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RELATION BETWEEN WIND VELOCITY
AND WIND PRESSURES

THESIS FOR THE DEGREE OF B. S.

Robert M. Branch

1931

THESIS

Wind pressure

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RELATION BETWEEN WIND VELOCITY AND
WIND PRESSURES

A Thesis Submitted to
The Faculty of
MICHIGAN STATE COLLEGE
of
AGRICULTURE AND APPLIED SCIENCE

By

Robert M. French

Candidate for the Degree of
Bachelor of Science

June 1931

THESIS

2001

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NOMENCLATURE

V---Velocity of wind in M.P.H. of air hitting plate.

V_1 ---Manometer reading.

V_t ---Average Velocity for entire Tunnel.

P---Pressure of wind in pounds per square inch.

P_1 ---Grains on balance.

D---Density of Medium.

K---Constant.

W---Weight of Air hitting Plate.

w---Weight of air in pounds per square foot.

H---Pressure head.

a---Cross-section area of air stream.

M---Mass of air at weight w.

g---Acceleration due to Gravity.

F---Force exerted by air on Plate.

C---Velocity coefficient for plate.

Because the modern tall building frame constitutes one of the most indeterminate structures in common use, in regard to wind stresses, it is of utmost importance to determine a proper uniform wind pressure and its distribution over the surface exposed. These facts are not generally recognized because the very tall building in which wind stresses are of major importance is of comparatively recent origin, and because the maximum forces (wind storms) for which they must be designed are of rare occurrence, and therefore, the structure inadequately designed for wind may serve for many years without giving any indication of weakness.

There is a present day avitation favoring the increase of the allowable working stresses used in the design of structural steel. This is based on the assumption that the actual stresses which will exist in the structure can be calculated within reasonable limits, due to the fact that steel structures, such as tall buildings, are so indeterminate as far as stresses produced by wind are concerned, that the wind wind velocities and resulting pressures are only approximations. As the height of these structures increases, these stresses become of major importance, and the determination of the proper uniform wind pressure is imperative.

The wind velocities published by the United States Weather Bureau are indicated velocities on the standard

four-cup anemometer, and the three-cup anemometer. The four-cup anemometer has an indicated velocity which is about 20 per cent high. However, the three-cup anemometer which has been used recently gives very accurate readings.

Because during tornadoes and hurricanes the instruments that are set to measure the velocities are destroyed by the storms that they are to measure, it is not known what the exact velocities the wind may attain. The following is taken from the Monthly Weather Review, January 1883:

"Summit of Mt. Washington, N.H., Jan. 3, 1883. The wind increased to a violent hurricane, breaking off the anemometer at the dial. At the time the instrument was broken, a velocity of 152 mi. per hour was registered. It was impossible to replace the anemometer during the violence of the storm. In order to measure the rain fall, the observer was compelled to crawl to the rain gauge, it being impossible to stand before the force of the wind. The storm continued during the 4th."

From the Bulletin of the American Meteorological Society, December, 1935, the following is taken:

"On February 23, 1886, the mean hourly velocity (at the summit of Mt. Washington) for 24 hours was 111 miles per hour, and in January, 1878, the extraordinary velocity of 183 miles per hour occurred."

During the Miami hurricane no satisfactory records were secured due to the fact that the apparatus of the Weather Bureau was located on a low building surrounded by tall buildings. The observer estimated the velocity to have been between 110 and 120 miles per hour. An anemometer at Allison Hospital, on Miami Beach, only a few miles away was blown down with the maximum velocity recorded as 128 miles per hour.

Some of the high wind velocities on record are as follows:

120 M.P.H.	Oct. 13, 1913, Pensacola, Fla.
120 " " "	Sept. 8, 1900, Galveston, Tex. (Anemometer was blown down).
120 " " "	Aug. 7, 1899, San Juan, P.R.
115 " " "	Oct. 13, 1913, Mobile, Ala.
105 " " "	Aug. 20, 1904, St. Paul, Minn.
96 " " "	Feb. 23, 1912, New York
96 " " "	Dec. 23, 1930, Buffalo, N.Y.

Many other velocities exceeding 90 miles per hour have been recorded in different parts of the United States. These are the true velocities as the indicated velocities would appear to be 120 to 130 miles per hour. At times the extreme velocities up to 150 miles per hour might occasionally occur.

Wind pressures on large surfaces is usually less per unit area than on small surfaces. This is due to the gusty nature of the wind and also to the fact that the wind acts as a shaft or stream of air in motion rather than as

the body as a whole moving all parts with the same velocity. Mr. R. Fleming states in "Wind Formulas and Their Experimental Basis" :

"On the Forth Bridge two pressure boards were set up, one 30 ft. long and 15 ft. high, and 8 ft. from it a circular plate $1\frac{1}{2}$ sq. ft. in area. The maximum pressure registered on the small plate during the years 1884 to 1890 was 41 lbs. per sq. ft. The large board showed at the same time a pressure of 37 lbs. per sq. ft. The readings for the large board never exceeded 80 per cent of those recorded on the small plate at the same time, and generally were 50 to 70 per cent."

The same thing was noted by Mr. Julius Baire in the St. Louis tornado of May 28, 1896. Part of the approach of the Eads Bridge was damaged during the storm, and Mr. Baire calculated from the moment of stability, the overturning force exerted by the wind, also for a brick chimney and a grain elevator which was 115 feet high, and 200 feet long. In his conclusions he states the following:

"It gave evidence that wind pressure existed at least equivalent to or greater than 20 lbs., 30 lbs. and 85 to 90 lbs. per sq. ft., over considerable areas. Whatever the actual distribution may have been, the effects were those of such pressures uni-

formly distributed over the areas of the respective structures. These pressures were measured by their results in exactly the same manner in which they are ordinarily assumed to act, with the consequent elimination of all uncertainties usually involved in readings of pressure gauges or deductions from anemometer records, and the are to that extent positive and definite."

From this evidence it would be safe to give some reduction to the uniform pressure as the area exposed increases. A copy of the curve in which Mr. Paire plots the calculated pressures against their respective areas is given with this discussion. (Figure II).

According to the Newtonic Theory, V varies as $\frac{P}{D}$, or P varies as dv^2 , as stated in Sir Isaac Newton's great masterpiece, "Philosophia Naturalis Principia Mathematica", the revised edition, Book II, Section VIII, Prop. XLVIII. "The velocities of pulses propagated in an elastic fluid are in a ration compounded of the subduplicate ratio of the elastic force directly, and the subduplicate ratio of the density inversely, supposing the elastic force of the fluid to be proportional to its condensation." Or in other words:

$$V \text{ varies as } \frac{P}{D}, \text{ or } P \text{ varies as } dv^2.$$

Density of air is so near a constant that it may be

considered such for all practical purposes. Hence, we have the equation:

$$P = KV^2$$

The most difficult part of using this equation for practical calculations lies in determining the constant (K). Deriving theoretically from the Newtonic Theory, we have as follows:

For Air at 32 degrees F. and barometric pressure of
760 mm.

$$W = .0807 \text{ lbs./cu. ft.}$$

$$P = Wh$$

$$h = \frac{V^2}{2g}$$

$$P = \frac{WV^2}{2g} = \frac{.0807 \cdot V^2}{32.2} = .00136V^2 \quad (V \text{ is in ft./sec.})$$

Changing (V) to miles per hour from ft. per sec.:

$$P = .0027V^2$$

Thus we have as a constant, .0027. However, this is purely theoretical and is based on the assumption that air is acting as a liquid.

From the "Design and Construction of Metallic Bridges" by Burr and Falk:

$$W = \text{Wt. of air hittin target}$$

$$w = \text{Wt. in lbs./cu. ft.}$$

$$V = \text{Velocity in ft./Sec.}$$

$$a = \text{Area of Crosssection of wind stream}$$

$$\text{Then, } W = waV$$

$$M = \text{Mass of air of wt. } W$$

g = Acceleration due to gravity

$$\text{Then } F = Mv = \frac{Wv}{g} = \frac{wav^3}{g}$$

Let $a = 1$ sq. ft.

$$w = .0907$$

Replace v by V (miles per hour), we have:

$$F = .0054 V^3$$

This is known as Rankine's formula. This has for its constant .0054 which is exactly double that of the theoretical constant of the Newtonic Theory and it is readily seen why there is so much controversy over the correct value for this constant. The reason for this double value is that a cushion is formed in front of the plate and a suction in back of the plate. The first formula does not take this into consideration.

Smeaton has experimented a great deal on wind tests and gives as his formula $P = 1/200 V^3$. This constant is very near the Newtonic constant. However, some of the most careful experiments in recent years give constants varying from .0033 to .004 with many values of from .0017 to .007. This tremendous range is due to perhaps different conditions and instruments of varying accuracy. The U. S. Weather Bureau takes into consideration the effect of barometric pressure and their formula is $P = .004 B/30 V^3$, where B is the barometric reading.

Along with the study of various formulae of previous experimenters, a very careful laboratory study was made of wind pressures and their corresponding velocities. The

author was very fortunate in having access to a wind tunnel and very accurate velocity instruments, thanks to the generosity of Mr. E. A. Finney of the Civil Engineering department of Michigan State College, who is the owner of the apparatus.

A rod was suspended from two pivots on top of the wind tunnel, by thin metal straps. In this way the rod was always in a horizontal position as shown on Plat I. Masonite plates were made of different known areas and were made so that they were interchangeable on the rod, and always in a plane perpendicular to the rod. Hence, they were in a vertical position.

The forward strap had an arm extension which transferred the force to the left-hand pan of balance scales. These lever arms were so constructed that the force on the plate was transferred to the scales so that the grams on the scales were equal to the total wind pressure on the plate. A free body diagram of the forces and moment arms are shown on Plate II.

By means of rating curves, the total force on the plate (in grams) is converted to lbs./sq. inch, and the average tunnel velocity, (measured in units on the manometer) to the average velocity on the plate by multiplying by the constant (C). This in turn is changed to miles per hour by means of another rating curve.

The manometer gives the average velocity of the entire tunnel, but the plate is suspended at the center of the tunnel and the velocity at the center is much higher than

Area In Sq. Ft.

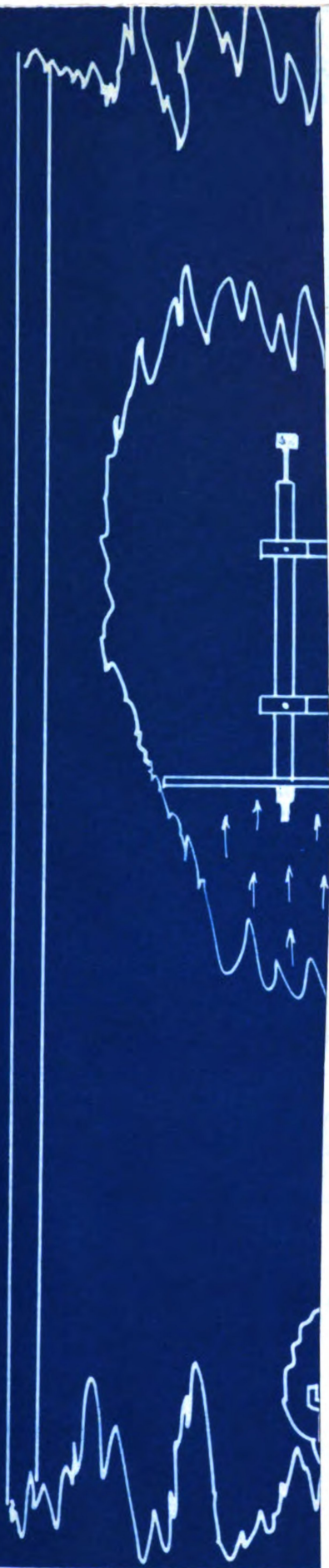
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RELATION BETWEEN PRESSURE & VELOCITY

By: Robt. M. Bunch

Fig. II.

[Signature]



DATE: May 1, 1931

RELATION BETWEEN PRESSURE & VELOCITY

By. Robt. M. Branch.

Fig. I.

Robt. M. Branch

the average tunnel velocity. To determine the exact relationship between the average velocity of the tunnel and the average velocity of the air striking the plate, three test runs were made over the surface of the plate, each at a different tunnel velocity. The first test was made with a tunnel velocity of 7.8 M.P.H. giving an average of 10.95 M.P.H. for the air striking the plate. Dividing the plate velocity by the average tunnel velocity gives the velocity coefficient for the plate. This coefficient derived from all tests was found to be practically a constant, the average being (1.4003) or practically (1.4). (See Table I) Multiplying the average tunnel velocity by this coefficient gives the correct average velocity over the entire plate which also is equal to the uniform wind load on this surface.

Tests were made on a plate six inches square or one quarter of a square foot. The velocity and corresponding pressure were measured and recorded with variations between 7 m.p.h. and 23 m.p.h. This gives an average constant for the formula $P = KV^2$, of .003614. The average constant (K) for the first test was .00358 and for the second test, .003625. The constants for all trials were between .0033 and .004, most of them being very close to .0036.

Curves were plotted with the velocity in M.P.H. as the abscissa and the pressure in lbs./sq. ft. as the ordinate. These curves are very clearly curves of the second power, agreeing with the equation $P = KV^2$.

TABULATED DATA FOR FINDING THE POINT OF AVERAGE
WIND VELOCITY

TABLE I

<u>Trial</u>	<u>Dist.</u> <u>Down</u> <u>On</u> <u>Plate</u>	Average Tunnel Velocity = 7.8		Average Tunnel $V_t = 10$ mph.		Average Tunnel $V_t = 11.1$ mph.	
		<u>Man.</u> <u>Rdg.</u>	<u>M.P.H.</u>	<u>Man.</u> <u>Rdg.</u>	<u>M.P.H.</u>	<u>Man.</u> <u>Rdg.</u>	<u>M.P.H.</u>
1.	0"	.02	6.4	.04	9.0	.045	9.5
2.	1"	.03	7.8	.05	10.0	.06	11.1
3.	2"	.04	9.0	.06	11.1	.08	12.8
4.	3"	.05	10.0	.08	12.8	.12	15.7
5.	4"	.09	13.6	.13	16.5	.16	18.2
6.	5"	.10	14.2	.16	18.2	.19	19.7
7.	6"	.13	<u>15.7</u>	.20	<u>20.2</u>	.24	<u>22.2</u>
Velocity Totals		73.7		97.8		109.2	
Dividing by 7:		10.95		13.98		15.59	
" " Av. V_t		1.402		1.398		1.401	

This gives a constant with an average of 1.4003, or practically $C = 1.4$.

To find the average velocity on the plate, the average tunnel velocity (v_t) must be multiplied by this constant (C). The reason for this change in velocities is due to the friction along the sides of the tunnel and also to the fact that the tunnel is so constructed that the inertia of the air tends to throw the path of highest velocity near the bottom of the tunnel.

TABULATED DATA

TABLE II

<u>No.</u> <u>Trial</u>	<u>P₁</u> <u>Grams.</u> <u>on</u> <u>Gal.</u>	<u>P</u> <u>" / sq. "</u>	<u>V₁</u> <u>mmom.</u> <u>Rdg.</u>	<u>V_t</u> <u>M.P.H.</u>	<u>V</u> <u>V_t x C</u>	<u>V²</u>	<u>K</u> <u>(P)</u> <u>V²</u>
1.	29	.25	.02	3.4	8.96	80.2	.0032
2.	54	.47	.03	7.8	10.93	119.0	.00323
3.	89	.78	.05	10.0	14.0	196.0	.00328
4.	91	.80	.06	11.1	15.55	243.0	.00333
5.	126	1.10	.08	13.8	17.92	321.0	.00353
6.	133	1.17	.08	12.8	17.92	321.0	.00375
7.	144	1.26	.10	14.3	20.02	402.0	.00315
8.	123	1.61	.12	15.7	22.05	486.0	.00332

TABULATED DATA

TABLE III

<u>No.</u> <u>Trial</u>	<u>P₁</u> <u>Grav.</u> <u>on</u> <u>Bal.</u>	<u>P</u> <u>#/sq."</u>	<u>V₁</u> <u>Mg/oz.</u> <u>dry</u>	<u>V_t</u> <u>M.P.W.</u>	<u>V</u> <u>x C</u>	<u>V₂</u>	<u>K</u> <u>(P)</u> <u>(V²)</u>
1.	19	.17	.015	5.25	7.35	54	.00315
2.	30	.265	.02	6.4	8.96	80.1	.00333
3.	48	.42	.03	7.8	10.92	112.5	.0035
4.	50	.44	.03	7.8	10.92	112.5	.00338
5.	70	.615	.04	9.0	12.6	159.	.00335
6.	74.2	.65	.05	10.0	14.0	186.	.0033
7.	90	.79	.05	10.1	14.12	200.	.00334
8.	110	.965	.06	11.15	15.6	243.	.00332
9.	122	1.07	.07	12.0	16.8	282.	.0037

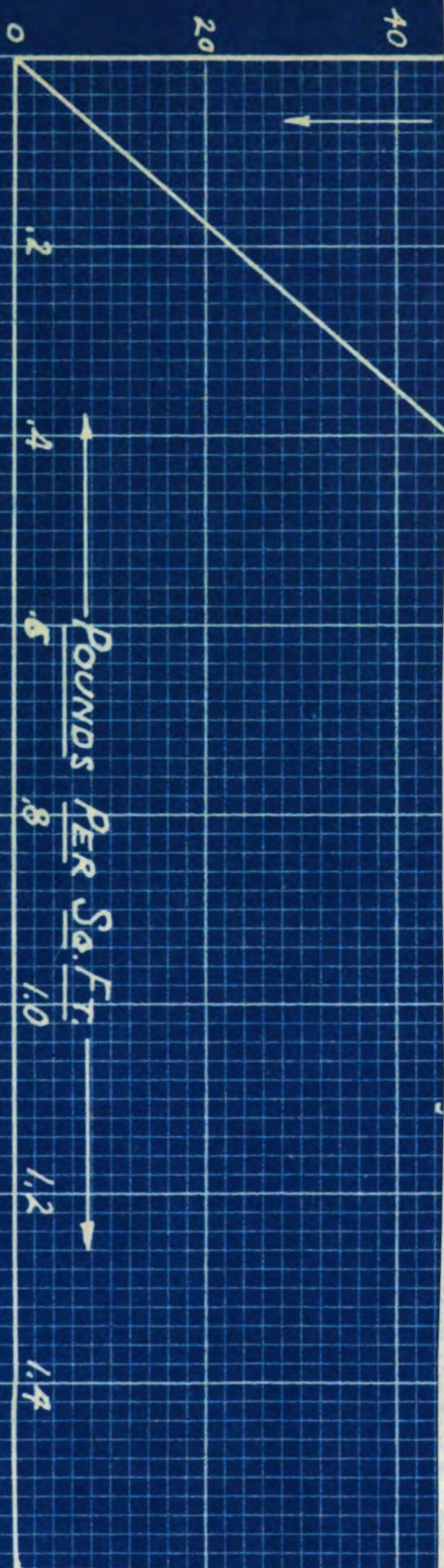


DATE: May 3, '31 RELATION BETWEEN PRESSURE & VELOCITY By: Robt. M. Brown

Fig. III

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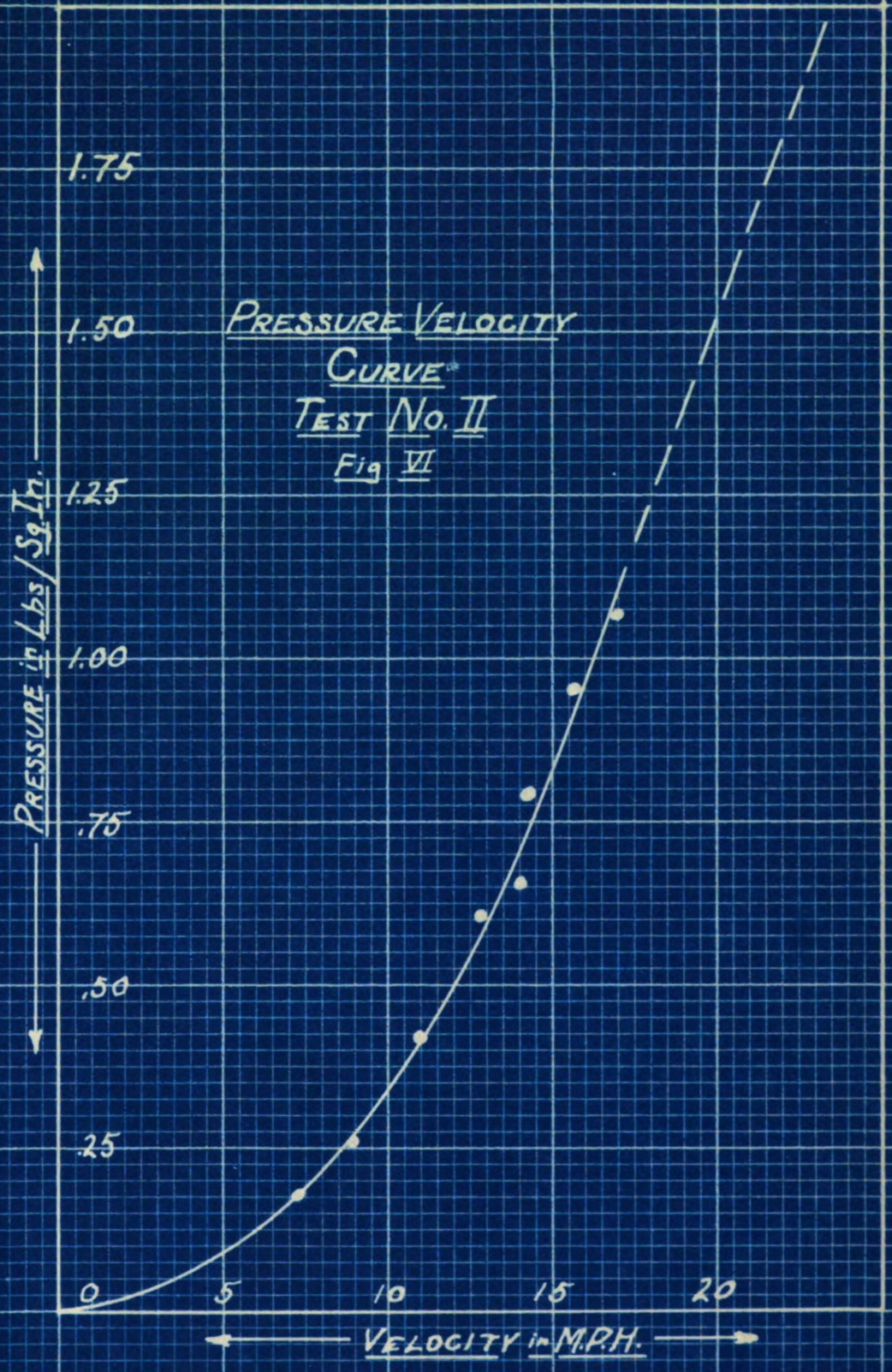
Y. Brant



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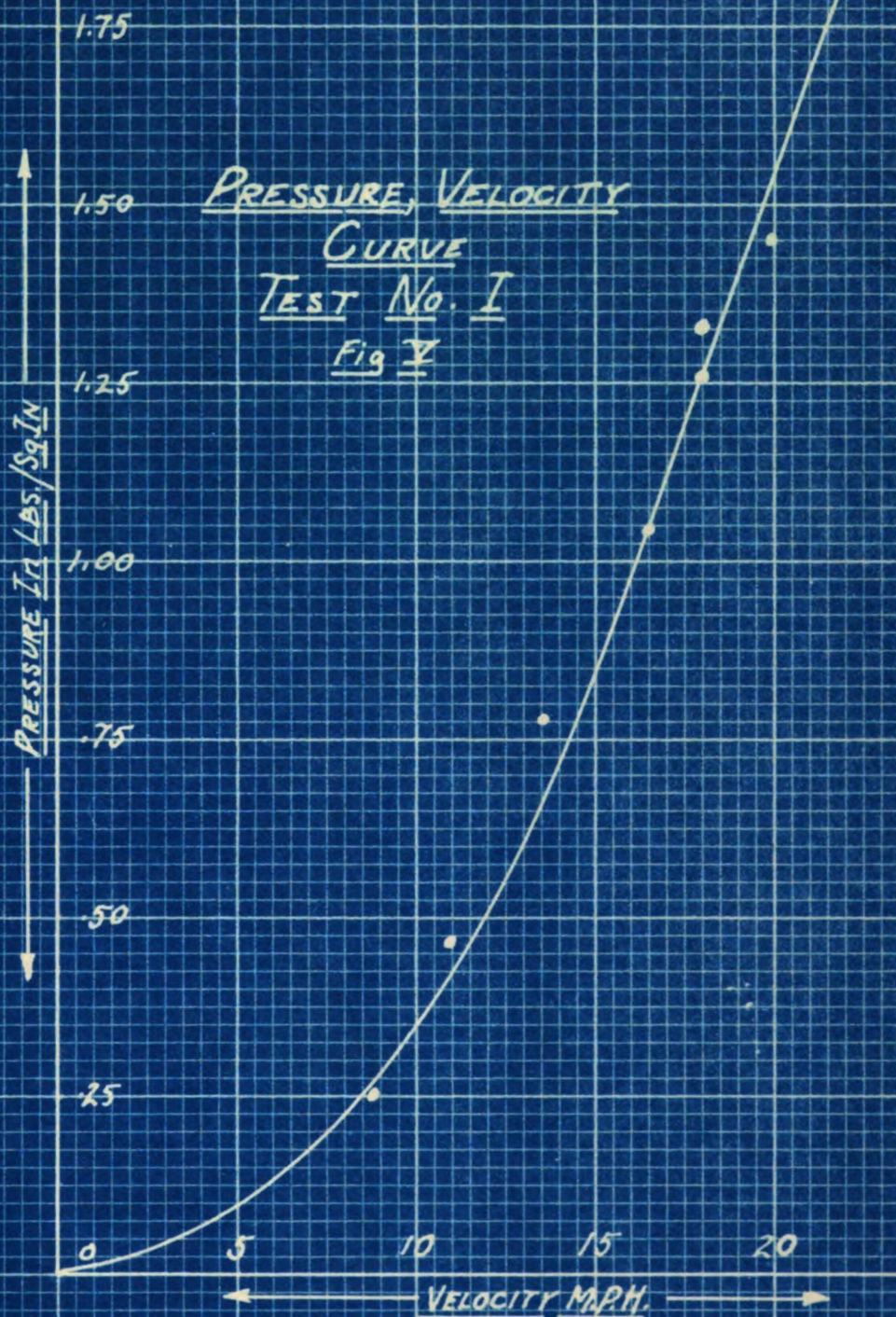
RELATION BETWEEN PRESSURES & VELOCITIES

By: Robt. M. Branch



Date: May 5 '31 RELATION BETWEEN VELOCITY PRESSURE By: Robt. M. Branch

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Date: May 10 '31

RELATION BETWEEN VELOCITY & PRESSURE

By: Robt. M. Branch

Robt. M. Branch

There has been a great controversy over the effect of the slope of an inclined surface on the side thrust of the wind load, although many experiments have been made along those lines. While the pressure on vertical surfaces is taken normal to the exposed surface and the intensity is equal to the assumed wind pressure, for non-vertical surfaces the pressure is also considered to be normal to the surface but of a much lower intensity, that is, for angles up to 60 degrees. From sixty degrees to the vertical position, the intensity is considered to be equal to the assumed wind pressure.

One of the first accurate tests and studies was made on this subject in 1803 by Tiberius Cavallo F.R.S. in his book entitled "The Elements of Natural or Experimental Philosophy", and in the chapter "Of Air in Motion Or Of The Wind", he writes:

"The forces of a fluid medium on a plane cutting the direction of its motion with different inclinations varied successively as the squares of the sines of these inclinations."

This same law is derived by Spofford in the "Theory of Structures", in the following manner:

"Let the wind be assumed as blowing horizontally against the surface (ab) or height (bc) and making an angle (i) with the horizontal. Let the length be one foot, perpendicular to the plane of the paper. (See Figure 9).

Let P = intensity per square foot of the horizontal wind force on a vertical surface.

P_n = intensity per square foot of normal wind force acting on surface (ab).

P_t = intensity per square foot of the tangential force acting on surface (ab).

The total horizontal pressure on surface (ab) then equals Ph .

The normal component of this pressure = $Ph \sin i$

The intensity of the normal component = $\frac{Ph \sin i}{ab}$

But $ab = \frac{h}{\sin i}$

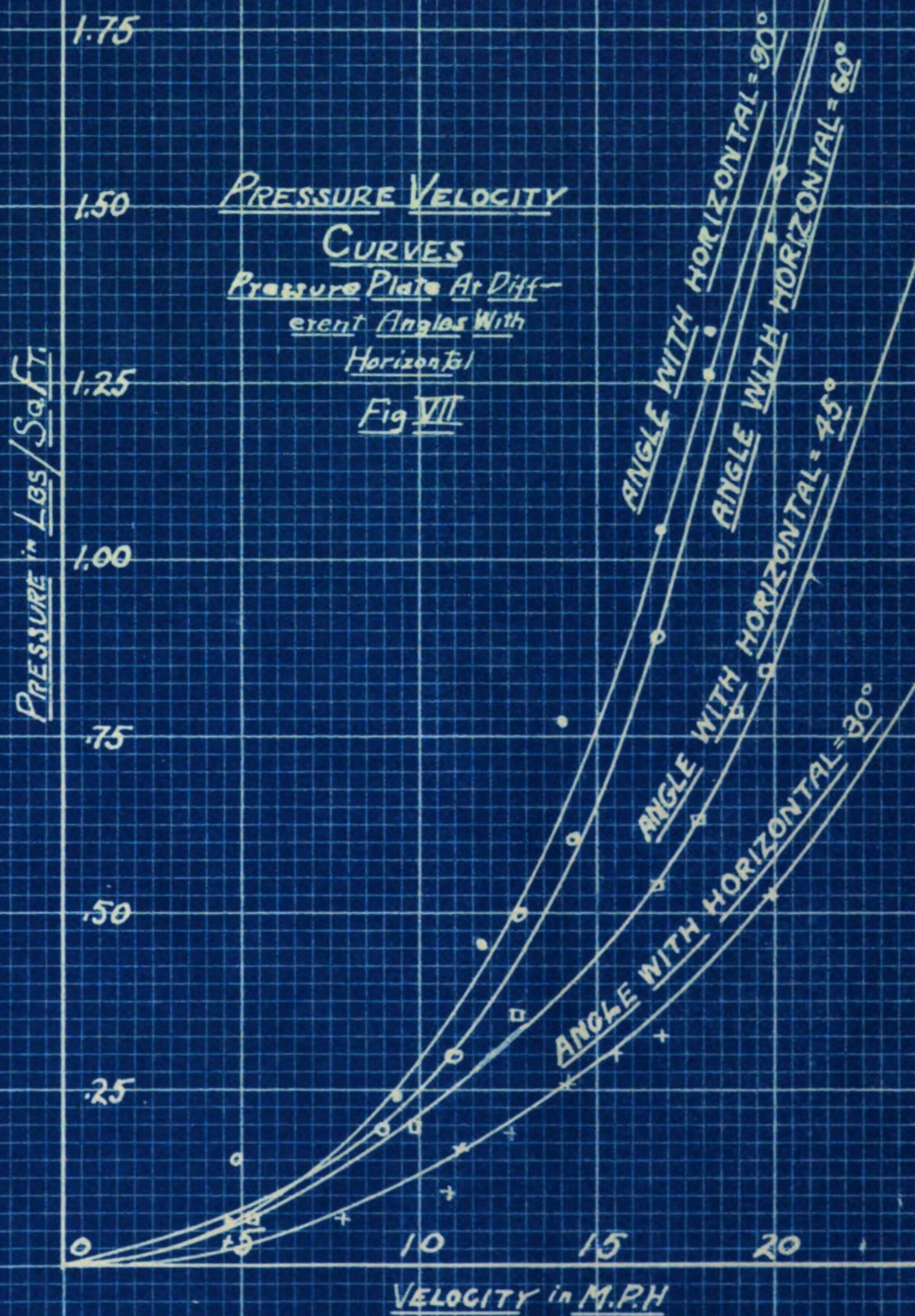
Therefore:

$$P_n = P \sin^2 i$$

However, this formula gives lower values than found in actual practice because it takes no allowance for the suction that probably exists on the windward side of the plate, and also the cushion on the lee and side. This also assumes that the wind blows in an horizontal plane, which is not a practical condition.

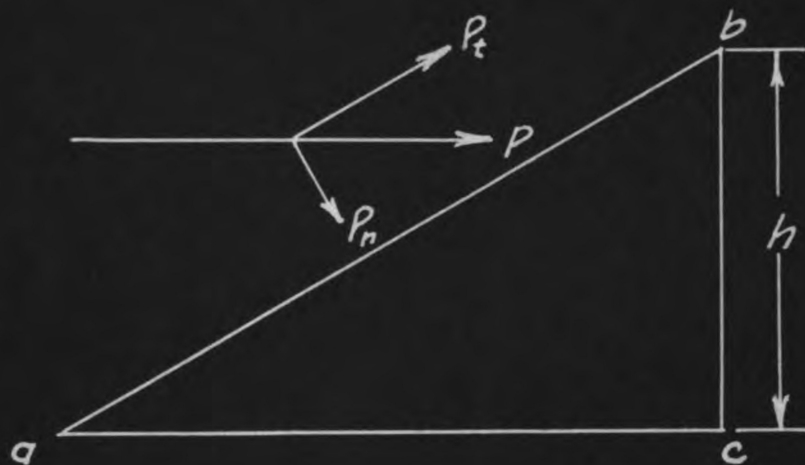
Some very careful experiments were made by Colonel Duchemin, a French Army Officer, who made his investigations in 1822. These were verified by S.P. Langley in 1880. Langley varied only 3 per cent with Duchemin. The result of their studies is the formula that is considered to be the best empirical formula in use today:

$$P_n = \frac{P \sin i}{1 \sin^2 i}$$



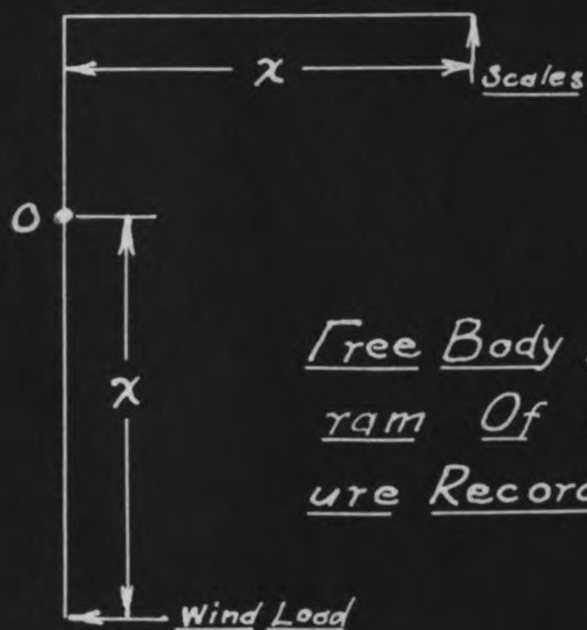
Date: May 25 '31 RELATION BETWEEN PRESSURE & VELOCITY By: Robt. M.

R. M. Band



$$\underline{P_n = P \sin i}$$

Fig VIII



Free Body Diagram
Of Pressure Recorder

Fig IX

TABULATED DATA

TABLE IV

Angle With Horizontal = 30°

<u>Trial</u> <u>No.</u>	P_1 <u>Grams On</u> <u>Balance</u>	P <u>#/sq. in.</u>	V_1 <u>Menord.</u> <u>Bar.</u>	$\frac{V}{V_1} t$ <u>M.F.T.</u>	$\frac{V}{V_1} \times C$ <u>V_t x C</u>
1.	7	.06	.01	3.5	4.9
2.	10.5	.09	.03	7.9	10.92
3.	21.0	.135	.04	9.0	12.6
4.	30.0	.265	.05	10.1	14.14
5.	34.0	.30	.06	11.18	15.6
6.	37.0	.328	.07	12.0	16.8
7.	60.	.525	.10	14.0	18.9

TABULATED DATA

TABLE V

Angle With Horizontal = 45°

<u>Trial</u> <u>No.</u>	<u>P₁</u> <u>Grams On</u> <u>Balance</u>	<u>P</u> <u>#/sq. "</u>	<u>V₁</u> <u>Merom.</u> <u>Rdg.</u>	<u>V</u> <u>"P.H.</u>	<u>V</u> <u>V₁ x C</u>
1.	29.5	.33	.03	7.8	10.93
2.	40.0	.35	.04	9.0	12.6
3.	53.5	.47	.06	11.15	15.6
4.	61.0	.54	.07	12.0	13.8
5.	73.0	.64	.08	12.8	17.9
6.	90.0	.78	.09	13.5	18.9
7.	95.0	.835	.10	14.2	19.9

TABULATED DATA

TABLE VI

Angle With Horizontal - 60°

<u>Trial</u> <u>No.</u>	<u>P</u> <u>Grassl On</u> <u>Balance</u>	<u>P</u> <u>#/sq. in.</u>	<u>V_l</u> <u>Vanom.</u> <u>def.</u>	<u>V_t</u> <u>V.P.H.</u>	<u>V</u> <u>V_t x C</u>
1.	18.0	.13	.01	3.5	4.9
2.	22.0	.13	.03	6.4	8.96
3.	33.0	.29	.03	7.8	10.92
4.	58.0	.51	.04	9.0	12.6
5.	70.0	.62	.05	10.1	14.14
6.	100.0	.88	.07	13.0	13.8
7.	120.0	1.55	.10	14.2	13.9

In conjunction with the experiment on the plate in a vertical position, tests were made on the plate in non-vertical positions. Three tests were run at 30° , 45° , and 60° . The velocity was varied from 4 to 21 miles per hour, and the velocity and pressure were recorded. From these values the pressure in pounds per square foot of surface and corresponding velocity in miles per hour were calculated.

Curves were drawn showing the relation between velocity and the pressures for each of the different angles of the plate. These curves very clearly show the decrease in the intensity due to the change in the angle made by the surface with the horizontal. Also, they very clearly prove that the intensity for angles of sixty degrees and greater, should be equal to the supposed wind load; the curve for sixty degrees is very little different from that for 90 degrees.

CONCLUSIONS

Although this study has been made under ideal conditions the results are very nearly that which would be found in practically all practical work. The constants derived experimentally check with previous studies on this study. The constant for the formula: $P = KV^3$ is found to be .003114, while the usual constant is taken as .004.



FIGURE 10 -- PRESSURE RECORDER

This gives a slight factor of safety which the engineer should always use in his computations.

There is not sufficient data on wind velocities to base definite conclusions as to the proper uniform load on the exposed surface for design. However, the results for the last twenty-five years seem to indicate that 30 pounds per square foot is sufficient to give the required factor of safety for most of our severe wind storms. "Mr. Reier writes in his paper on the St. Louis tornado:

"Much of the destruction in St. Louis was undoubtedly caused by an intensity of wind pressure that it would be neither possible nor expedient to provide against in ordinary structures, but much of it was also due to weak construction."

In the first part of the eighteenth century Cavallo wrote:

"A great many more experiments must be instituted by scientific persons before the subject can be sufficiently elucidated."

This same thought certainly takes place today; although many studies have been made of this force, designers still have the same difficulties to contend with. These are now increased many-fold because of the greater surfaces and higher structures now constructed.

Mr. Fleming in 1313 wrote:



FIGURE 11 -- WIND TUNNEL

"Structures have long been designed with satisfactory results to withstand wind pressure. The bracing at times may have been excessive, but in the absence of better knowledge on the subject, engineers cannot radically depart from present practice."

Since Mr. Fleming wrote this article, we have had several very severe disasters due to the wind. Undoubtedly many of these disasters would have been averted if the proper uniform wind load had been used in design.

In all cities the minimum wind load should not be less than 30 pounds per square foot, and in the tornado zones a minimum of 35 pounds per square foot of surface should be used. Some of the low uniform pressures used in building design are as follows:

30#/sq.ft. in Atlanta, Boston, Evansville, Jackson, Miami, Richmond, and Tacoma.
35#/sq.ft. in Pittsburg and Omaha.

While all other cities that the author has reports on use 30 pounds per square foot, it is quite significant that Miami has only 20 pounds for the design load, and this city is the one that has suffered the most in the history of this country. Mr. F. W. Dawley, assistant professor of Applied Mechanics at Kansas State Agricultural College, recommends using 35 pounds per square foot, in all building design, in all cities. This is very probably high for many cities, but from the results of this study it seems that

velocities of 90 miles per hour should be designed for, which from the formula derived, $P = .003314 V^3$, gives a pressure of 30 pounds per square foot, and subsequently in some cities in the tornado areas, velocities of 93.5 M.P.H. should be designed for, giving the pressure of 35 pounds per square foot.

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