AN INVESTIGATION OF HEAT
TRANSFER COEFFICIENTS FROM A
STEAM HEATED PLATEN

Thesis for the Degree of M. S.
MICHIGAN STATE COLLEGE
James Myron Trebilcock
1950

This is to certify that the

thesis entitled

AN INVESTIGATION OF HEAT
TRANSFER COEFFICIENTS FROM A
STEAM HEATED PLATEN

presented by

James Myron Trebilcock

has been accepted towards fulfillment
of the requirements for

Master's degree in Chemical Engineering

Carl Cooper
Major professor

Date September 14, 1950

O-169

AN INVESTIGATION OF HEAT TRANSFER COEFFICIENTS FROM A STEAM HEATED PLATEN

By

James Myron Trebilcock

A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Chemical Engineering

1950

ACKNOWLEDGMENT

The author is deeply indebted to Professor C. M. Cooper for his valuable advice and guidance. Appreciation is also expressed to Mr. W. E. Clippinger for his assistance in the mechanical aspects of the investigation.

INTRODUCTION

(a) Definition of Drying

Drying in its broadest sense means the removal of a liquid (especially water) from a solid, from a gas, or even from another liquid. The chemical engineering unit operation of drying, however, concerns itself only with the removal of a liquid by vaporization from a solid-liquid mixture in which the solid forms the continuous phase. This latter definition, of course, eliminates dehumidification, the dehydration of liquids, evaporation, distillation, filtration, crystallization, centrifuging, and other more or less remotely related fields which might fall under the more general definition of drying.

(b) Types of Dryers

Even when drying is considered in the more restricted sense, it covers a wide variety of different types of equipment. The type which is best suited to a particular application depends upon the characteristics of the solid-liquid system to be dried, and upon the requirements of the separation with regard to product quality and economy.

One way of classifying dryers might be according to whether the material being dried has a definite form, such as sheet, thread, block, etc., or whether it is a free flowing bulk material such as powder, crystals, flakes, or grains.

Another classification is based on the way in which vaporization is produced. The so-called direct dryers employ a stream of air or gas, perhaps heated in an external apparatus, to supply the heat and act as a carrier for the vapor. The so-called indirect dryers use no air or gas, but supply the heat through heat transfer surface built into the apparatus. There are also dryers which are a combination of direct and indirect action. Some examples of direct dryers are the tray and compartment dryers, the spray dryer, the through circulation dryer and the tunnel dryer. Some examples of indirect dryers are the rotary shelf dryer, the screw conveyor dryer, the agitated pan dryer, the vacuum rotary dryer, the indirect rotary dryer, and the drum dryer.

(c) Scope of this investigation

This investigation concerns itself with the indirect type of dryer when applied to free-flowing materials. More particularly it relates to dryers of this type in which the solid-liquid mixture is moved across the heated surface mechanically. Dryers which fall in this category include the rotary shelf dryer, the jacketed screw conveyor, the agitated pan dryer, the vacuum rotary dryer, and perhaps the indirect rotary dryer.

(d) The Rotary Shelf Dryer

The rotary shelf dryer consists of circular steel plates fitted in a horizontal position inside a vertical cylindrical shell. A rotating central shaft turns arms which carry diagonal plows. Material fed continuously to the center of the top plate is moved outward by the plows to successive concentric circles of material until it drops through a slot onto the plate below. Here the plows are oriented so as to move the material toward a slot in the center of the plate. Usually about ten plates are used. Vapors from the drying action move toward a vapor pipe at the top while the dry solid comes out the bottom. Each plate is constructed with interior channels with steam between for heating.

Dryers of this type have been known for some time but have not been promoted commercially. The name rotary shelf dryer is the name given to them by Riegel. Thorpe calls them rotating rabble dryers.

A great deal of interest has been shown recently in the use of this type of dryer for desolventizing soybean or cottonseed flakes after solvent extraction. Economies over the use of jacketed screw conveyors have been claimed although data on either of these types of dryers are badly lacking.

The investigation made here is particularly applicable to this type of dryer the apparatus being constructed so as to be as similar as possible to this type.

(e) The Jacketed Screw Conveyor

This type of dryer consists of a circular jacketed conveyor in which material is heated and dried as it is conveyed. The conveying of the material is accomplished by a revolving screw inside the conveyor and frequently this screw is also heated. The heating medium depends upon the temperature sensitivity of the material being dried and may be hot water, steam, or a high-temperature heat transfer medium such as Dowtherm.

Since this dryer produces evaporation by moving a solid across a heated surface coefficients should be of the same order of magnitude as for the rotary shelf dryer and should be similarly affected by variables of velocity, bed depth, and temperature difference. Because the jacketed screw conveyor dryer is made up of multiple units it is perhaps not so well adapted to large installations as is the rotary shelf dryer.

(f) The Agitated Pan Dryer

This type of dryer usually consists of a shallow circular pan jacketed on the bottom and partway up the sides for steam or other heating mediums. A central vertical shaft supports an agitator to stir the material in the pan and bring fresh material in contact with the hot surface. The agitator can be designed to scrape the inside surface or set to a very close clearance.

In many respects this dryer is similar to a rotary shelf dryer but is operated batchwise instead of continuously. Similar coefficients would be expected on these two dryers as long as the same type of material is used in both cases. However the agitated pan dryer has been used largely for the combined evaporation and drying of slurries.

(g) The Vacuum Rotary Dryer

This type of dryer consists of a stationary cylindrical shell mounted horizontally in which a set of agitator blades mounted on a revolving central shaft stir and agitate the material being dried. Heat is furnished by circulating a suitable heating medium through a jacket around the shell. The dryer is charged through a manhole at the top of the shell and discharged through one or more manholes at the bottom of the dryer.

The tumbling action in this type of dryer should help to remove any superheat from the heated solid. Heat transfer is obtained however by moving the solid across the heated surface as in the previous type. Like the agitated pan dryer it is designed for batch operation. Like the jacketed screw conveyor full use of the heat transfer surface at the top of the cylinder is not obtained.

(h) The Indirect Rotary Dryer

Indirect rotary dryers consist of a rotating cylinder inclined to the horizontal with material fed to one end and removed from the opposite end. Drying however is accomplished entirely indirectly with heat being conducted to the material through the metal shell or tubes. Wet feed may enter the dryer through a screw conveyor or gravity chute. It passes through the dryer by virtue of the latters slope and rotation. The product discharges from the dryer through peripheral openings in the shell.

This dryer depends upon gravity for agitation of the of the solid. There is no positive means for forcing the solid to move across the surface. When caking occurs there is very little, if any of this type of action. The investigation made here is therefore of little interest in connection with this dryer.

(i) The Drum Dryer

This type of dryer consists of a revolving heated metal drum. Drying is accomplished by applying a liquid material, solution, slurry, or paste to the drum. The drum conducts heat to the wet film to evaporate the water during a partial revolution of the drum. The dry material is scraped from the drum by a stationary knife.

The scraping action in this type of dryer is for removing the solid only. The solid and the surface move together and there is no motion of one relative to the other. It is therefore not related to the work of this thesis.

(j) Advantages of Dryers Based on Moving Solids Across a Heated Surface

Dryers in which solids are moved across a heated surface may advantageously be used for one or more of the following reasons.

(1) Like other indirect dryers all the heat goes into the product or vapor. No heat is required for raising the temperature of a carrier gas.

(2) Since no air is used organic solvents or solids are not likely to produce explosions.

(3) The gentle agitation is not likely to produce the large quantities of dust often formed in direct dryers.

(4) The equipment is conveniently made vapor tight allowing operation under pressure or vacuum or recovery of the vapors.

(5) If vapors are to be recovered there is no diluting air or gas stream.

(6) Continuous as well as batch equipment is convienently constructed.

(7) Heat transfer coefficients may be quite good in comparison with some other types of dryers. It was a purpose of this investigation to determine if this is the case.

(k) Previous Work

A survey of the literature for the past 15 years was made by searching Chemical Abstracts. No applicable work was found under the subjects drying apparatus, driers, rotary shelf driers, shelf driers, and indirect driers. The Chemical Engineers Handbook gives data on vacuum rotary dryers, jacketed screw conveyors, indirect rotary dryers, and agitated pan dryers. The only data that was applicable to this investigation was that on the agitated pan dryer. Coefficients from 5 to 75 B.t.u./hr. sq. ft. °F. were quoted for these dryers but no mention was made of the material dried, depth of bed or how the coefficients varied with the different variables. Walker Lewis McAdams & Gilliland and Badger & McCabe give descriptions of some of the different types of dryers but make no mention of theory or design data. Riegels Chemical Machinery describes rotary shelf dryers and jacketed screw conveyors but gives no information on which to base the heat transfer area required in the design of these dryers.

(1) Method of Attack

From theoretical heat transfer considerations it might be reasoned that poor coefficients would be obtained. Between the surface and the bulk of the material there is a stationary layer of solid the thickness of which depends upon the distance between the surface and the plows. If this solid acts as an effective insulator, very poor coefficients should be obtained. In view of the use of this type of equipment in the past and in view of the current interest it would seem that this is not the case. The work of this thesis is directed toward determining in a quantitative way what sort of coefficients are obtainable.

The system of sand and water was chosen for the drying material. This was decided upon because of its convenience for run and of the fewer uncontrolled variables presented by this mixture. The sand-water mixture probably gives the highest coefficients attainable with this apparatus with lower coefficients being obtained with materials that adsorb water or solvents.

APPARATUS

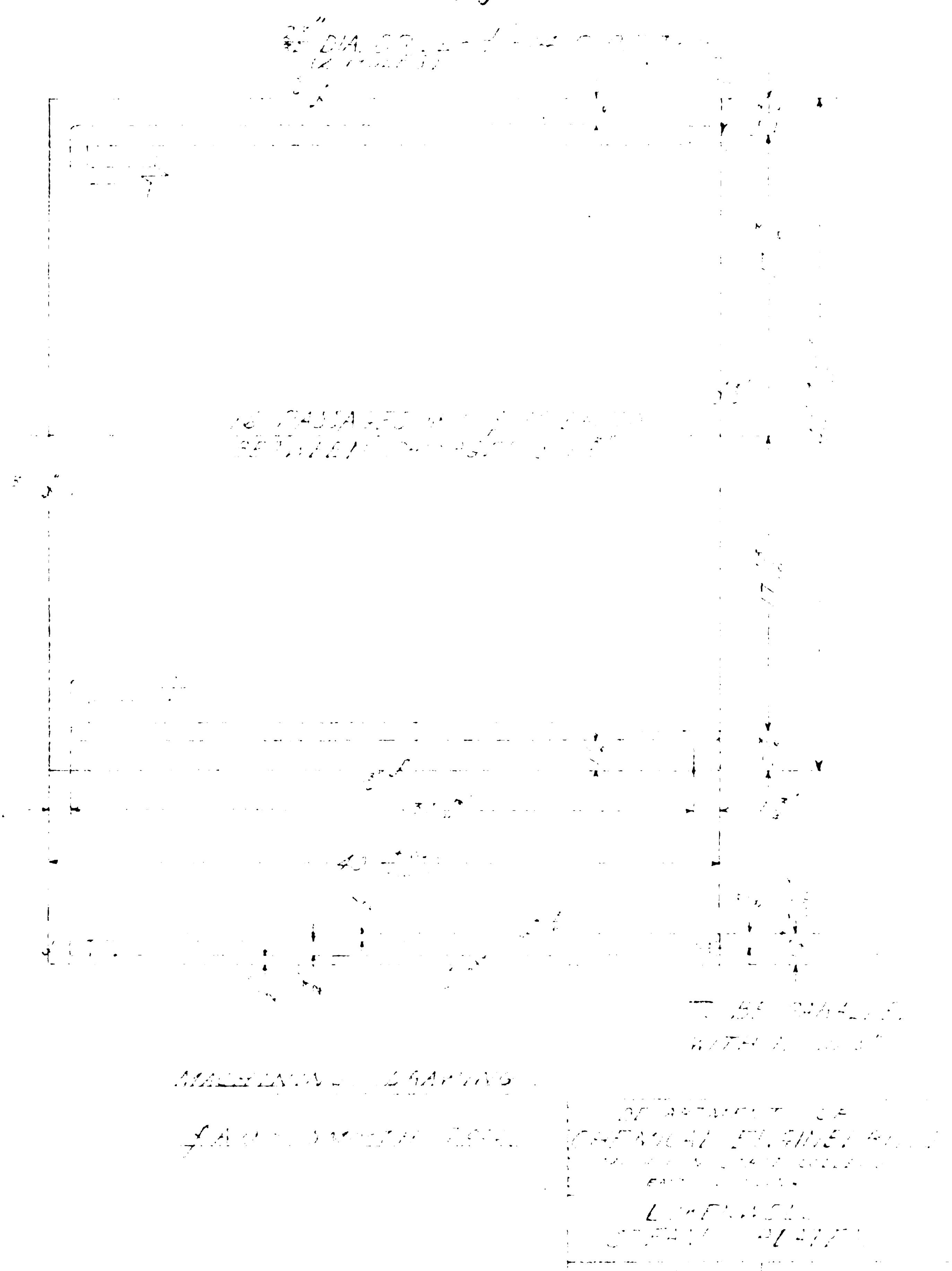
The initial problem of this investigation was to design a piece of equipment that would assimilate as near as possible conditions in an industrial rotary shelf dryer. It was also paramount that this apparatus maintain constant speeds of rotation under varying loads and that it be sturdy and rugged enough to be available for further study.

The problem of obtaining a constant temperature plate was solved when the Lukens Steel Company of Coatesville, Pa. donated a Lukenweld Steam Platen to Michigan State College. The plate was forty inches square and one and three-quarters inches thick (Fig. 1). Because of its construction and operation this type of plate is well suited for the purpose of this investigation. The platen maintains a very uniform heat distribution and is able to withstand high steam pressures.

From this point a drawing of the equipment was made (Fig. 2). The motor, speed reducer, 2-1 gear reducer, regulator valve and steam trap were equipment of the Chemical Engineering department at Michigan State. Using pulleys from motor to speed reducer it was seen that the rotational velocities commonly used industrially could be obtained.

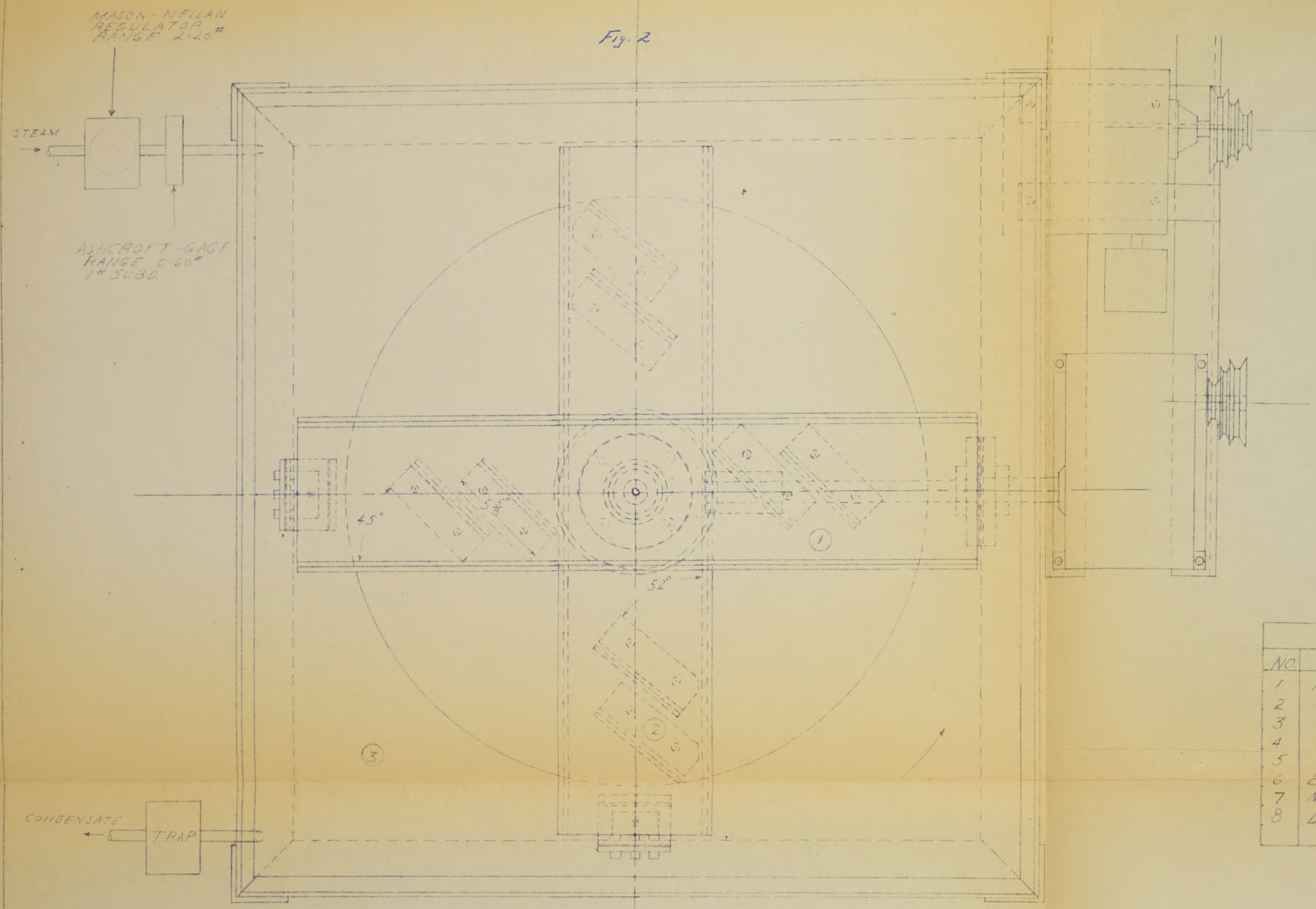
The 2-1 gear reducer required a 1 1/4" vertical shaft so the platen was sent to a local tool and die shop and a hole was bored in the center of the plate 1 5/8" diameter. This hole was then bushed with a 1/8" thick steel bushing

Fig. 1

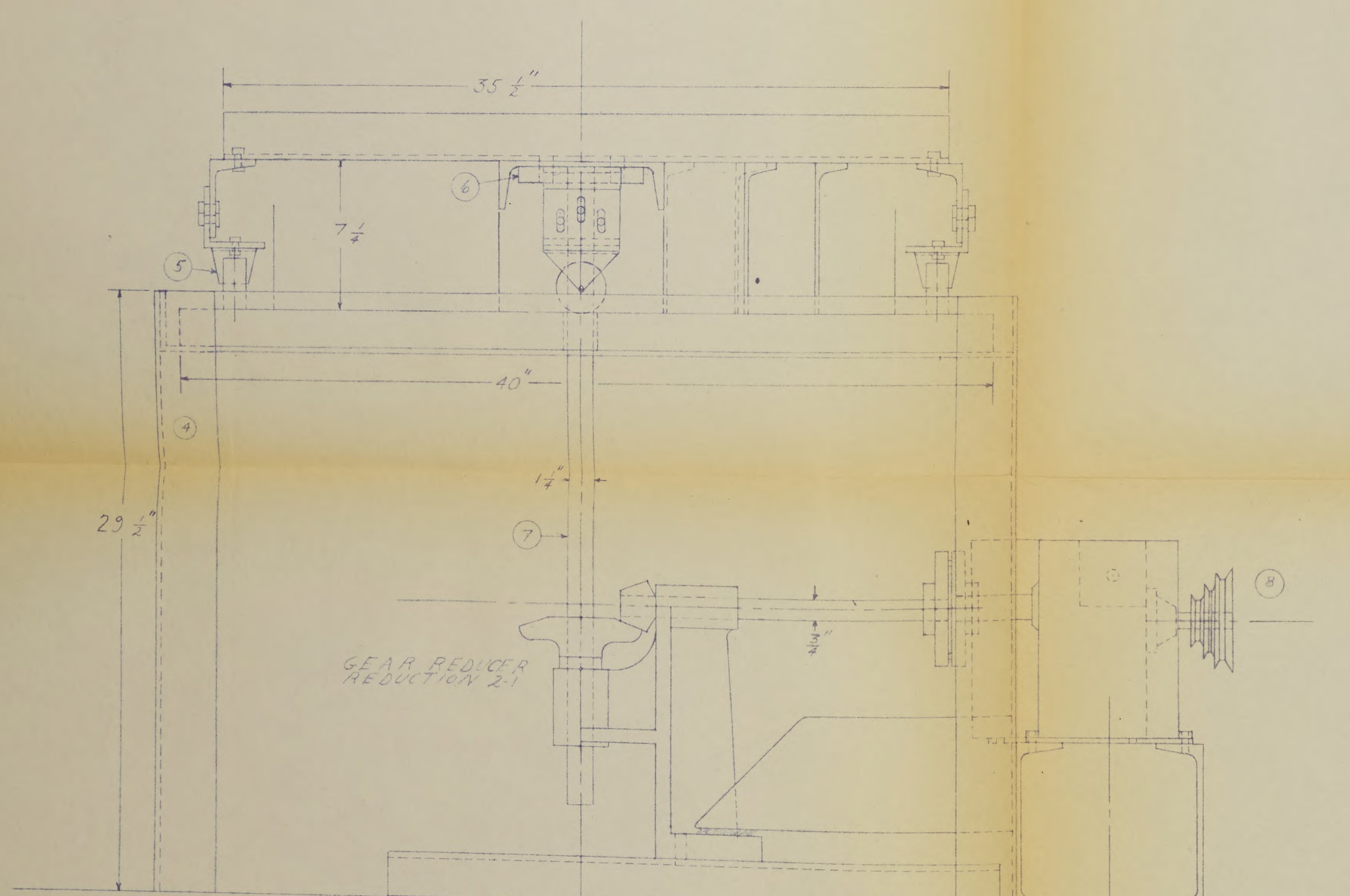


Copied from Lukens drawing.

Fig. 2



MATERIAL'S LIST		
NO.	TITLE	MATL.
1	PLOW ARMS	8"-11.5#-STEEL CHANNEL
2	PLOWS	8"-11.5#-STEEL CHANNEL
3	PLATEN	STEEL (SEE DETAIL)
4	SUPPORT	3×3×¼ STEEL ANGLE
5	CASTERS	1" O.D.-⅞ FACE-C.I. CASTERS
6	BLIND FLANGE	6" O.D.-¾"-C.I. FLANGE
7	MAIN SHAFT	1¼" O.D. C.R. STEEL
8	DRIVE PULLEY	2"-3"-4" Al. PULLEYS FOR ¾" SHAFT



DEPARTMENT OF
CHEMICAL ENGINEERING
MICHIGAN STATE COLLEGE
EAST LANSING

DRIER
ASSEMBLY

SCALE: 3/16" = 1" MATL: SEE ABOVE DATE: 8-1-50	DRAWN: JMT

by freezing the bushing and pressing into the plate. The bushing extended 1/8" into the passages on either side of the center land.

The main shaft driven by the 2-1 gear reducer extended up through the platen and had 1/16" clearance. The shaft was key driven by the large horizontal gear and a blind flange 6" in diameter and 3/4" thick was welded to the top end of the shaft to be attached by bolts to the plow arms.

The plow arms were constructed of 8"-11.5#/ft. channel iron. Two arms each 35 1/2" long were cut and connected at right angles to each other with their flat faces together. These arms were held together by 3/4" bolts that extended through both plow arms and the blind flange on the top of the main shaft.

The eight plows were constructed of 8"-11.5#/ft. channel iron with one flange removed. The plows were connected to the plow arms with 3/8" bolts. The four plows that were attached to the bottom channel iron plow arm were milled .220" shorter than the other four plows to give all the plows the same clearance with the plate.

Four supports riding on C.I. casters were constructed for the ends of the plow arms to reduce the thrust on the main shaft to a minimum. These supports were constructed from 8"-11.5#/ft. channel iron and 3 x 3 x 1/4" angle iron. The bolt holes connecting the channel and angle iron were slotted to allow the clearance of the plows from the plate to be varied. The C. I. casters were 2" diameter wheels with a 7/8" face.

The speed reducer and the 2-1 gear reducer shafts were connected by a flexible coupling and the motor and speed reducer were belt driven by cone pulleys of 2,3 and 4 inch diameters.

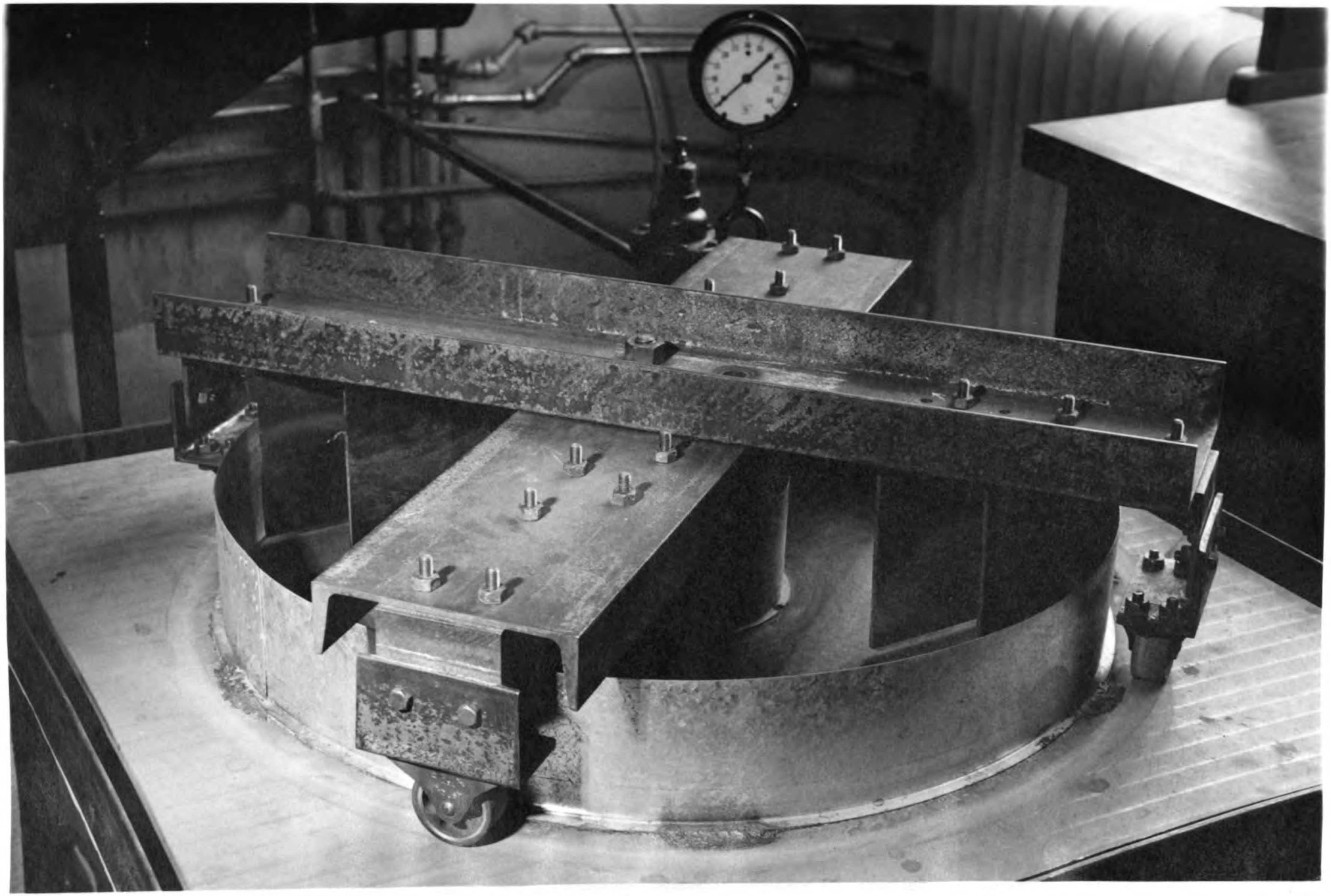
When the drive unit was assembled it was moved under the plate and shimmed so that the main shaft was perfectly vertical and did not bear in the plate. A flat piece of insulation 1/2" thick was then placed on the bottom side of the plate to prevent the drive unit from becoming excessively heated.

The next step was to build two retaining walls to prevent the mixture from moving outside the drying bed. This was done by soldering two circular sheets of 18 gauge sheet metal to the plate. The inside wall just cleared the leading edge of the innermost plows and was approximately five inches high and 8 1/2" in diameter. This wall also prevented any sand from getting in the hole through which the main shaft turned. The outer circular wall just cleared the leading edge of the outermost plows and was approximately five inches high and 30 1/2" in diameter.

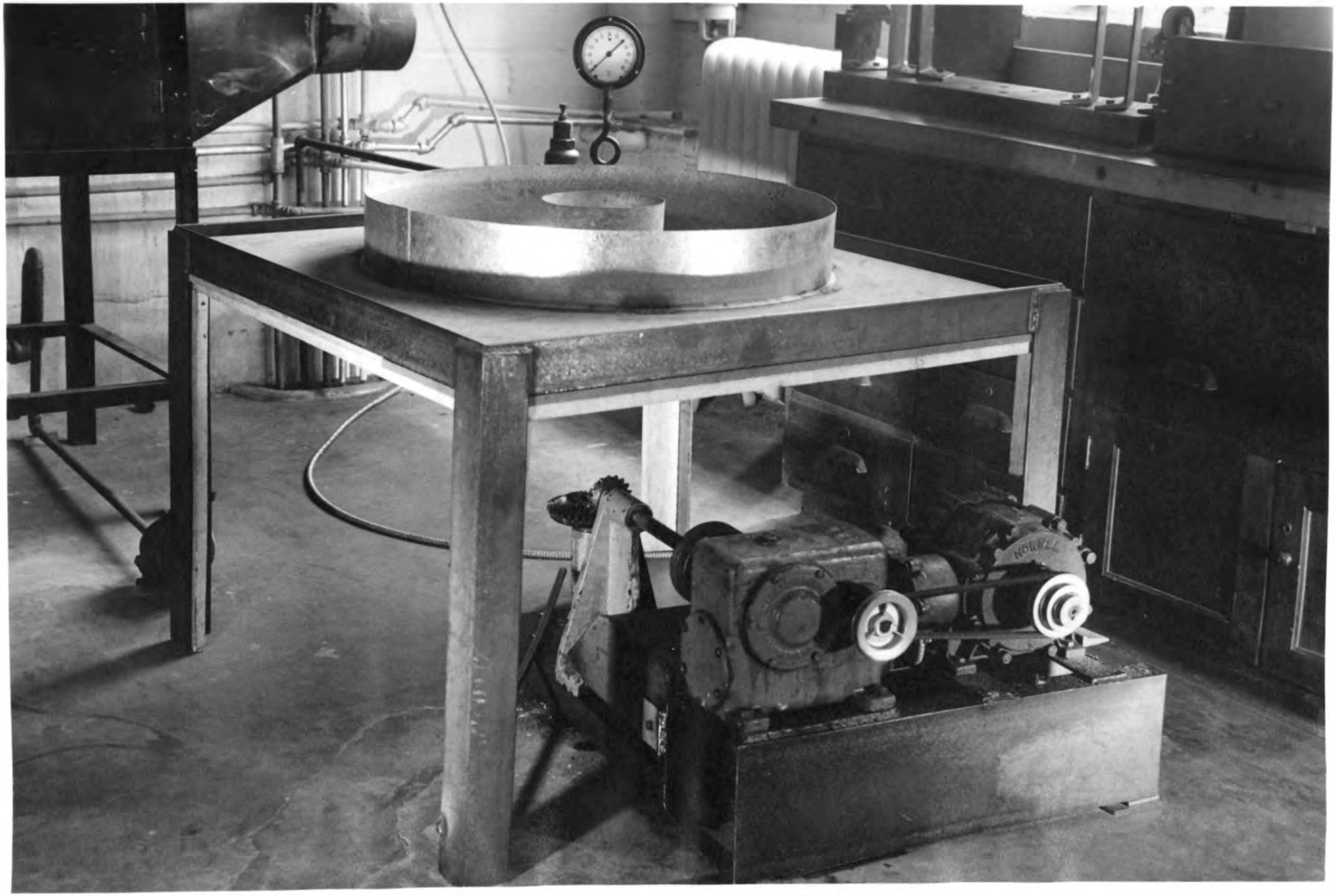
The final step was that of piping the steam in and out of the platen. One-half inch steel pipe was used.

In the original construction all plow angles were 45°. When a trial run was made it was seen that the outermost plows were not shearing the material and moving it inward. Instead these plows were just pushing the mixture in front of them. It was obvious that these plows turning on the larger radius were offering too much face to the oncoming material. The angles were adjusted slightly and it was found that when the plows were on 52° angles that they exhibited a good plowing action. They also covered the same bed area and over lapped each other slightly. The final plow angles used were 45° for the inside plows with 1/2" overlap and 52° for the outside plows with a very slight overlap.

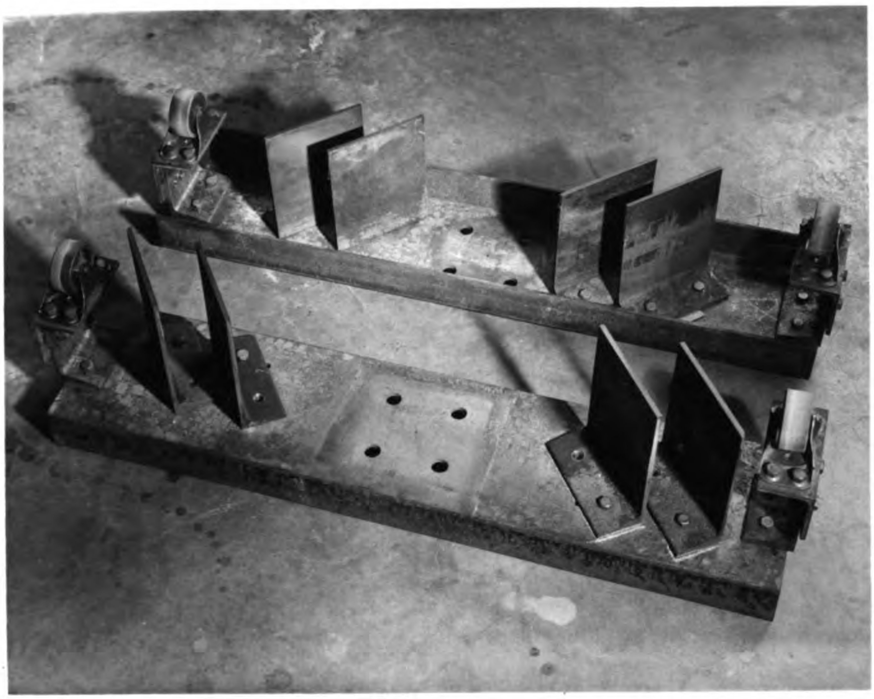
The sand used for this investigation was the white Ottawa sand from Ottawa, Illinois. This sand is of a fairly fine grain size as can be seen from the included sieve analysis. The sieve analysis was included to give an idea of the size of the drying material and as was mentioned before this substance probably gives the highest coefficients obtainable with this apparatus.



Photograph showing steam
platen and plow arms



Photograph showing steam
platen, support, and drive unit



Photograph showing plow
arms with plows attached

PROCEDURE

The steam was turned on and adjusted to the correct pressure for the particular run by means of the steam pressure regulator valve. This was done some time before the run started to assure the plate of being at a uniform temperature. During the time that the plate was heating up steam was bled through the cock at top of steam trap to remove the air from the system.

The low pressure runs were made when the gauge registered on the first mark. The gauge had been previously tested on a dead weight tester in the pressure range from five to twenty pounds per square inch gauge. When the runs were completed the gauge was tested at the very low pressures by calibrating using a column of water. It was found that the first mark on the gauge corresponded to a pressure of 1.63 pounds per square inch gauge and this is the reason for the odd steam pressure for the low pressure run. During all of the runs the barometer read approximately 740 mm of Hg and this small correction was applied to the absolute pressures and boiling points.

The sand and water mixture was made up by weight and thoroughly mixed to assure a uniform composition of the material to be dried. The final mixture was then weighed as a check on the preceding weights and the temperature of the mixture then taken. This was done by immersing a thermometer into the mixture.

The motor was started and the apparatus checked to make sure that the dryer was in operating order. The time was then noted and the sand and water mixture was dumped on the plate to commence the run.

Sampling was done at five minute intervals ± ten seconds. The sampling was done by means of a rectangular scoop approximately two inches deep by two inches wide by nine inches long. This was used to obtain a representative sample of the mixture across the drying bed. The samples were taken just after the mixture had been moved toward the center of the bed by the outermost plows and were taken parallel to the plow arms across the width of the bed. The sample was then thoroughly mixed in the scoop and a representative sample was taken from the scoop by selecting portions from one end to the other with a spatula. These portions were immediately placed in a dry weighed weighing bottle, covered and weighed on the analytical balance. The remainder of the sample in the scoop being returned to the drying bed.

After being weighed the uncovered weighing bottles were placed in an electrically heated oven at 130°C. for at least eight hours.

The preceding sampling procedure was continued at five minute intervals until the material appeared practically dry and then the time intervals were lengthened to ten minutes until the material appeared as dry as it was possible to obtain with the drying apparatus. This was easily noted after some experience by observing the final moisture content of some of the previous runs. In runs 19 and 21 ten minute intervals were used during the complete run due to the longer drying times expected.

When all the sampling had been completed and the samples dried in the oven for at least eight hours they were removed and placed in a dessicator. After cooling they were weighed and the per-cent moisture was then calculated.

The weighing bottles were then cleaned and the material removed from the plate and another run was started exactly as in the preceding manner using different variables of rotation, bed depth or steam pressure.

In plotting the drying curves the initial moisture content was calculated from the amount of water added to the original mixture. The sand that was used had been removed from the drying bed for a short time and was almost perfectly bone dry. This method of calculating the moisture content of the original charge was used because the larger weights reduced errors and also because it was difficult to obtain a representative sample of the original mixture. The difficulty encountered was when the original mix was placed in the pail prior to placing on the drying bed the more moist material was toward the bottom of the pail. After the material had been placed on the bed the material was thoroughly mixed and the sand-water mixture was consistent. In all but the first few runs at 15 psig steam pressure and 3/4" bed depth the initial moisture contents are the same.

OTTAWA SAND SIEVE ANALYSIS

Openings Inches	Tyler Mesh	Sample Wts. gms.	Per Cent	Per Cent Cumulative Weights
.0232	28	10	1.0	1.0
.0164	35	350	35.0	36.0
.0116	48	325	32.5	68.5
.0082	65	190	19.0	87.5
.0058	100	75	7.5	95.0
.0041	150	30	3.0	98.0
Pass	200	15	1.5	99.5

Run #1

Steam pressure-15 psig
RPM-3/4
Plow clearance from plate-1/16"
Bed depth-3/4"

Composition of drying mixture

Weight of dry sand (lbs.)	27 3/4
Weight of water added (lbs.)	3 1/2
Total weight (lbs.)	31 1/4

Initial temperature of mixture-83°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.38
5	18	21.4330	33.7235	12.2905	32.6783	1.0452	8.50
10	19	21.3150	29.9660	8.6510	29.6042	.3618	4.18
15	20	20.9988	28.8346	7.8358	28.6374	.1972	2.52
20	21	21.9413	28.7424	6.8011	28.6434	.0990	1.45
25	22	19.9070	30.0503	10.1433	30.0220	.0283	.28
30	23	21.5698	30.3626	8.7928	30.3352	.0274	.31
35	24	20.5037	28.6751	8.1714	28.6746	.0005	.006
45	25	46.7351	54.6471	7.9120	54.6466	.0005	.006
55	26	49.3762	58.5687	9.1925	58.5680	.0007	.008

Date: 7/15/50

Run #2

Steam pressure-15 psig
RPM-1.5
Plow clearance from plate-1/16"
Bed depth-3/4"

Composition of drying mixture

Weight of dry sand (lbs.)	27 7/8
Weight of water added (lbs.)	3 3/8
Total weight (lbs.)	31 1/8

Initial temperature of mixture-98°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							10.90
5	10	19.4331	24.3663	4.9332	24.0440	.3223	6.54
10	11	19.7382	24.0152	4.2770	23.8680	.1472	3.45
15	12	19.7156	23.1684	3.4528	23.1130	.0554	1.61
20	13	22.3375	24.3694	2.0319	24.3594	.0100	.49
25	14	20.9367	22.9418	2.0051	22.9405	.0013	.07
35	15	21.3170	24.7144	3.3974	24.7137	.0007	.02
45	16	21.1210	23.3538	2.2328	24.3530	.0008	.04

Date: 7/15/50

Run #3

Steam pressure-15 psig
RPM-3
Plow clearance from plate-1/16"
Bed depth-3/4"

Composition of drying mixture

Weight of dry sand (lbs.)	28 1/4
Weight of water added (lbs.)	3 1/16
Total weight (lbs.)	31

Initial temperature of mixture-84°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							9.88
5	2	19.5052	24.2700	4.7648	23.9992	.2708	5.68
10	3	20.5524	25.3588	4.8064	25.2094	.1494	3.11
15	4	18.3110	22.6120	4.3010	22.5538	.0582	1.35
20	5	18.8730	20.8740	2.0010	20.8730	.0010	.05
30	6	18.4208	21.4540	3.0332	21.4534	.0006	.02
40	7	19.3895	22.5051	3.1156	22.5049	.0002	.006
50	8	19.9685	22.7366	2.7681	22.7358	.0008	.03

Date: 7/16/50

Run #4

Steam pressure-8.5 psig
RPM-3/4
Flow clearance from plate-1/16"
Bed depth-3/4"

Composition of drying mixture

Weight of dry sand (lbs.)	27 1/4
Weight of water added (lbs.)	3 1/2
Total weight (lbs.)	30 3/4

Initial temperature of mixture-110°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.40
5	20	20.9988	28.5143	7.5155	27.9310	.5833	7.76
10	21	21.9413	30.6240	8.6827	30.1548	.4692	5.40
15	22	19.9070	28.4416	8.5346	28.0760	.3656	4.28
20	23	21.5698	30.5076	8.9378	30.2426	.2650	2.97
25	24	20.5037	30.3488	9.8451	30.1552	.1936	1.97
30	25	46.7351	55.3848	8.6497	55.3026	.0822	.95
35	26	49.3762	56.4683	7.0921	56.4666	.0017	.02
40	27	20.9797	25.3226	4.3429	25.3220	.0006	.01
50	28	17.4224	21.8701	4.4477	21.8694	.0007	.02

Date: 7/16/50

Run #5

Steam pressure-8.5 psig
RPM-1.5
Plow clearance from plate-1/16"
Bed depth-3/4"

Composition of drying mixture

Weight of dry sand (lbs.)	27 1/4
Weight of water added (lbs.)	3 1/2
Total weight	30 3/4

Initial temperature of mixture-100°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.40
5	2	19.5052	27.7188	8.2136	27.1491	.5697	6.93
10	3	20.5524	28.7458	8.1934	28.3492	.3966	4.84
15	4	18.3110	26.4612	8.1502	26.1837	.2775	3.40
20	5	18.8730	26.9108	8.0378	26.7456	.1652	2.06
25	6	18.4208	27.7622	9.3414	27.7005	.0617	.66
30	7	19.3895	25.9102	6.5207	25.9094	.0008	.01
35	8	19.9685	25.5960	5.6275	25.5952	.0008	.01
45	18	21.4330	26.8870	5.4540	26.8869	.0001	.002

Date: 7/16/50

Run #6

Steam pressure-8.5 psig
RPM-3
Plow clearance from plate-1/16"
Bed depth-3/4"

Composition of drying mixture

Weight of dry sand (lbs.)	27 1/4
Weight of water added (lbs.)	3 1/2
Total weight (lbs.)	30 3/4

Initial temperature of mixture-83°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.40
5	10	19.4331	31.8512	12.4181	30.9109	.9403	7.58
10	11	19.7382	27.1564	7.4182	26.7981	.3583	4.83
15	12	19.7156	29.8350	10.1194	29.5150	.3200	3.16
20	13	22.3375	30.1485	7.8110	30.0407	.1078	1.38
25	14	20.9367	26.1104	5.1737	26.1097	.0007	.01
30	15	21.3170	27.8802	6.5632	*	*	*
40	16	21.1210	25.6846	4.5636	25.6843	.0003	.007
50	17	21.7204	27.0074	5.2870	27.0070	.0004	.007

* Sample spilled.

Date: 7/17/50

Run #7

Steam pressure-1.63 psig
RPM-3/4
Plow clearance from plate-1/16"
Bed depth-3/4"

Composition of drying mixture

Weight of dry sand (lbs.)	27 1/4
Weight of water added (lbs.)	3 1/2
Total weight (lbs.)	30 1/2

Initial temperature of mixture-79°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.48
5	23	21.5698	31.0100	9.4402	30.0864	.9236	9.79
10	24	20.5037	30.1898	9.6861	29.5018	.6880	7.12
15	25	46.7351	58.6402	11.9051	57.9413	.6961	5.85
20	26	49.3762	60.7264	11.3502	60.2510	.4754	4.19
25	1	18.5223	26.4906	7.9683	26.2264	.2642	3.32
30	2	19.5052	26.9562	7.4510	26.7662	.1900	2.55
35	3	20.5524	28.9936	8.4412	28.8716	.1220	1.45
40	4	18.3110	25.5528	7.2418	25.5178	.0350	.48
45	5	18.8730	26.4270	7.5540	26.4122	.0148	.20
50	6	18.4208	25.2534	7.0326	25.4522	.0012	.02
60	7	19.3895	26.2900	6.9005	26.2880	.0020	.03
70	8	19.9685	26.4900	*			

* Sample not needed for run.

Date: 7/17/50

Run #8

Steam pressure-1.63 psig
RPM-1.5
Plow clearance from plate-1/16"
Bed depth-3/4"

Composition of drying mixture

Weight of dry sand (lbs.)	27 3/8
Weight of water added (lbs.)	3 1/2
Total weight (lbs.)	30 3/4

Initial temperature of mixture-96^{o}F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.40
5	12	19.7156	27.9558	8.2402	27.3096	.6462	7.85
10	13	22.3375	33.3234	10.9859	32.6664	.6570	5.98
15	14	20.9367	30.8683	9.9316	30.4402	.4281	4.32
20	15	21.3170	30.8666	9.5496	30.5845	.2821	2.96
25	16	21.1210	29.9010	8.7800	29.7514	.1496	1.70
30	17	21.7204	29.6376	7.9172	29.5648	.0728	.92
35	18	21.4330	30.9766	9.5436	30.9759	.0007	.007
40	19	21.3150	27.1946	5.8796	27.1945	.0001	.001
50	20	20.9988	29.2216	8.2223	29.2226	-.0010	----
60	21	21.9413	29.3500	7.4087	29.3500	.0000	0.00

Date: 7/17/50

Run #9

Steam pressure-1.63 psig
R.P.M.-3
Plow clearance from plate 1/16"
Bed depth-3/4"

Composition of drying mixture

Weight of dry sand (lbs.)	27 1/4
Weight of water added (lbs.)	3 1/2
Total weight (lbs.)	30 3/4

Initial temperature of mixture-87°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.40
5	2	19.5052	26.8566	7.3514	26.2240	.6326	8.60
10	3	20.5524	31.5898	11.0374	30.9642	.6256	5.66
15	4	18.3110	28.2922	9.9812	27.9072	.3850	3.86
20	5	18.8730	26.9041	8.0311	26.7314	.1727	2.15
25	6	18.4208	30.2176	11.7968	30.1614	.0562	.48
30	7	19.3895	26.3574	6.9679	26.3572	.0002	.003
35	8	19.9685	27.3886	7.4201	27.3884	.0002	.003
45	9	18.6536	24.4723	5.8187	24.4722	.0001	.002
55	10	19.4331	26.7300	7.2969	26.7292	.0008	.01

Date: 7/10/50

Run #10

Steam pressure-15 psig
RPM-3/4
Flow clearance from plate-1/16"
Bed depth-1 1/4"

Composition of drying mixture

Weight of dry sand (lbs.)	45 1/2
Weight of water added (lbs.)	5 3/4
Total weight (lbs.)	51 1/4

Initial temperature of mixture-80°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.20
5	2	19.5052	26.9448	7.4396	26.3995	.5453	7.33
10	3	20.5524	28.5920	8.0396	28.1588	.4332	5.39
15	4	18.3110	27.1146	8.8036	26.7570	.3576	4.06
20	5	18.8730	26.6302	7.7572	26.3779	.2523	3.25
25	6	18.4208	26.5988	8.1780	26.4244	.1744	2.14
30	7	19.3895	26.6564	7.4669	26.7288	.1276	1.71
35	8	19.9685	28.9544	8.9859	28.8728	.0816	.91
40	9	18.6536	27.4202	8.7666	27.4054	.0148	.17
45	10	19.4331	26.3920	6.9589	26.3534	.0386	.56
55	11	19.7382	25.5670	5.8288	25.5698	-.0028	----

Date: 7/18/50

Run #11

Steam pressure-15 psig
RPM-1.5
Plow clearance from plate-1/16"
Bed depth-1 1/4"

Composition of drying mixture

Weight of dry sand (lbs.)	45 1/2
Weight of water added (lbs.)	5 3/4
Total weight (lbs.)	51 1/4

Initial temperature of mixture-86°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.20
5	2	19.5052	30.0883	10.5831	29.3292	.7591	7.18
10	3	20.5524	28.6756	8.1232	28.2794	.3971	4.88
15	4	18.3110	29.2094	10.8984	28.7908	.4186	3.84
20	5	18.8730	29.4346	10.5616	29.2054	.2292	2.17
25	6	18.4208	28.2752	9.8544	28.1207	.1545	1.57
30	7	19.3895	26.7923	7.4028	26.7482	.0441	.60
35	8	19.9685	27.0896	7.1211	27.0886	.0010	.01
40	9	18.6536	23.3374	4.6838	23.3364	.0010	.02
50	10	19.4331	24.1662	4.7331	24.1656	.0006	.01

Date: 7/19/[illegible]

Run #12

Steam pressure-15 psig
RPM-3
Plow clearance from plate-1/16"
Bed depth-1 1/4"

Composition of drying mixture

Weight of dry sand (lbs.)	45 1/2
Weight of water added (lbs.)	5 3/4
Total weight (lbs.)	51 1/4

Initial temperature of mixture-113°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.20
5	12	19.7156	28.0840	8.3684	*	*	*
10	13	22.3375	30.9158	8.5783	30.5392	.3766	4.39
15	14	20.9367	29.6686	8.7319	29.4210	.2746	2.84
20	15	21.3170	28.4832	7.1662	28.3672	.1160	1.62
25	16	21.1210	29.3818	8.2608	29.3586	.0232	.28
30	17	21.7204	27.3406	5.6202	27.3398	.0008	.01
40	18	21.4330	28.4335	7.0005	28.4330	.0005	.01

Date: 7/19/50

Run #13

Steam pressure-8.5 psig
R.P.M.-3/4
Plow clearance from plate-1/16"
Bed depth-1 1/4"

Composition of drying mixture

Weight of dry sand (lbs.)	45 1/2
Weight of water added (lbs.)	5 3/4
Total weight (lbs.)	51 1/4

Initial temperature of mixture-105°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.20
5	14	20.9367	29.9726	9.0359	29.2184	.7524	8.35
10	15	21.3170	31.2716	9.9546	30.7159	.5557	5.58
15	16	21.1210	29.5860	8.4650	29.2070	.3790	4.48
20	17	21.7204	30.3202	8.5998	29.9890	.3312	3.85
25	18	21.4330	29.3698	7.9368	29.1054	.2644	3.34
30	19	21.3150	29.8314	8.5164	29.6006	.2308	2.71
35	20	20.9988	28.3553	7.3565	28.2216	.1337	1.82
40	21	21.9413	30.5808	8.6395	30.4660	.1148	1.33
45	22	19.9070	29.2456	9.3386	29.1988	.0468	.50
50	23	21.5698	27.6426	6.0728	27.6420	.0006	.01
55	24	20.5037	26.2042	5.7005	26.2040	.0002	.003
65	25	46.7351	54.8226	8.0875	54.8242	-.0016	----

Date; 7/20/50

Run #14

Steam pressure-8.5 psig
R.P.M-1.5
Plow clearance from plate-1/16"
Bed depth-1 1/4"

Composition of drying mixture

Weight of dry sand (lbs.)	45 1/2
Weight of water added (lbs.)	5 3/4
Total weight (lbs.)	51 1/4

Initial temperature of mixture-81°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.20
5	2	19.5052	28.1470	8.6418	27.4098	.7372	8.54
10	3	20.5524	27.4616	6.9092	27.0236	.4380	6.35
15	4	18.3110	29.1360	10.8250	28.6086	.5274	4.87
20	5	18.8730	26.4518	7.5788	26.1601	.2917	3.84
25	6	18.4208	24.5778	6.1570	24.4030	.1748	2.84
30	7	19.3895	28.3676	8.9781	28.1746	.1930	2.15
35	8	19.9685	28.6800	8.7115	28.5680	.1120	1.29
40	9	18.6536	27.4076	8.7540	27.3912	.0164	.19
45	10	19.4331	25.1596	5.7265	25.1588	.0008	.01
55	11	19.7382	26.6948	6.9566	26.6943	.0005	.01

Date: 7/20/50

Run #15

Steam pressure-8.5 psig
RPM-3
Plow clearance from plate-1/16"
Bed depth-1 1/4"

Composition of drying mixture

Weight of dry sand (lbs.)	45 1/2
Weight of water added (lbs.)	5 3/4
Total weight (lbs.)	51 1/4

Initial temperature of mixture-108°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.20
5	13	22.3375	34.1529	11.8154	33.2394	.9135	7.74
10	14	20.9367	32.2970	11.3603	31.6358	.6612	5.83
15	15	21.3170	33.6376	12.3206	33.0854	.5522	4.48
20	16	21.1210	31.4016	10.2806	31.1048	.2968	2.89
25	17	21.7204	29.7064	7.9860	29.5524	.1540	1.93
30	18	21.4330	34.3158	12.8828	34.2224	.0934	.73
35	19	21.3150	30.2350	8.9200	30.2342	.0008	.01
40	20	20.9988	29.5532	8.5544	29.5527	.0005	.01
50	21	21.9413	29.5990	7.6577	29.5988	.0002	.001

Date: 7/21/[illegible]

Run #16

Steam pressure-1.63 psig
R. 1-3/4
Plow clearance from plate-1/16"
Bed depth-1 1/4"

Composition of drying mixture

Weight of dry sand (lbs.)	45 1/2
Weight of water added (lbs.)	5 3/4
Total weight (lbs.)	51 1/4

Initial temperature of mixture-75°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.20
5	1	18.5223	27.9008	9.3785	26.9760	.9248	9.87
10	2	19.5052	28.2616	8.7564	27.5363	.7253	8.28
15	3	20.5524	33.0558	12.5034	32.0838	.9720	7.77
20	4	18.3110	28.3710	10.0600	27.7000	.6710	6.67
25	5	18.8730	30.0524	11.1794	29.4462	.6062	5.43
30	6	17.4205	30.2415	11.8205	29.6600	.5815	4.75
35	7	19.3895	30.9064	11.5159	30.4600	.4464	3.88
40	8	19.5685	31.5599	11.9914	31.1466	.4133	3.45
45	9	18.6536	28.2176	10.5640	28.0086	.2090	2.84
50	10	19.4551	28.1150	8.0019	27.9166	.1984	2.29
55	11	19.7382	28.9440	9.2058	28.7796	.1644	1.79
60	13	22.3375	32.0722	9.7347	31.9616	.1106	1.14
65	14	20.9367	30.7199	9.7832	30.6466	.0733	.75
70	15	21.3170	33.2170	11.9000	33.2080	.0090	.08
75	16	21.1210	27.3822	6.2612	27.3800	.0022	.04
85	17	21.7204	28.6306	6.9102	28.6294	.0012	.02

Date: 7/21/50

Run #17

Steam pressure-1.63 psig
RPM-1.5
Flow clearance from plate-1/16"
Bed depth-1 1/4"

Composition of drying mixture

Weight of dry sand (lbs.)	45 1/2
Weight of water added (lbs.)	5 3/4
Total weight (lbs.)	51 1/4

Initial temperature of mixture-103°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.20
5	11	19.7382	31.5484	11.8102	30.4934	1.0550	8.93
10	13	22.3375	33.6386	11.3011	32.7884	.8502	7.52
15	14	20.9367	32.8336	11.8769	32.0608	.7728	6.50
20	15	21.3170	32.6256	11.3086	32.0229	.6027	5.84
25	16	21.1210	32.3295	11.2085	31.8428	.4867	4.34
30	17	21.7204	30.7198	8.9994	30.4086	.3112	3.46
35	18	21.4330	32.7732	11.3402	32.4642	.3090	2.72
40	19	21.3150	35.4200	14.1050	35.1562	.2638	1.87
45	20	20.9958	30.3532	9.3544	30.2324	.1208	1.29
50	21	21.9413	33.3198	11.3785	33.2700	.0498	.44
55	22	19.9070	31.2474	11.3404	31.2490	*	*
60	23	21.5698	29.0132	7.4434	29.0278	*	*
70	24	20.5037	29.7602	9.2565	29.6370	*	*

* Samples spilled.

Date; 7/22/50

Run #18

Steam pressure-1.63 psig
RPM-3
Plow clearance from plate-1/16"
Bed depth-1 1/4"

Composition of drying mixture

Weight of dry sand (lbs.)	45 1/2
Weight of water added (lbs.)	5 3/4
Total weight (lbs.)	51 1/4

Initial temperature of mixture-78°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.20
5	1	18.5223	23.9086	10.3653	27.9895	.9191	8.66
10	2	19.5052	28.9038	9.3966	28.1649	.7989	7.87
15	3	20.5524	29.3024	8.8300	28.8690	.5134	5.81
20	4	18.3110	27.2410	8.9300	26.0144	.4266	4.78
25	5	18.8730	28.2450	9.3720	[illegible]	.3314	3.54
30	6	18.4208	28.1794	9.7506	[illegible]	.2928	2.39
35	7	19.3095	28.2456	8.8861	28.1180	.1276	1.44
40	8	19.9685	31.3976	11.4291	31.3456	.0520	.46
45	9	18.6536	27.7201	9.0665	27.7199	.0002	.002
55	10	19.4331	27.6626	8.2295	27.6625	.0001	.001

Date: 7/22/55

Run #19

Steam pressure-1.63 psig
R.M-1.5
Flow clearance from plate-1/16"
Bed depth-1 1/4"
Drying bed covered

Composition of drying mixture

Weight of dry sand (lbs.)	45 1/2
Weight of water added (lbs.)	5 3/4
Total weight (lbs.)	51 1/4

Initial temperature of mixture-81°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.20
10	1	18.5223	28.6502	10.1279	27.7602	.8900	8.78
20	2	19.5052	28.3294	8.8242	27.7082	.6212	7.05
30	3	20.5524	32.9166	12.3642	32.2876	.6290	5.10
40	4	18.3110	29.7062	11.3952	29.3153	.3904	3.43
50	5	18.8730	32.0278	13.1548	31.8004	.2274	1.73
60	6	18.4208	30.6266	12.2058	30.5890	.0376	.31
70	7	19.3895	27.1140	7.7245	27.1140	.0000	0.00
80	8	19.9685	29.0500	9.0815	29.0510	-.0010	----

Date: 7/23/50

Run #20

Steam pressure-15 psig
R.P.M.-3
Plow clearance from plate-3/8"
Bed depth-1 1/4"

Composition of drying mixture

Weight of dry sand (lbs.)	45 1/2
Weight of water added (lbs.)	5 3/4
Total weight (lbs.)	51 1/4

Initial temperature of mixture-81°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.20
5	9	18.6536	29.7056	11.0520	28.8100	.8956	8.10
10	10	19.4331	31.6224	12.1893	30.8740	.7484	6.14
15	11	19.7382	31.6576	11.9194	31.1706	.4870	4.08
20	13	22.3375	33.3264	10.9889	33.0210	.3054	2.78
25	14	20.9367	33.5930	12.6563	33.4164	.1766	1.40
30	15	21.3170	31.8860	10.5690	31.8754	.0106	.10
35	16	21.1210	30.2808	9.1598	30.2808	.0000	0.00
45	17	21.7204	33.2514	11.5310	33.2519	-.0005	----

Date: 7/24/50

Run #21

Steam pressure-15 psig
R.H.-0
Bed depth-1 1/4"

Composition of drying mixture

Weight of dry sand (lbs.)	45 1/2
Weight of water added (lbs.)	5 3/4
Total weight (lbs.)	51 1/4

Initial temperature of mixture-81°F.

Time in Min.	Sample No.	W_1	W_2	W_3	W_4	W_5	% Moist.
0							11.20
10	9	18.6536	29.9736	11.3200	29.5530	.4206	3.71
20	10	19.4331	29.1542	9.7211	29.0152	.1390	1.43
30	11	19.7302	30.5054	10.7672	30.4046	.1008	.94
40	13	22.3375	34.3708	12.0333	34.3002	.0706	.59
50	14	20.9567	30.9858	10.0491	30.9636	.0222	.22
60	15	21.3170	31.8250	10.5080	31.[illegible]	.0010	.01

Date: 7/24/50

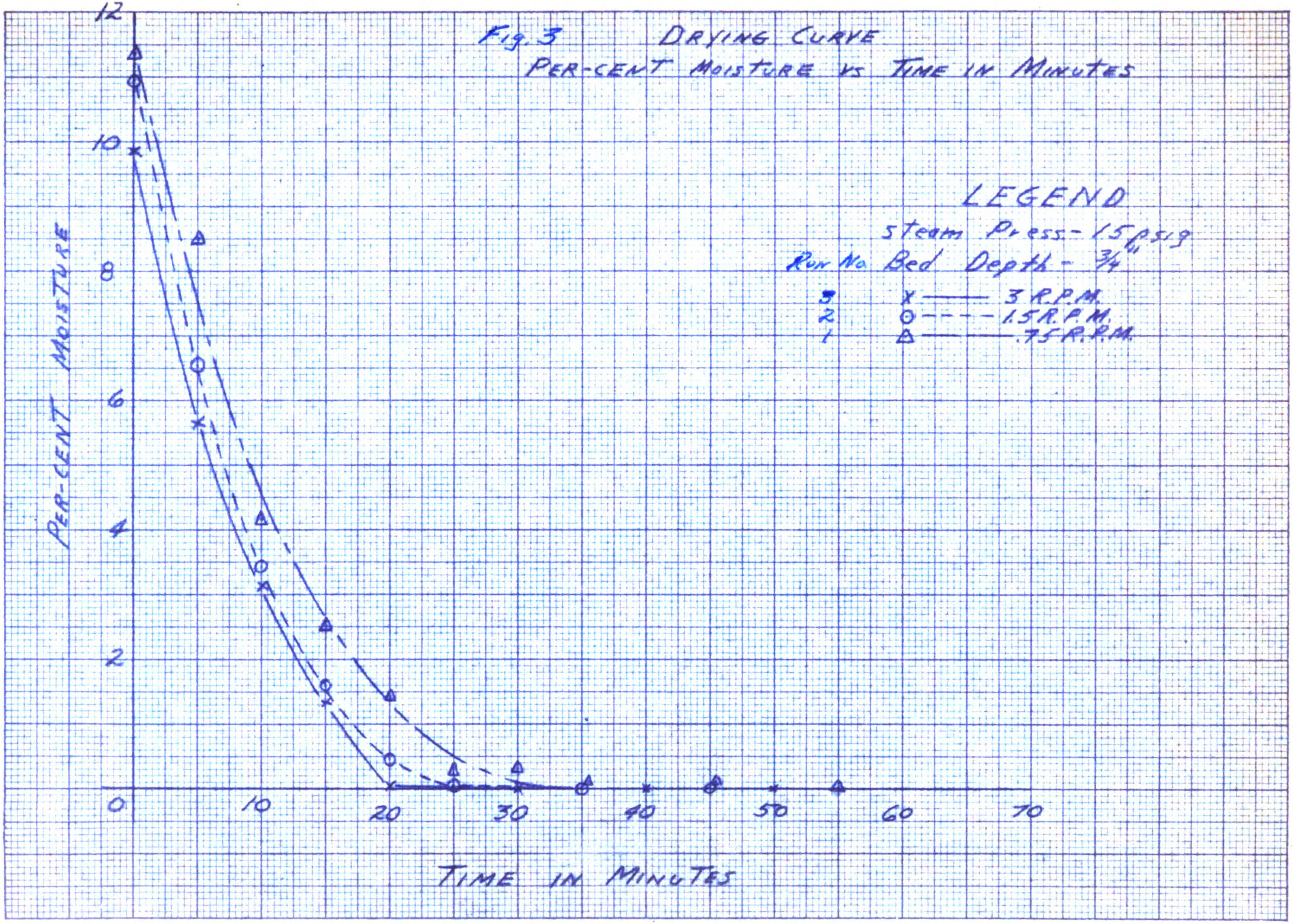


Fig. 3 DRYING CURVE
PER-CENT MOISTURE vs TIME IN MINUTES
LEGEND
Steam Press - 15 psig
Run No. Bed Depth - 3/4"
3 X —— 3 R.P.M.
2 O - - - 1.5 R.P.M.
1 △ —— .75 R.P.M.
PER-CENT MOISTURE
TIME IN MINUTES
0
2
4
6
8
10
12
10
20
30
40
50
60
70

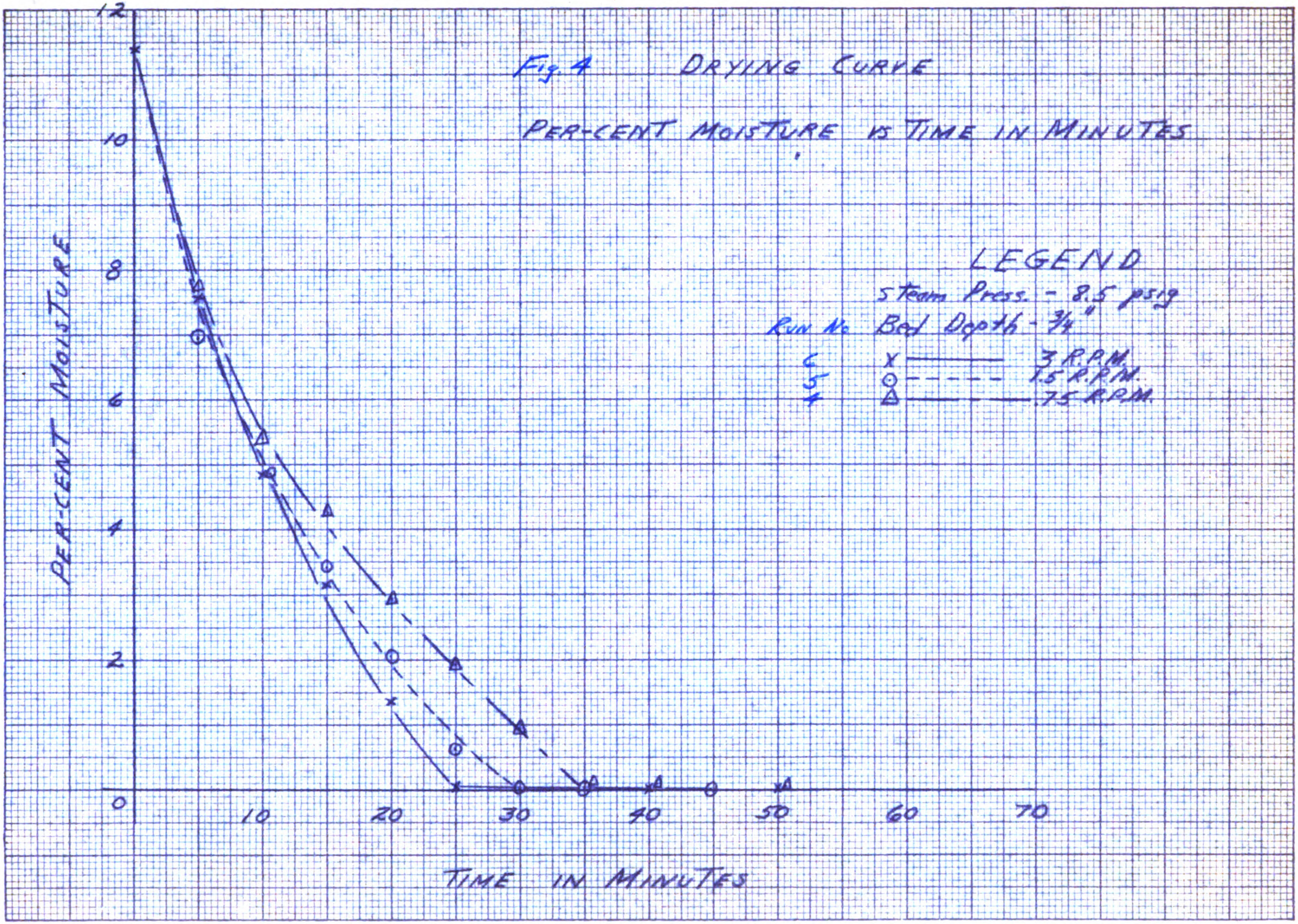


Fig. 4 DRYING CURVE
PER-CENT MOISTURE vs TIME IN MINUTES
LEGEND
Steam Press. - 8.5 psig
Run No. Bed Depth - 3/4"
6 X —— 3 R.P.M.
5 ⊙ - - - 1.5 R.P.M.
4 △ — — .75 R.P.M.
PER-CENT MOISTURE
12
10
8
6
4
2
0
10
20
30
40
50
60
70
TIME IN MINUTES

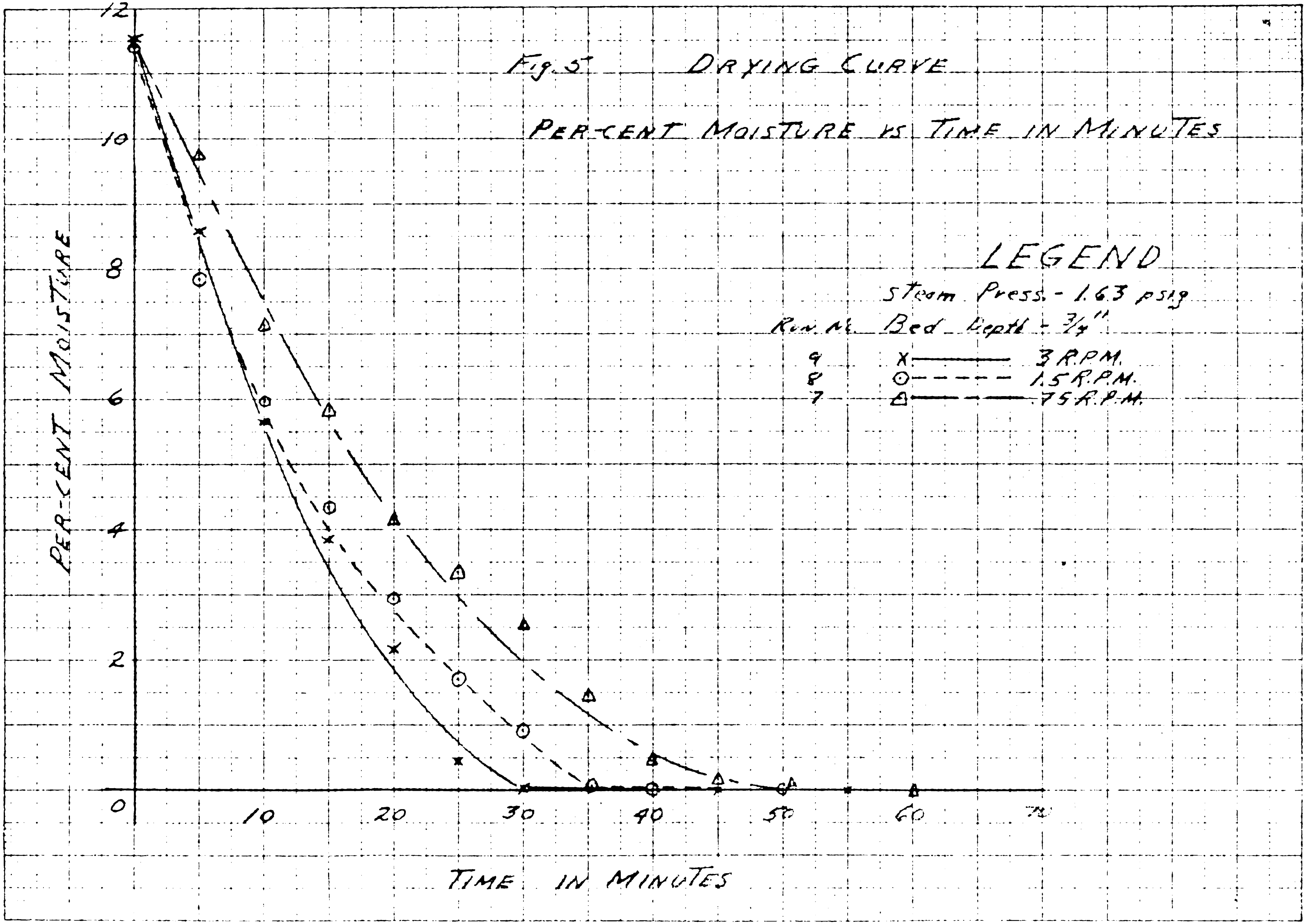


Fig. 5 DRYING CURVE
PER-CENT MOISTURE vs TIME IN MINUTES
LEGEND
Steam Press. - 1.63 psig
Run No. Bed Depth - 3/4"
9 X 3 R.P.M.
8 ⊙ 1.5 R.P.M.
7 △ .75 R.P.M.
PER-CENT MOISTURE
TIME IN MINUTES
0
2
4
6
8
10
12
10
20
30
40
50
60
70

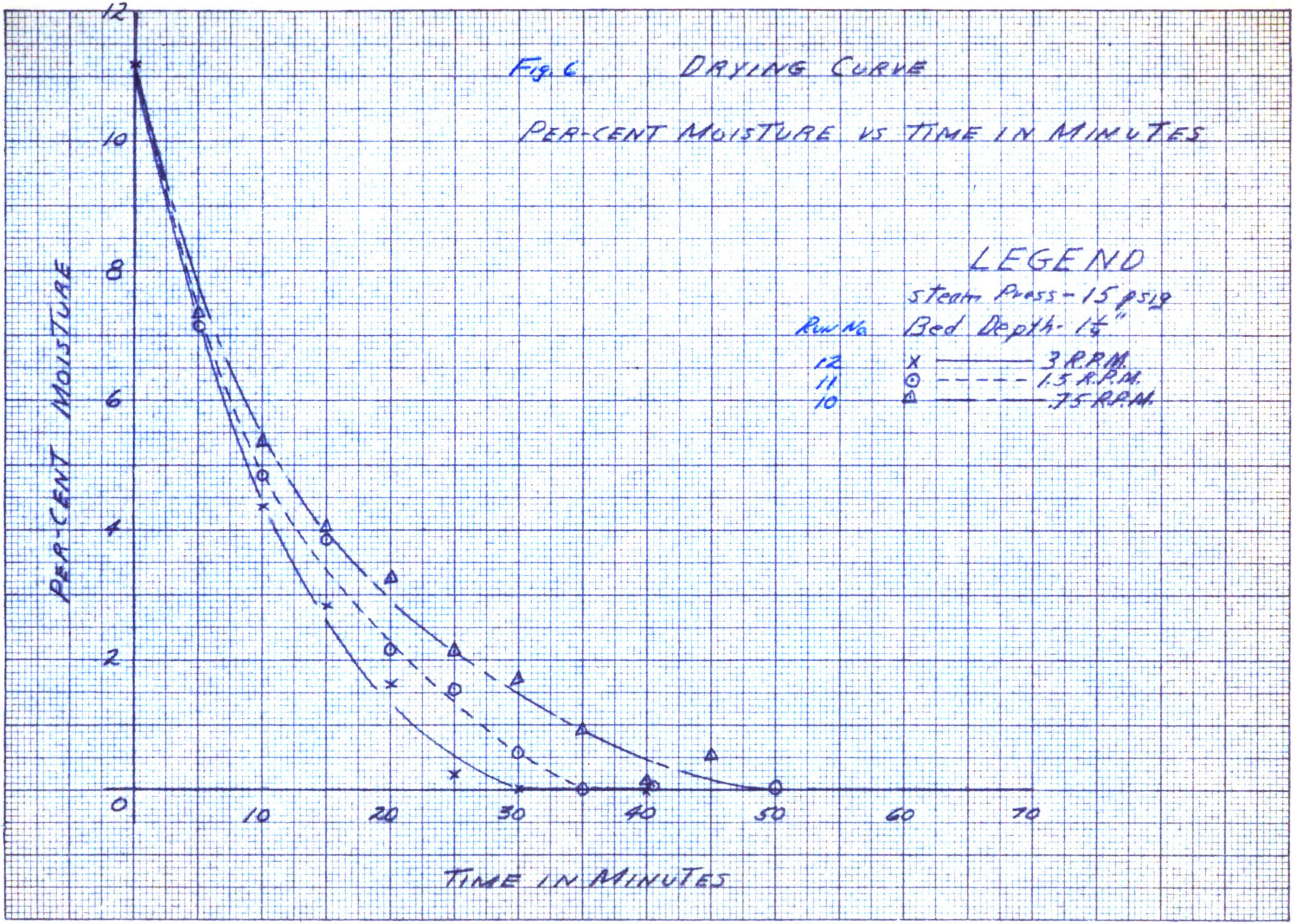


Fig. 6 DRYING CURVE
PER-CENT MOISTURE VS TIME IN MINUTES
LEGEND
Steam Press - 15 psig
Bed Depth - 1¼"
Run No.
12 × —— 3 R.P.M.
11 ⊙ - - - - 1.5 R.P.M.
10 △ —— .75 R.P.M.
PER-CENT MOISTURE
0
2
4
6
8
10
12
10
20
30
40
50
60
70
TIME IN MINUTES

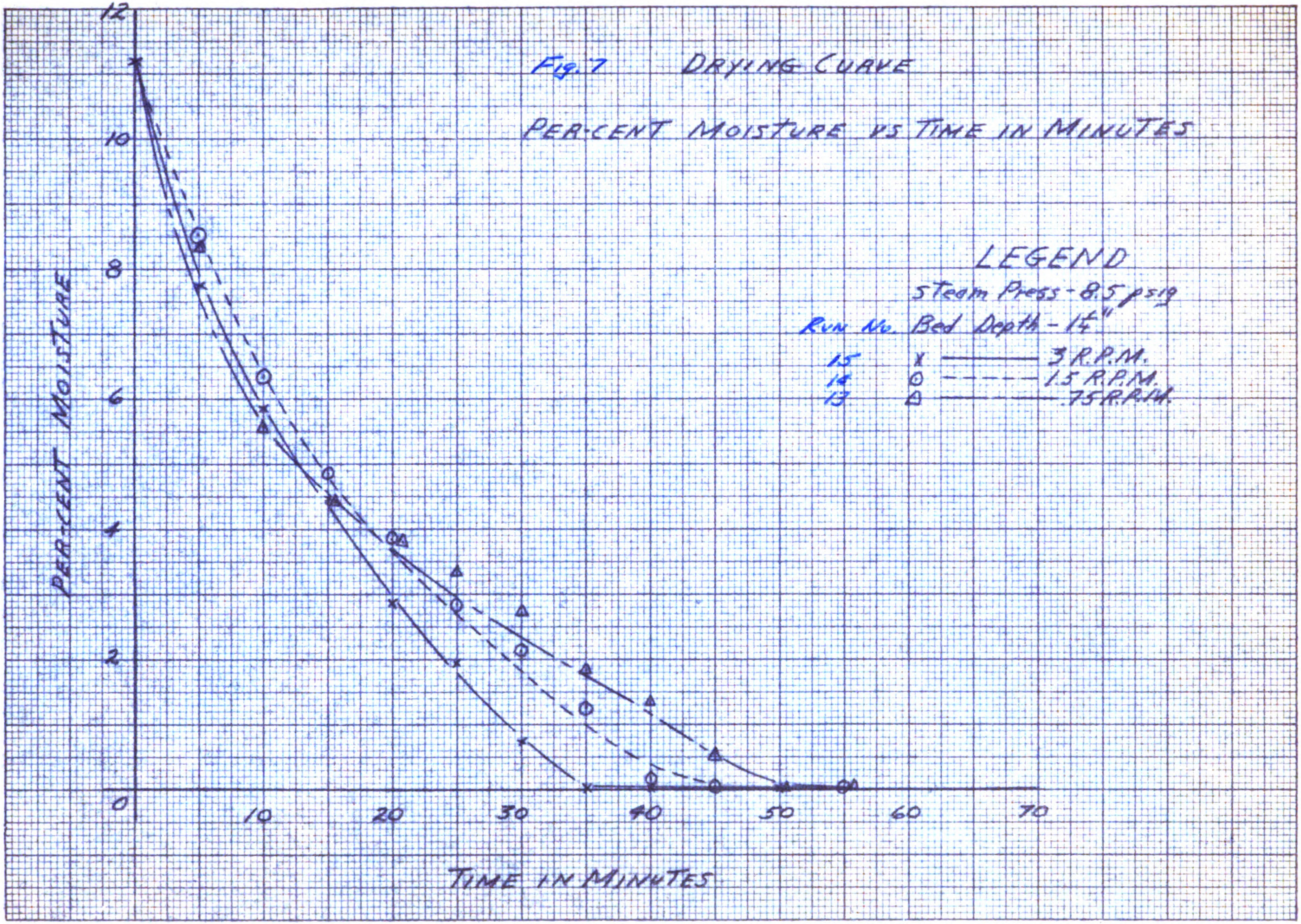


Fig. 7 DRYING CURVE
PER-CENT MOISTURE VS TIME IN MINUTES
LEGEND
Steam Press - 8.5 psig
Run No. Bed Depth - 1¼"
15 X 3 R.P.M.
14 O 1.5 R.P.M.
13 Δ .75 R.P.M.
PER-CENT MOISTURE
TIME IN MINUTES
12
10
8
6
4
2
0
10
20
30
40
50
60
70

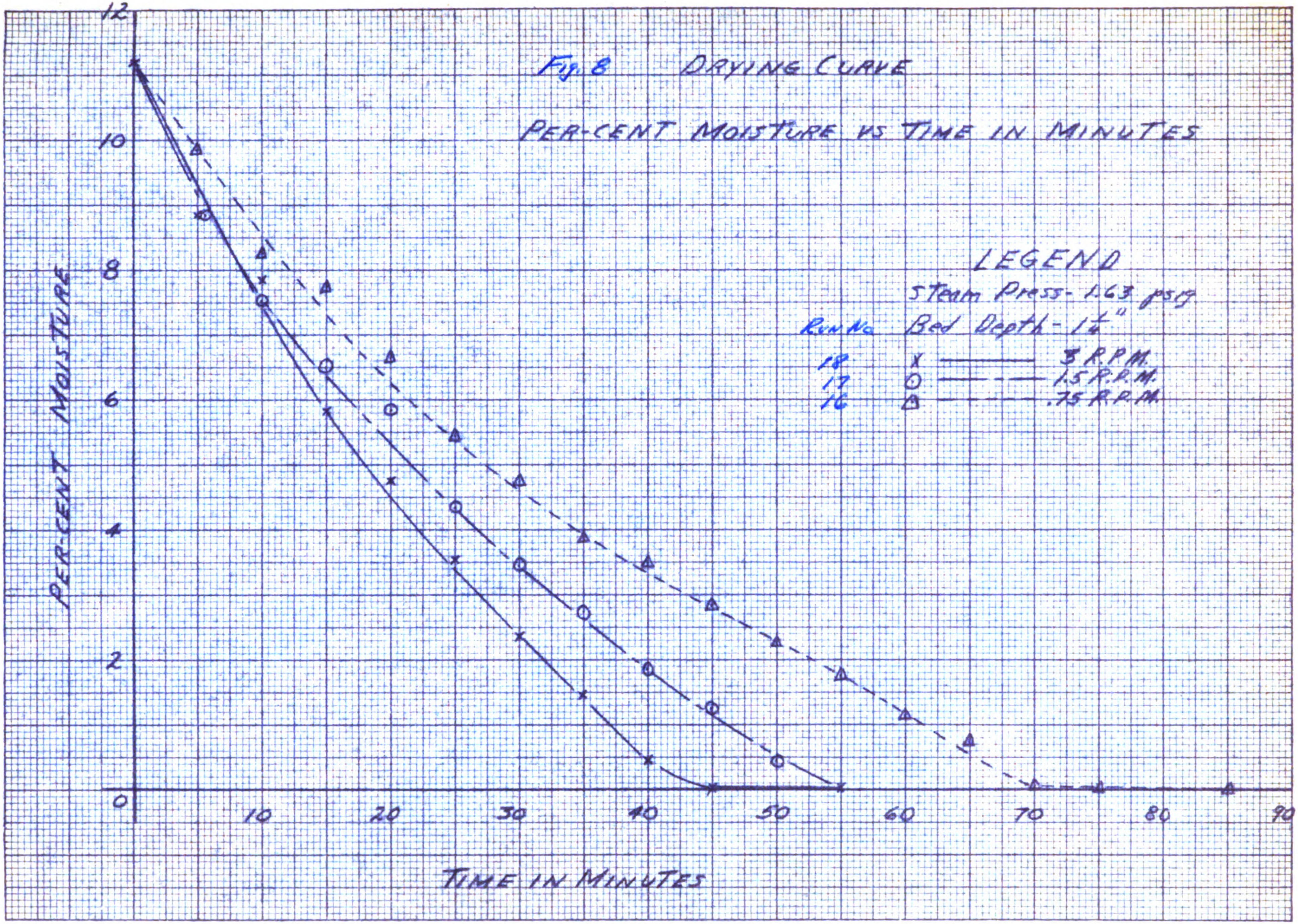


Fig. 8 DRYING CURVE
PER-CENT MOISTURE VS TIME IN MINUTES
LEGEND
Steam Press - 1.63 psig
Bed Depth - 1¼"
Run No.
18 X 3 R.P.M.
17 O 1.5 R.P.M.
16 Δ .75 R.P.M.
PER-CENT MOISTURE
TIME IN MINUTES
0
2
4
6
8
10
12
10
20
30
40
50
60
70
80
90

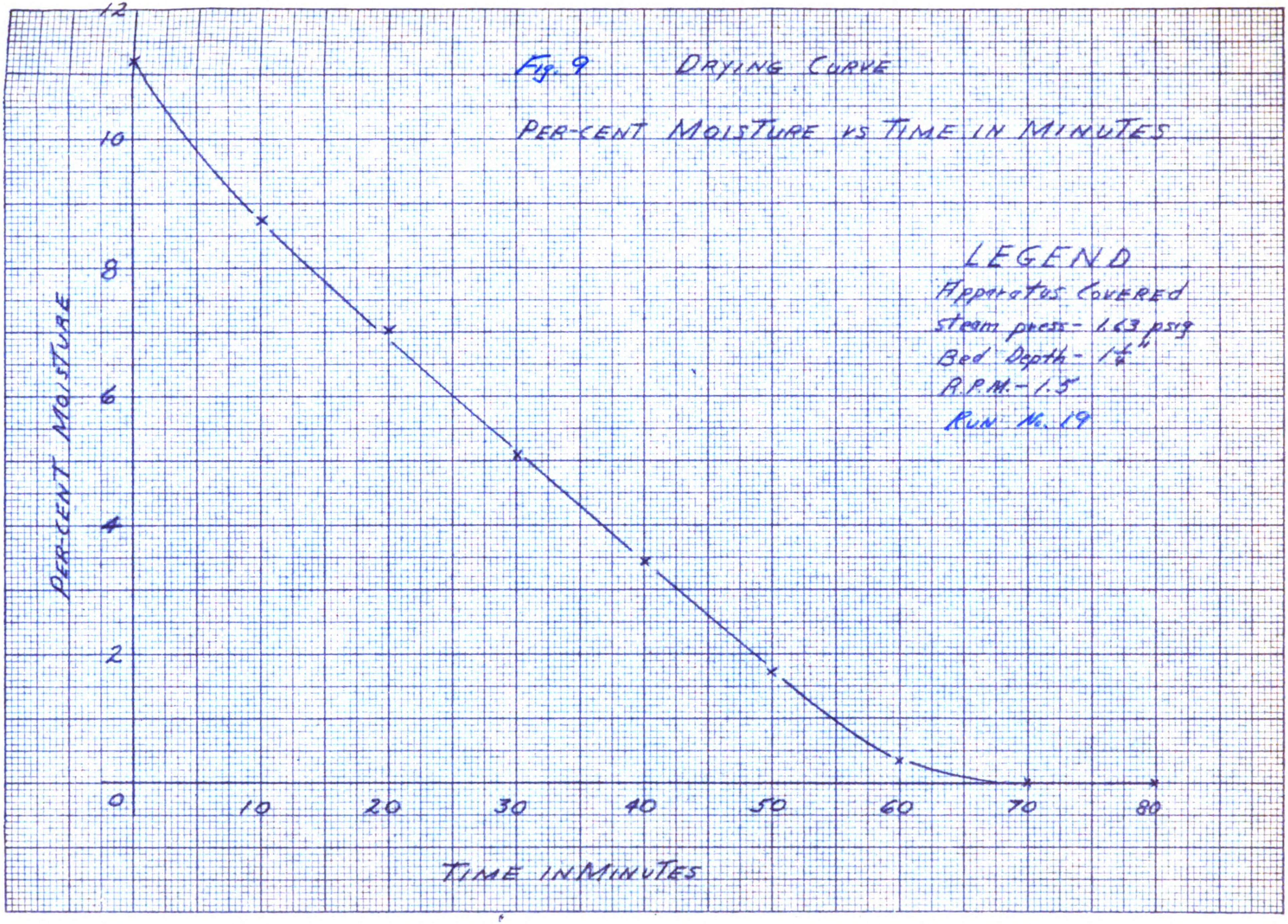


Fig. 9 DRYING CURVE
PER-CENT MOISTURE VS TIME IN MINUTES
LEGEND
Apparatus Covered
steam press - 1.63 psig
Bed Depth - 1¼"
R.P.M. - 1.5
Run No. 19
PER-CENT MOISTURE
0
2
4
6
8
10
12
10
20
30
40
50
60
70
80
TIME IN MINUTES

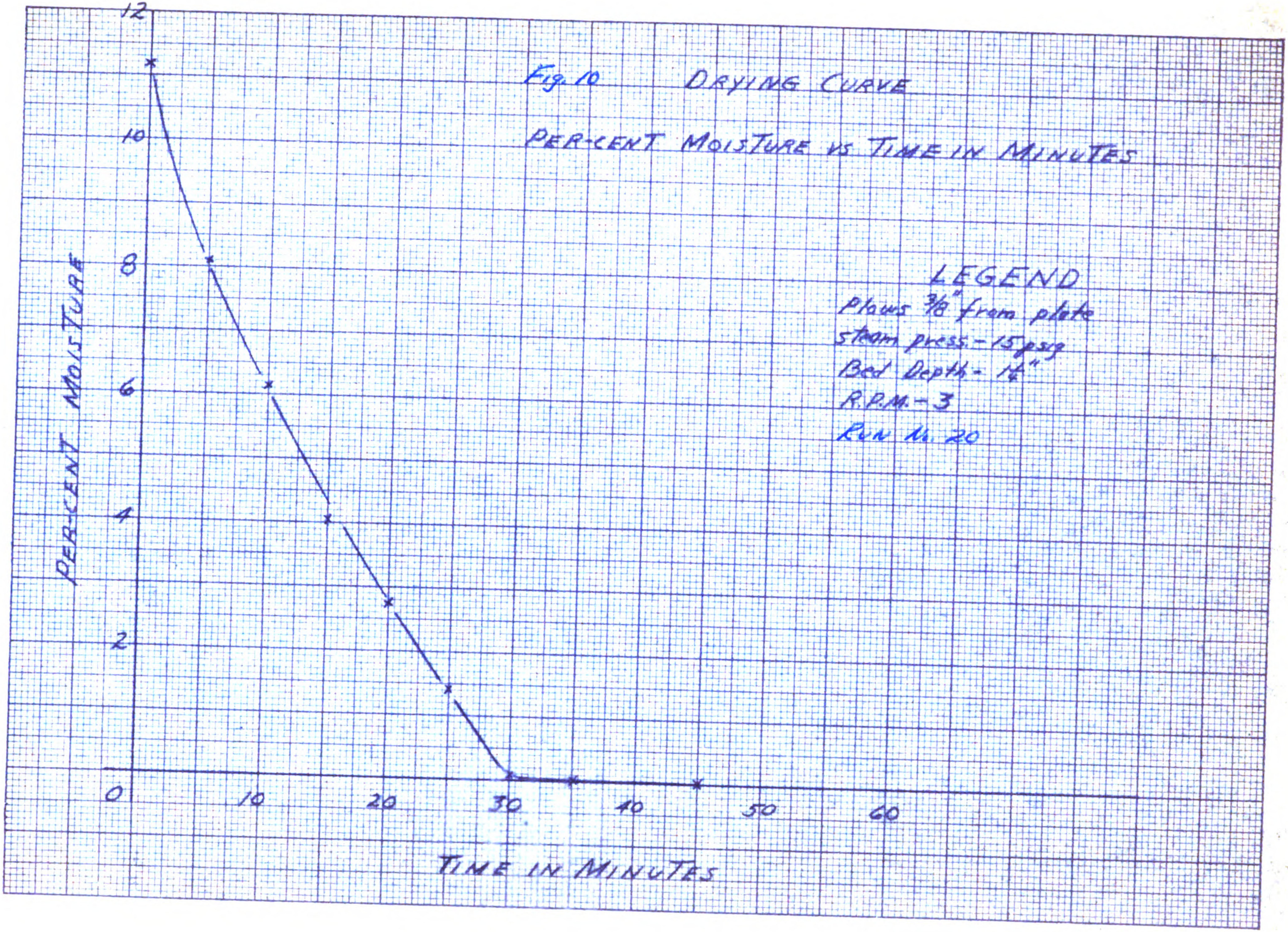


Fig. 10 DRYING CURVE
PER-CENT MOISTURE vs TIME IN MINUTES
LEGEND
Plows 3/8" from plate
steam press - 15 psig
Bed Depth - 1/4"
R.P.M. - 3
Run No. 20
PER-CENT MOISTURE
TIME IN MINUTES
12
10
8
6
4
2
0
10
20
30
40
50
60

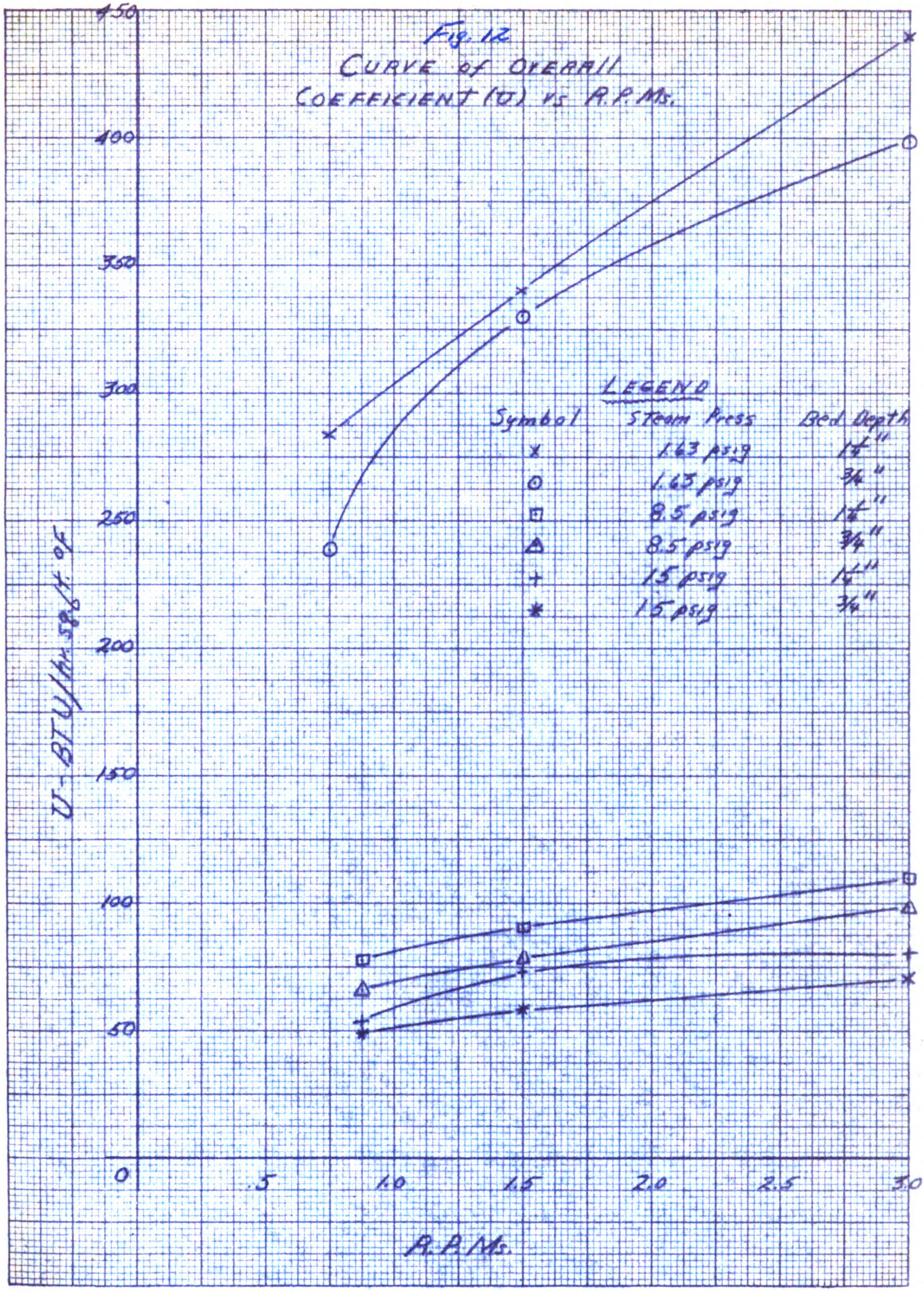


Fig. 12
CURVE of OVERALL
COEFFICIENT (U) vs R.P.Ms.
LEGEND
Symbol | Steam Press | Bed Depth
x | 1.63 psig | 1¼"
o | 1.63 psig | ¾"
□ | 8.5 psig | 1¼"
△ | 8.5 psig | ¾"
+ | 15 psig | 1¼"
* | 15 psig | ¾"
U - BTU/hr. sq. ft. °F
450
400
350
300
250
200
150
100
50
0
.5
1.0
1.5
2.0
2.5
3.0
R.P.Ms.

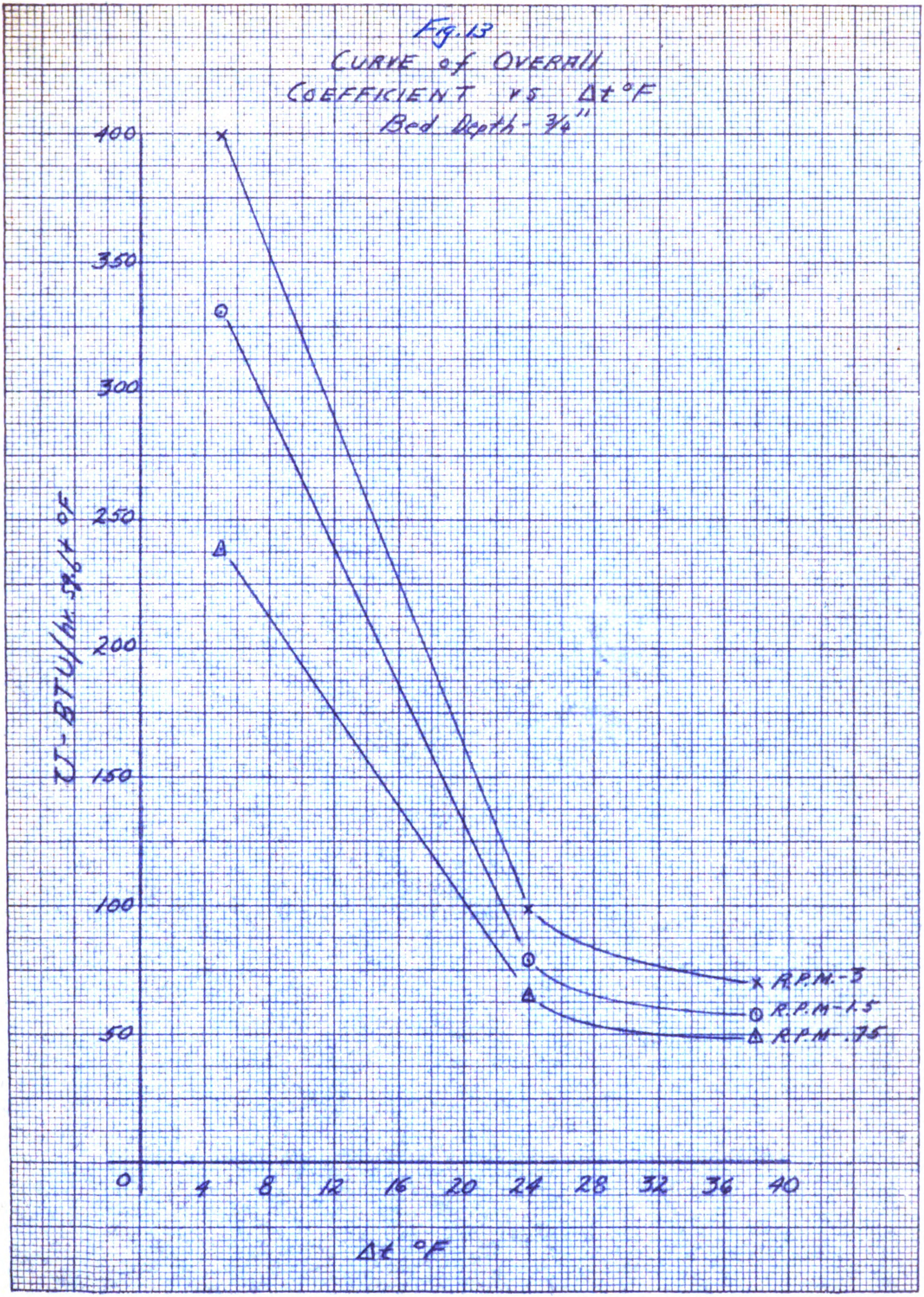


Fig. 13
Curve of Overall
Coefficient vs Δt °F
Bed Depth - 3/4"
U - BTU/hr. sq. ft °F
400
350
300
250
200
150
100
50
0
4
8
12
16
20
24
28
32
36
40
Δt °F
R.P.M. - 3
R.P.M. - 1.5
R.P.M. - .75

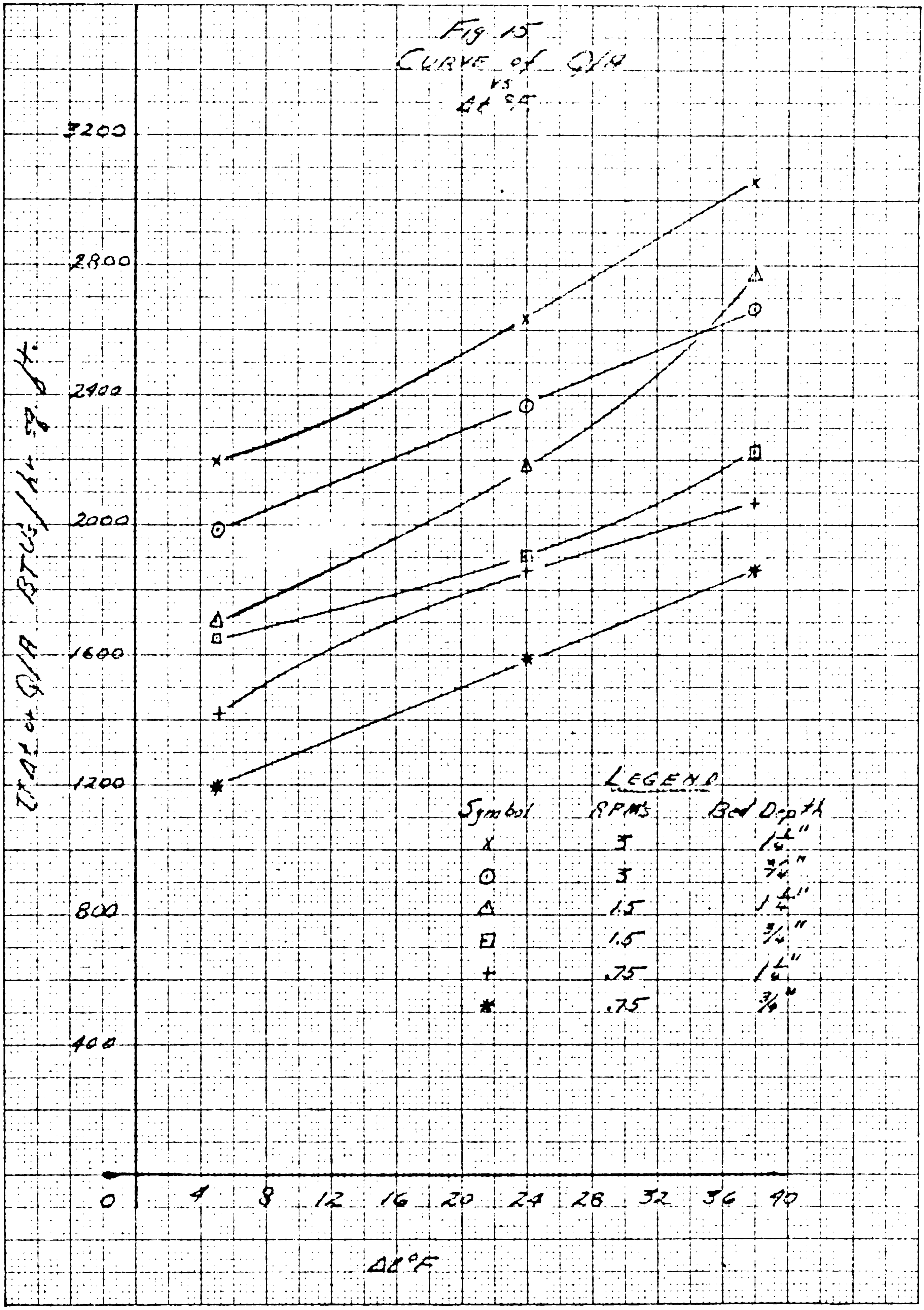


Fig 15
Curve of Q/A vs Δt °F
3200
2800
2400
2000
1600
1200
800
400
0
4
8
12
16
20
24
28
32
36
40
Δt °F
Legend
Symbol RPMs Bed Depth
x 3 1¼"
⊙ 3 ¾"
Δ 1.5 1¼"
⊡ 1.5 ¾"
+ .75 1¼"
✱ .75 ¾"

CALCULATED DATA

Area=4.71 sq. ft.

Run No.	Steam Press. (psig)	RPM	Bed Depth inches	Initial Temp. of Mixture (°F.)	Δt	U	$U_{\Delta t}$
1	15	3/4	3/4	83	38	49.0	1860
2	15	1.5	3/4	98	38	58.7	2230
3	15	3	3/4	84	38	70.1	2665
4	8.5	3/4	3/4	110	24	66.5	1595
5	8.5	1.5	3/4	100	24	79.4	1905
6	8.5	3	3/4	83	24	98.8	2370
7	1.63	3/4	3/4	79	5	239.0	1195
8	1.63	1.5	3/4	96	5	331.0	1655
9	1.63	3	3/4	87	5	398.0	1990
10	15	3/4	1 1/4	80	38	54.5	2070
11	15	1.5	1 1/4	86	38	73.0	2775
12	15	3	1 1/4	113	38	80.5	3060
13	8.5	3/4	1 1/4	105	24	77.6	1862
14	8.5	1.5	1 1/4	81	24	91.0	2185
15	8.5	3	1 1/4	108	24	110.0	2640
16	1.63	3/4	1 1/4	75	5	284.0	1420
17	1.63	1.5	1 1/4	103	5	341.0	1705
18	1.63	3	1 1/4	78	5	440.0	2200
19*	1.63	1.5	1 1/4	81	5	291.0	1455
20	15	3	1 1/4	81	38	86.1	3270
21	15	0	1 1/4	81	38	42.2	1600

* Run No. 19 & 17 are the same except that the dryer is covered in Run No. 19.

Note: All runs with the exception of No. 20 have a plow clearance with the plate of 1/16"

DISCUSSION

The drying curves are all consistent in so far as the slower agitation runs required the longer drying times. In some cases, for example in Fig. 7, it is seen that the instantaneous drying rates of the slower agitation runs are larger than those of the increased agitation runs during the initial time intervals. This is noted where the slopes of the curves are steeper and cross under the curves for the faster agitated runs. This is the case in Fig. 7 where the curve at .75 r.p.m. shows a faster drying rate during the first 10 or 12 minutes of the run than the other runs at increased agitations. The reasons for this lie in the initial temperature differences of the mixtures and also by the fact that the worst source of inconsistencies probably exists during the initial stages of the runs when the charge is being heated up.

It may seem rather inconsistent that the overall coefficients obtained decrease with an increasing temperature difference as shown in Fig. 13 & 14. It is believed that this can be explained by the fact that in run no. 21-Fig. 11, in which no agitation was used, it was noted that the material on the top and bottom of the bed was dry while the material in the center was still moist. Eventually all the material became dry but the material on the top and bottom of the bed were dry some time before the material in the middle. The material next to the plate would be expected to become dry first since it was in contact with the hot surface. The material on top becoming dry sooner than the material under it leads to the conclusion that air currents were assisting the drying process. If this was the case, the apparatus was not entirely an indirect dryer. This phenomenon was suspected before run no. 21 and that is the reason for run no. 19-Fig. 9. In this run a cardboard box was placed over the drying apparatus and it was seen that the drying time was increased as compared to the same run with no cover in Fig. 8. While this method of covering the dryer was not air tight it served the purpose of protecting some of the surface from stray air currents. This run showed a somewhat lower coefficient that the similar run no. 17 indicating that air currents over the bed were helping to dry the mixture.

From the above observation it is seen that if steam at atmospheric pressure were used giving a zero temperature difference there would be some drying by the air currents and the overall coefficients would be infinite. Since the temperature difference in the runs using the low steam pressure were small (5°F.) this is believed to be the reason for the extremely high coefficients obtained for these runs. Of course the runs at the higher steam pressures were all assisted by the air currents so the coefficients obtained here will be higher than those in a sealed rotary shelf dryer that is the common installation industrially.

The curves in Fig. 12 show an increase of overall coefficients with increased rate of agitation and this is as would be expected due to higher agitation rates bringing more material in contact with the hot surface and breaking up the mixture to allow the moisture to escape.

When the initial wet mixture was placed on the drying bed not all of the heat transfer area was utilized during the initial stages of the run. Since the sand was moist it tended to agglomerate together and with a plow clearance of only 1/16" the trailing space behind the plows was bare of material. When the next set of plows moved material onto this space it left a bare space in the same manner and so on. This was the case until the material became drier and tended to be more granular and free flowing and then there was a constant shallow layer under the plows and also a slight amount of material fell behind the plows. This is not the case in the industrial installation where the material moves in one direction across the plate but in this case, due to the limited equipment, the mixture was raked back and forth. In accounting for the slightly increased coefficients with greater bed depth it seems possible that this unused area was different for the two bed depths. It seems that with the greater bed depth that there would be more of a tendency for the wet material to fall behind the plows and utilize some of the space left bare by the plows. Theoretically one would expect the same coefficients for all bed depths.

In run no. 21-Fig. 11 in which no agitation was used a longer drying time was required than in the similar runs using agitation. As the drying time is increased the drying rate falls off. This is because the insulating layer of dry sand is becoming thicker as the material is drying. When this layer of dry sand becomes thicker it offers more resistance to the passage of heat and thereby reduces the heat transferred to the moist material above the dry sand layer. During the agitated runs this extreme decrease in drying rate was not present. Also during the run with no agitation it was noted when the run was completed that a thin black scale had formed on the drying bed. The run was only conducted for one hour and the scale was probably not too serious although continued operation would build up the scale and reduce the heat transfer and thereby the capacity. The absence of the scale is another distinct advantage of using agitation while drying.

The curves of Fig. 15 show the expected increase of heat transferred per unit area with an increase in temperature difference.

In run no. 20-Fig. 10 in which the plow clearance was increased to 3/8" a higher heat transfer coefficient was obtained. In this run all the heat transfer area was utilized during the run and this probably accounts for the higher coefficients. Since only one run was made at this increased plow clearance as a matter of curiosity no valid conclusions can be drawn due to the limited investigation.

As was mentioned before the outermost plow angle was adjusted to 52° to obtain a suitable plowing action from these plows.

The temperature difference used throughout in the calculations was the difference between the temperature of the steam at the existing pressure and the temperature at which water vapor was formed at the existing atmospheric pressure.

The bed area used in the calculations was the entire area included between the two circular retaining walls.

CONCLUSIONS

1. Heat transfer coefficients were obtained for the drying of wet sand by plowing it across a heated surface. For a variety of conditions these coefficients ranged upward from 49 Btu's/hr. transferred per square foot of heated surface per degree Fahrenheit temperature difference between the surface and the boiling point of the water.

2. It may be necessary to lower the above figure somewhat when a correction is made for drying caused by stray air currents.

3. The rate of plowing was varied from 6 times per minute at any given point to 24 times per minute, the coefficients being consistently greater at the higher rates.

4. Bed depths of 3/4" and 1 1/4" were used, greater coefficients being noted at the greater depths.

5. Temperature differences ranging from 5°F. to 38°F. were used. Much higher coefficients were noted at the lower differences. This may be due in part to the effect of air currents.

6. One run in which the plow clearance was increased from 1/16" to 3/8" showed an increase rather than a decrease in coefficient.

7. For the same plowing action, the angle between the plow edge and it's path must be less for plows raking toward the center of the plate than for those raking toward the periphery.

RECOMMENDATIONS FOR FURTHER WORK

An investigation conducted in the same manner as this one only employing an air tight system would give more of an indication of the heat transfer coefficients that could be expected industrially. It would also show to what extent higher coefficients at low temperature differences are due to air currents.

The effect of bed depth and plow angle could be studied more thoroughly. A different method of agitation might also be studied such as a plow that would cover the complete bed and just scrape the bottom thereby moving the material over it and tumbling it behind the plow.

The effect of different drying materials such as fibrous materials and those that adsorb moisture and show distinct falling rate periods could be investigated.

The effect of plowing the material continuously in one direction could be studied as opposed to this method of moving the material back and forth.

CALCULATIONS

(1) Drying bed area

Diameter of outer retaining wall-30.56"
Diameter of inner retaining wall- 8.50"

$$\frac{\pi}{4 \times 144} \quad (30.56)^2 - (8.5)^2 = 4.71 \text{ Sq. ft.}$$

(2) Per cent moisture

$$\frac{\text{loss. in wt. of sample}}{\text{sample wt.}} \times 100 = \% \text{ moisture}$$

(3) Sample calculation for Run #16 (Fig. 8)

Steam pressure-1.63 psig
RPM-3/4
Bed depth-1 1/4"
Plow clearance from plate-1/16"
Initial temperature of mixture-75°F.

Wt. of bone dry sand-45.5 lbs.
Wt. of water at start of run-5.75 lbs.
Time to dry mixture-70 minutes
Final moisture content of mixture-0.08%

$$\frac{(100) \times Y}{45.5 + Y} = .08 \qquad Y = .0364 \text{ lbs. of water at end of run.}$$

$$\begin{array}{r} 5.7500 \\ -\ .0364 \\ \hline 5.7136 \end{array}$$ wt. of water removed in drying.

Heat required as sensible heat and heat of vaporization.

Sensible heat of H_2O | Latent ht. of H_2O | Sensible heat of sand

$$q = (5.7136)(1)(211-75) + (5.7136)(971) + (45.5)(.23)(211-75)$$

q=7750 BTU/70 minutes

$$7750 \frac{\text{BTU}}{70 \text{ min.}} \times \frac{60 \text{ min.}}{1 \text{ hr.}} = 6650 \text{ BTU/hr.}$$

$q = UA\Delta t$ A=4.71 sq. ft.   Temp. of 1.63 psig steam=216°F.
$\Delta t = 216-211 = 5°F.$

$$U = \frac{q}{A\Delta t} = \frac{6650}{4.71 \times 5} = 284 \text{ BTU/ hr. sq. ft. °F.}$$

The coefficients for all the runs were calculated in the same manner as the above calculation.

NOMENCLATURE

W_1	Weight of weighing bottle
W_2	Weight of weighing bottle + sample
W_3	Sample weight (W_2-W_1)
W_4	Weight of weighing bottle + sample after drying
W_5	Weight of water removed in drying (W_2-W_4)
q	Heat transferred to drying mixture, BTU/hr.
U	Overall heat transfer coefficient, BTU/hr. sq. ft. ^{o}F.
A	Area of drying bed, sq. ft.
Δt	Temperature difference between drying surface and boiling point of the water, ^{o}F.
RPM	Revolutions per minute of plow arms

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