechanical Engineering, in January, 1960; completed the requirements for the Master of Science degree in May, 1960, at Oklahoma State University.

Professional Experience: Employed as a Project Engineer at NACA, Langley Field, Virginia, from 1947 to 1949; is a Reserve Officer in the United States Air Force and presently serving in the grade of Captain.