THE DEHYDRATION OF WHITE POTATOES

by

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INTRODUCTION

The purpose of the work described here was to determine the effect of air velocity, humidity and temperature on the drying rate of white potatoes. Mathematical statements of these effects are useful in designing dehydrators. In spite of the very large industry which sprang up during the war to supply dehydrated potatoes to the armed forces, no study of this sort has appeared in the literature.

The theory of drying has received a great deal of attention by many authors. The usual approach has been through diffusion theory, since drying is primarily a diffusional process. The drying period is generally divided into two periods: the first when the surface of the material is wet with free water, and the second after this free water has been removed from the surface. Sometimes another period intermediate between the above two is recognized. In this period, part of the surface is wet and part has no free water present. In the first period, the drying rate is not a function of the average moisture content and therefore is constant under constant conditions of air velocity, humidity and temperature. In the second period the controlling factor is the rate of diffusion of water in either the liquid or vapor form to the surface of the material, and the drying rate falls off as the moisture content decreases. This is discussed by Sherwood (1) and Newman (2). In the same paper, Sherwood shows that the Fourier equations of heat conduction are analogous to those which apply to the drying of solids when internal liquid diffusion is the controlling factor.

Newman (3) gives differential equations based on strict diffusional theory. These are a function of the geometrical shape of the drying material, such as the slab, the cylinder or the sphere. Tables for the solution of these equations are included. These equations do not give drying rates, but rather the ratio of the difference between the final moisture content and the equilibrium moisture content and the difference between the initial moisture concentration and the equilibrium moisture content.

These theoretical equations apply with considerable accuracy to many materials. In a great many cases, however, they fail to represent the true conditions. One of the reasons for this is the shrinkage and subsequent change of surface area during drying. Other reasons are the movement of water through the material by other means than diffusion, such as by capillarity, gravity, and convection; and the variation in diffusivity with moisture content. Hougen, McCauley, and Marshall (4) discuss the limitations of diffusion equations in drying calculations.

Drying theory in general is discussed clearly in Badger and McCabe (5, p. 280-320) and in Perry (6, p. 1480-1522).

In actual practice, theoretical drying rates are difficult to calculate without experimental data. Perry (6, p. 1482) gives the following equation for the constant rate period:

$$G = 0.021\,(V'\rho)^{0.8}$$

where G represents the rate of vaporization in pounds per hour per square foot per millimeter Hg difference between the vapor pressure of water at the surface temperature and the partial pressure of water vapor in the air, ρ is the air density in pounds per cubic foot and V' is the air velocity past the wet surface in feet per second.

The falling rate period is much more difficult to handle without experimental data. Simplifying assumptions, such as that the rate of drying curve during this period is a straight line between the origin and critical point where the constant rate period stops, must be made. These lead to large inaccuracies.

Little data on drying rates of vegetables are available in the literature. Christie and Matsumoto (7) give data on carrots, peas, and cabbage. Brown and Kilpatrick (8) give data on completely cooked and riced potatoes including drying rates at different temperatures, humidities, and air velocities. Van Arsdel (9) gives a small amount of data on Klamath Russet potatoes in 5/32" strips.

The data here presented and correlated were obtained through the Kansas Industrial Development Commission's project on dehydration at Kansas State College.

EQUIPMENT

The dehydrator, shown in Plate I, was designed by the author for use on the Kansas Industrial Development Commission's dehydration project at Kansas State College. The construction was of double-wall plywood with glass wool blanket insulation between the walls. The drying section (marked A) was two feet square by five feet long. Two doors opened outward to permit easy placing of the trays, which, except for the middle tray, were supported on angle iron slides three inches apart. The mid-

Plate I

Equipment used in the dehydration of white potatoes

A - Drying section of the dehydrator

B - Abrasive peeler

C - Dicer

D - Continuous blancher

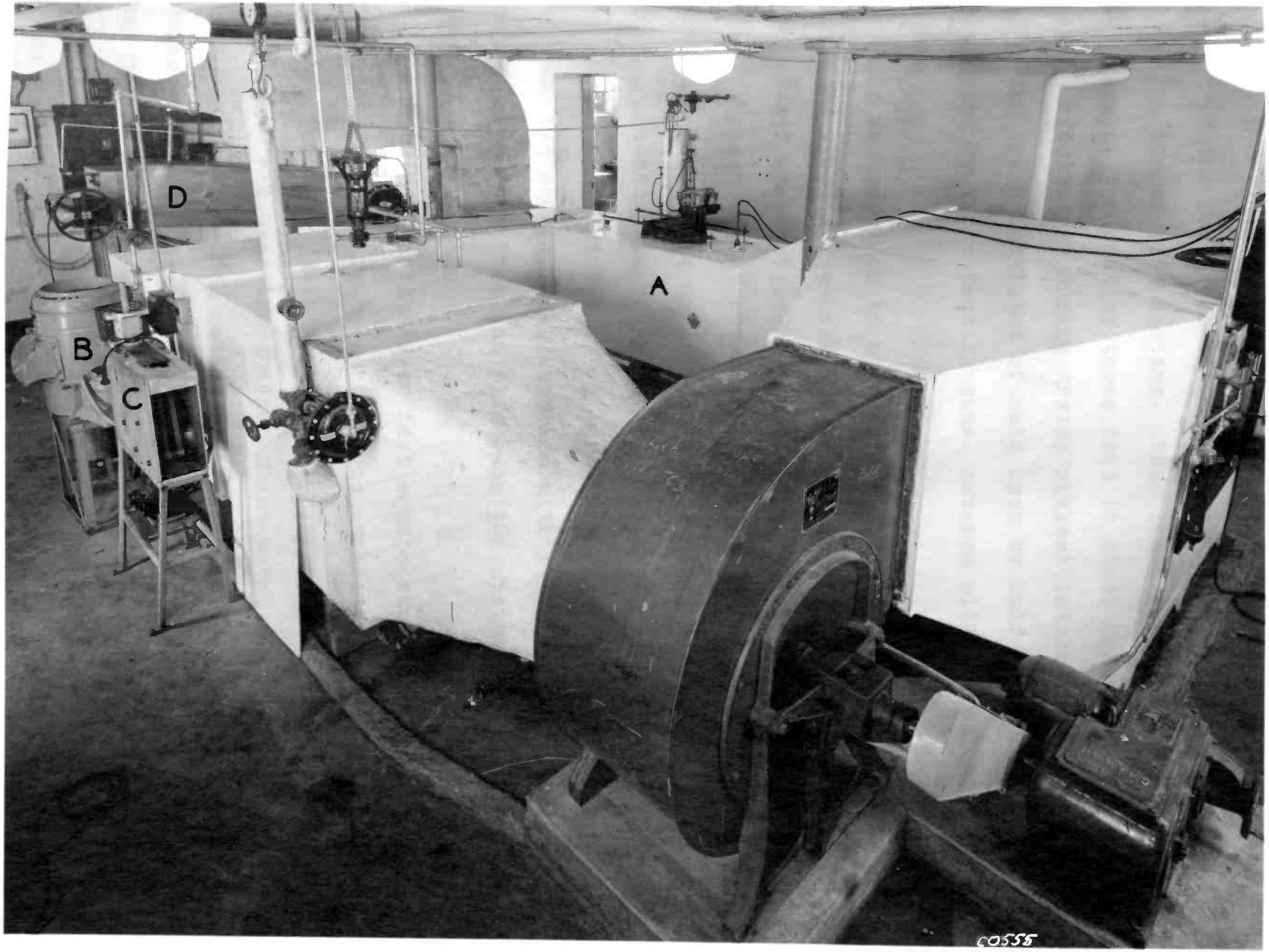

PLATE I

dle tray was supported by steel rods extending through holes in the top of the dryer and attached to a frame placed on a pair of scales on top of this section. Thus the drying section held seven trays, two feet by three feet in size, and permitted weighing the middle tray during drying without interrupting the process. The trays consisted of half inch by half inch angle iron frames two by three feet in size, covered with 16-mesh Monel screen.

Air was supplied by a Buffalo Limit Load, number $3\frac{3}{4}$, blower driven by a one-and-a-half horsepower Reeves Vari-speed Motodrive. This blower was designed to supply 5,000 cubic feet of air per minute against a static pressure of one inch of water. The Reeves drive had a speed range of four to one which gave an air velocity range of about three to one.

Heat was furnished by an Aerofin single bank coil with a face area of nine square feet, supplied with steam at a pressure of 100 pounds per square inch and placed on the upstream side of the blower.

An enlarged section four feet square was placed in the corner just ahead of the drying section and connected to it by a two-foot reducing section. This served as a plenum chamber to smooth out the flow of air over the trays. Sheet metal vanes with a 90-degree curvature on a 12-inch radius were placed diagonally across this corner on 12-inch centers to further direct the air flow and to reduce the pressure loss caused by the change of direction. This arrangement limited the maximum variation in air velocity over the cross section of the dryer to 10 percent.

The complete unit was assembled in the form of a rectangle so that air could be recirculated. Three dampers controlled the flow of the air. The exhaust air was conducted out of the building through an asbestos-covered sheet metal duct. The three dampers were connected by linkages so that the inlet and exhaust dampers operated together, but the recirculation damper operated inversely to the first two. Thus, when the inlet and exhaust dampers were closed, the recirculation damper was open; and when the first two were one quarter open, the latter was one quarter closed. This damper system was designed to assist in the control of the humidity. A section just ahead of the heating coil was fitted with a steam jet for further increasing the humidity of the air. The steam jet was used only when the humidity attained by total recirculation of the air was insufficient.

A Bristol Free-Vane, pneumatic type wet- and dry-bulb temperature controller-recorder was used to control the temperature and humidity of the air. The dry-bulb temperature was maintained constant by regulating the flow of steam to the heating coil with a Bristol Synchro-Valve. The wet-bulb was controlled by two means, positioning the dampers and blowing steam into the air. The dampers were regulated by a Bristol Damper Operator, and the steam jet by another Bristol Synchro-Valve. These two were so adjusted that the dampers were completely closed before the steam valve opened. Thus if the humidity attained by total recirculation was less than that for which the controller was set, steam would automatically be blown into the air stream to bring the wet-bulb temperature up to the desired point. Reproducible and essentially constant conditions of temperature and humidity could be maintained through a drying cycle.

The air velocity was controlled manually by setting the Reeves Motodrive to some point on its scale, thus controlling the speed of the fan. The air velocity was measured with a standard, sharp-nosed pitot tube obtained from the Miriam Company at a point just ahead of the trays but inside the drying section and in the center of the duct. The pressure differences so obtained were read from a Miriam inclined tube draft gauge with a scale 11 inches long whose range was from zero to one-half inch of water. The smallest division on the scale was 0.01 inch and readings could be estimated to 0.002 inch. At 150^{o}F. this is equivalent to approximately 200 feet per minute which is the minimum air velocity measurable with this instrument. This does not represent the accuracy of this instrument since the velocity varies as the square root of the pressure difference. Thus a pressure difference of 0.004 inch indicates a velocity of 275 feet per minute and 0.01 inch indicates 440 feet per minute. Obviously the accuracy increases as the velocity increases.

The accessory equipment used included an abrasive peeler, dicer and blancher. The peeler was a standard commercial model. The dicer was designed and built by the Shop Practice Department of Kansas State College. It produced half-cubes, 3/8 by 3/8 by 3/16 inches. The blancher was designed by Mr. A. E. Messenheimer of the Machine Design Department and constructed by the Building and Repair Department, both of the College. It consisted of a continuous canvas belt which moved through a steam chamber six feet long. The belt was driven by a half horsepower Reeves Vari-speed Motodrive through a gear reducer so that the time in the chamber was variable between two and twelve minutes. The load on the belt was held at one cube thickness by a spreader placed just above the belt at the entrance to the chamber. During operation live steam at atmospheric pressure was blown into the chamber. The whole blancher was built on an incline so that air could more easily escape from the chamber and water drain out. A vent was provided in the top of the chamber and a drain in the bottom. This device gave absolutely reproducible blanching conditions, which was considered essential for this study.

MATERIALS

The potatoes used in this project were Cobblers grown in the Kaw valley near Manhattan. They were harvested in September, 1944, and held in storage at the College until March, 1945. At the time of their use they were sound, firm, and had not sprouted, though if held out of storage for more than a week they showed rapid deterioration. Two other lots of potatoes of the same variety (Cobblers) were used for comparative purposes. One was grown in Western Kansas near Ulysses, the other in the Red River valley in South Dakota. These were obtained through the courtesy of Topeka Dehydration, Incorporated.

METHODS

A preliminary study indicated that the time interval between cold storage and dehydration had little effect on the drying rate, though it is known to affect the quality of the final product. Nevertheless a standard interval of three days out of storage was used.

Each run was made using 38 pounds of potatoes. These were peeled in the abrasive peeler, trimmed by hand, and diced. Care was taken that the potatoes were covered with clean water at all stages to prevent discoloration. The cubed potatoes were washed thoroughly to remove all the liberated starch granules. If this were not done the tendency to "case-harden", or form a hard crust on the surface during drying, was much greater, and the dried potatoes stuck to the trays badly. The potatoes were then blanched in the continuous blancher for exactly five minutes. The standard test for peroxidase using guaiacol was invariably negative after this treatment. As the blanched potatoes fell off the belt at the end of the blancher, they were caught in a tub of cold water and washed again. Finally they were spread evenly on five of the seven trays and placed in the five middle positions in the dryer. The two remaining trays were left in place to assure uniform air flow over all of the trays.

During the blanching and washing period, the dehydrator was heated to operating temperature and the controller was adjusted. This preliminary heating eliminated the usual lag in reaching the maximum drying rate. As soon as the trays were in place, the dehydrator was started again and the weight of the middle tray recorded in pounds and ounces. Subsequent weighings were made at 10-minute intervals. Longer intervals were found to give insufficient data. When no change in weight was observed for 10 minutes, the drying was stopped and the dehydrated potatoes removed from the trays. The tare weight of the tray and supporting frame was subtracted from the weights and the net weight was plotted versus time. The final moisture content was determined by the Bidwell-Sterling method. Von Loesecke (10, p. 260-264) gives the procedure for both the peroxidase test and the Bidwell-Sterling moisture determination.

DATA

A total of 40 runs were made, 36 of which were on Kaw Valley Cobblers. The remaining four were on Western Kansas Cobblers and Red River Cobblers. The data taken on each run are presented in Figs. 1-40 in the form of drying curves for runs 115 to 155 (run 138 is omitted). Three series are included. In one, consisting of runs 115-119 and 130-136, the temperature and humidity were held constant and the velocity of the air varied. In another, composed of runs 120-129, the air velocity and humidity were constant while the temperature was varied. In the third series, comprising runs 131, 137, and 139-151, the humidity was the variable quantity and the air velocity and temperature were constant.

The range over which the air velocity was varied is 402 to 1275 feet per minute. Since the velocities were measured ahead of the trays, the above figures were corrected from the measured velocity to give actual velocity over the trays by multiplying the measured velocity by the ratio $\frac{24}{20.5}$. The 24 is the height of the drying section and the 20.5 is the free height not occupied by the trays. There were five levels of air velocity in this range corre-

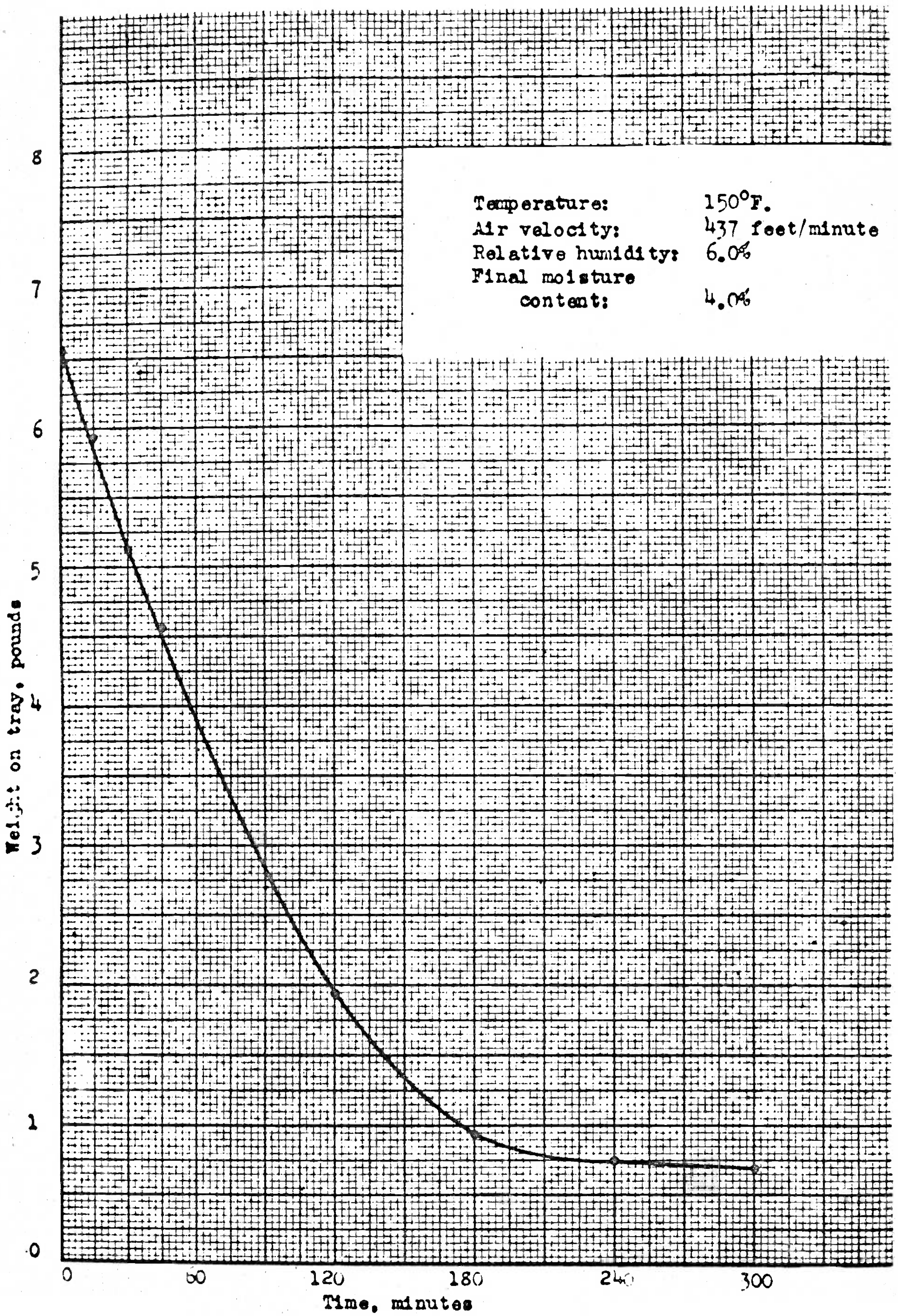

Fig. 1. Drying curve for run 115.

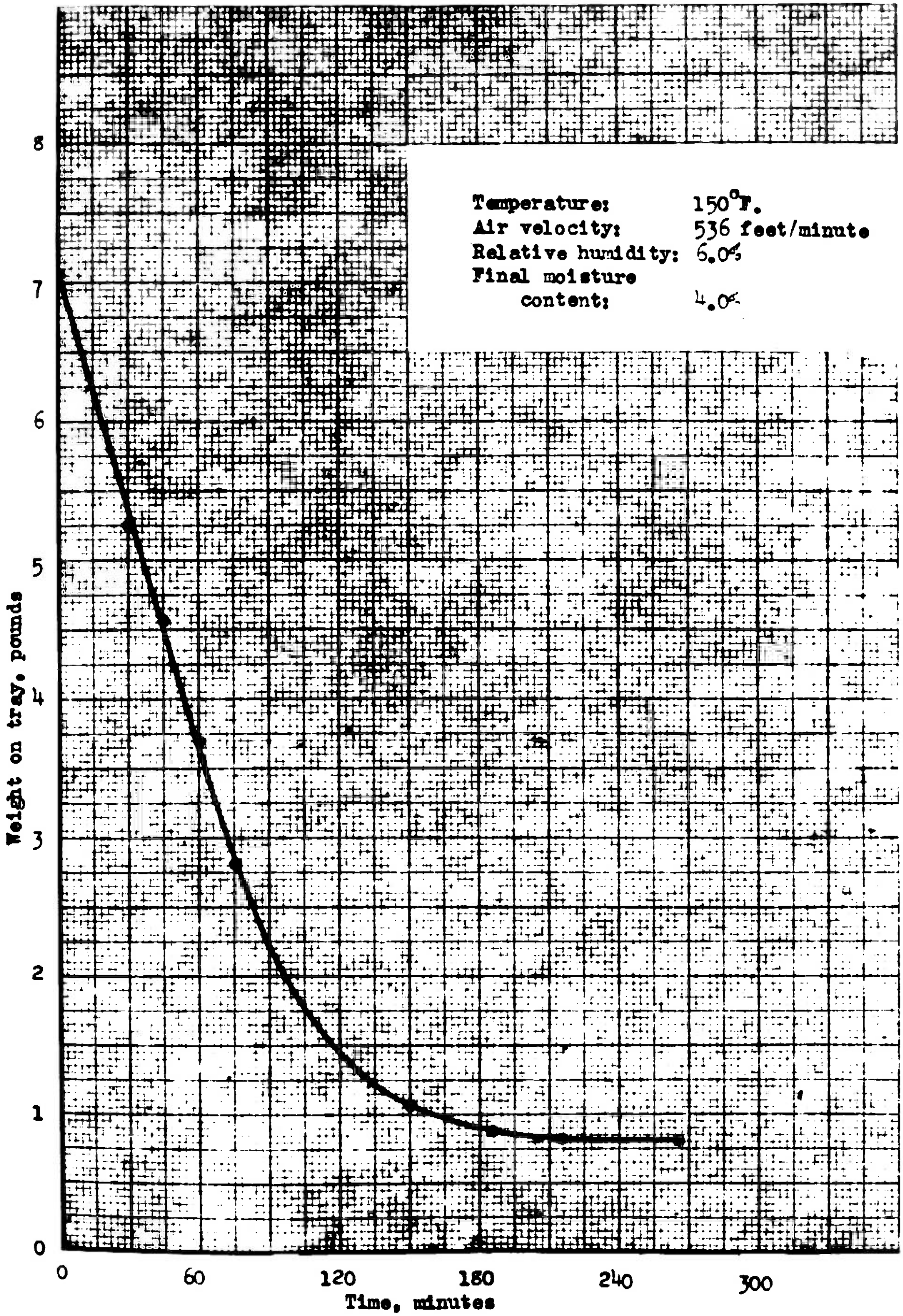

Fig. 2. Drying curve for run 116.

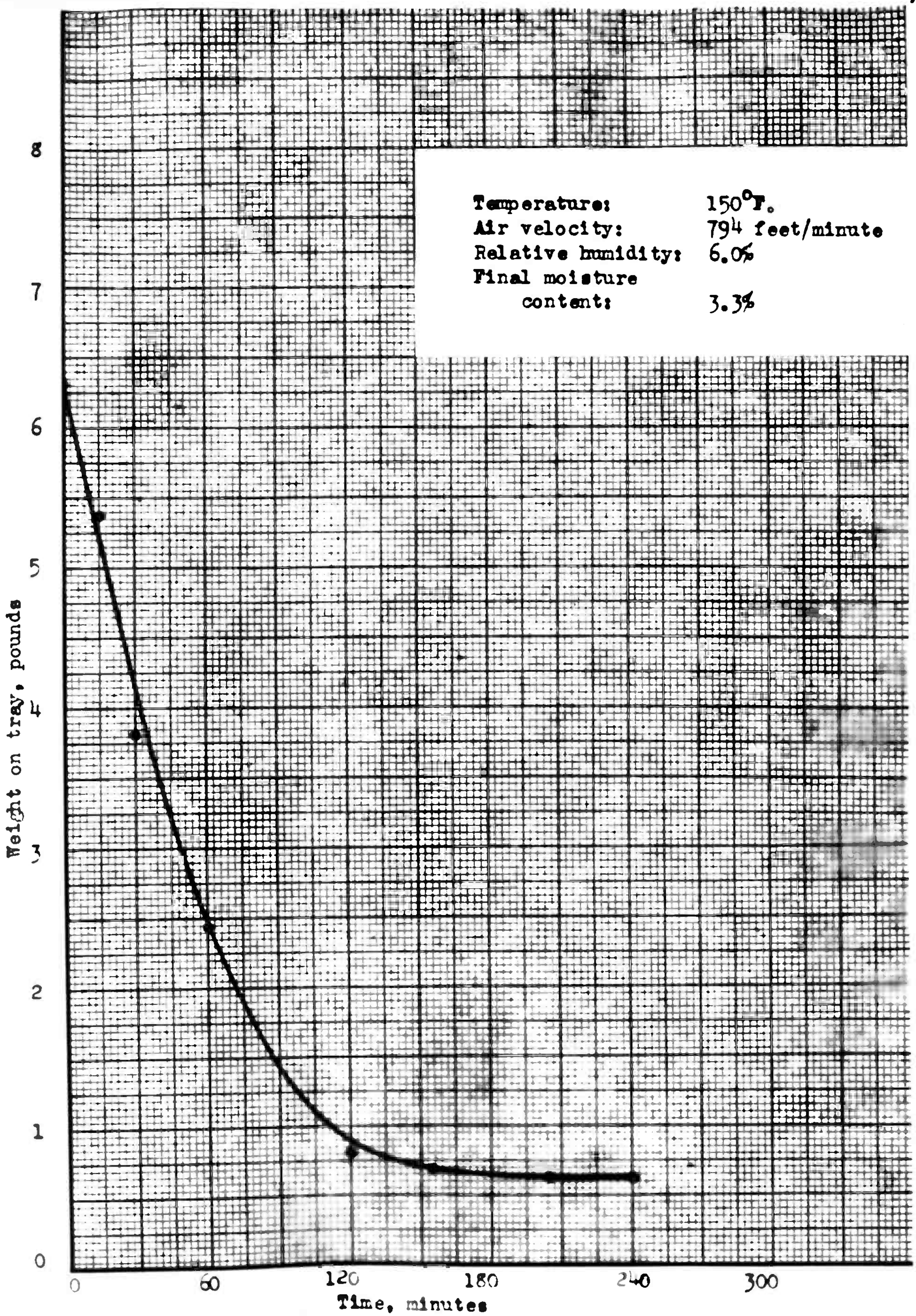

Fig. 3. Drying curve for run 117.

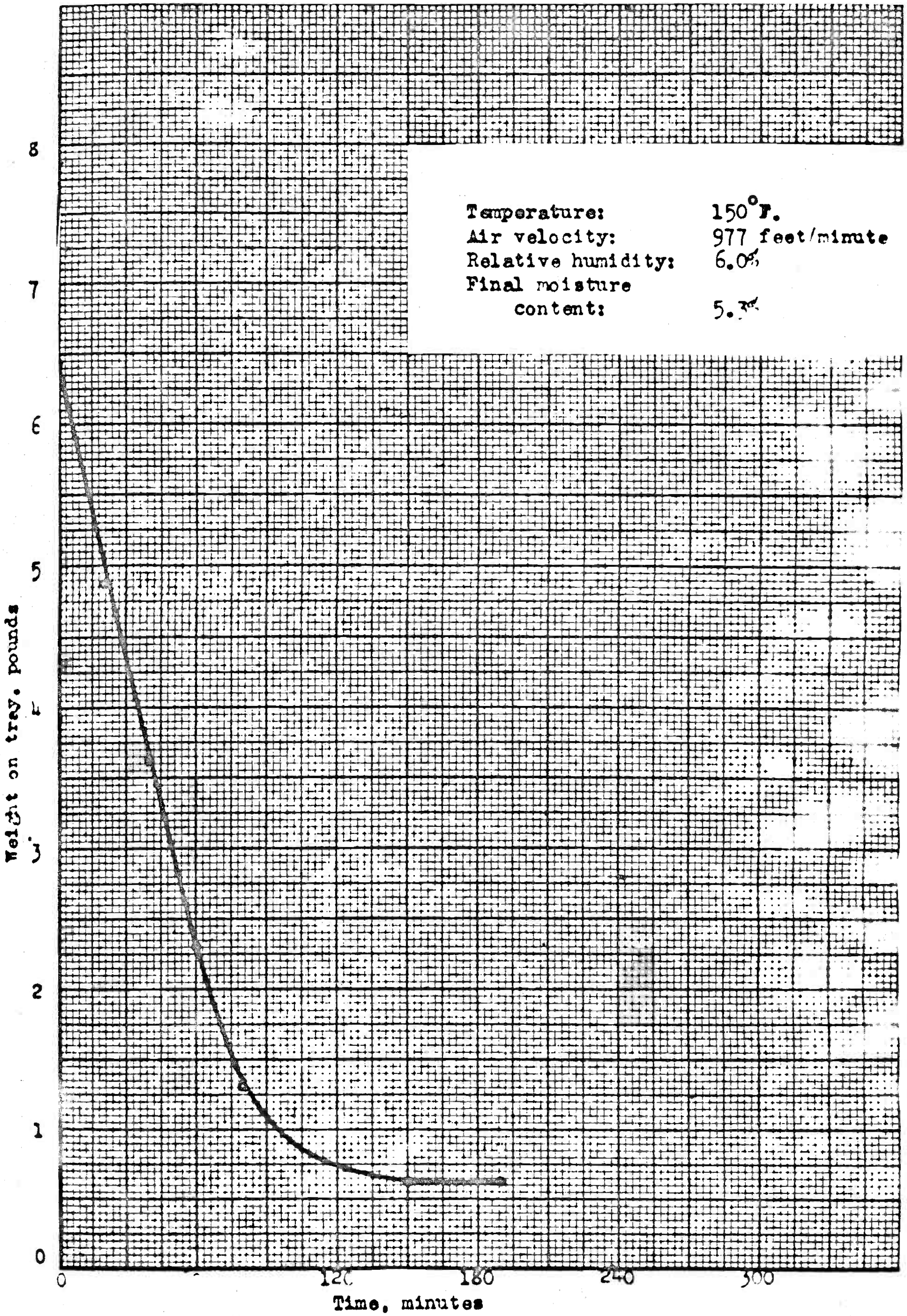

Fig. 4. Drying curve for run 118.

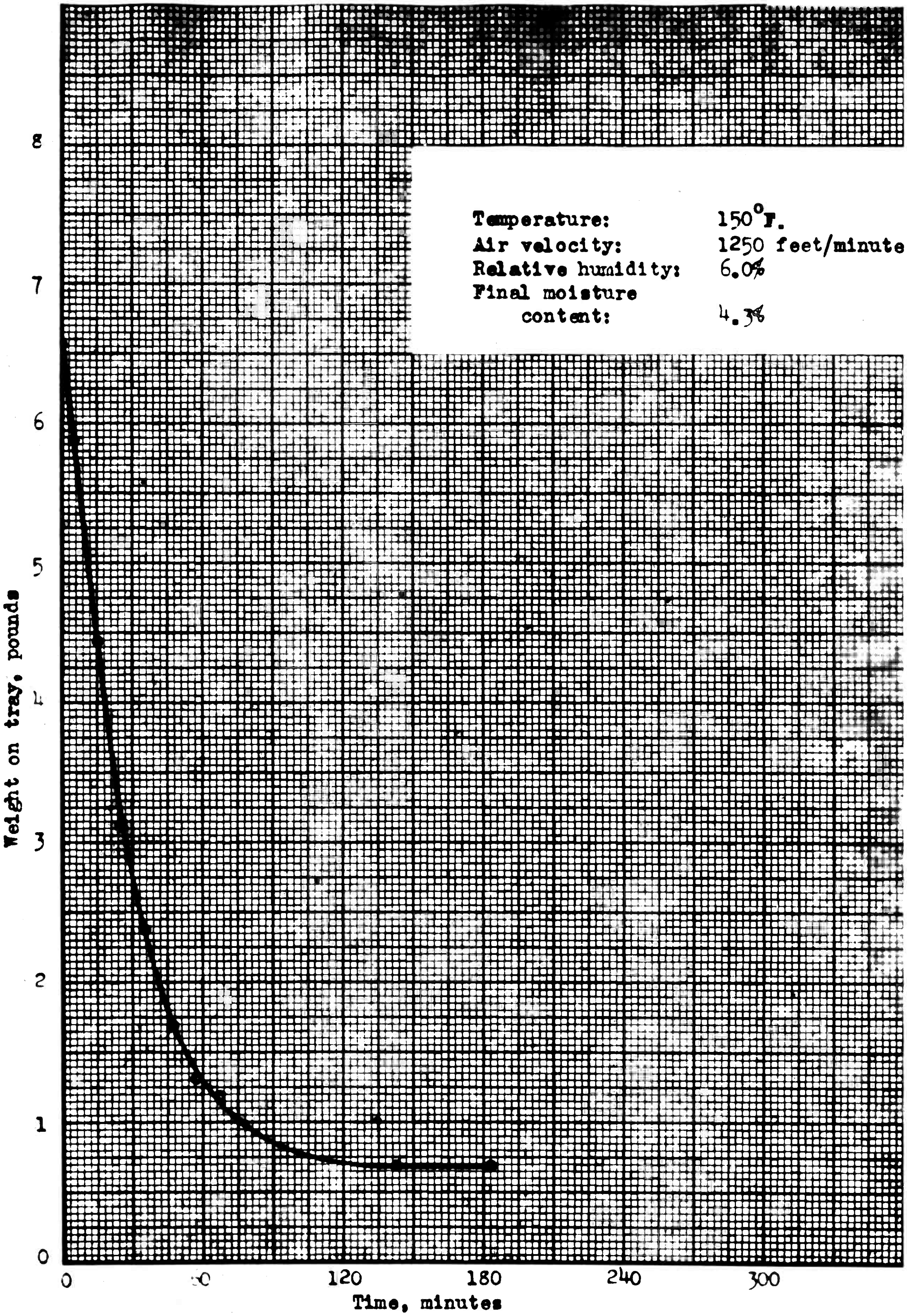

Fig. 5. Drying curve for run 119.

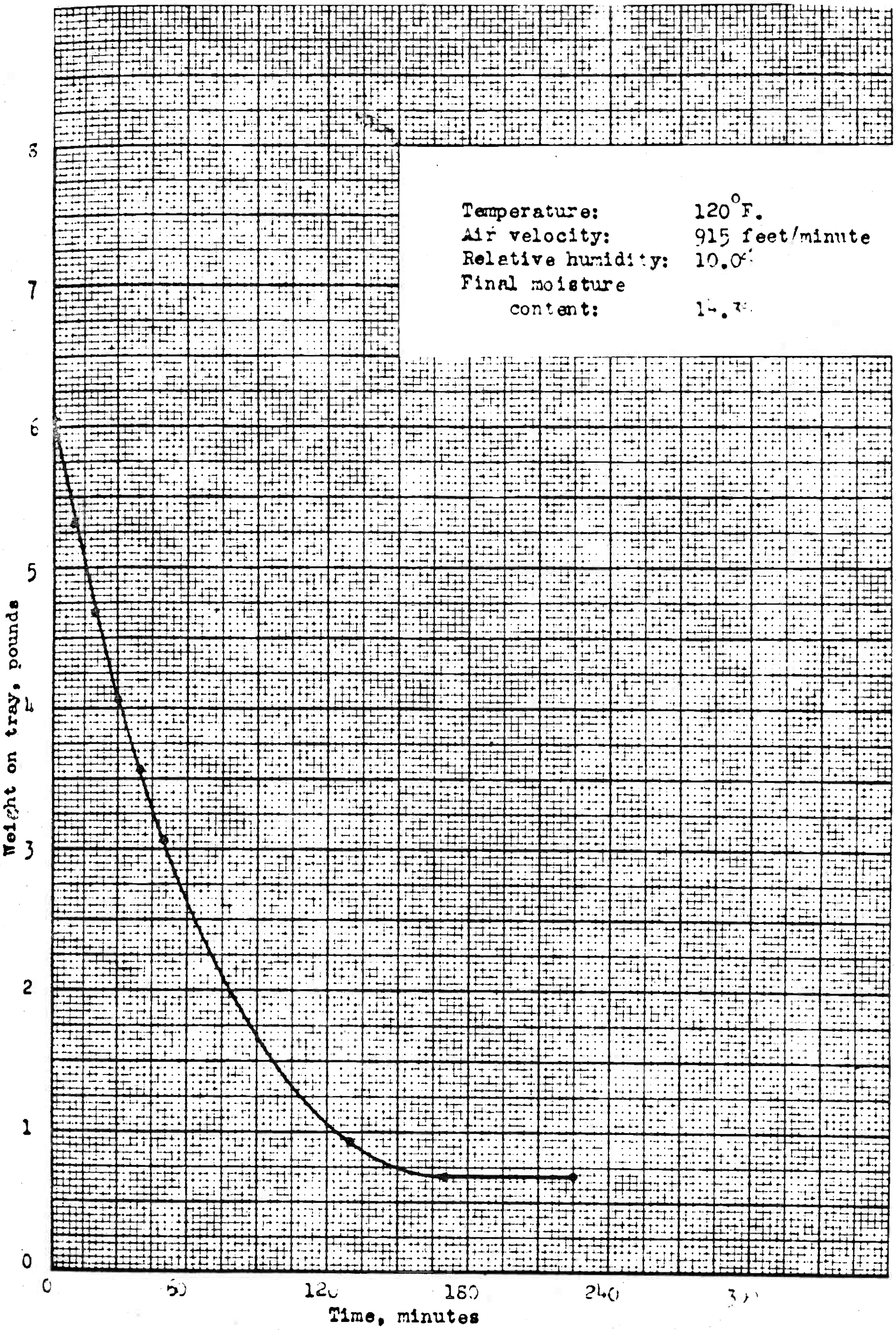

Fig. 6. Drying curve for run 120.

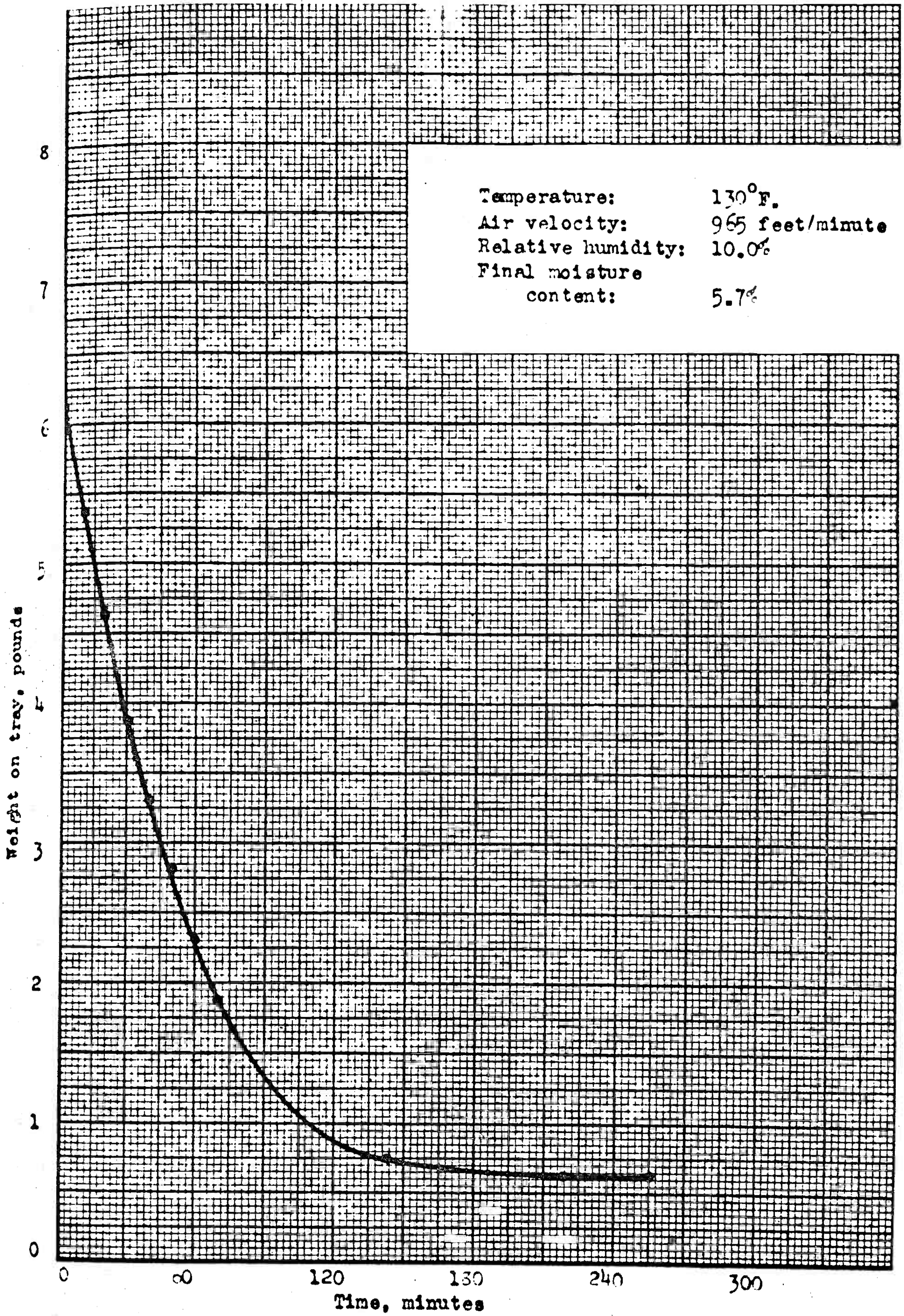

Fig. 7. Drying curve for run 121.

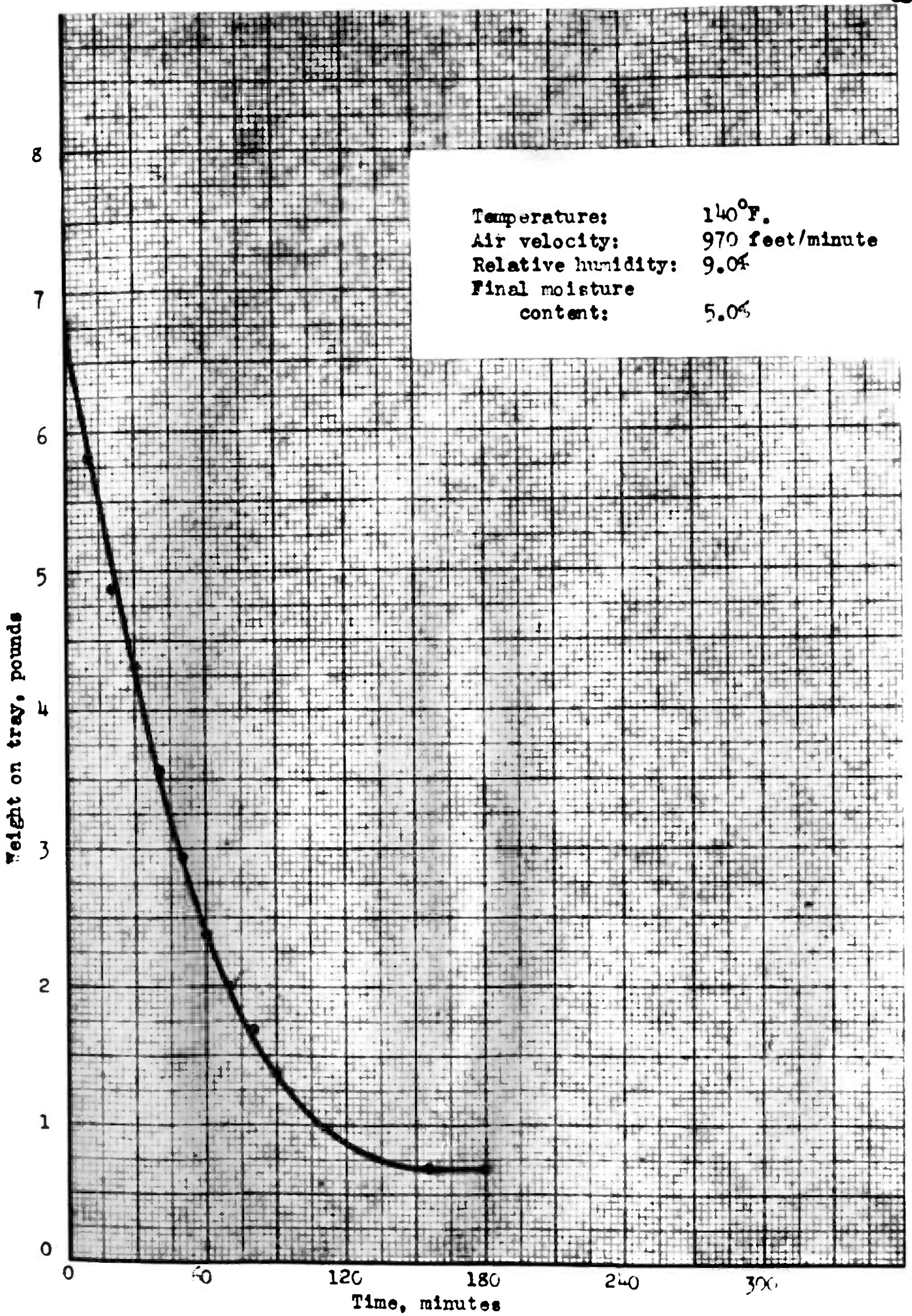

Fig. 8. Drying curve for run 122.

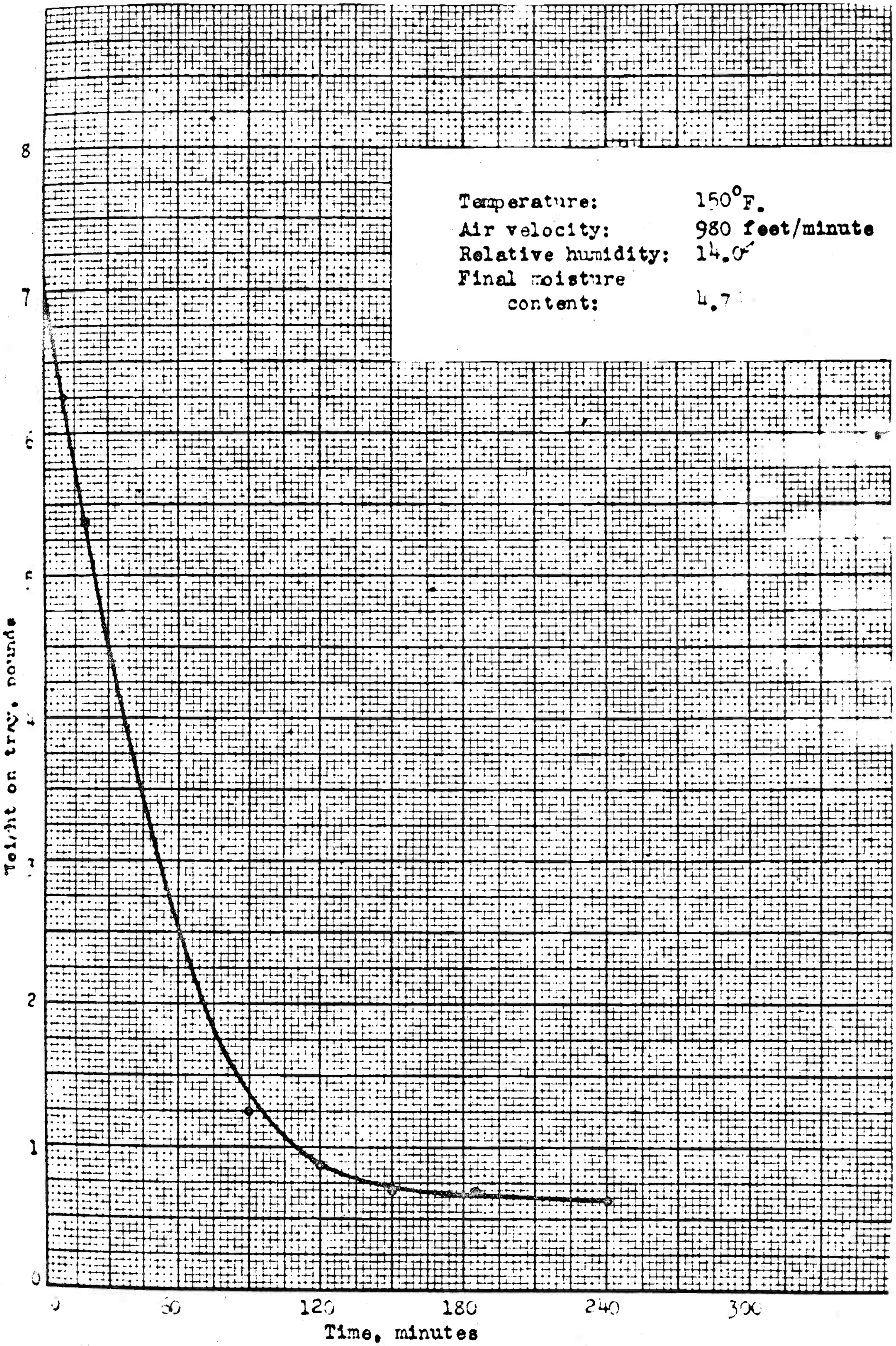

Fig. 9. Drying curve for run 123.

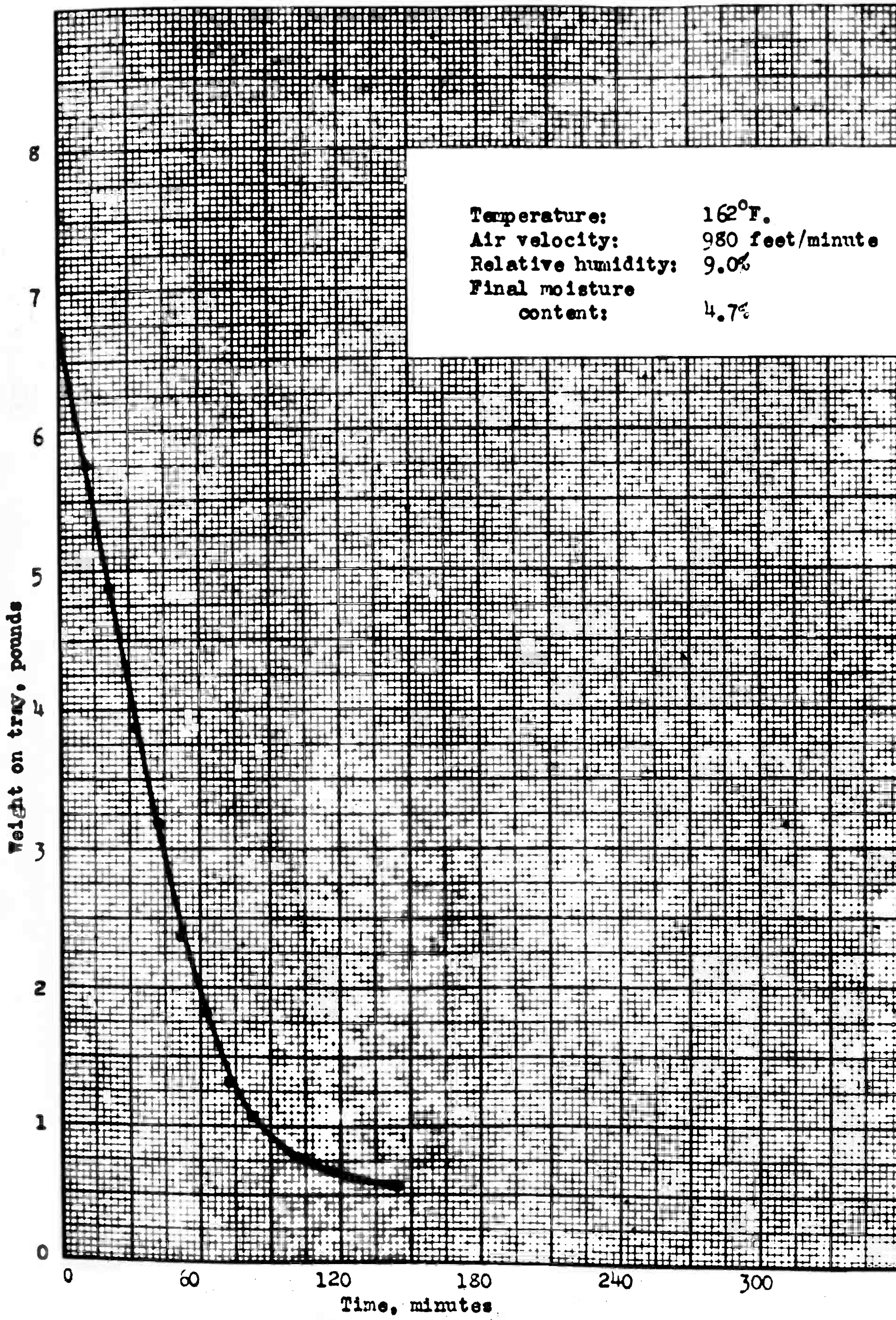

Fig. 10. Drying curve for run 124.

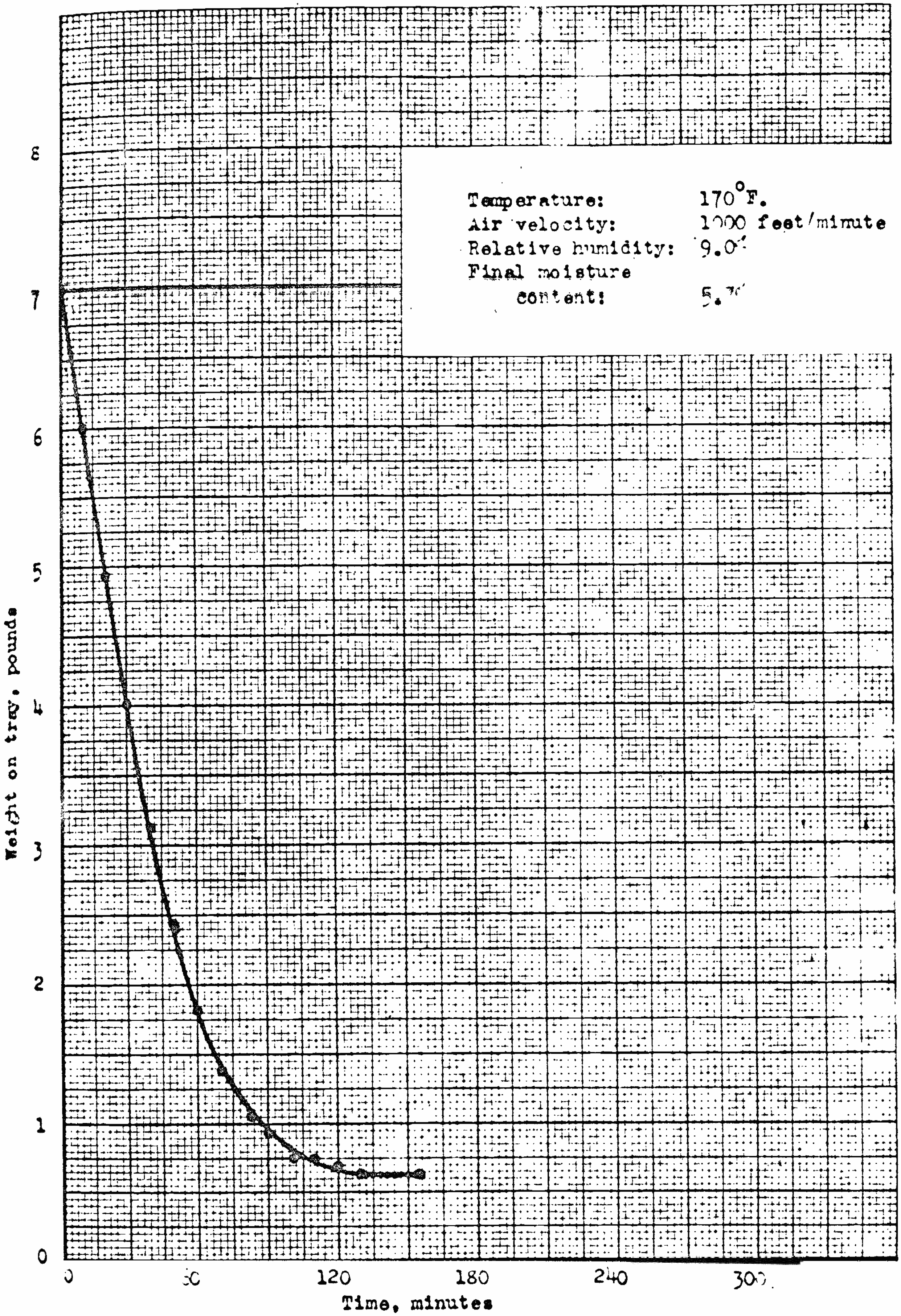

Fig. 11. Drying curve for run 125.

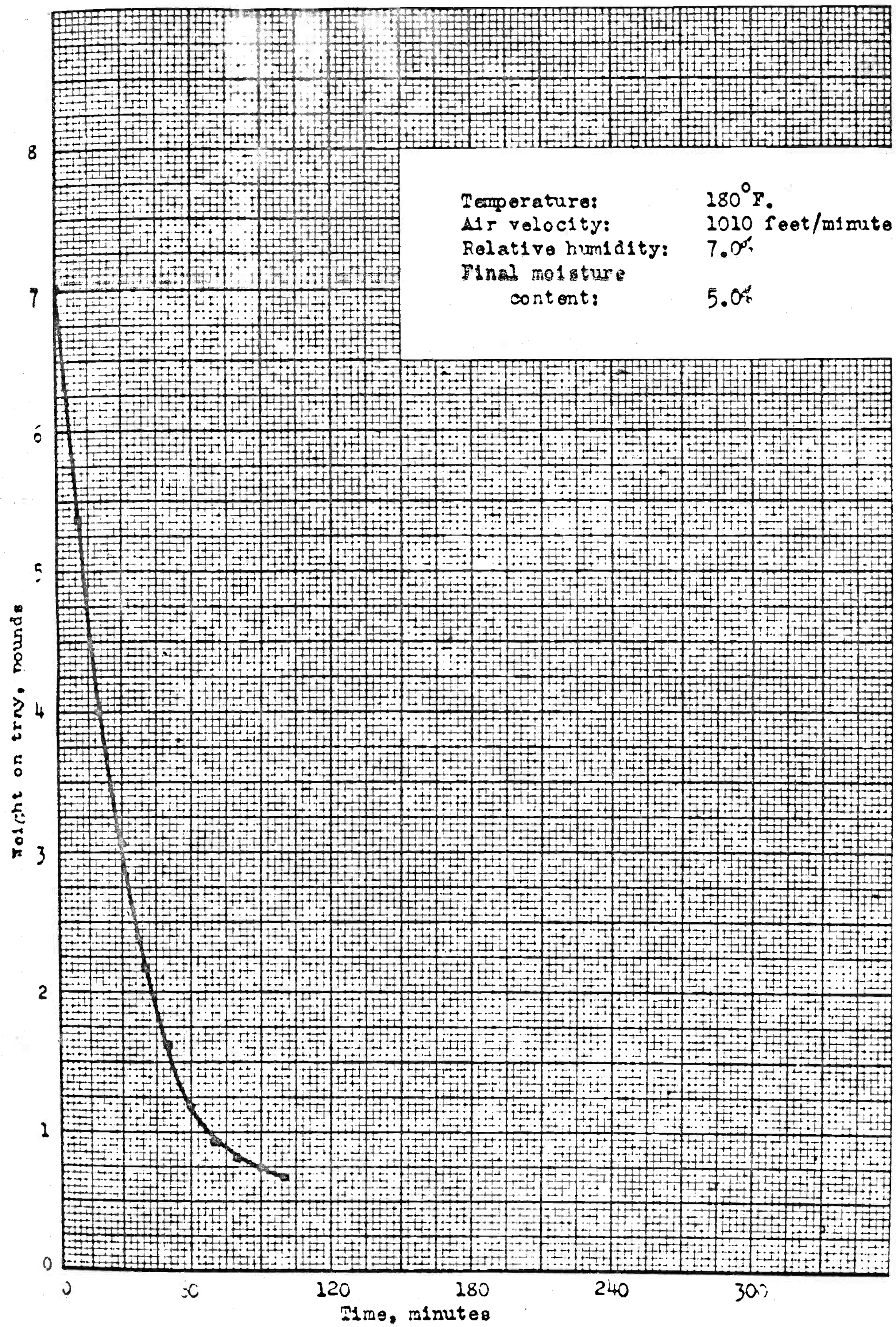

Fig. 12. Drying curve for run 126.

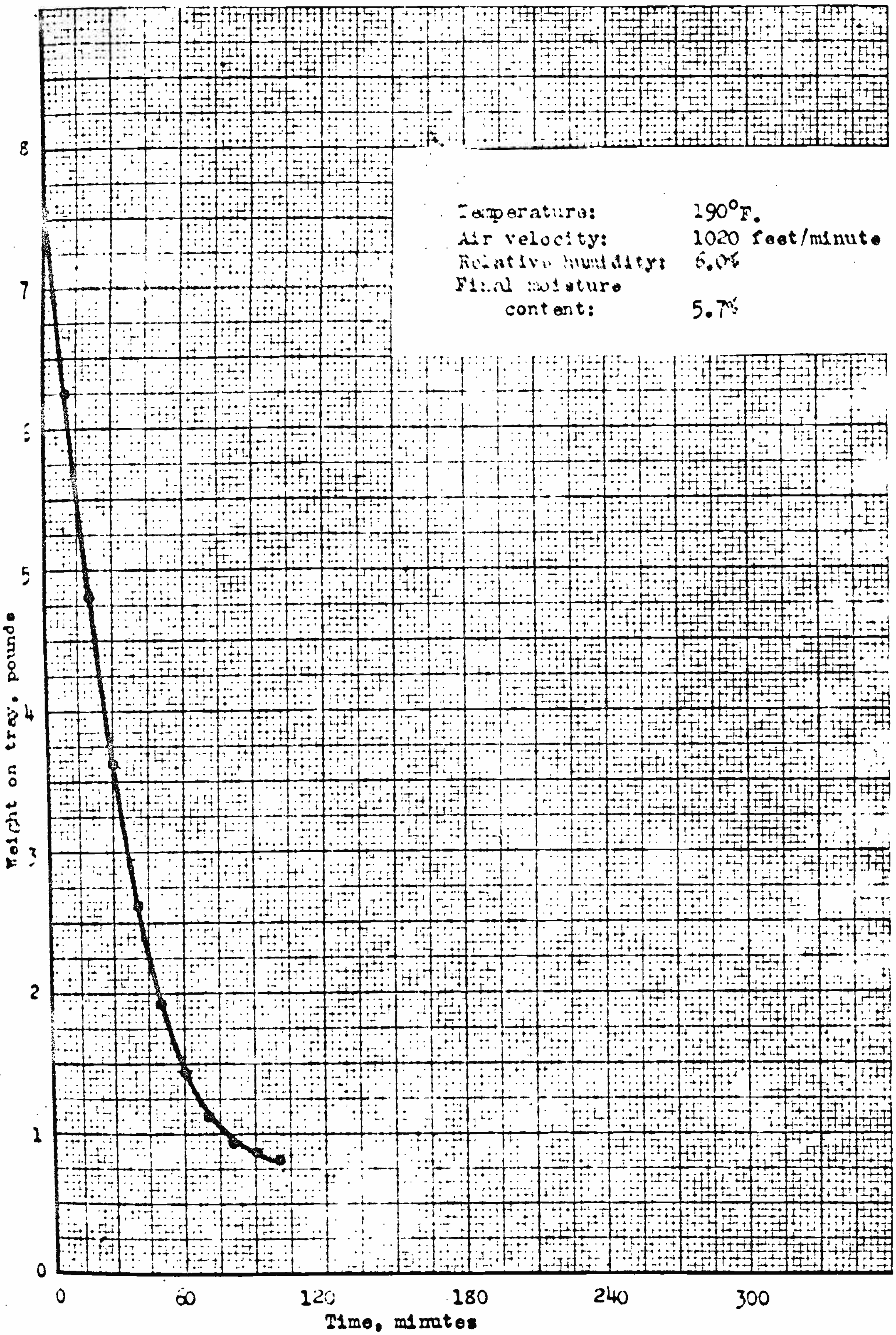

Fig. 13. Drying curve for run 127.

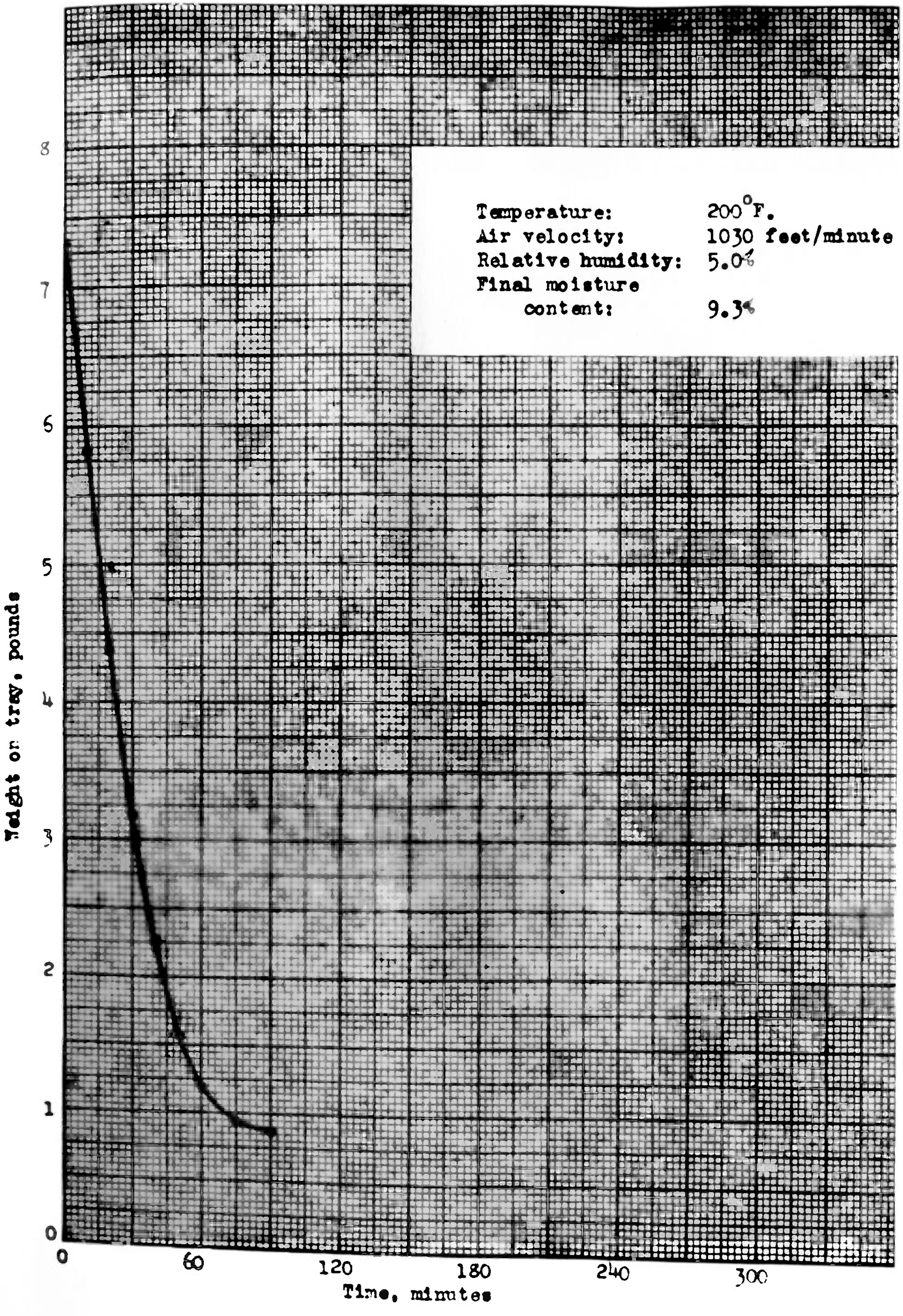

Fig. 14. Drying curve for run 128.

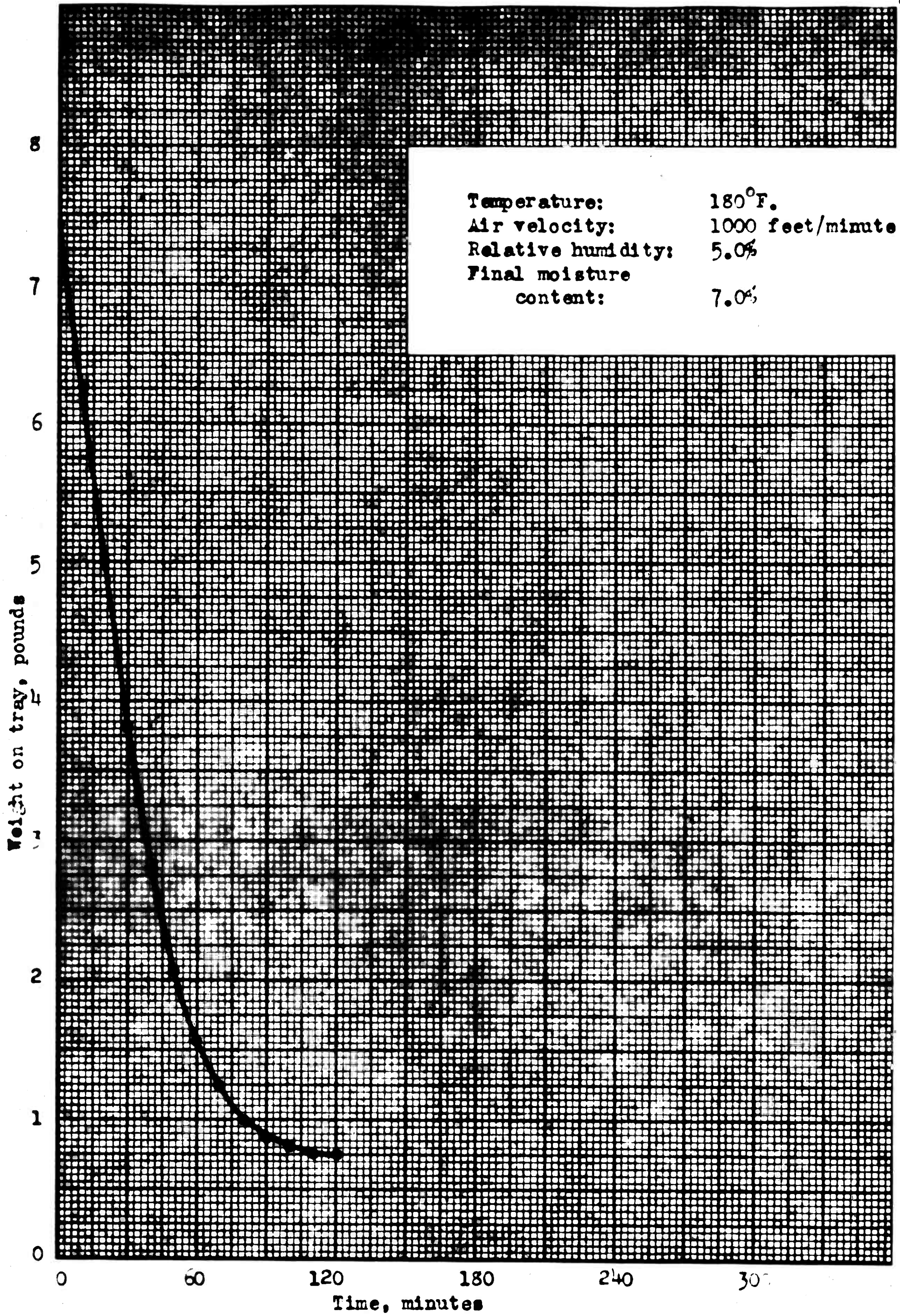

Fig. 15. Drying curve for run 129.

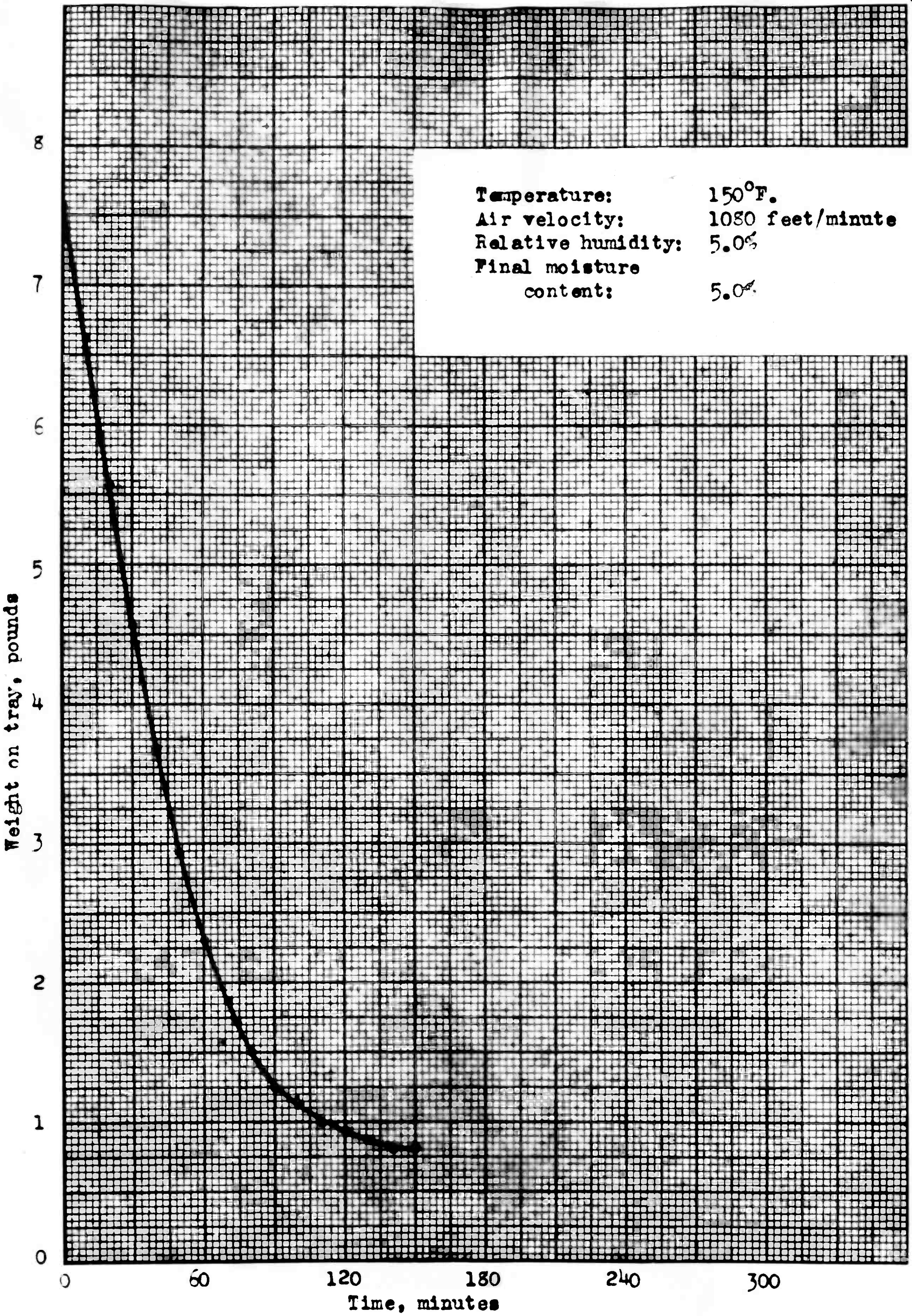

Fig. 16. Drying curve for run 130.

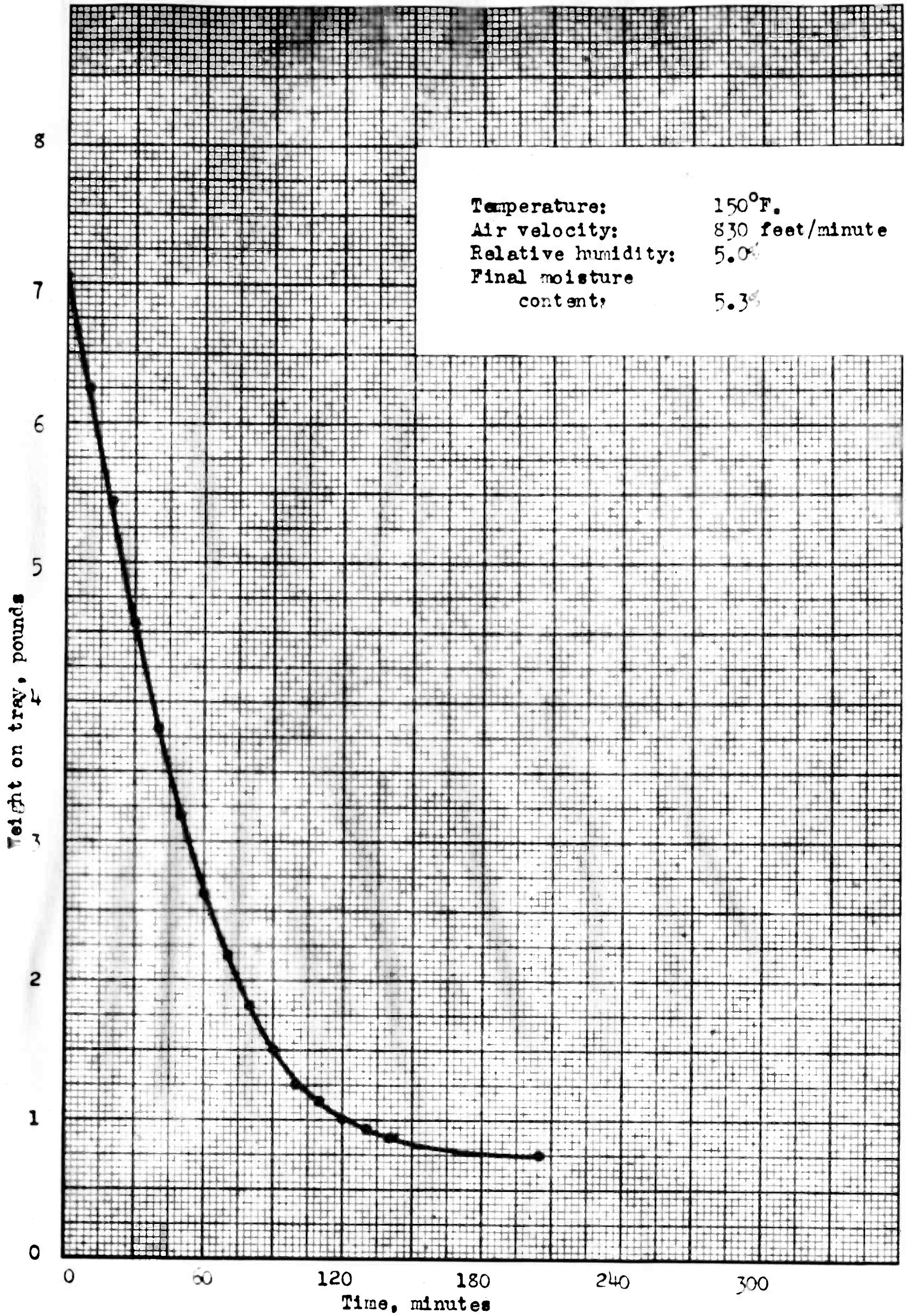

Fig. 17. Drying curve for run 131.

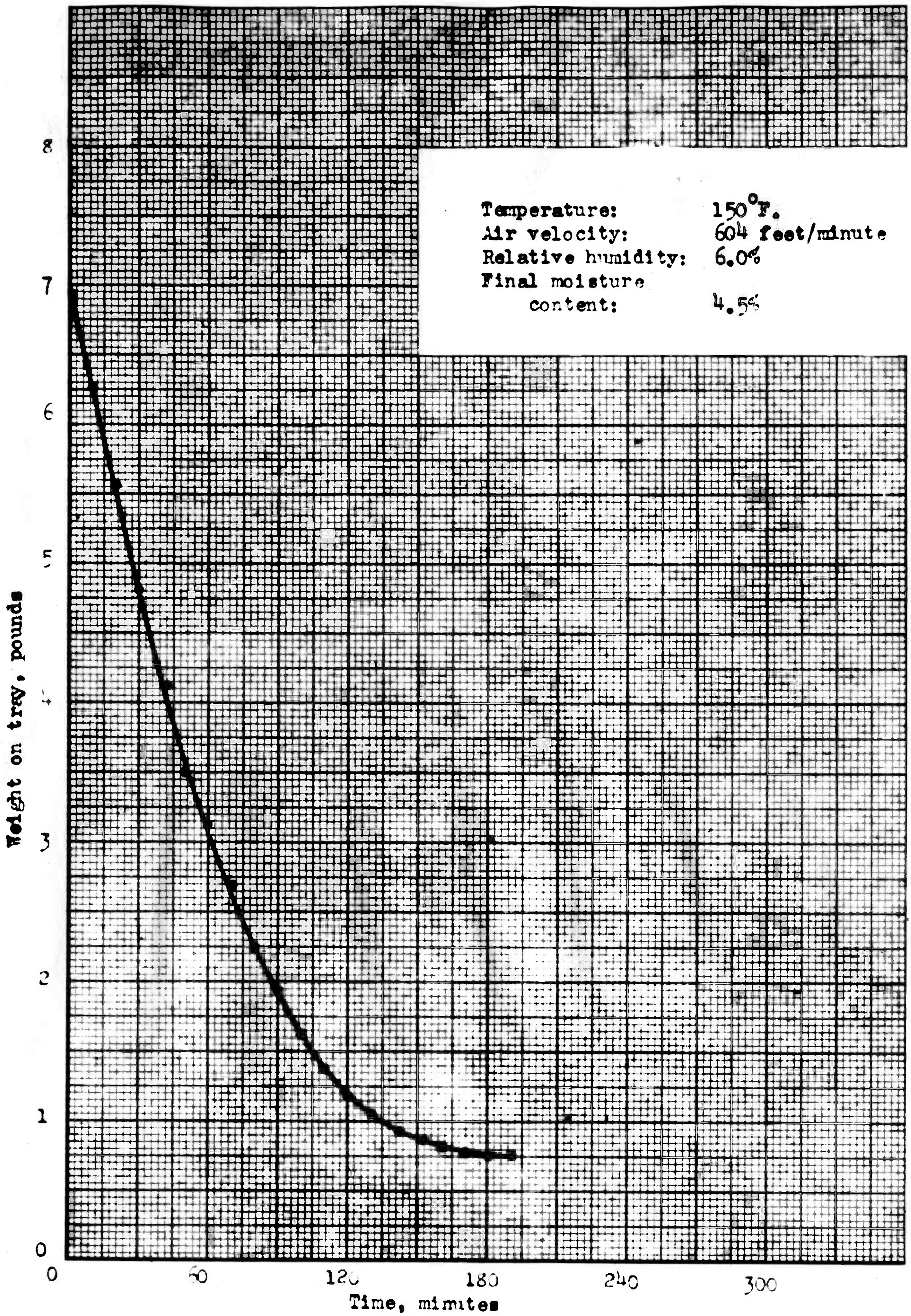

Fig. 18. Drying curve for run 132.

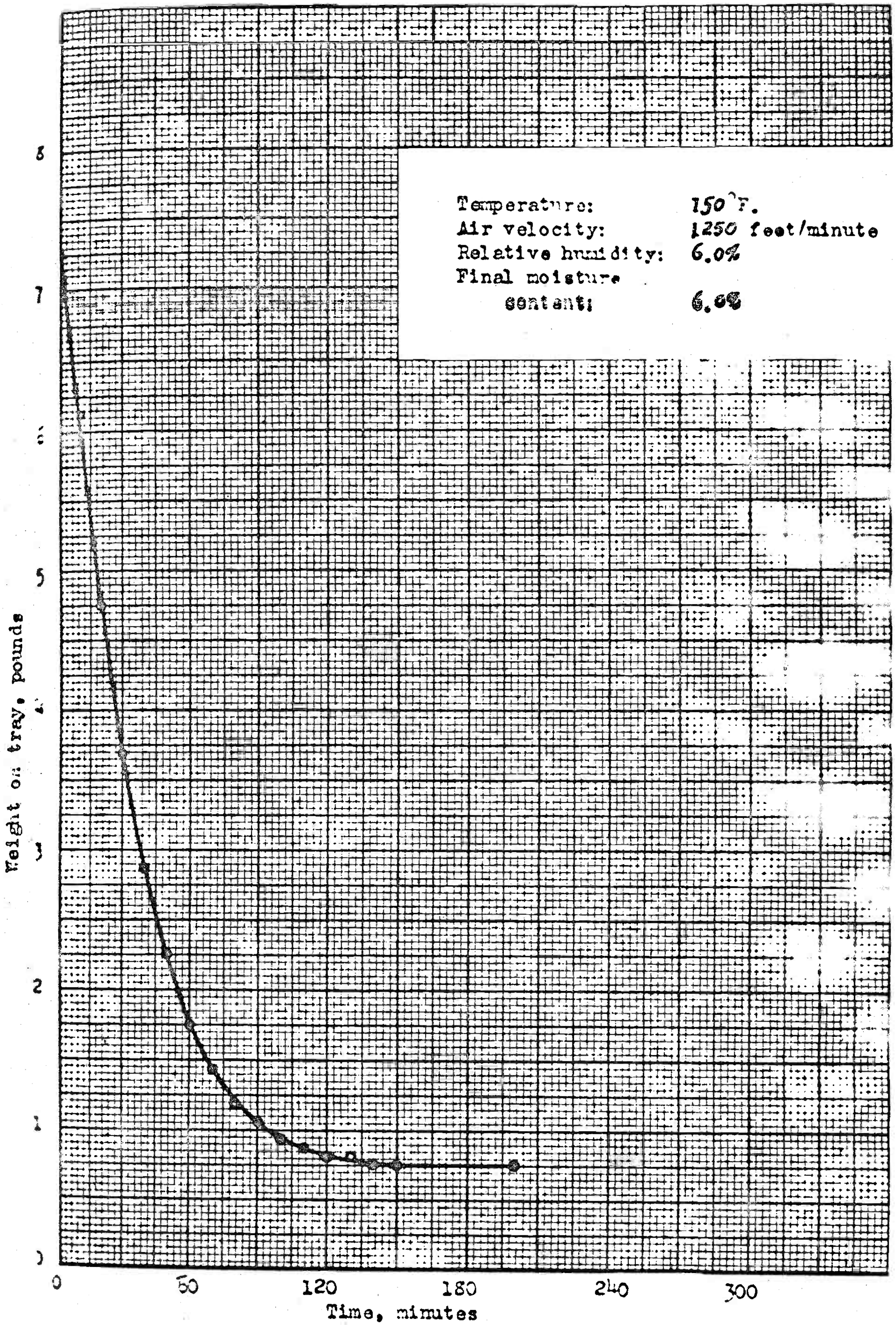

Fig. 19. Drying curve for run 133.

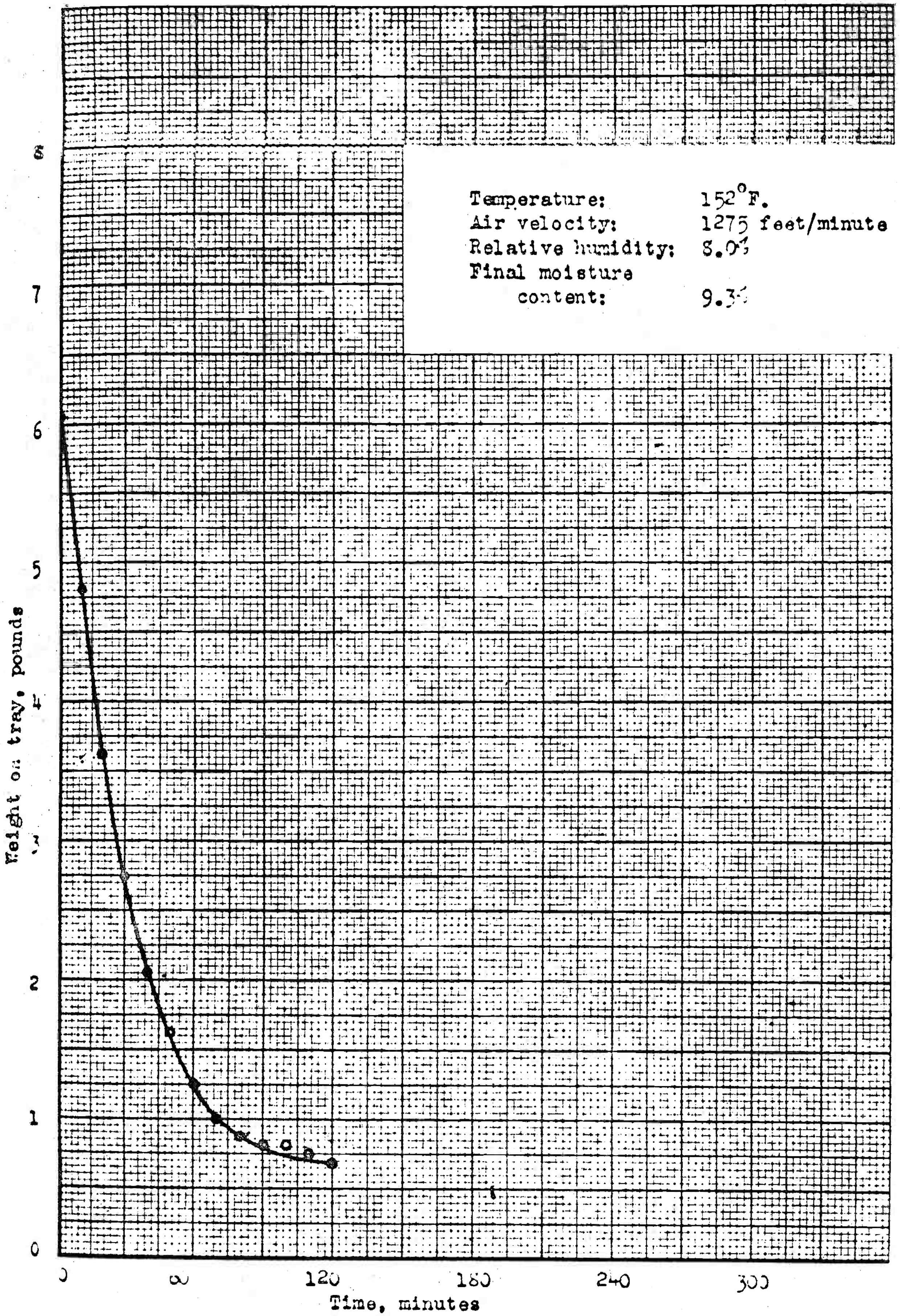

Fig. 20. Drying curve for run 134.

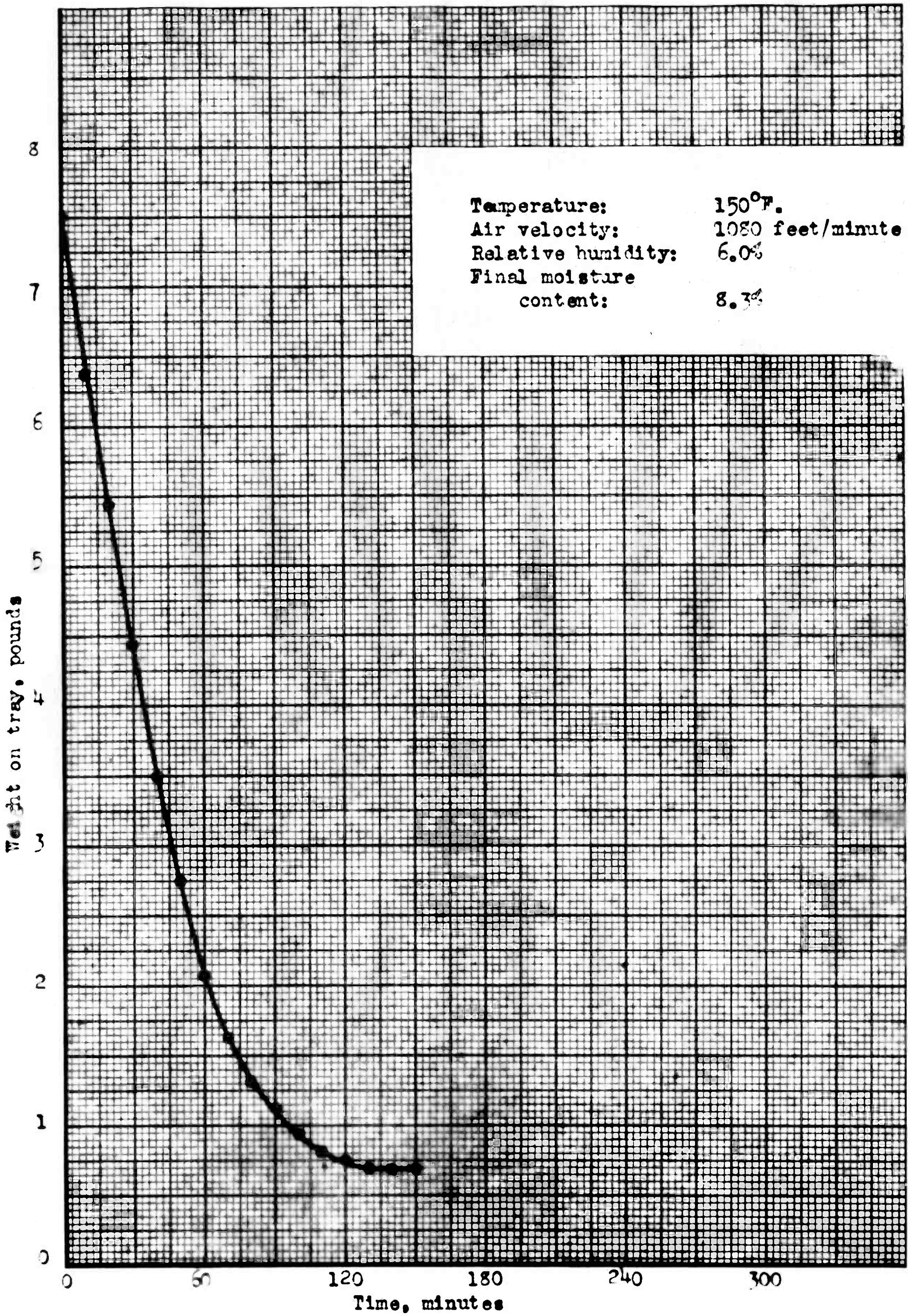

Fig. 21. Drying curve for run 135.

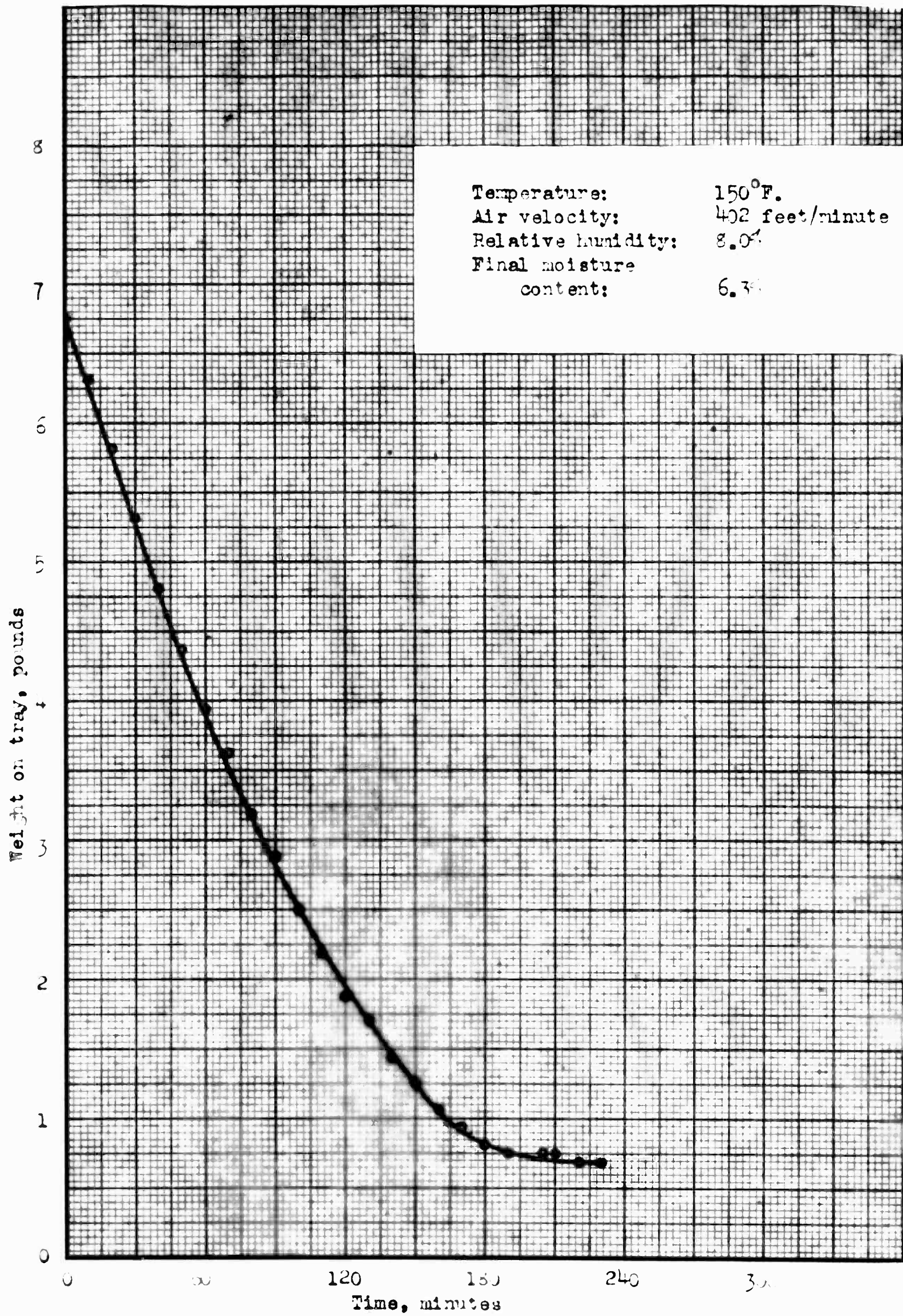

Fig. 22. Drying curve for run 136.

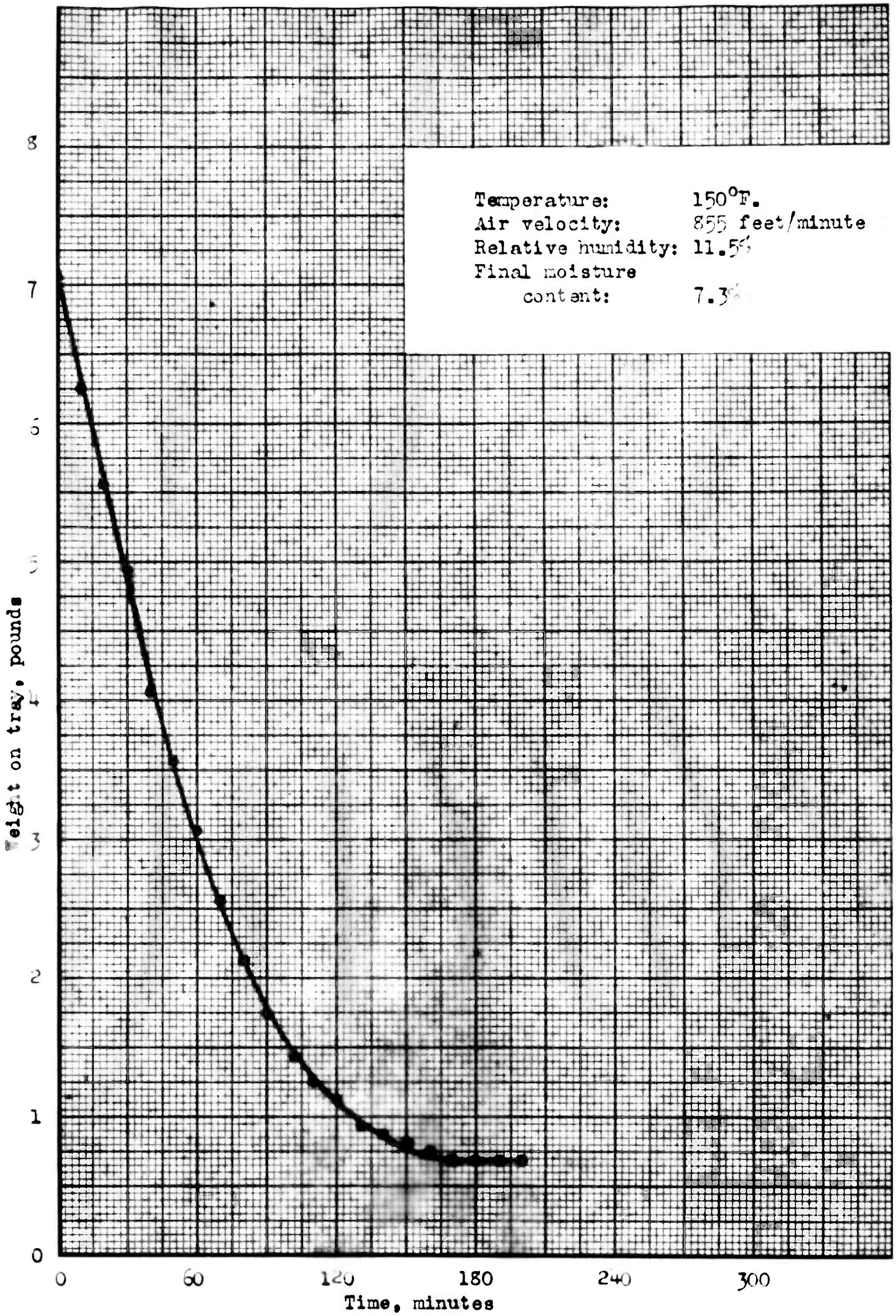

Fig. 23, Drying curve for run 137.

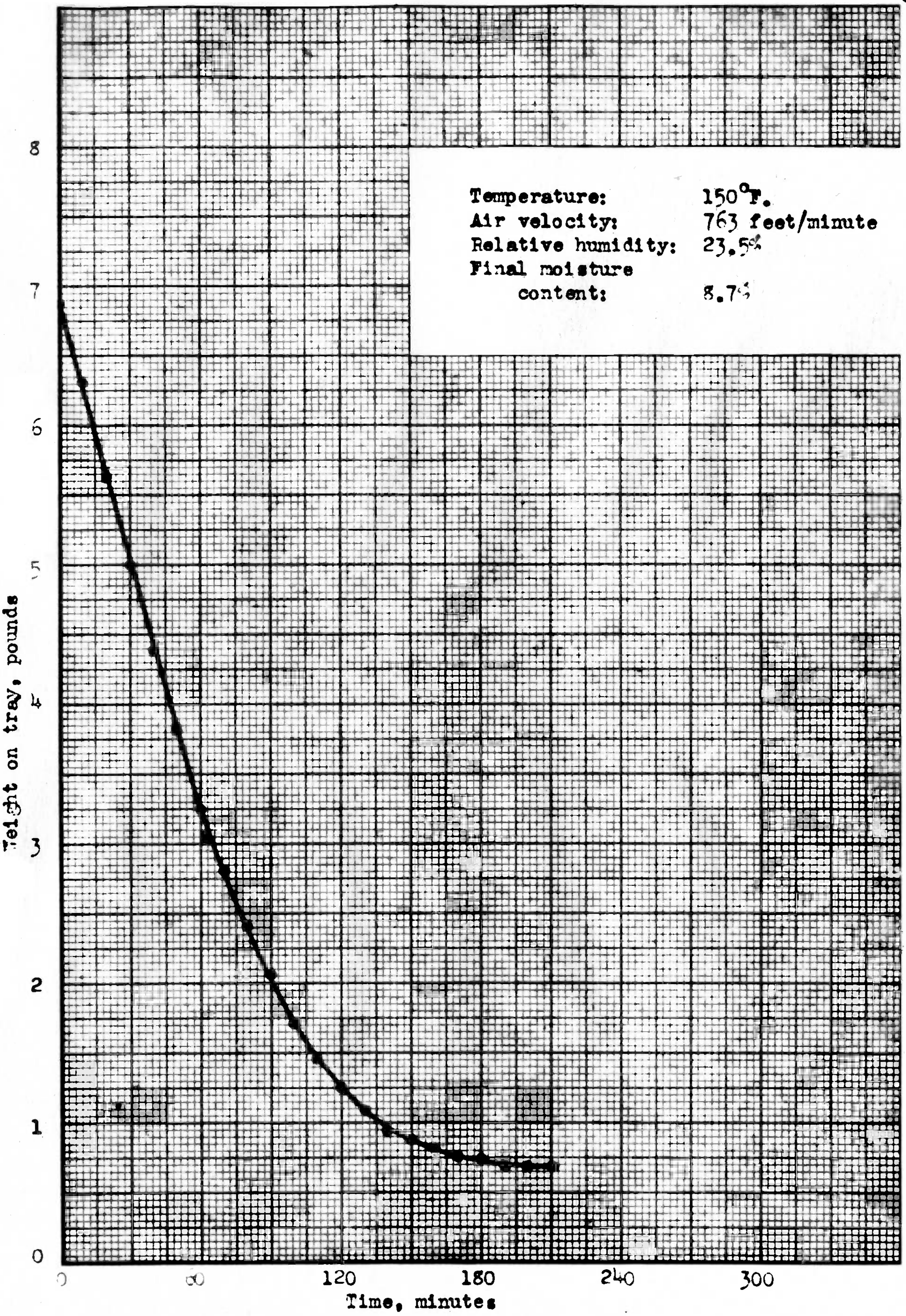

Fig. 24. Drying curve for run 139.

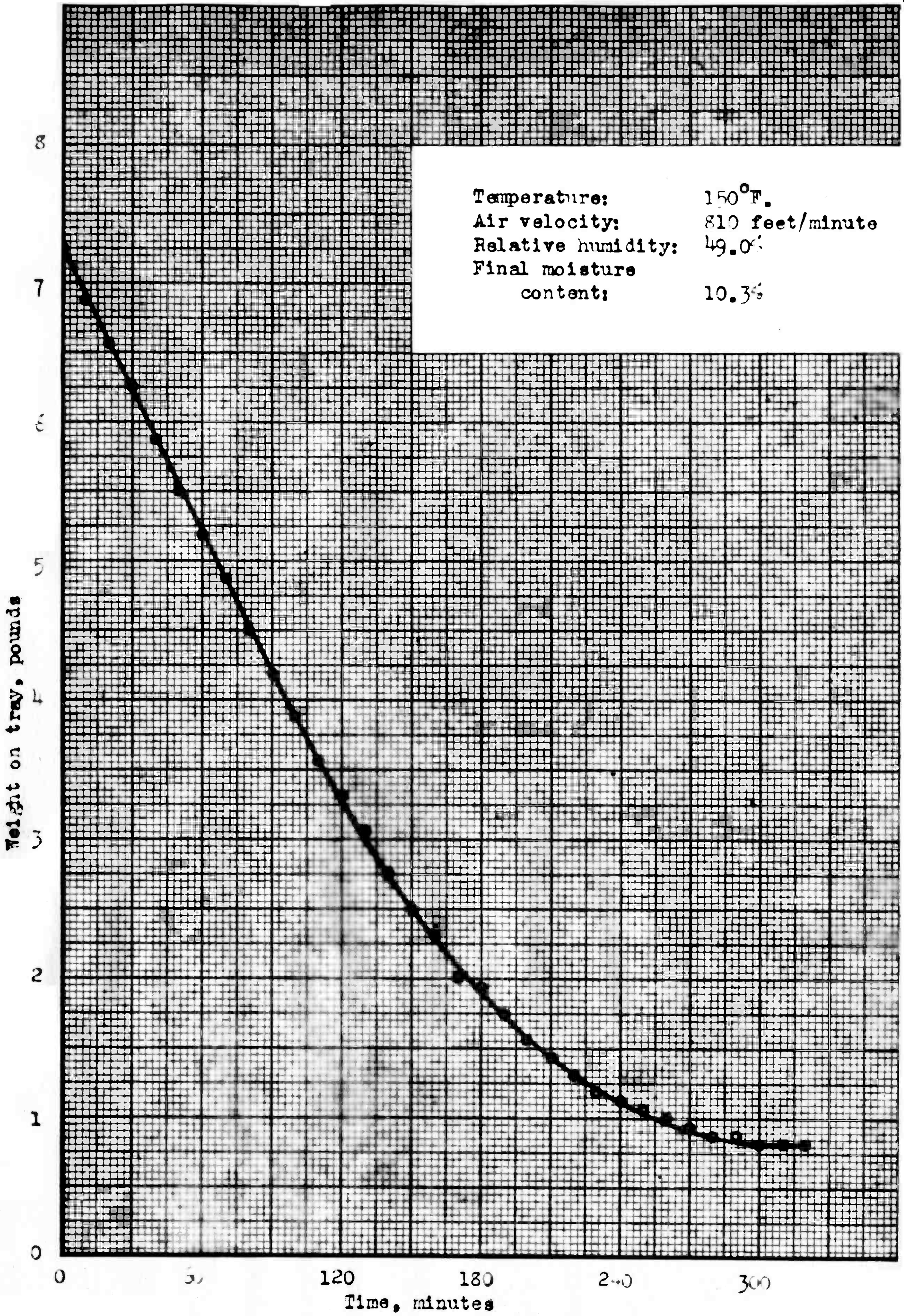

Fig. 2[illegible]. Drying curve for run 140.

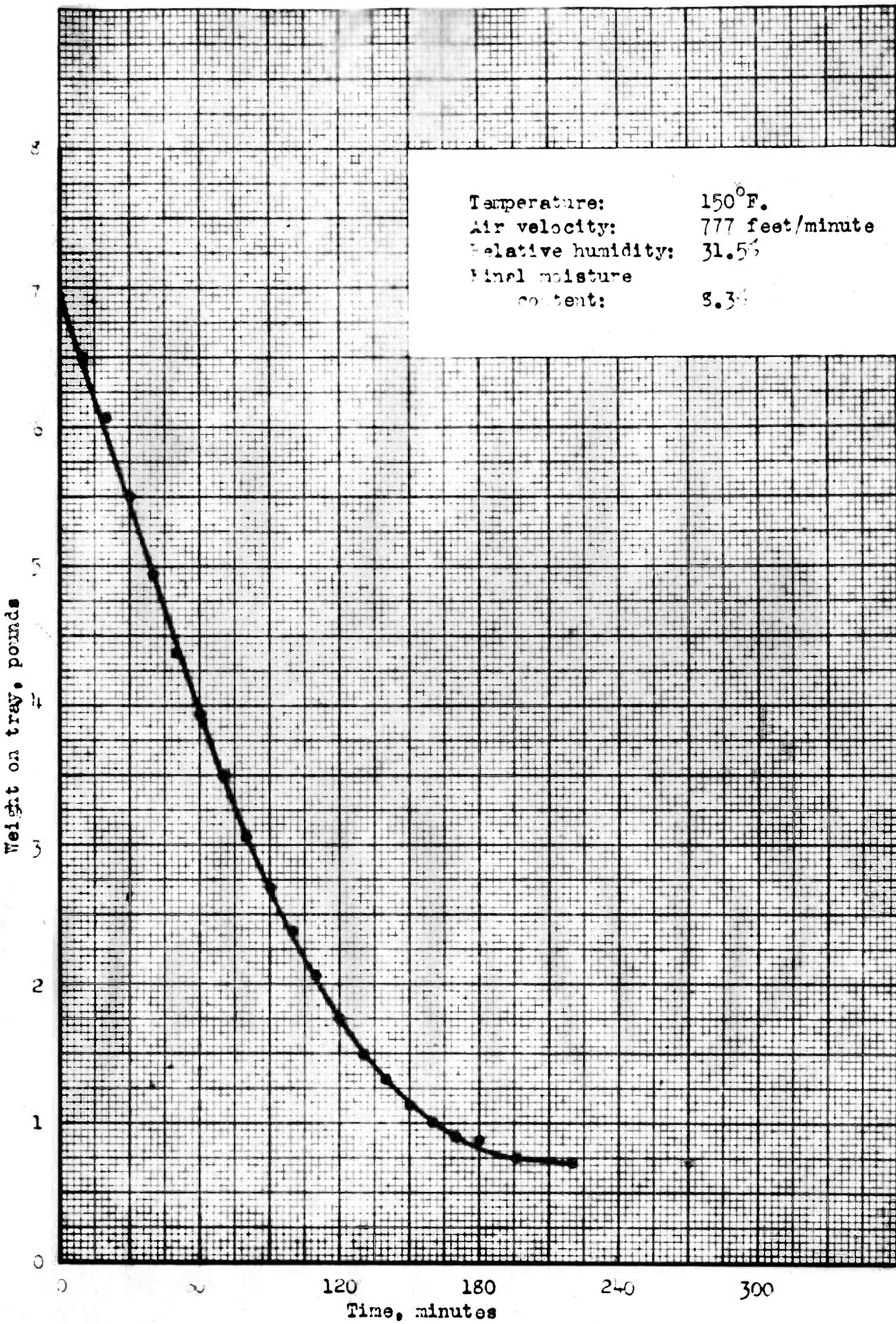

Fig. 26. Drying curve for run 141.

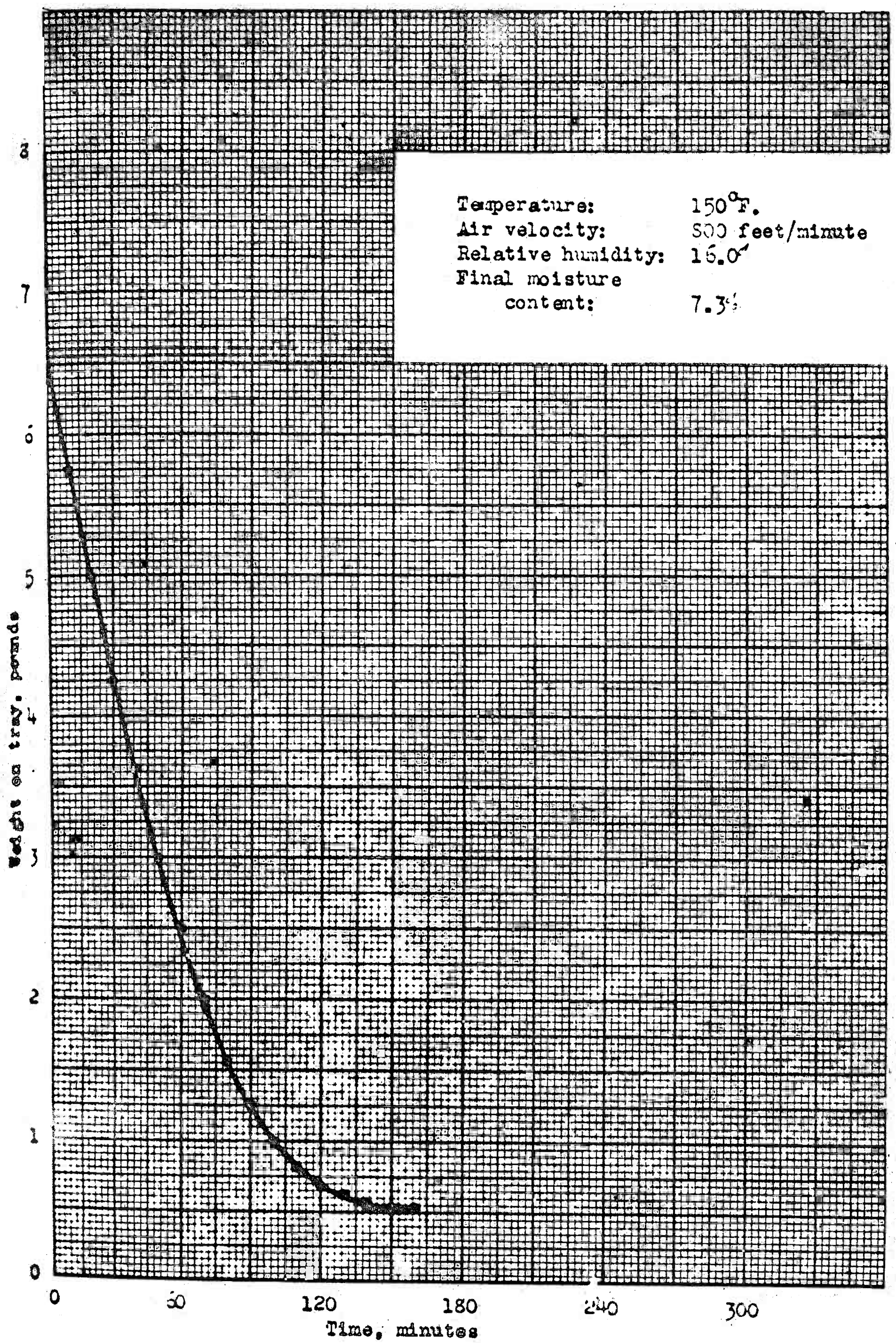

Fig. 27. Drying curve for run 142.

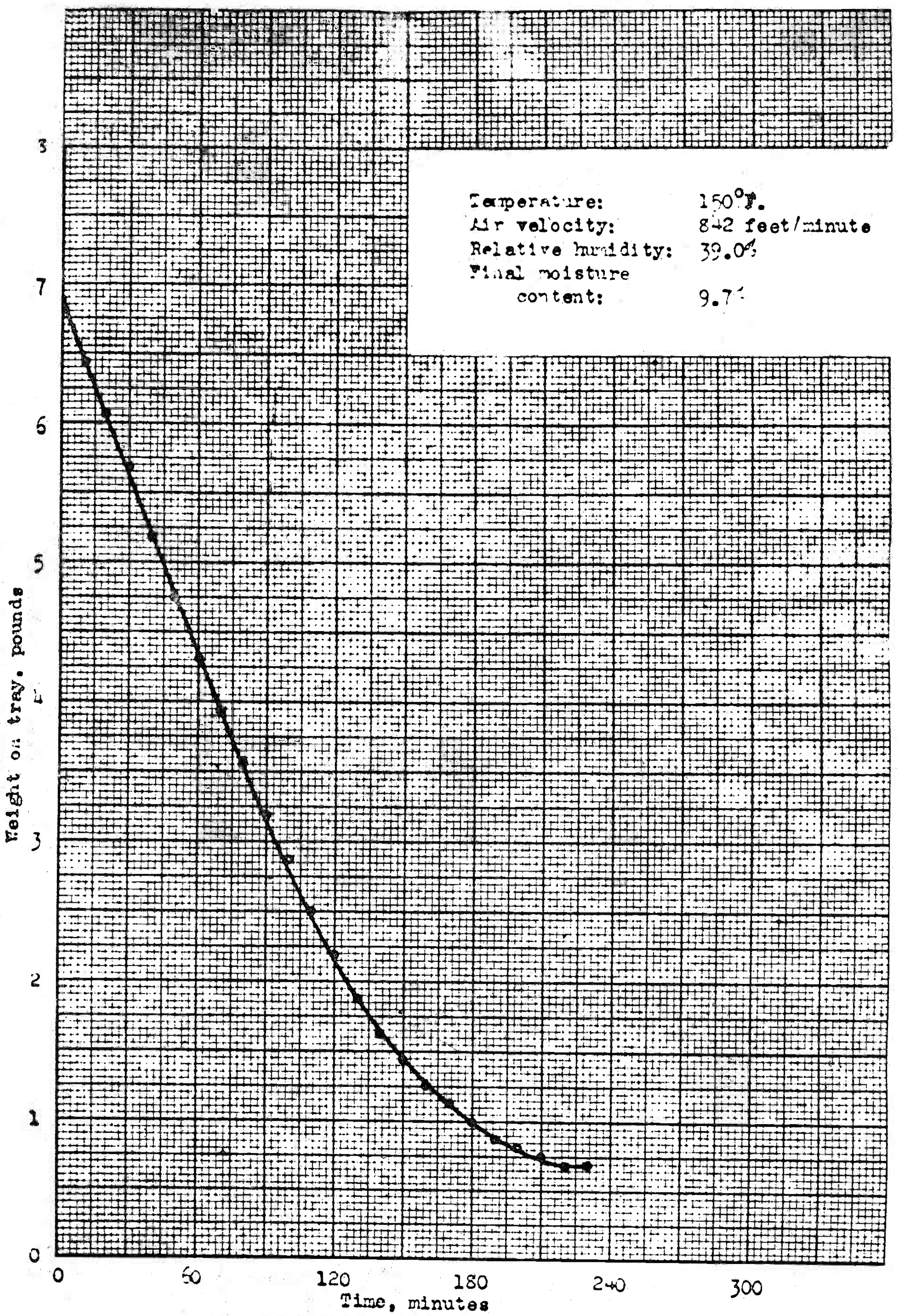

Fig. 28. Drying curve for run 143.

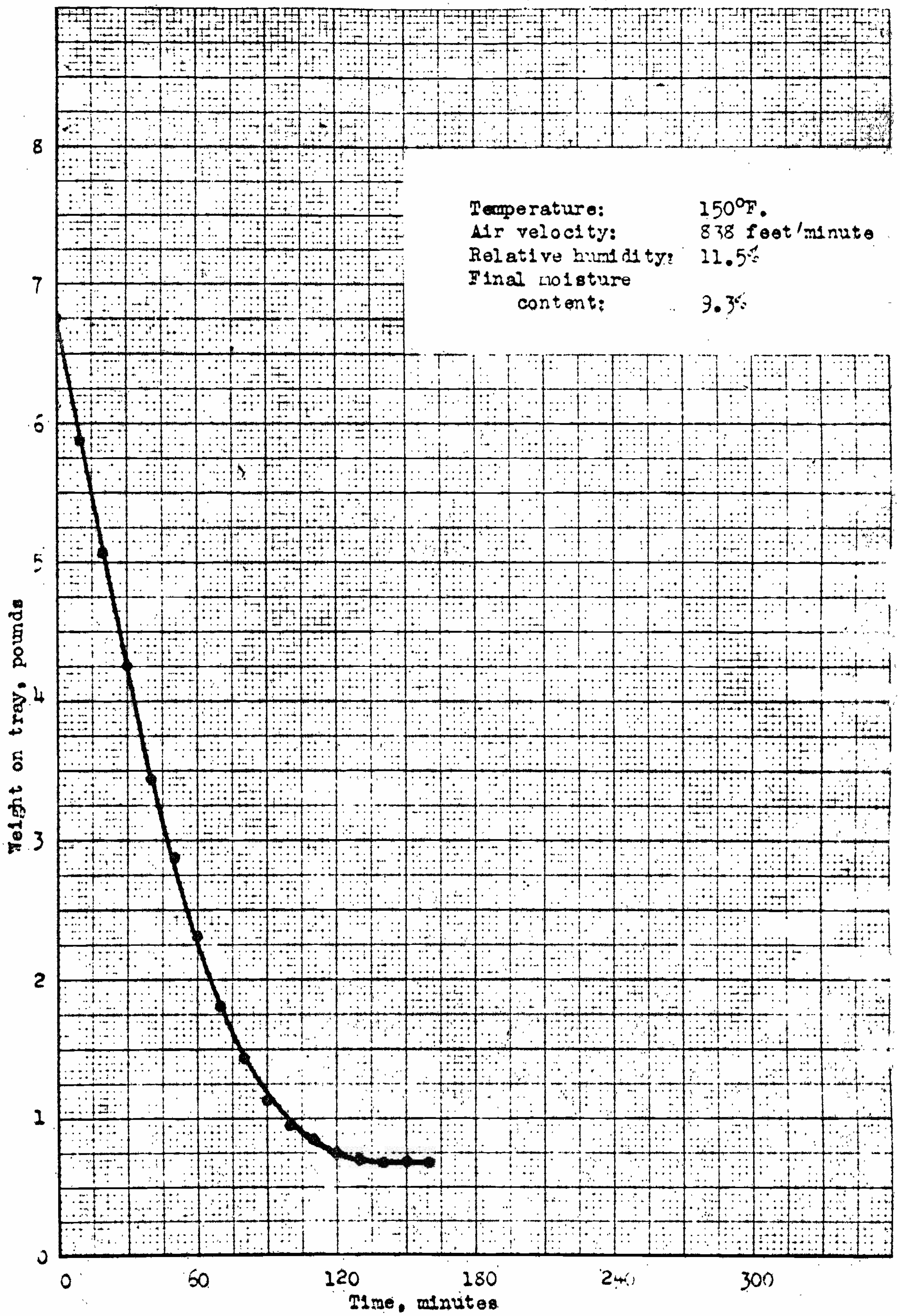

Fig. 29. Drying curve for run 144.

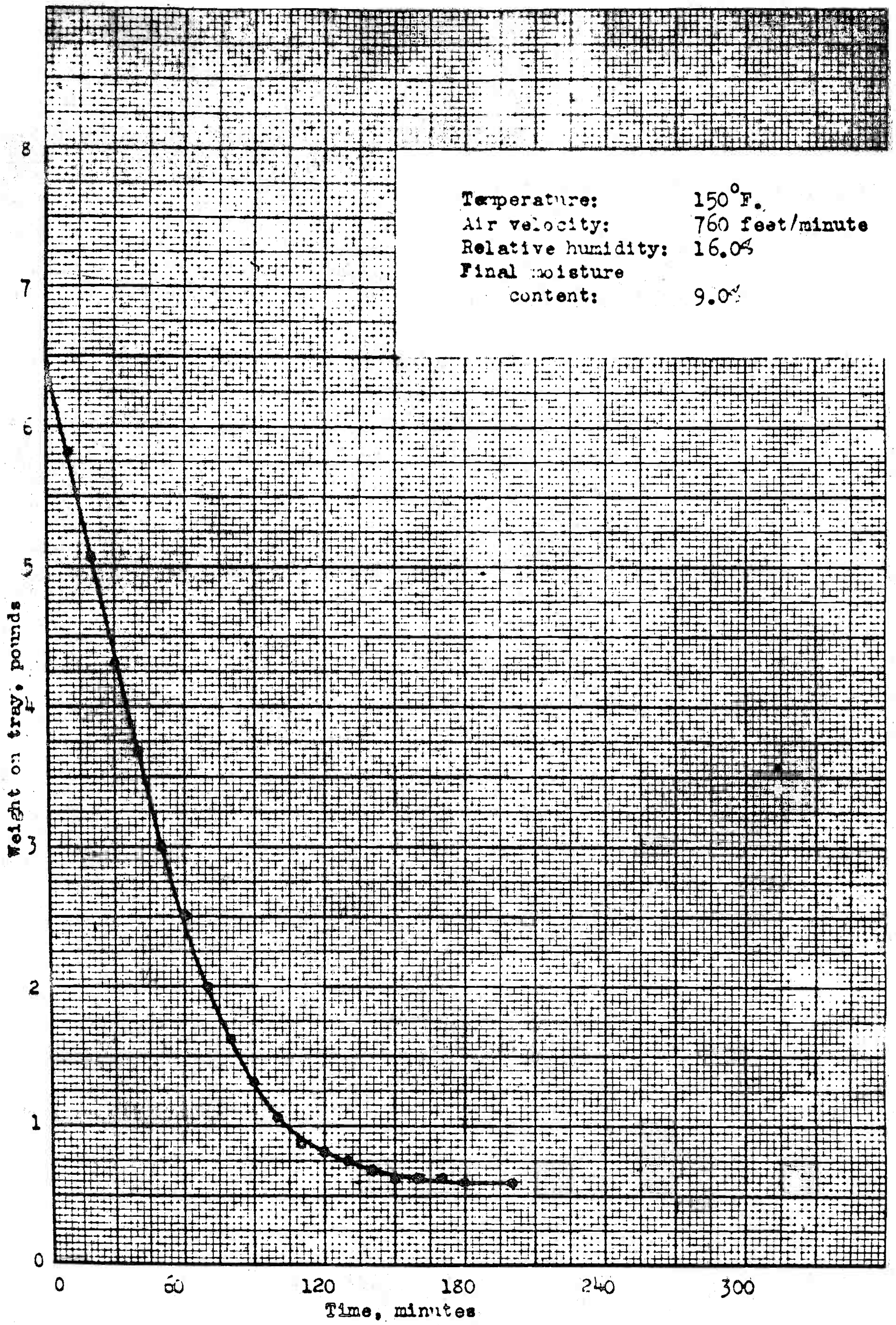

Fig. 30. Drying curve for run 145.

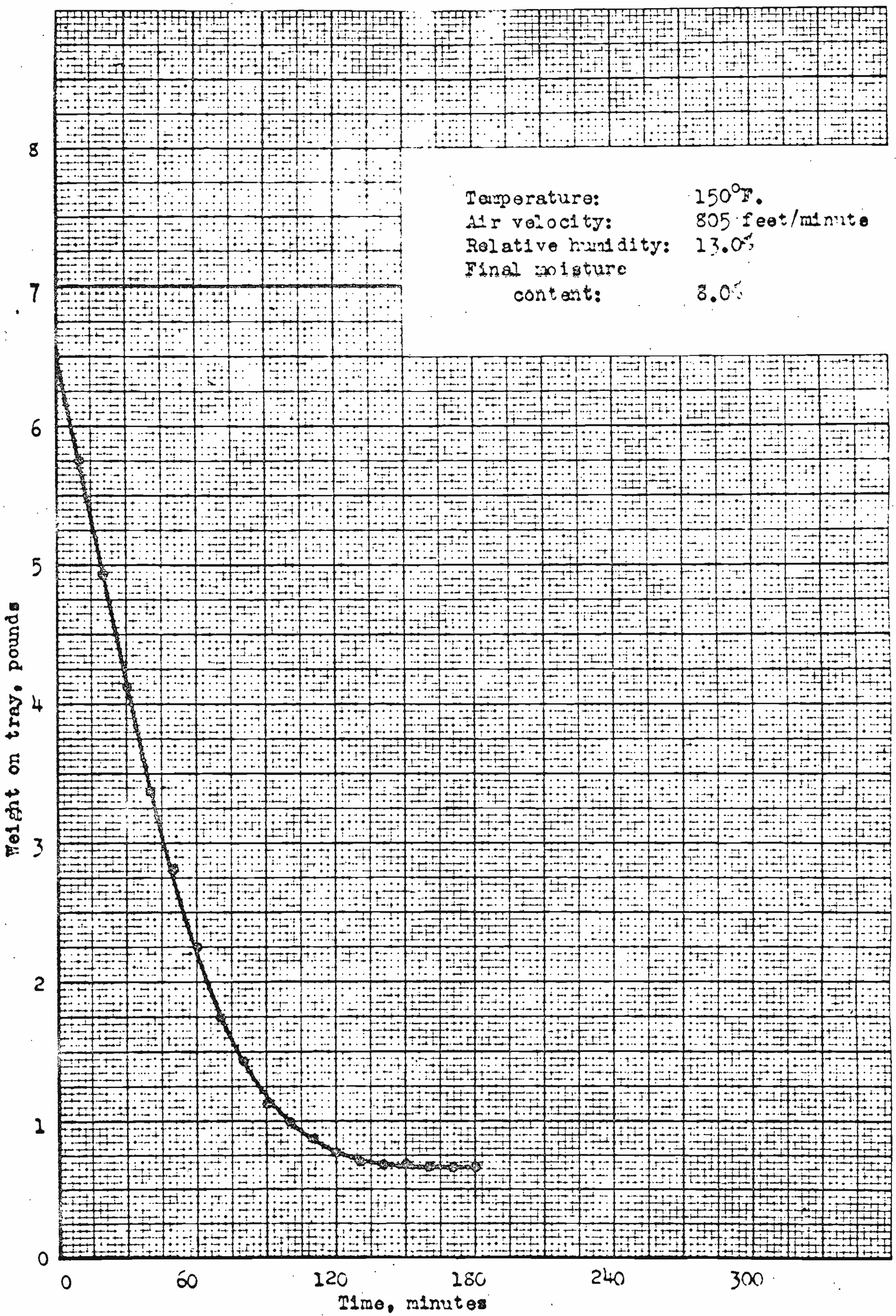

Fig. 31. Drying curve for run 146.

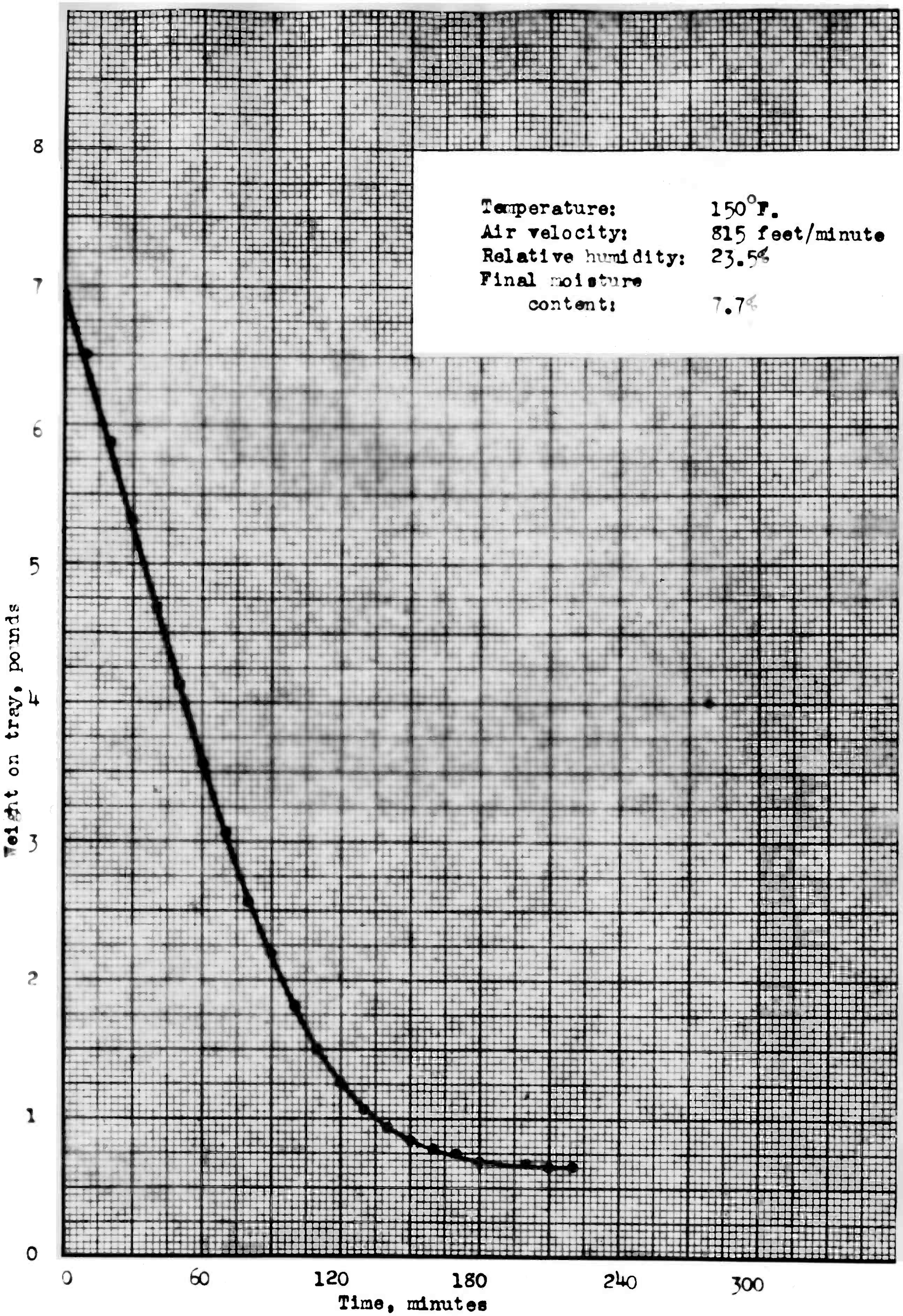

Fig. 32. Drying curve for run 147.

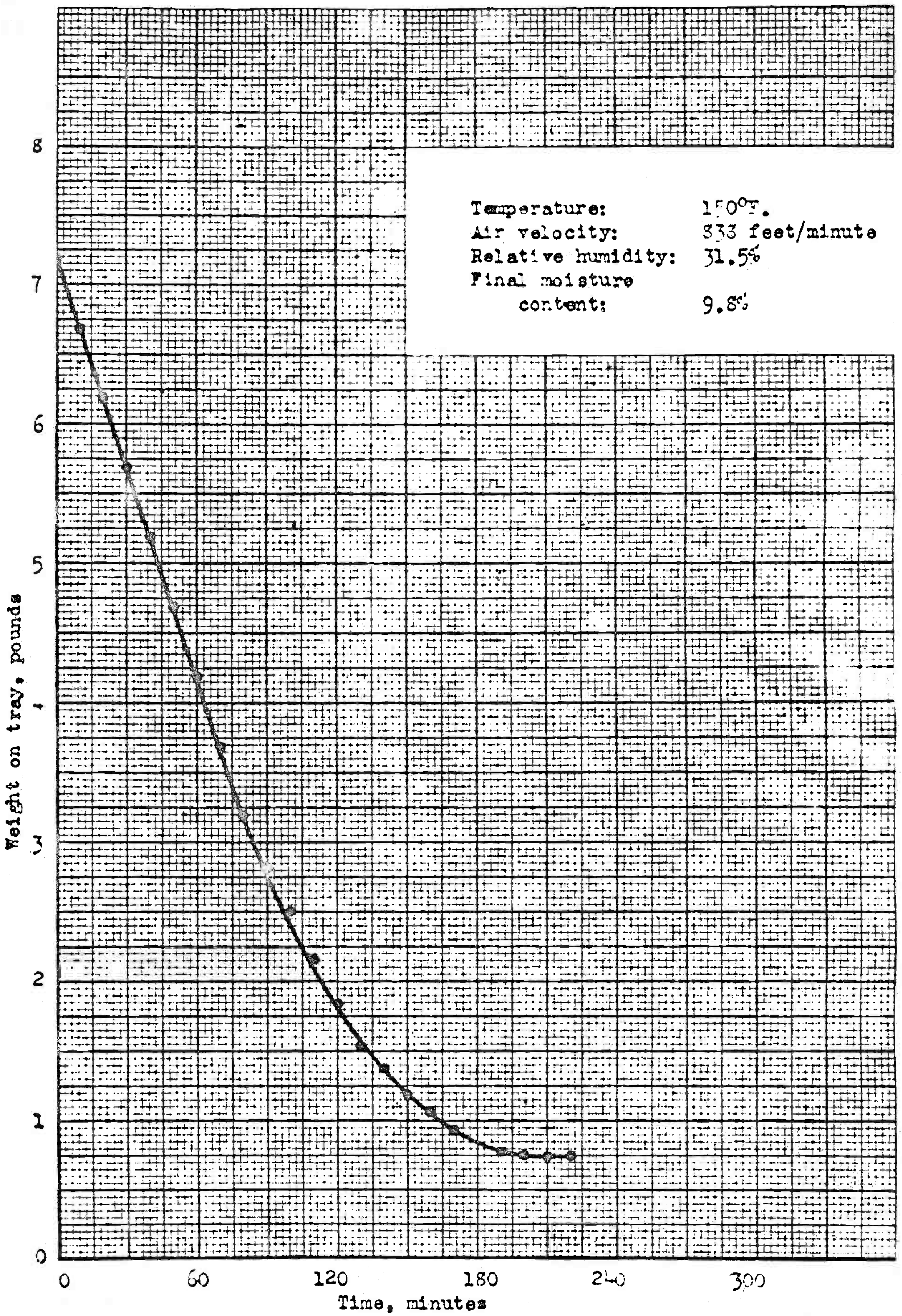

Fig. 33. Drying curve for run 148.

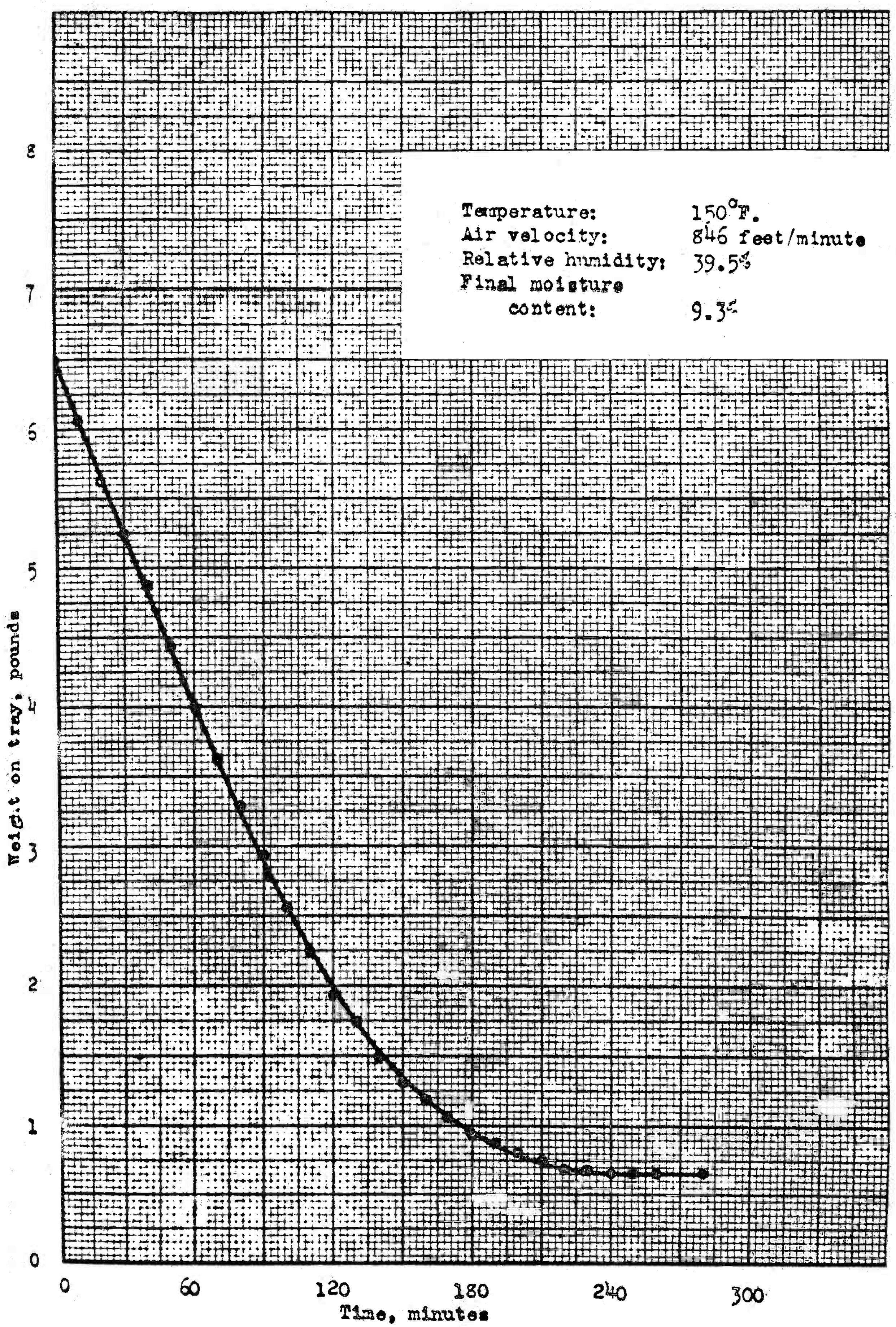

Fig. 34. Drying curve for run 149.

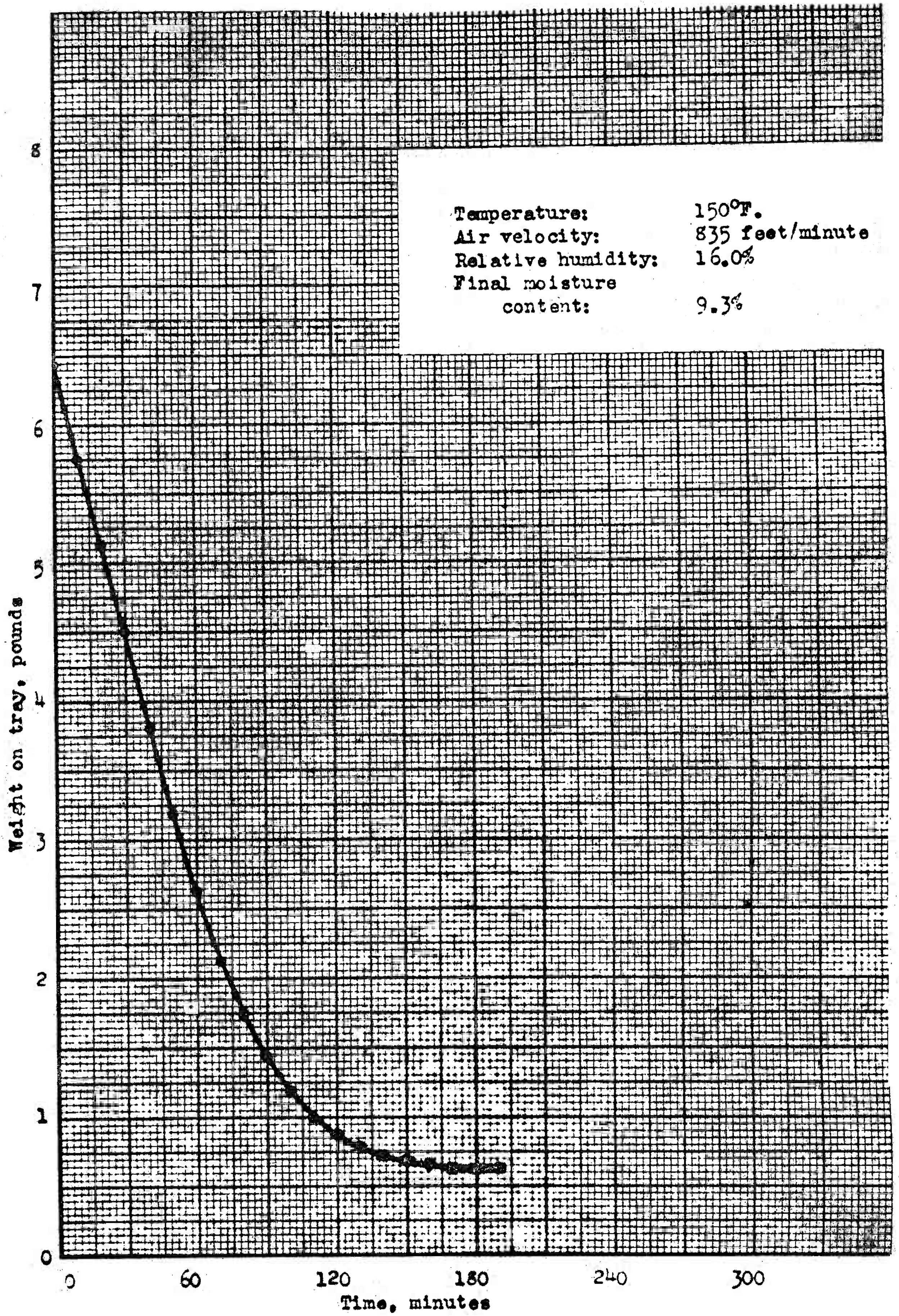

Fig. 35. Drying curve for run 150.

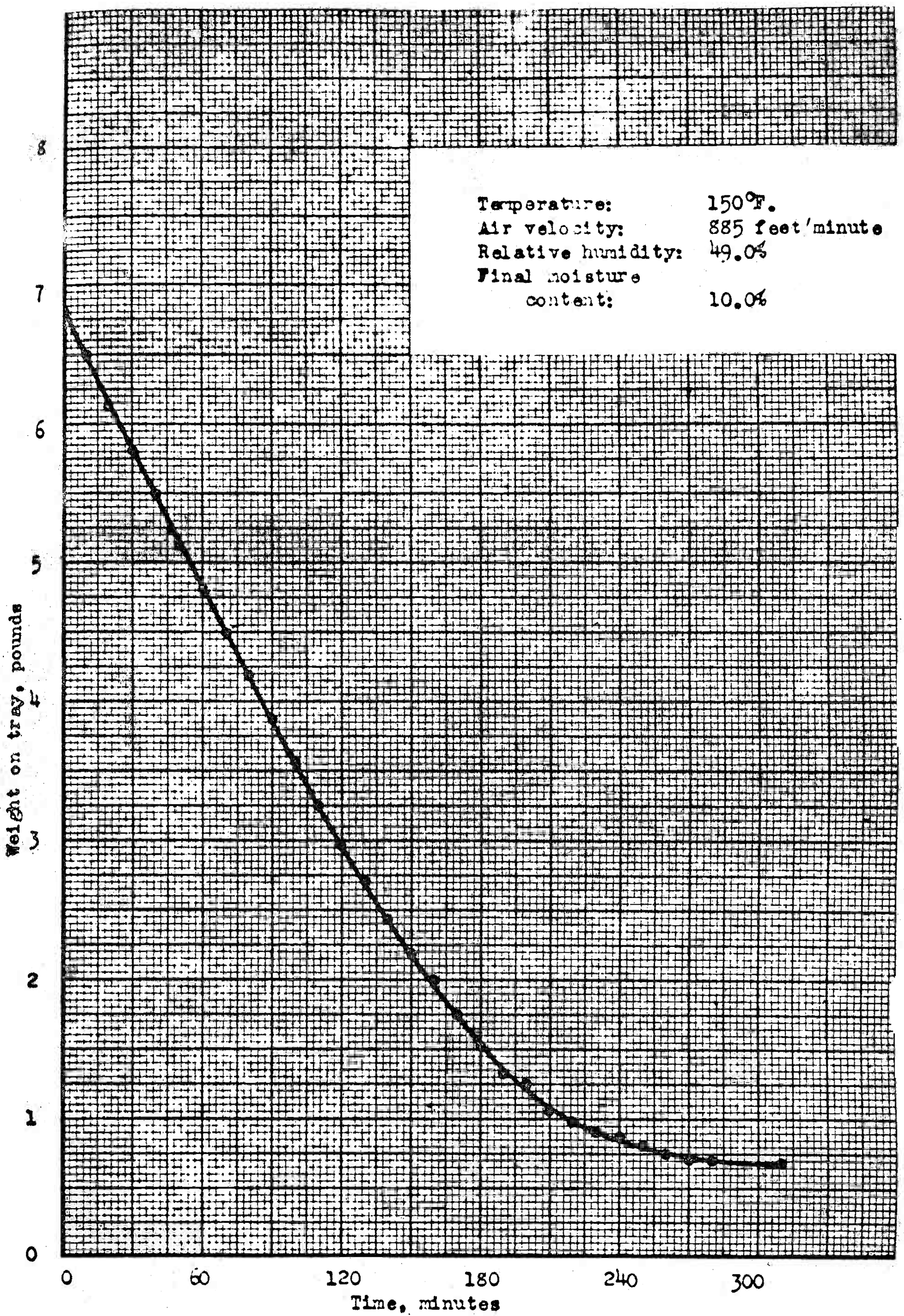

Fig. 36. Drying curve for run 151.

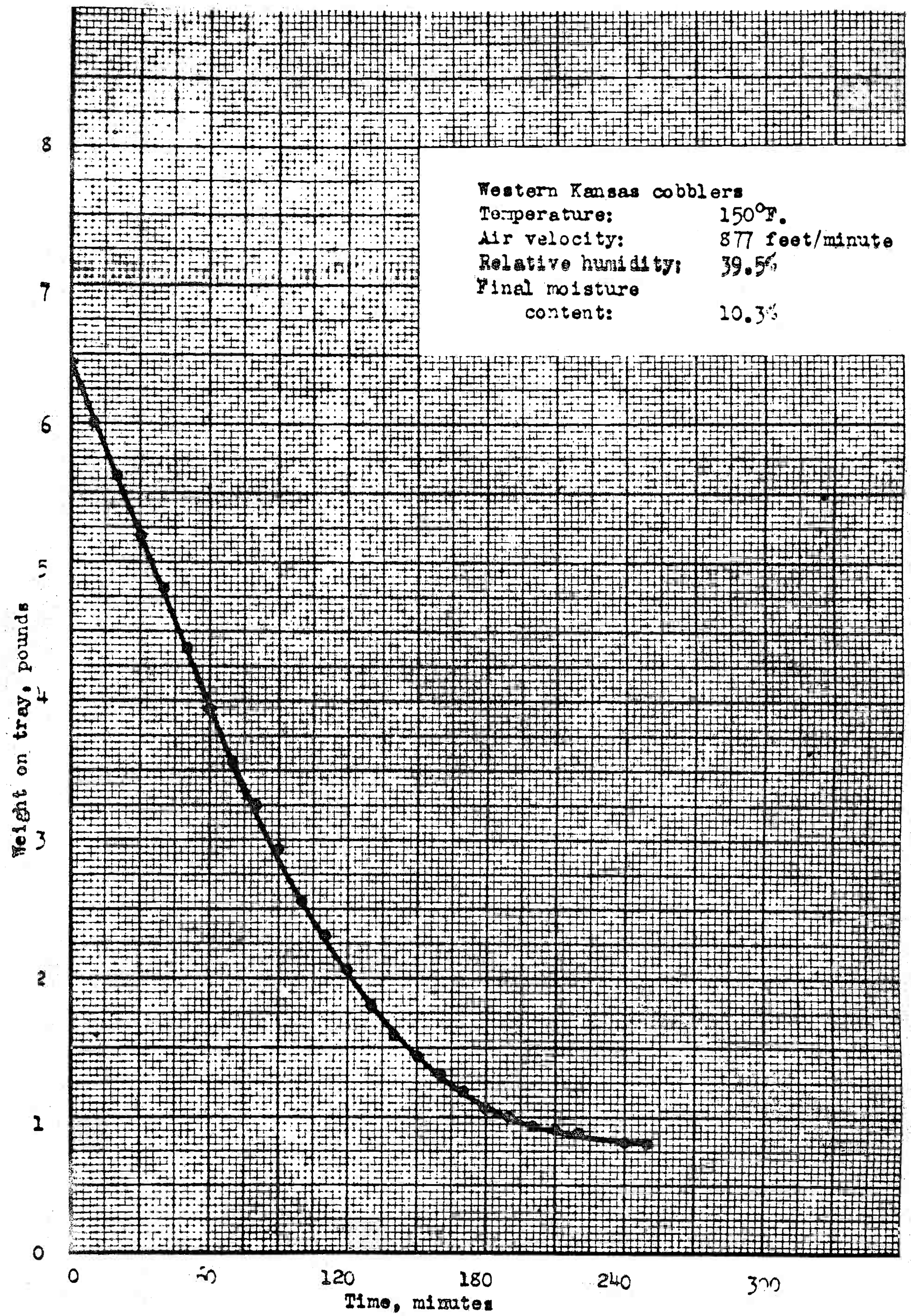

Fig. 37. Drying curve for run 152.

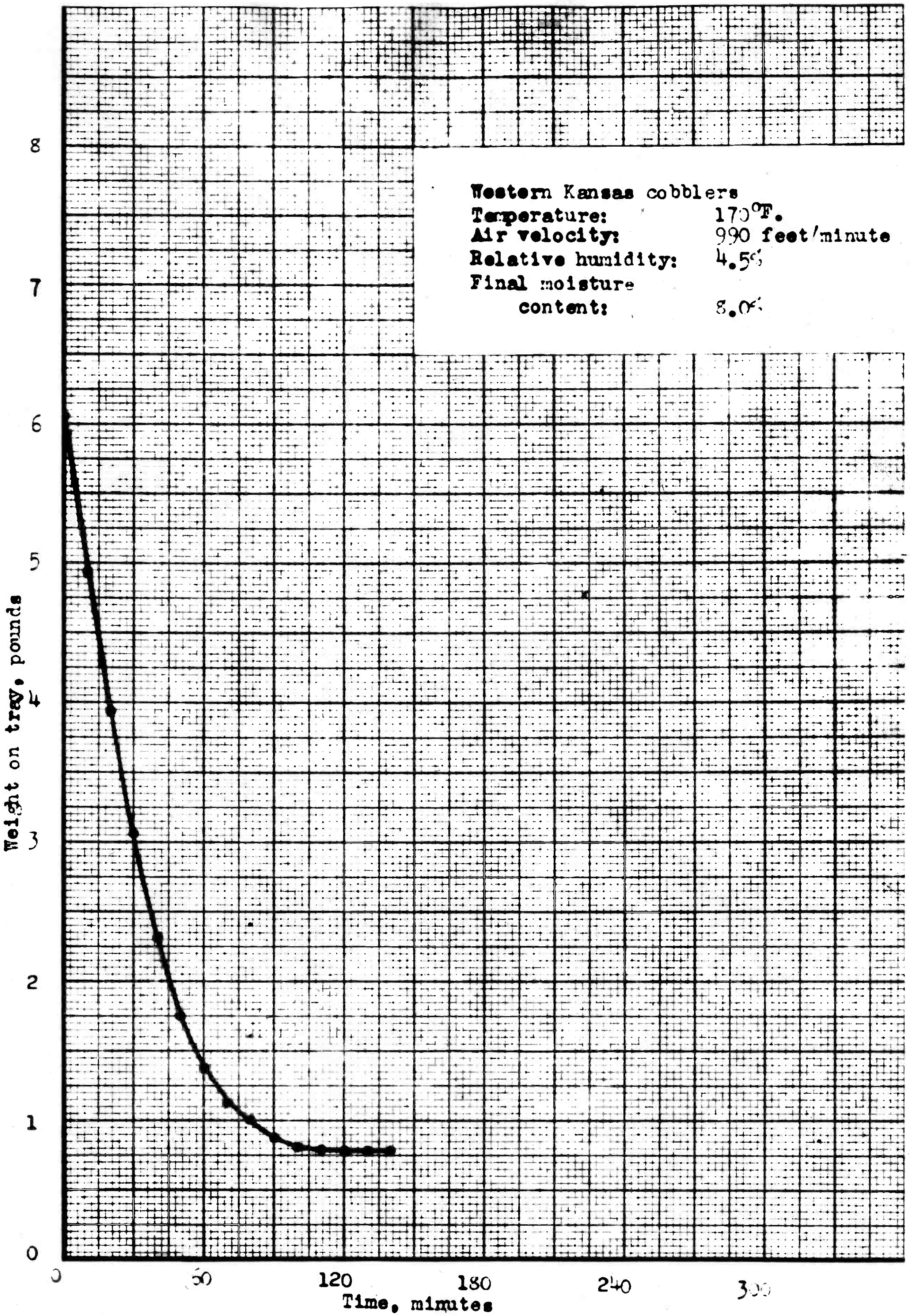

Fig. 38. Drying curve for run 153.

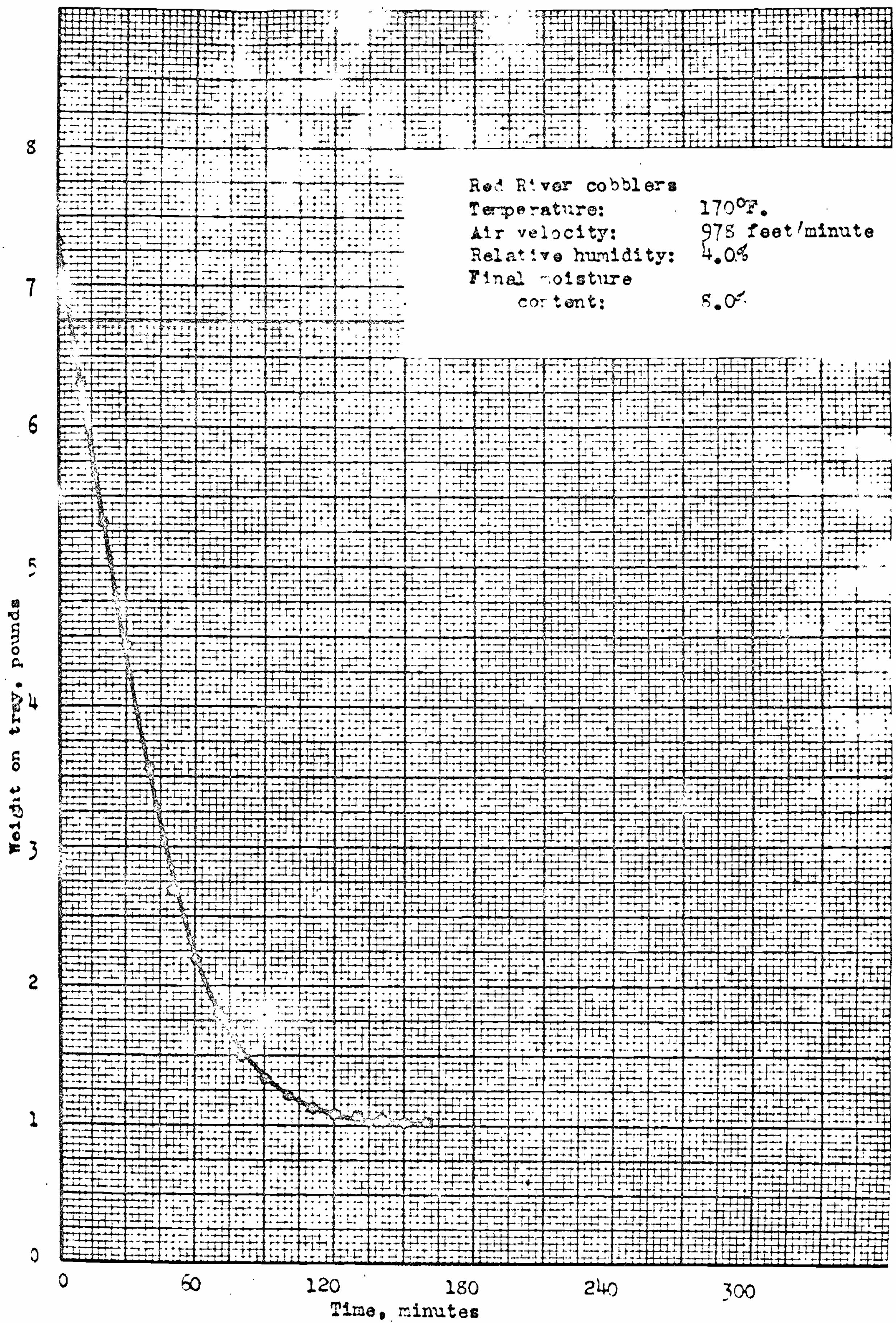

Fig. 39. Drying curve for run 154.

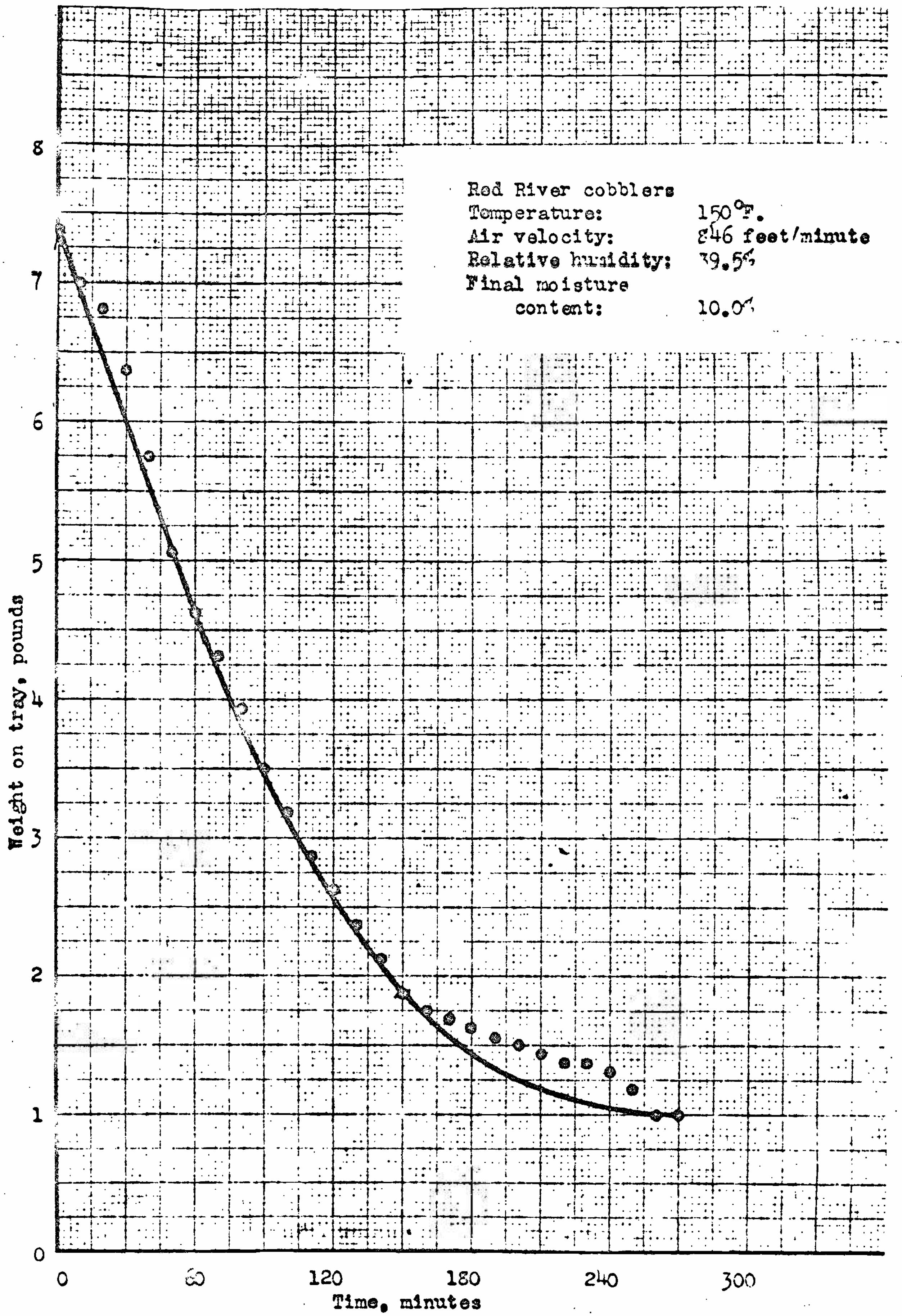

Fig. 40. Drying curve for run 155.

sponding to five settings of the Reeves drive on the blower. It was possible to absolutely reproduce the r.p.m. of the blower, but it was impossible to measure the air velocity with corresponding accuracy, particularly in the lower ranges. The corrected velocity is shown in each case.

The temperature range used was 120 to 200°F. and the relative humidity was varied from 5 to 49 percent.

In Fig. 40 showing run 155, the break in the weights recorded was caused by difficulty in weighing. Apparently the tray caught on the side of the dryer and consequently did not show the correct loss in weight. This condition was noticed and corrected at the end of the run. The curve was drawn smoothly missing these false points. This was the only run in which trouble of this sort occurred.

CORRELATION OF DATA

It will be noticed that the shapes of the drying curves are much alike, and it is difficult to observe the effect of a change in drying conditions on the drying rate. For this reason these curves were differentiated by measuring the slope of the curve at 10-minute intervals. This was done by sight using a straight edge; greater accuracy than this method gave was not justified. The moisture content of the final product was found by analysis, and the moisture contents at each of the above points calculated. Plots of the instantaneous drying rate, in pounds water evaporated per minute per square foot of tray area ($-\frac{1}{A}\frac{dW}{d\theta}$, where A is the tray area in square feet, W is the weight on the tray in pounds, and θ is time in minutes), versus the percent water (M) were then constructed for each run. These are shown in Figs. 41-45. The constant drying rate period stands out sharply on these curves. The break is not consistent, but the average moisture content at this point, called the critical moisture content, is 83.5 percent. The deviation from this is not great in most cases. The largest variations occurred in the early runs where an insufficient number of weights was taken to make this point definite.

The effect of the different variables can readily be observed from these curves. Figures 41 and 42 show the effect of air velocity on the drying rate; Fig. 43 shows the effect of temperature, and Figs. 44 and 45 show the effect of humidity.

The variables that were selected as most fundamental for correlating these data are $V\rho$, the mass velocity of air over the tray; T, the absolute temperature in degrees Rankine; and $p_{wb} - p_a$, the difference between the vapor pressure of water at the wet-bulb temperature and the partial pressure of the water vapor in the air in atmospheres. The value of these variables for each run is presented in Table 1. Duplicate runs are grouped together in each series. The drying rates at moisture contents of 80, 60, 40, and 20 percent and during the constant drying rate period are included.

The correlation of these data was attempted on the assumption that an exponential equation of the form:

$$\left[\frac{1}{A}\frac{dW}{d\theta}\right]_M = k(V\rho)^{n_1}(p_{wb} - p_a)^{n_2}(T)^{n_3} \qquad (2)$$

would satisfactorily represent the data. This assumption was based

Table 1. Mass velocity, absolute temperature and vapor pressure difference for each run with values of the drying rate at five points.

Run	V_G, Lbs. per sq. ft. per min.	T, °R.	Pwb − Pa, atmos.	$-\frac{1}{A}\frac{dW}{d\theta}$, lbs. per min. per sq. ft. Constant rate	Moisture content 80%	60%	40%	20%
Variable air velocity								
115	28.0	610	0.025	0.0080	0.0059	0.0036	0.0021	0.0009
136	26.8	610	0.023	0.0080	0.0062	0.0025	0.0025	0.0002
116	34.4	610	0.025	0.0095	C. R.*	0.0044	0.0023	0.0009
132	38.7	610	0.025	0.0117	0.0084	0.0048	0.0027	0.0010
119	50.2	610	0.022	0.0119	0.0095	0.0043	0.0024	0.0010
131	53.5	610	0.022	0.0140	0.0107	0.0058	0.0029	0.0011
118	62.5	610	0.025	0.0115	C. R.*	0.0066	0.0034	0.0014
130	69.6	610	0.024	0.0168	0.0140	0.0071	0.0037	0.0015
135	69.2	610	0.024	0.0168	0.0139	0.0058	0.0031	0.0014
119	80.1	610	0.024	0.0237	0.0108	0.0065	0.0025	0.0010
133	80.1	610	0.024	0.0208	0.0143	0.0068	0.0035	0.0012
134	81.7	612	0.021	0.0204	0.0150	0.0058	0.0028	0.0009
Variable temperature								
120	62.6	580	0.016	0.0104	0.0079	0.0041	0.0025	0.0010
121	64.3	590	0.018	0.0125	0.0098	0.0040	0.0019	0.0007
122	63.6	600	0.017	0.0115	0.0103	0.0044	0.0025	0.0010
123	62.4	610	0.016	0.0141	0.0108	0.0040	0.0022	0.0007
124	62.0	622	0.025	0.0141	0.0127	0.0057	0.0025	0.0009
125	62.5	630	0.025	0.0167	0.0133	0.0065	0.0030	0.0010
126	62.1	640	0.026	0.0268	0.0186	0.0083	0.0046	0.0018
129	61.5	640	0.031	0.0203	0.0185	0.0079	0.0042	0.0016
127	61.8	650	0.021	0.0222	0.0182	0.0097	0.0052	0.0020
128	61.3	660	0.029	0.0248	0.0220	0.0117	0.0066	0.0023
Variable humidity								
131	53.5	610	0.022	0.0140	0.0107	0.0057	0.0029	0.0011
137	55.1	610	0.021	0.0124	0.0084	0.0046	0.0025	0.0009
144	54.0	610	0.021	0.0139	0.0127	0.0056	0.0031	0.0013
146	52.0	610	0.021	0.0132	0.0113	0.0051	0.0025	0.0008
142	51.2	610	0.018	0.0125	0.0082	0.0048	0.0027	0.0009
145	48.6	610	0.018	0.0120	0.0101	0.0050	0.0026	0.0009
150	53.5	610	0.018	0.0108	0.0099	0.0048	0.0026	0.0009
139	48.9	610	0.015	0.0100	0.0088	0.0044	0.0025	0.0009
147	52.2	610	0.015	0.0094	0.0082	0.0049	0.0027	0.0009
141	49.1	610	0.013	0.0083	0.0071	0.0040	0.0023	0.0008
148	52.9	610	0.013	0.0083	C. R.*	0.0041	0.0023	0.0008
143	52.6	610	0.010	0.0071	0.0059	0.0037	0.0021	0.0010
149	52.9	610	0.010	0.0069	0.0060	0.0034	0.0019	0.0006
140	49.9	610	0.008	0.0056	0.0048	0.0028	0.0015	0.0008
151	54.5	610	0.008	0.0056	0.0048	0.0031	0.0017	0.0007

*C. R.--At 80% moisture these runs were still in the constant drying rate period.

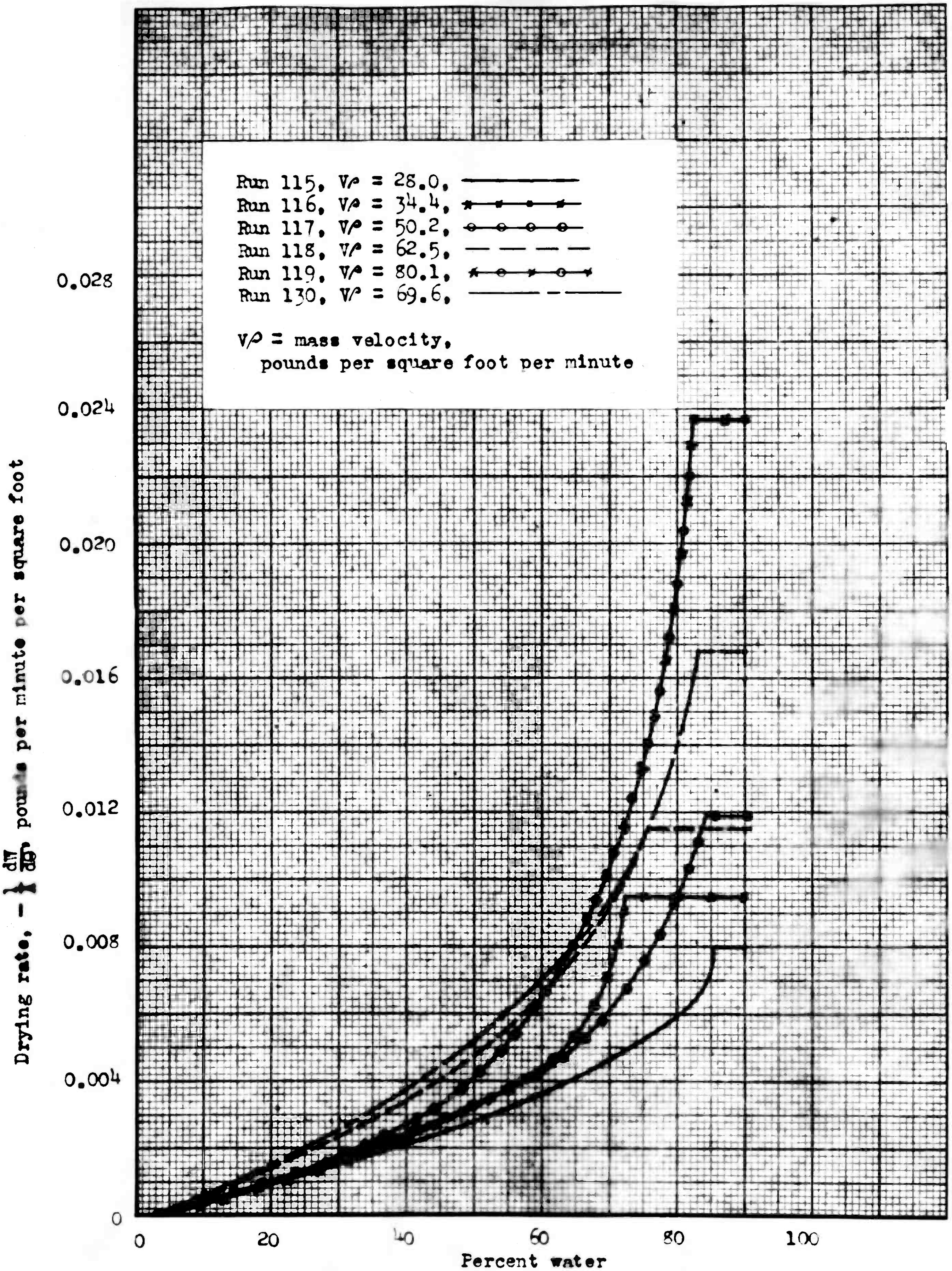

Fig. 41. Effect of air velocity on drying rate.

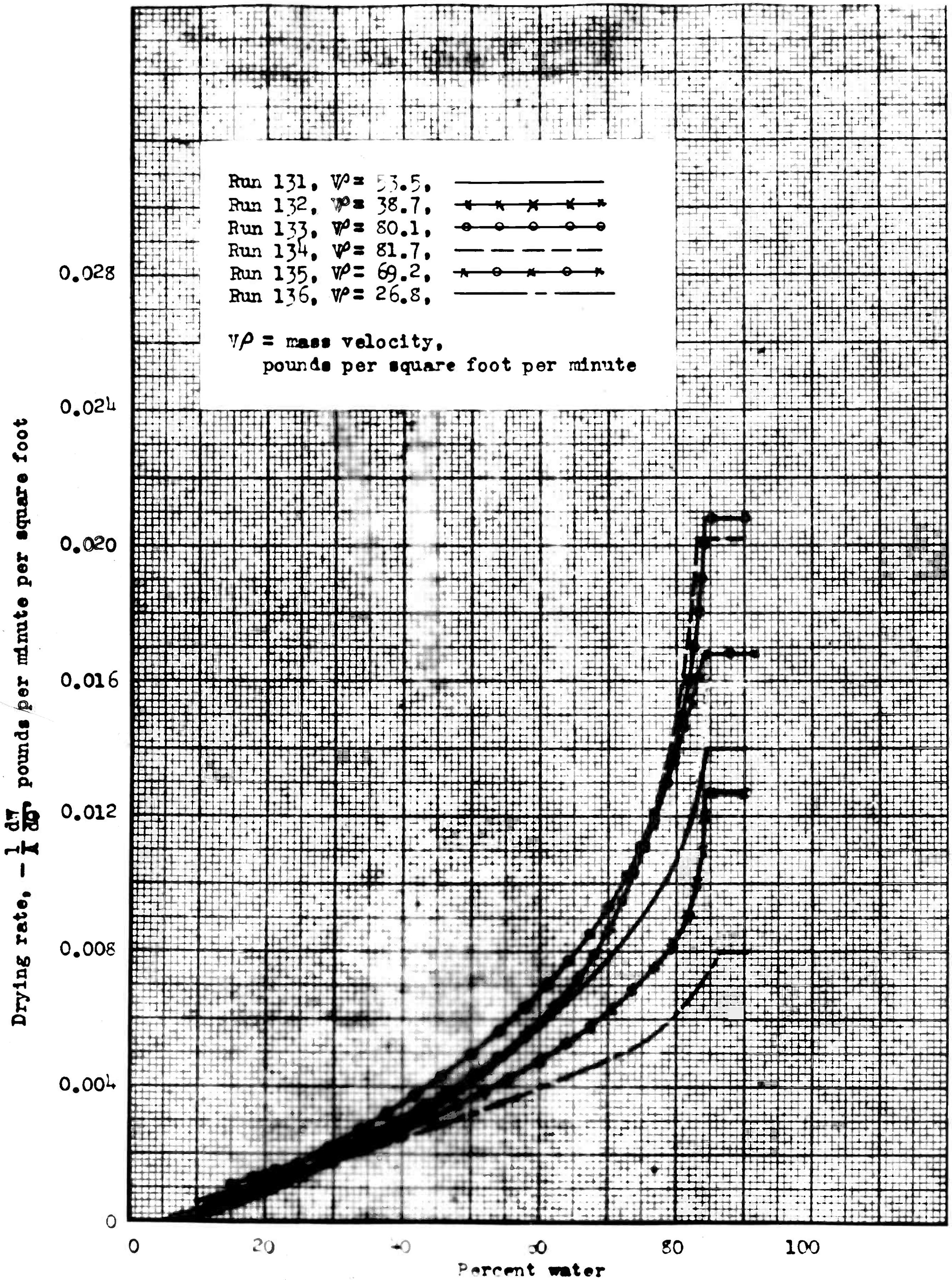

Fig. 42, Effect of air velocity on drying rate.

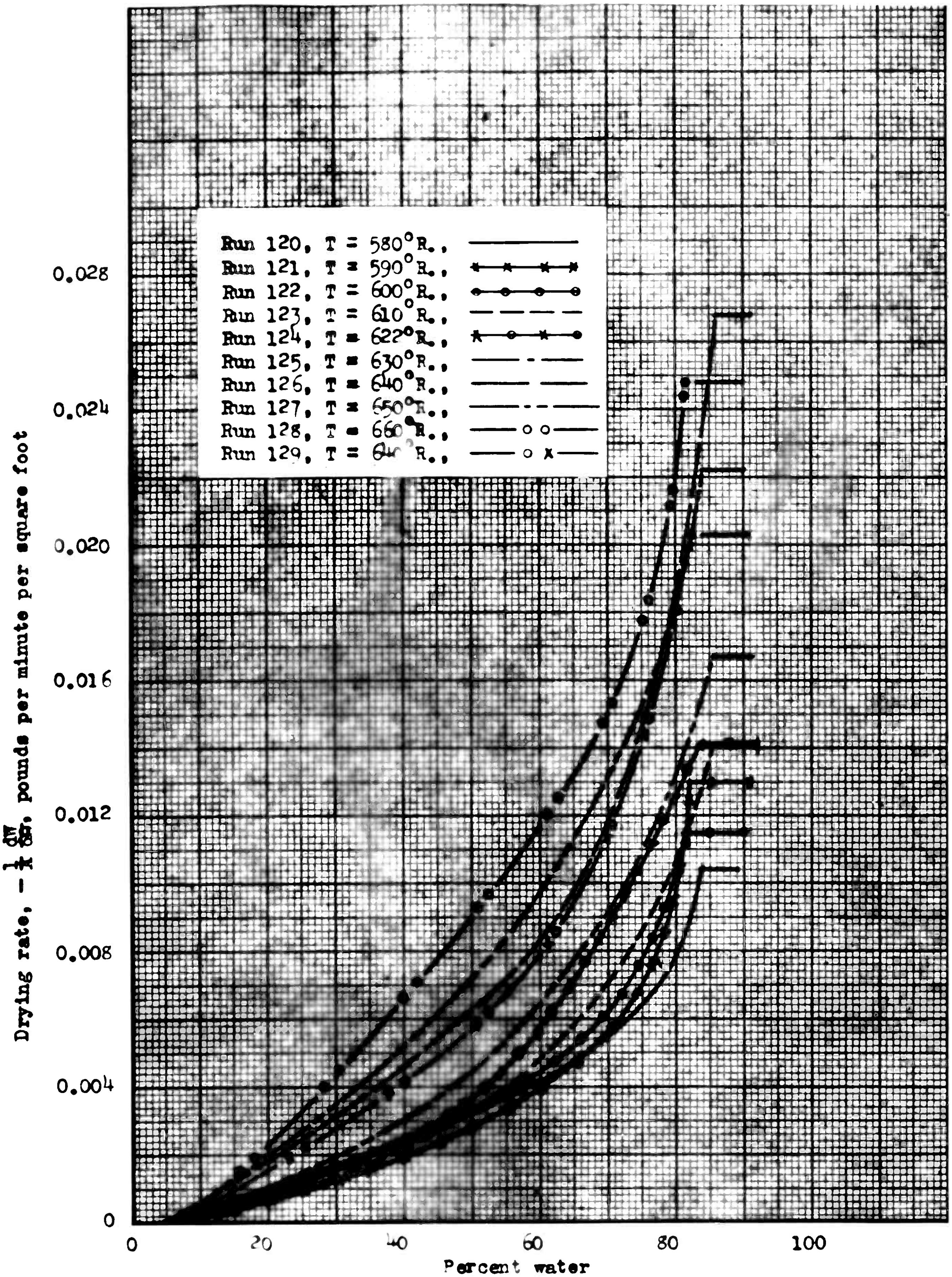

Fig. 43. Effect of temperature on drying rate.

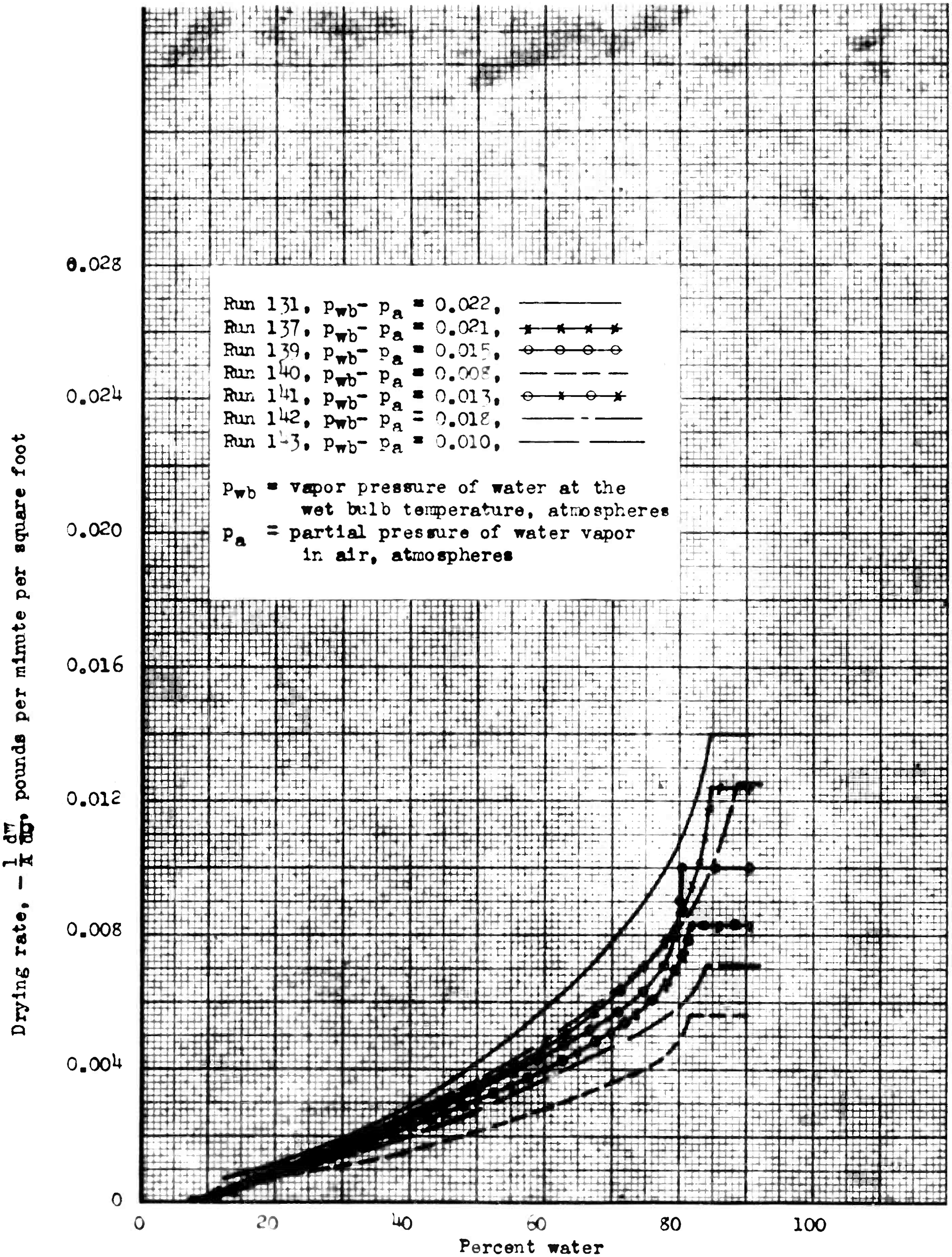

Fig. 44. Effect of humidity on drying rate.

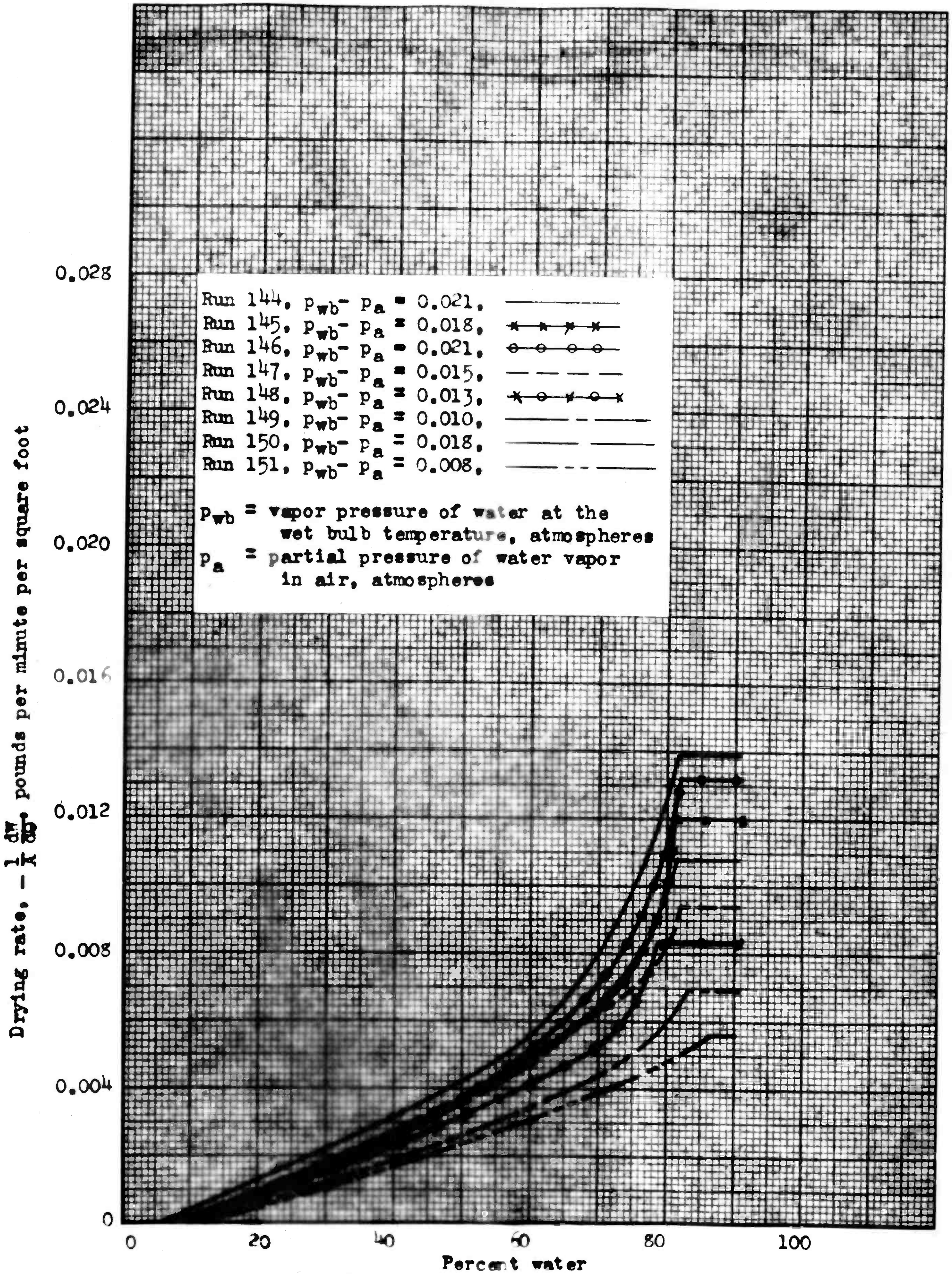

Fig. 45. Effect of humidity on drying rate.

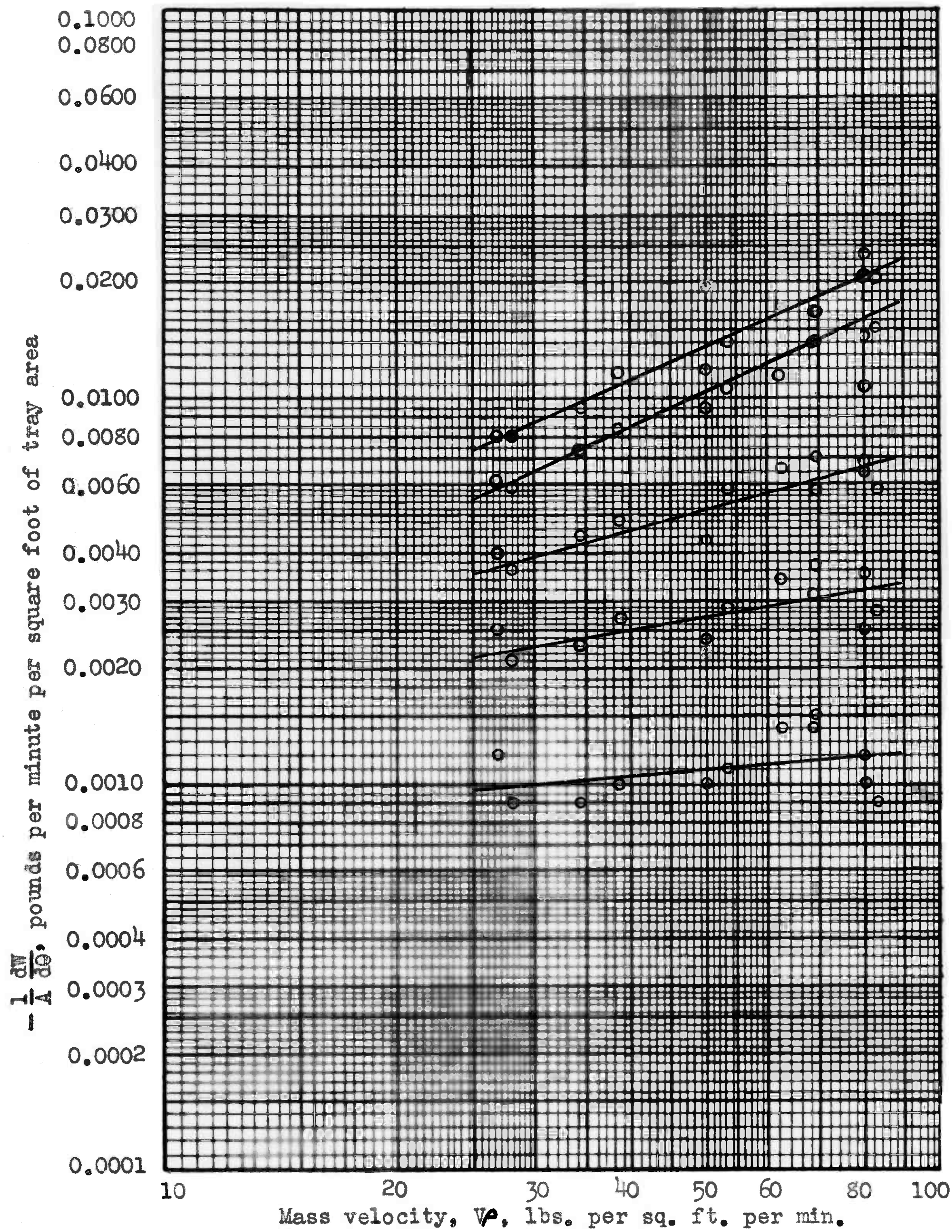

Fig. 46. Effect of mass velocity on drying rate at 20, 40, 60 and 80% moisture and the constant rate period.

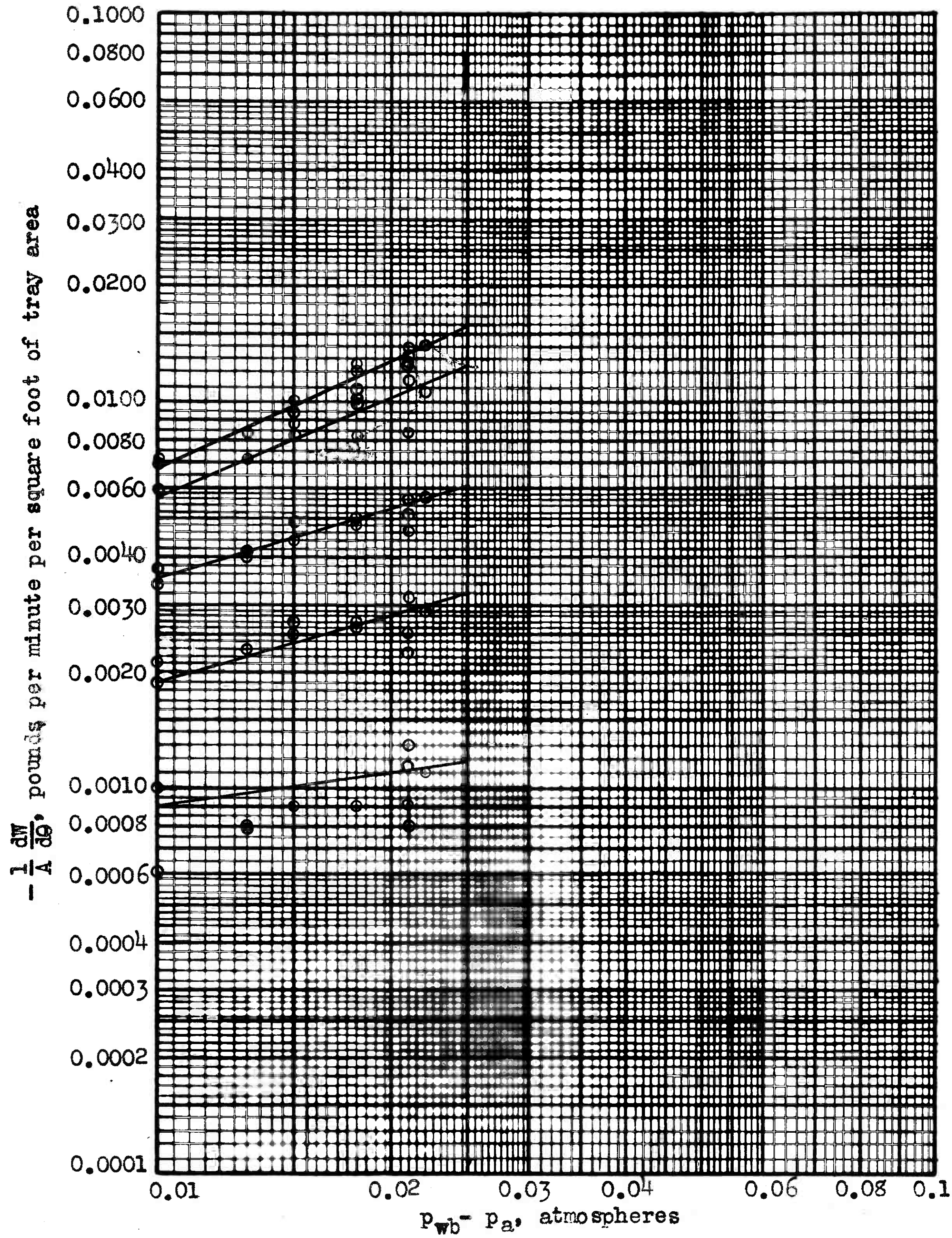

Fig. 47. Effect of humidity on drying rate at 20, 40, 60 and 80% moisture and the constant rate period.

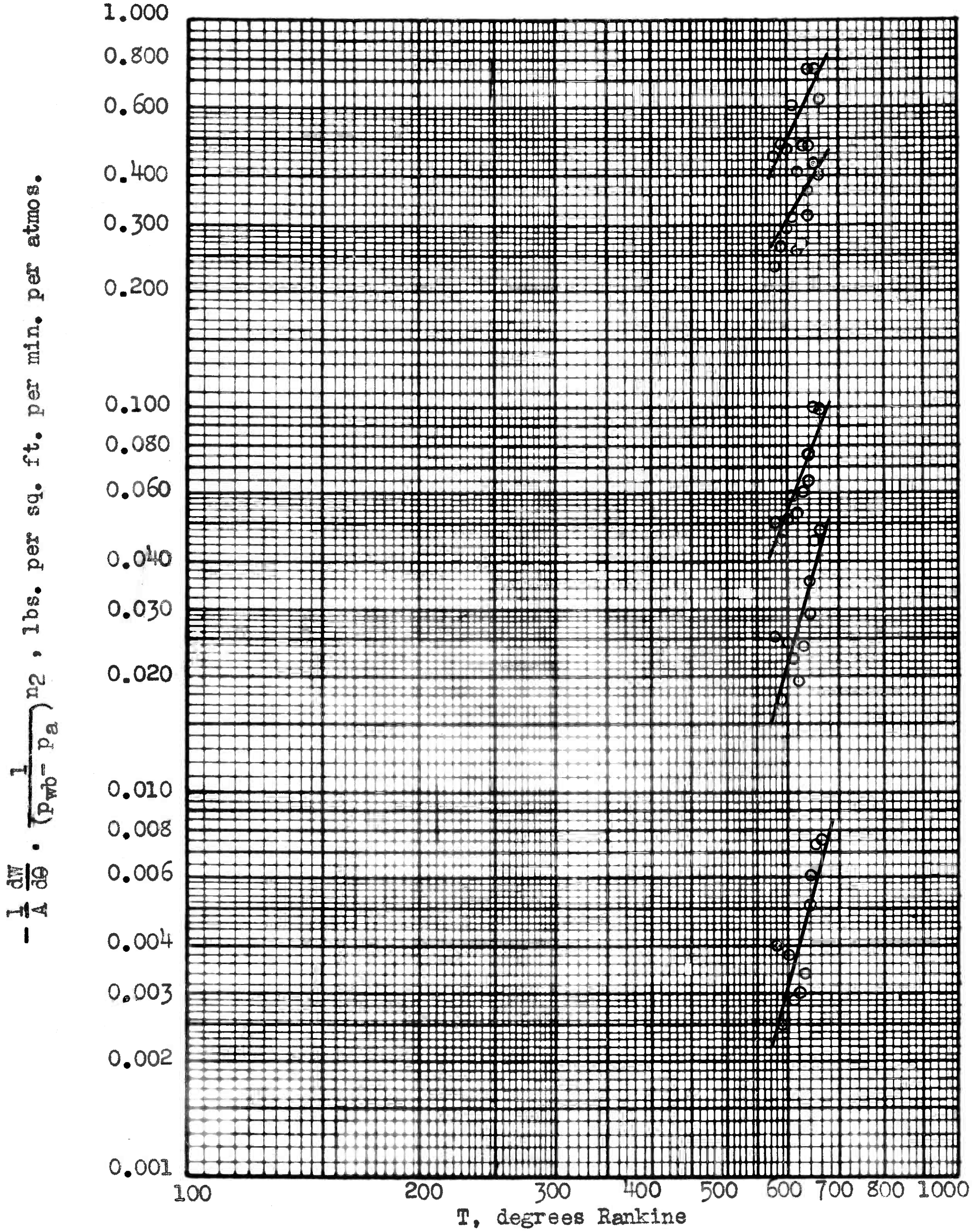

Fig. 48. Effect of temperature on drying rate at 20, 40, 60 and 80% moisture and the constant rate period.

on the approximately straight line relationship shown by the plots of drying rate versus each of the three variables successively on logarithmic scales in Figs. 46, 47, and 48. In the variable velocity and variable humidity plots the remaining two variables were constant so that the slope of the line represents the exponent.

The equation for the effect of the mass velocity, $V\rho$, can be written as:

$$\log \left[-\frac{1}{A}\frac{dW}{d\theta}\right]_{M,\ T,\ (p_{wb} - p_a)} = \log c_1 - n_1 \log(V\rho) \qquad (3)$$

The values of c_1 and n_1 were determined by the method of Davis (11, p. 9-11), by which the variables were substituted into the above equation for each run in the series, giving a group of equations relating c_1 and n_1. The arithmetical averages of the upper half and of the lower half of these equations were found and the two resulting equations solved simultaneously.

The procedure for the effect of $p_{wb} - p_a$ is exactly the same. In the variable temperature series, however, the change in the function, $p_{wb} - p_a$, with temperature had to be accounted for. This was done by plotting the function, $-\frac{1}{A}\frac{dW}{d\theta}\cdot\frac{1}{(p_{wb} - p_a)}{}^{n_2}$, versus the absolute temperature. The values of c_1, c_2, c_3, n_1, n_2, and n_3 for the constant rate period and moisture contents of 80, 60, 40, and 20 percent are shown in Table 2.

The value of k in equation (2) for the constant rate period, and moisture contents of 80, 60, 40, and 20 percent were calculated for each run by calculating the values of $(V\rho)^{n_1}$, $(p_{wb}-p_a)^{n_2}$, and $(T)^{n_3}$ and solving this equation for k. These constants were

Table 2. Value of the constants in the logarithmic equations relating drying rate to each variable and of k in equation (2).

	Variable						
	$V\rho$		$(p_{wb} - p_a)$		T		
	c_1	n_1	c_2	n_2	c_3	n_3	k
Constant rate	4.87×10^{-4}	0.852	0.448	0.912	4.20×10^{-10}	3.26	1.25×10^{-11}
80% moisture	2.70×10^{-4}	0.933	0.254	0.821	1.34×10^{-11}	3.73	2.52×10^{-13}
60% moisture	6.19×10^{-4}	0.544	0.056	0.604	3.02×10^{-17}	5.49	3.19×10^{-18}
40% moisture	6.89×10^{-4}	0.353	0.025	0.559	9.36×10^{-22}	6.97	2.32×10^{-22}
20% moisture	3.85×10^{-4}	0.267	0.004	0.330	3.59×10^{-25}	7.90	1.29×10^{-25}

averaged for each condition. Table 3 gives the value of these constants for each run, the average k and the percent deviations from the average.

DISCUSSION

The value of the exponent, n_1, for the mass velocity in the constant rate period as given in Table 2 is seen to be 0.852. This is in good agreement with the value of the exponent (0.8) as given in equation (1). It is also in close agreement with the exponent, 0.83, used by Sherwood (12, p. 40) for the Reynolds number, $\frac{DV\rho}{\mu}$, in calculating the effective film thickness for the vaporization of liquids into air, and a similar equation given by McAdams (13, p. 168) for heat transfer to fluids in turbulent flow in pipes.

The increase in the mass velocity exponent from the constant rate period to 80 percent moisture is surprising. It may be explained, however, by assuming that shortly after the critical moisture content was passed, part of the surface of the cubes being dried was still wet. The increased turbulence resulting from increased velocities would create a disproportionate increase in the drying rate in this case. At the lower moisture contents the effect of mass velocity was almost negligible. If liquid diffusion in the material were the controlling factor, this variable would have had no effect.

The effect of the humidity of the air on the drying rate, as expressed by the function, $p_{wb} - p_a$, is seen to decrease as the moisture content decreases.

Table 3. Values of k in equation (2) for each run.

Run	Constant rate: k x 10^{-11}	Constant rate: % deviation	80% moisture: k x 10^{-13}	80% moisture: % deviation	60% moisture: k x 10^{-18}	60% moisture: % deviation	40% moisture: k x 10^{-22}	40% moisture: % deviation	20 moisture: k x 10^{-25}	20 moisture: % deviation
115	1.12	-10.4	2.13	-15.5	2.79	-12.5	1.99	-14.2	1.24	-3.9
116	1.12	-10.4	C.R.*	....	3.04	- 4.7	2.18	- 6.0	1.19	-7.8
117	1.15	- 8.0	2.26	-10.3	2.63	-17.6	1.98	-14.6	1.23	-4.7
118	0.82	-32.8	C.R.	....	3.30	+ 3.4	2.42	+ 4.3	1.56	+20.9
119	1.41	+12.8	2.69	+ 6.7	2.94	- 7.8	1.66	-28.4	1.05	-18.6
120	1.30	+ 4.0	2.46	+ 2.4	3.55	+11.3	3.26	+40.5	2.10	+62.8
121	1.31	+ 4.8	2.64	+ 4.8	2.90	- 9.1	1.97	-15.1	1.06	-17.8
122	1.21	- 3.2	2.66	+ 5.6	3.08	- 3.4	2.46	+ 6.0	1.43	+10.8
123	1.53	+22.4	2.78	+10.3	3.22	+ 0.9	2.06	-11.2	0.97	-24.8
124	0.96	-23.2	2.18	-13.5	2.62	-17.9	1.54	-33.6	0.83	-35.6
125	1.09	-12.8	2.18	-13.5	2.77	-13.2	1.76	-24.1	0.87	-32.5
126	1.60	+28.0	2.68	+ 6.4	3.18	- 0.3	2.30	- 0.9	1.39	+ 7.7
127	1.54	+23.2	3.04	+20.6	3.86	+21.0	2.62	+12.9	1.49	+15.5
128	1.23	- 1.6	2.69	+ 6.8	3.72	+16.6	2.53	+ 9.1	1.32	+ 2.3
129	1.04	-16.8	2.30	- 8.7	2.74	-14.1	1.90	-18.1	1.53	+18.6
130	1.13	- 9.6	2.29	- 9.1	3.47	+ 8.8	2.60	+12.1	1.65	+27.9
131	1.28	+ 2.4	2.36	- 6.4	3.42	+ 7.2	2.34	+ 0.9	1.34	+ 3.9
132	1.25	+ 0.0	2.24	-11.1	3.12	- 2.2	2.62	+12.9	1.27	- 1.5
133	1.23	- 1.6	2.69	+ 6.8	3.06	- 4.1	2.33	+ 0.4	1.27	- 1.5
134	1.34	+ 7.2	2.35	- 6.8	2.80	-12.2	1.94	-16.4	0.94	-27.4
135	1.13	- 9.6	2.29	- 9.1	2.83	-11.3	2.23	- 3.9	1.54	+19.4
136	1.26	+ 0.8	2.55	+ 1.2	3.34	+ 4.7	2.51	+ 8.2	1.65	+27.9
137	1.15	- 8.0	1.89	-25.0	2.75	-13.8	2.09	- 5.6	1.10	-14.7
139	1.39	+11.2	2.88	+14.3	3.42	+ 7.2	2.62	+12.9	1.28	- 0.8
140	0.98	-21.6	2.64	+ 4.8	3.20	+0.3	2.25	- 3.0	1.41	+ 9.3
141	1.31	+ 4.8	2.64	+ 4.8	3.42	+7.2	2.62	+12.9	1.25	- 3.1
142	1.41	+12.8	2.44	- 3.2	3.28	+2.8	2.54	+ 9.5	1.22	- 5.4
143	1.35	+ 8.0	2.95	+17.5	3.51	+10.0	2.58	+11.2	1.61	+24.8
144	1.32	+ 5.6	2.89	+14.7	3.36	+ 5.3	2.60	+12.1	1.61	+24.8
145	1.42	+13.6	2.93	+16.3	3.50	+ 9.7	2.43	+ 4.7	1.19	- 7.7
146	1.28	+ 2.4	2.68	+ 6.4	3.15	- 1.3	2.14	- 7.8	1.00	-22.4
147	1.23	- 1.6	2.56	+ 1.6	3.70	+16.0	2.76	+19.0	1.26	- 2.3
148	1.23	- 1.6	C.R.	.....	3.32	+4.1	2.56	+10.3	1.14	-11.6
149	1.31	+ 4.8	2.60	+ 3.2	3.26	+2.2	2.42	+ 4.3	0.97	-24.8
150	1.19	- 4.8	2.15	-14.7	3.20	+0.3	2.28	- 1.7	1.16	-10.1
151	1.27	+ 1.6	2.38	- 5.6	3.49	- 6.3	2.42	+ 4.3	1.20	- 7.0
Ave.	1.25x	± 9.7	2.52	± 9.2	3.19	± 8.1	2.32	±11.5	1.29	±15.6

C.R.* - constant rate. At 80% moisture these runs were still in the C.R. period.

It is interesting to note that the effect of temperature alone, unaccompanied by changes in the humidity function, is the reverse of the effects of the other two variables. As the moisture content decreases the effect of temperature on the drying rate increases.

Curves calculated from this equation for conditions corresponding to runs 127 and 140 are shown in Figs. 49 and 50. The agreement is very good with run 140, not quite so good for 127. By plotting the inverse of the drying rate function, $-\frac{d\theta}{dW}$, versus the weight per square foot of tray area, a curve was obtained which could be integrated to give the drying time between any two moisture contents. The only additional data necessary for this is the original tray loading in pounds per square foot of tray area. These curves are given on Figs. 49 and 50. Graphical integration of these curves gave values of drying time from 90 to 10 percent moisture for run 127 and from 90 to 20 percent moisture for run 140 of 114 and 307 minutes respectively. These compare with experimental values of 96 and 275 minutes.

The following example will illustrate the use of these data in a practical problem:

A tunnel dehydrator, whose width is to be five feet and which will hold a stack of 25 trays, five by three feet, leaving a free height of six feet, is to be constructed. It is desired to dehydrate 1500 pounds of cubed potatoes, similar to Kaw Valley Cobblers, having a critical moisture content of 83.5 percent, from an original moisture content of 90 percent to a final moisture content of 10 percent. The tray loading is to be one pound per square foot,

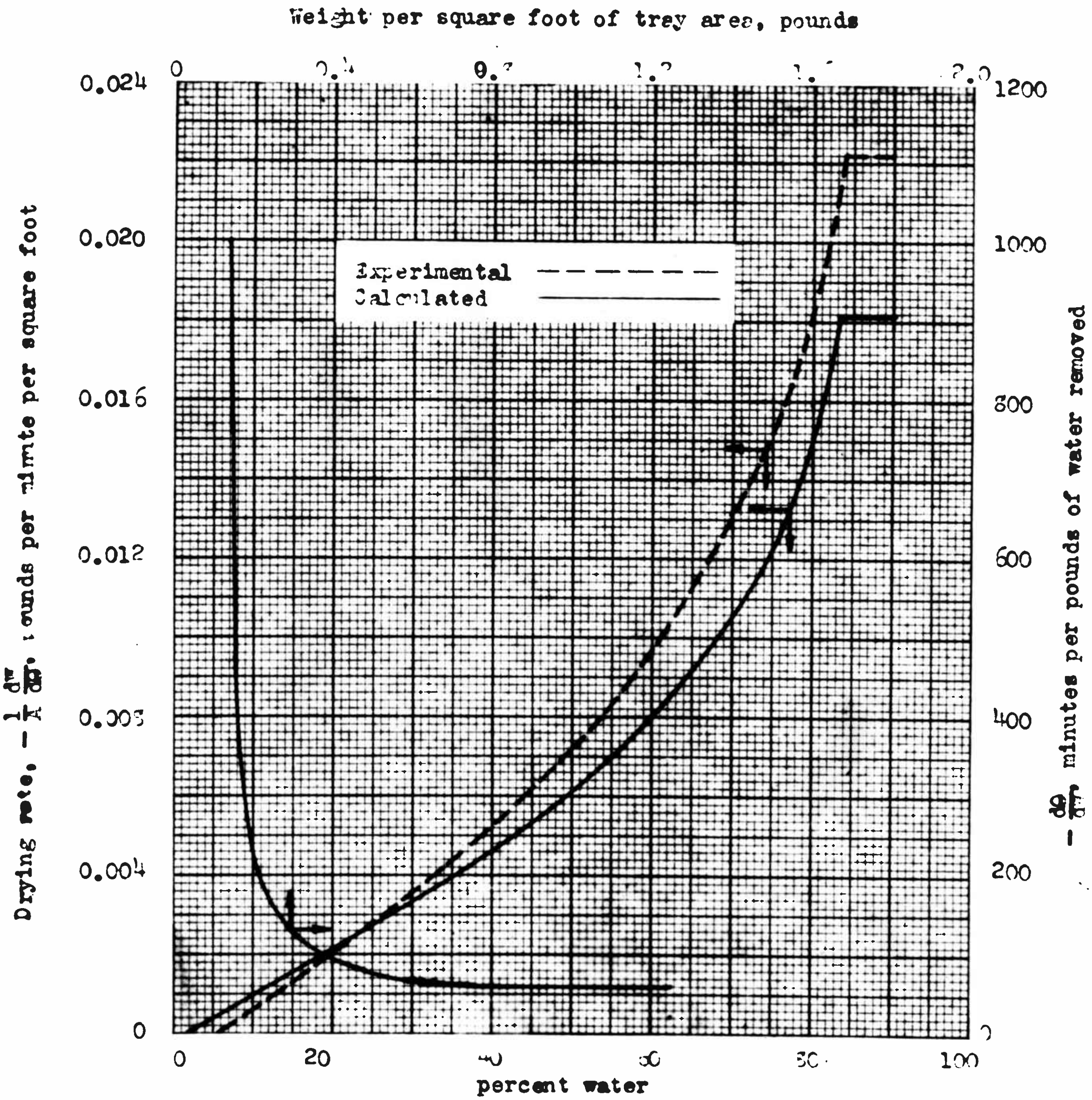

Fig. 49. Calculated drying rate curve for run 127
and graphical integration for drying time.

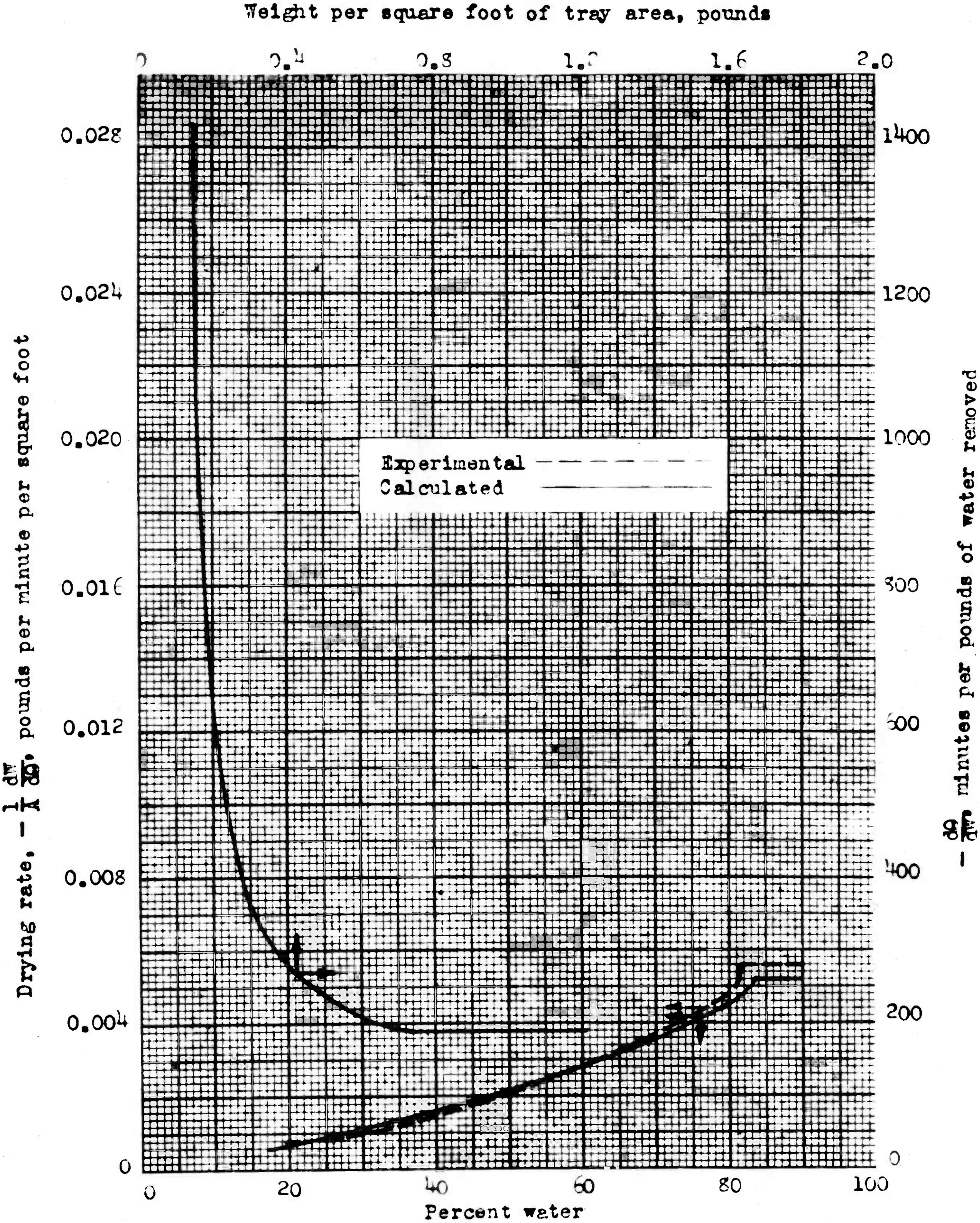

Fig. 50. Calculated drying rate curve for run 140 and graphical integration for drying time.

which means that 100 trays, or four stacks of 25 each, are to be charged per hour. Air will enter at the dry end of the tunnel with a dry-bulb temperature of 150°F. and a wet-bulb of 84°F. The air velocity over the trays countercurrent to their direction will be 800 feet per minute. It is desired to calculate the length of the tunnel required and the time that potatoes must be in the tunnel.

By a series of material balances over the potatoes and air, the condition of the air at the points in the tunnel at which the moisture content of the potatoes would be 20, 40, 60, 80, 83.5 and 90 percent was determined. Then using equation (2) and Table 2 the drying rate in pounds per minute per square foot of tray area was calculated at each of these points. Figure 51 shows the drying rate curve for this tunnel.

The reciprocal of the drying rate was then plotted versus the weight of potatoes per square foot of tray area (Fig. 51) and this curve integrated graphically. The resulting time was 286 minutes. Four stacks of trays, or a total of 12 feet measured horizontally, are to be put through the tunnel per hour. Thus the length of the tunnel was determined to be 57 feet.

Figure 52 gives comparative drying rate curves for two other samples of potatoes, Red River Cobblers and Western Kansas Cobblers. The outstanding differences between these potatoes and those used in this work were the lower initial moisture content and the lower critical moisture content. The curves indicate that the data probably could be used in calculations on potatoes similar to those used.

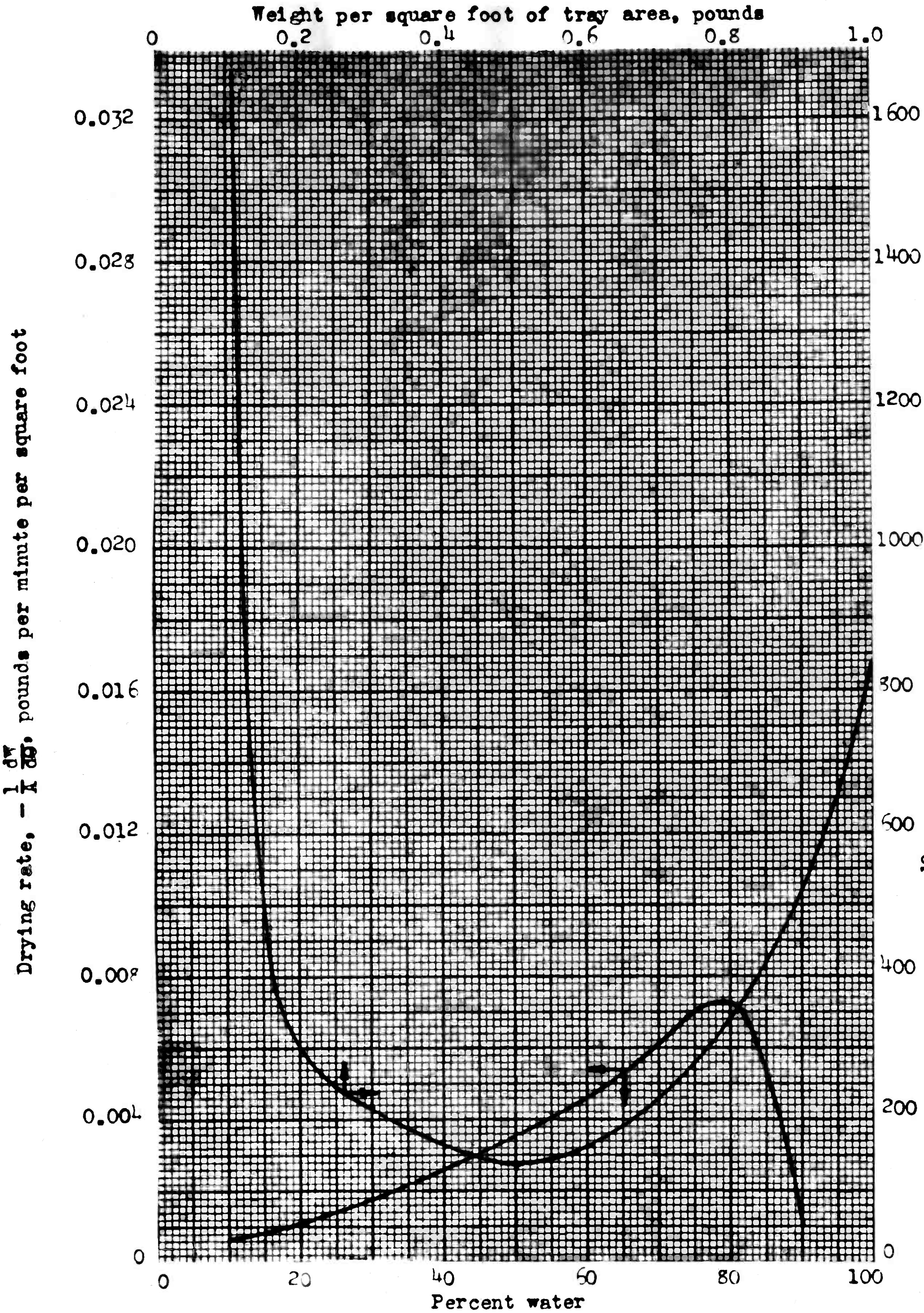

Fig. 51. Drying rates in a countercurrent tunnel and graphical integration for drying time.

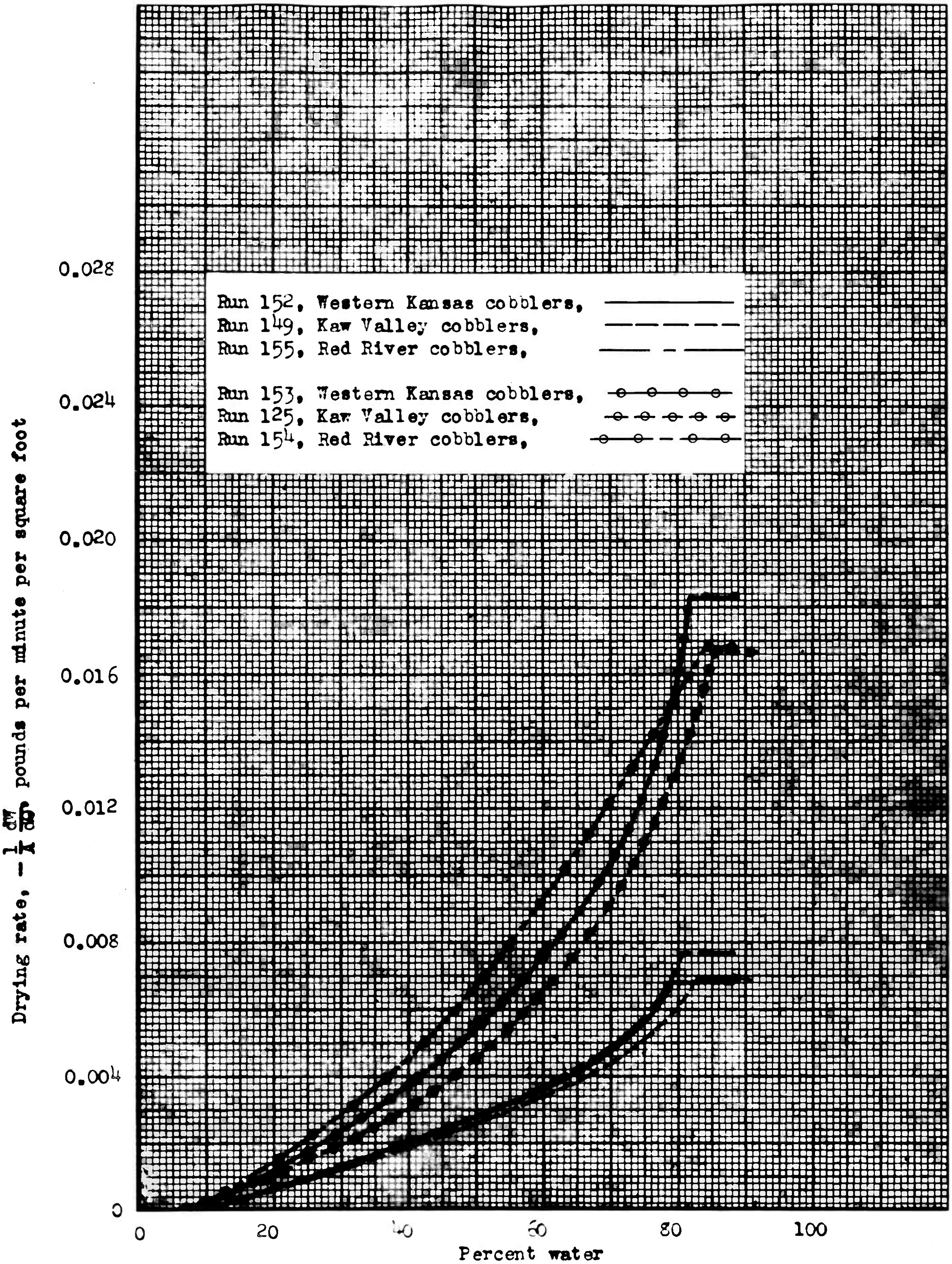

Fig. 52. Comparison of drying rates of Red River Valley, Western Kansas and Kaw Valley cobblers. Runs 152, 149, and 155 were identical as were runs 153, 125, 154.

SUMMARY

Data on drying rates of Kaw Valley Cobblers are presented and correlated into an equation of the form:

$$\left[\frac{1}{A}\frac{dW}{d\theta}\right]_M = k\,(V\rho)^{n_1}(p_{wb} - p_a)^{n_2}(T)^{n_3}$$

The use of this equation in the design of a potato dehydrator is illustrated.

ACKNOWLEDGMENT

The author wishes to express his appreciation to Dr. John W. Greene for his help in correlating these data and his assistance in organizing and checking this presentation of the data.

SYMBOLS USED

A tray area, square

D diameter, feet

G rate of vaporization, pounds per hour per square foot per millimeter Hg difference between the vapor pressure of water at the surface temperature and the partial pressure of water vapor in the air.

M moisture content, percent

V air velocity, feet per minute

V' air velocity in feet per second

W weight on tray, pounds

c constant

k constant

n constant

p_a partial pressure of water vapor in the air, atmosphere

p_{wb} vapor pressure of water at the wet-bulb temperature, atmospheres

θ time, minutes

μ viscosity

ρ density of air in pounds per cubic foot

Subscripts

1 variable air velocity series

2 variable humidity series

3 variable temperature series

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