AMS- 373

COOLING RATES OF GRAIN

a laboratory study with full exposure to near-maximum airflow

UNITED STATES DEPARTMENT OF AGRICULTURE
Agricultural Marketing Service
in cooperation with
Agricultural Experiment Station
PURDUE UNIVERSITY

PREFACE

The research on which this report is based is part of a larger project on the aeration and storage of grain in commercial storages. The work was conducted under the general supervision of Leo E. Holman, supervisory project leader.

Research on the maximum rate at which grain will cool when exposed to a near-unlimited volume of air was undertaken to establish basic data which would contribute to a better understanding of the principles of grain aeration. It was anticipated that the information from the cooling tests could be used in analyzing problems of bulk cooling, such as those encountered in commercial grain aeration. However, further study of the effect of air velocity on the cooling rates of grain is needed to use fully the data presented for predicting the cooling rates of bulk grain.

The data presented should have direct application where grain is cooled by passing it through drying equipment and "blasting" it with unheated air during cold weather. The limits of temperature reduction that can be expected in selected time intervals can be estimated from the data presented. Such information should be especially useful in the further design and development of equipment for rapid precooling of grain for storage or shipping.

The authors are indebted to G. W. Isaacs, Agricultural Engineering Department, Purdue University, for suggestions on the conduct of the experimental work and also for his assistance in summarizing and presenting the data.

This research was conducted in cooperation with the Agricultural Experiment Station, Purdue University, Lafayette, Ind.

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Washington, D. C. March 1960

COOLING RATES OF GRAIN
A Laboratory Study with Grain Fully Exposed to Near-Maximum Airflow

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SUMMARY

The rate at which grain cools when exposed in thin layers to relatively large volumes of cooling air was determined for seven grains and seeds. Wheat, grain sorghum, rough rice, and oats required from 2.2 to 6.8 seconds to cool halfway from their initial grain temperature to the cooling air temperature. The larger seeds of corn, soybeans, and pea beans required from 7.5 to 14.4 seconds for the same temperature reduction. Ovendry grain required less cooling time than grain at higher moisture levels.

The half-response theory as expressed by the equation $TR = ae^{-k\theta}$ describes with practical accuracy the rate at which grain cools when the volume of cooling air imposes no limitation. The experimental constants for use with this equation are presented in the appendix for seven grains.

The accuracy of the results of these tests depends on the validity of the assumptions that (a) the amount of cooling air used imposed no limitation of significance on the cooling rate, and (b) the unmeasured temperature losses were tolerable. Although neither of these assumptions was entirely correct, the errors in each assumption had an opposite effect on cooling time and one tended to offset the other.

The usefulness of these data in predicting the time required to cool grain in bulk aeration systems depends on how the velocity of the air past the seed affects the rate of heat transfer from the seed to the air. There is considerable evidence that a thin layer which is part of a large bulk of grain, aerated with airflow rates commonly used, cannot be assumed to cool in the same way as the thin layer cools under exposed conditions. Further study of the effect of air velocity on the cooling rate is needed to use these data fully in predicting cooling rates of bulk grain.

Considering the rapid rate at which grain is cooled with sufficient exposure to the cooling air, an investigation of methods and equipment for precooling grain before shipping or storage appears warranted.

INTRODUCTION

The rate at which grain is cooled depends on the rate of heat transfer from the grain to the air. This report describes tests to determine the cooling rate of grain under fully exposed conditions. The cooling rate measured in these tests is the rate at which a thin layer of grain gives up heat when exposed to a continuous blast of air great enough to transfer heat from the grain to the cooling air at the maximum rate. Grains and seeds included in the tests were soft red winter wheat, shelled corn, soybeans, grain sorghum, rough rice, oats, and pea beans.

Theoretically, if all the resistance to heat transfer were at the kernel surface, the grain would cool according to Newton's law of cooling. This law states that a material cools at a rate proportional to the temperature difference between the cooling fluid and the material being cooled. Thus the heat transfer rate is proportional to the temperature difference; the equation is commonly written as:

$$\frac{dQ}{d\theta} = C\,(t-t_a) \qquad (1)$$

Where

Q = quantity of heat
θ = time
C = constant of proportionality
t = temperature of grain at time θ
t_a = temperature of cooling air

And since Q is proportional to $(t-t_a)$ and heat is being lost as t approaches t_a

$$\frac{d\,(t-t_a)}{d\theta} = -k\,(t-t_a)$$

Or

$$\frac{d\,(t-t_a)}{(t-t_a)} = -k\,d\theta$$

Where k = grain cooling constant

Integrating between the lower limits of t_g (initial grain temperature at time 0) and the upper indefinite limits of t (grain temperature at time θ)

$$\int_{t_g}^{t} \frac{d\,(t-t_a)}{(t-t_a)} = -k\int_{0}^{\theta} d\theta$$

$$\ln\,(t-t_a) - \ln\,(t_g-t_a) = -k\theta + 0$$

$$\ln\frac{(t-t_a)}{(t_g-t_a)} = -k\,\theta$$

$$\frac{t-t_a}{t_g-t_a} = e^{-k\theta} \qquad (2)$$

The general form of equation (2), $y = ae^{bx}$, is called the half-life or half-response equation. Applied to cooling grain, the equation describes a condition where the material being cooled loses half its heat in a given time interval, three-fourths its heat in twice that time interval, and so on.

An analysis of bulk drying systems by Hukill 1/ was based on the assumption that the drying rate at any time was proportional to the excess moisture in the grain above equilibrium conditions and thus that the grain dried according to the half-response theory. Although this assumption is not valid for all conditions, it is useful in predicting the performance of proposed drying systems. The resistance to vapor flow in the kernel imposes an additional deterrent to drying as the grain approaches moisture levels considered safe for normal storage. It was expected that the cooling process, which is limited largely to sensible heat transfer, would be more adequately described by the half-response theory. On the other hand, the velocity of the air around the grain is a less significant factor in determining drying rates than it is in establishing heat transfer rates.

EQUIPMENT USED

The equipment used in the tests, shown in figure 1, included the following:

Exposure box and fan for forcing air through a small sample of grain (fig. 2).--The air was forced up through an insulated column 12 inches square over which the grain sample was placed. Air straighteners were used to provide more uniform velocity through the grain sample. The thermocouples shown in figure 2 were connected in series 120 degrees apart. Radiation shields were mounted directly above the thermocouples to prevent heat pickup from the grain being cooled.

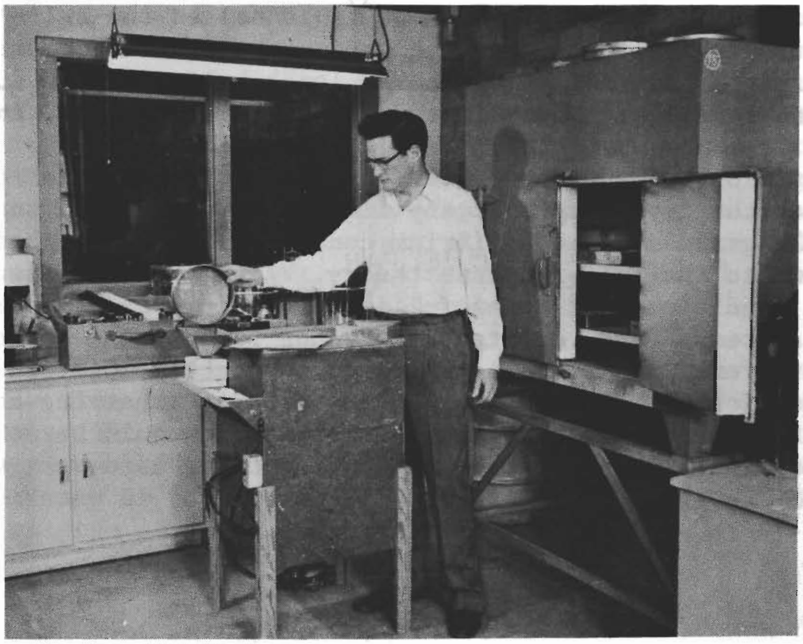
Sieve pans for containing the grain during exposure.--For each grain, the following U. S. Standard sieve pans and sample sizes were used:

Grain	Sieve size, number	Sample size, gm.
Wheat	50	50
Corn	30	75
Soybeans	30	75
Grain sorghum	50	45
Rough rice	100	35
Oats	1/ 60	25
Pea beans	30	80

1/ Modified by placing two thicknesses of fly-screen underneath the sieve screen.

A 7-inch inside-diameter ring was constructed of plywood and inserted in the sieve pans to improve the uniformity of air velocity through the grain.

1/ Hukill, William V. Basic Principles in Drying Corn and Grain Sorghum. Agricultural Engineering 28:335-340. 1947.



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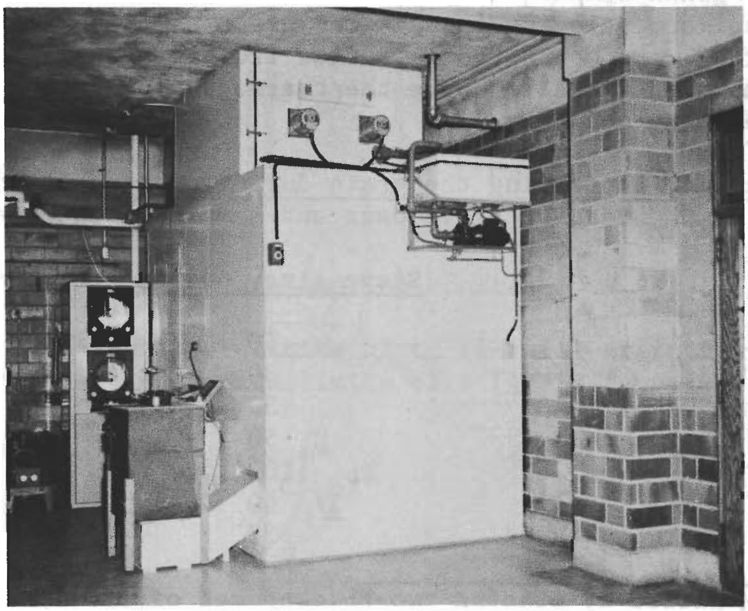

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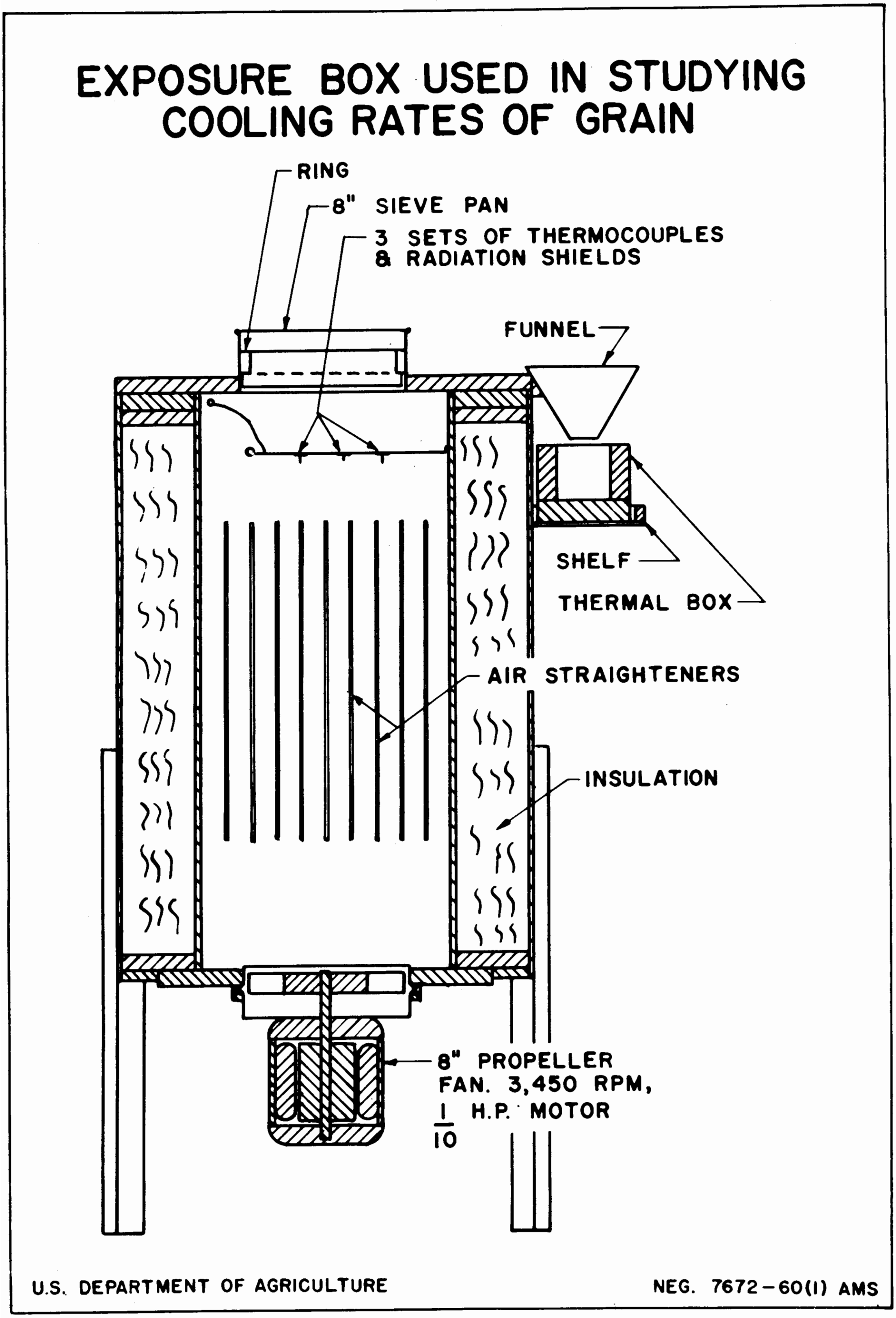
Figure 1.--(A) Equipment used in grain cooling rate studies, including oven, exposure box, thermal boxes, sieve pan, salve tins, and potentiometer. (B) The controlled climate chamber shown below was used for the cooling tests below room temperature.


EXPOSURE BOX USED IN STUDYING
COOLING RATES OF GRAIN
RING
8" SIEVE PAN
3 SETS OF THERMOCOUPLES
& RADIATION SHIELDS
FUNNEL
SHELF
THERMAL BOX
AIR STRAIGHTENERS
INSULATION
8" PROPELLER
FAN. 3,450 RPM,
1/10 H.P. MOTOR
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NEG. 7672-60(1) AMS

Figure 2

Thermal boxes for establishing grain temperatures.--These boxes were constructed of 1-inch rigid insulation of expanded polystyrene plastic having a conductivity coefficient rating of about 0.23 BTU/ft^2 hr. °F./in. The boxes were cube-shaped and made to fit the sample size. A thermocouple junction was placed at the center of each box. The thermocouple leads extended from the box to a potentiometer for indicating grain temperature.

Controlled climate chamber for conditioning the air for tests conducted below room temperature.--A walk-in air-conditioned room with independent temperature and relative humidity control was used.

Potentiometer.--A portable precision potentiometer was used for all temperature measurements. A switching arrangement was developed to facilitate reading of both grain and air temperature with the same instrument.

Laboratory oven for heating the grain.

Stop watch for timing test runs.

TEST PROCEDURE

Cooling tests were made with seven grains, each tested at two moisture levels: (1) ovendry, and (2) between 9.6 and 13.6 percent moisture (wet basis). All grains were cooled through three temperature ranges: 200° F. to room temperature (about 75° F.), 140° F. to room temperature, and room temperature to 40° F. For each test, a series of samples was used to find the grain temperature reduction after each of at least four different exposure periods. In each of the wheat tests, for example, one sample was exposed for 5 seconds, the amount of cooling recorded, and the sample discarded. A similar sample was exposed for 10 seconds, another for 15, and so on through the cooling range. Each test was repeated three times.

Preliminary tests for cooling wheat were made with 200-gram samples. The cooling air was warmed appreciably when first passed through a sample of this size. The sample was then reduced in size until a minimum amount of warming of the cooling air resulted. The sample of each of the seeds and grains used in the tests weighed from 25 to 80 grams and covered the bottom of the sieve pan about one kernel thick. The velocity of air through the grain was adjusted to just below that which would blow the seed out of the sieve pan. With the air straighteners shown in figure 2 and with the plywood ring around the inside edge of the sieve pan, the airflow caused the grain to agitate uniformly over the screened bottom of the sieve pan.

In the tests where grain was cooled from 200° F. and from 140° F. down to room temperature, samples of grain of predetermined moisture and weight were placed in covered tin salve boxes and allowed to come to the desired initial temperature in the laboratory oven. A few minutes before each test, a thermal box was placed in the oven and allowed to come to oven temperature. The grain sample was then poured from the tin box into the thermal box before removal from the oven. This transfer was completed as quickly as possible, and then the thermal box was removed from the oven and set on the shelf on the side of the exposure box. After the thermocouple in the thermal box came to temperature equilibrium with the grain, the initial grain temperature was recorded. The grain was then dumped into the sieve pan on the exposure box with the fan in operation. A stop watch was started at the instant the grain hit the sieve pan. At the end of a selected time interval, the sieve pan was quickly removed from the exposure box and the contents dumped into a second thermal box at room temperature. The exposure times ranged from 5 to 75 seconds. The temperature of the cooling air was recorded before and after the sample was exposed and was reported as an average of the two readings. Also, the final temperature of the sample of grain was recorded after the grain and the thermocouple reached temperature equilibrium in the thermal box.

The tests where the grain was cooled from room temperature to 40° F. were made inside the controlled climate chamber. Each sample was placed in a thermal box at room temperature and then taken into the controlled climate chamber. The rest of the procedure was the same as described above.

The amount the grain cooled was expressed in terms of "temperature ratio" rather than actual temperatures. The temperature ratio,

$$\frac{t - t_a}{t_g - t_a}$$

was calculated for each sample exposed to the cooling air. The results were reported in terms of the time required to cool the grain to temperature ratios of 1/2 to 1/10, which represented 1/2 to 9/10 of the cooling that could be done under the conditions of the test. This was done to make the results of the various tests more comparable, since three different initial grain temperatures and two different cooling air temperatures were used. Further, there was no attempt to maintain a constant temperature of the cooling air used at room conditions. Thus, it was helpful to express the difference between the initial grain temperature and the cooling air temperature as 100 percent, or as 1.0.

The value of the temperature ratio for each test was then expressed in terms of its natural logarithm, to provide a linear relationship with cooling time. The data, the natural logarithm of the temperature ratio, and the cooling time, for the three replications of each test were pooled and a regression line fitted by the method of least squares. Values for the slope, k, and the intercept, a, were determined for the equation, temperature ratio (TR) = $ae^{-k\theta}$. The equation for each test condition was then solved for the time required to cool the grain to a TR of 1/2 and 1/10 (1/2 and 9/10 of the cooling). The error associated with each regression line fitted by the least squares method was determined statistically.

The time required to cool the grain 1/2 of the way and 9/10 of the way from the initial grain temperature to the cooling air temperature was also determined graphically. The temperature ratios attained after selected periods of exposure to the cooling air were plotted against cooling time for each replication of each test. A smooth curve was drawn through TR = 1 at 0 time and all plotted points. The time required for the grain to reach TR = 1/2 and TR = 1/10 was read from each curve. A simple average was taken of the time values from the three replications and compared with values determined by the analytical least squares method described above.

The statistical significance of the difference between the cooling times determined analytically and those determined graphically was also assessed.

DISCUSSION OF RESULTS

The time required for each of the seven grains to cool halfway (TR = 1/2) and 9/10 of the way (TR = 1/10) from its initial temperature to the cooling air temperature is summarized in table 1. The variation in cooling time for the different treatments is reflected in the range of cooling times shown. Wheat, grain sorghum, rough rice, and oats required from 2.2 to 6.8 seconds to cool from the initial grain temperature halfway to the air temperature. The larger seeds of corn, soybeans, and pea beans required from 7.5 to 14.4 seconds for the same temperature reduction. The smaller grains required from 13.1 to 23.0 seconds and the larger ones from 34.6 to 51.1 seconds to accomplish 90 percent of the possible temperature reduction. The time required to cool the grain to temperature ratios other than those given in table 1 can be determined from the equation $TR = ae^{-k\theta}$ by using the experimental constants given with the cooling curve for each test in figures 5 through 11 in the appendix. Cooling curves for selected tests also are illustrated in figure 3.

The three replications of each treatment provided data from which the error associated with each cooling curve was determined. The standard deviation from the regression line of the reverse relationship of cooling time versus the natural logarithm (ln) of the temperature rates (TR) was determined to allow the standard deviation to be expressed in terms of seconds of cooling time rather than in terms of ln TR. The standard deviation ranged from 0.2 to 0.8 seconds for the smaller seeds of wheat, grain sorghum, rough rice, and oats, and from 0.2 to 1.0 seconds for the larger seeds of corn, soybeans, and pea beans (see figs. 5 through 11, appendix).

The oven-dried grain cooled faster in all tests than the grain at moisture levels ranging from 9.6 to 13.6 percent. This difference--10 to 25 percent less cooling time for the ovendry grain compared to the more moist grain--was attributed to the higher thermal capacity of moist grain.

Some differences in cooling time resulted from the different ranges through which grain cooled. In general, the higher the initial temperature of the grain, the longer the cooling time. However, the differences in cooling time in the tests with 200° F. initial grain temperature and those with 140° F. initial grain temperature were small and not always in the same order. The time required to cool the grain 1/2 of the way to the air temperature was consistently less when the cooling range was from room temperature down to 40° F. The faster cooling in the lower cooling range was not as evident by the time the grain was cooled 9/10 of the way to the air temperature. The variation in the amount of unmeasured temperature losses while handling the grain at the different test temperatures probably accounted for a part of the differences in the measured cooling time. On the other hand, the tendency toward slower cooling for the grain with higher initial temperature may be due to the failure of the experimental data to confirm fully the theory that the cooling rate is proportional to the temperature difference.

Table 1.--Summary of cooling rate data for seven exposed grains and seeds

Grain or seed and cooling range	Time required to cool grain 1/2 of the way to air temperature		Time required to cool grain 9/10 of the way to air temperature	
	Moist grain 1/	Dry grain 2/	Moist grain 1/	Dry grain 2/
	Seconds	Seconds	Seconds	Seconds
Wheat (soft red winter):				
200° F. to room 3/	6.8	5.3	22.9	17.6
140° F. to room	5.8	5.2	23.0	17.8
Room to 40° F.	5.1	4.1	19.7	15.2
Average	5.9	4.9	21.9	16.9
Shelled corn:				
200° F. to room	12.6	11.6	48.4	43.3
140° F. to room	12.4	11.4	48.2	43.5
Room to 40° F.	11.6	10.3	45.2	42.0
Average	12.3	11.1	47.3	42.9
Soybeans (large yellow):				
200° F. to room	13.4	11.0	53.1	40.0
140° F. to room	12.9	10.2	50.0	39.4
Room to 40° F.	12.6	8.6	51.6	40.1
Average	13.0	9.9	51.5	39.8
Grain sorghum:				
200° F. to room	4.4	4.1	16.1	14.4
140° F. to room	4.3	3.6	16.2	13.1
Room to 40° F.	3.6	2.9	16.0	13.4
Average	4.1	3.5	16.1	13.6
Rough rice:				
200° F. to room	3.9	3.8	16.3	15.1
140° F. to room	4.1	3.5	16.4	14.9
Room to 40° F.	3.8	3.4	15.8	14.8
Average	3.9	3.4	16.2	14.9
Oats:				
200° F. to room	4.4	3.6	18.4	14.4
140° F. to room	4.6	3.0	18.2	14.0
Room to 40° F.	3.6	2.2	18.4	14.1
Average	4.2	2.9	18.3	14.2
Pea beans:				
200° F. to room	14.4	11.0	52.5	38.9
140° F. to room	13.5	9.6	50.5	36.4
Room to 40° F.	12.0	8.3	50.0	33.6
Average	13.6	9.6	51.0	36.3

1/ Moist grain was at moisture levels ranging from 9.6 percent for shelled corn to 13.6 percent for pea beans.
2/ Dry grain was dried in an air oven to less than 2 percent moisture.
3/ Room temperature ranged from 68° to 92° F. but for most tests was near 75° F.

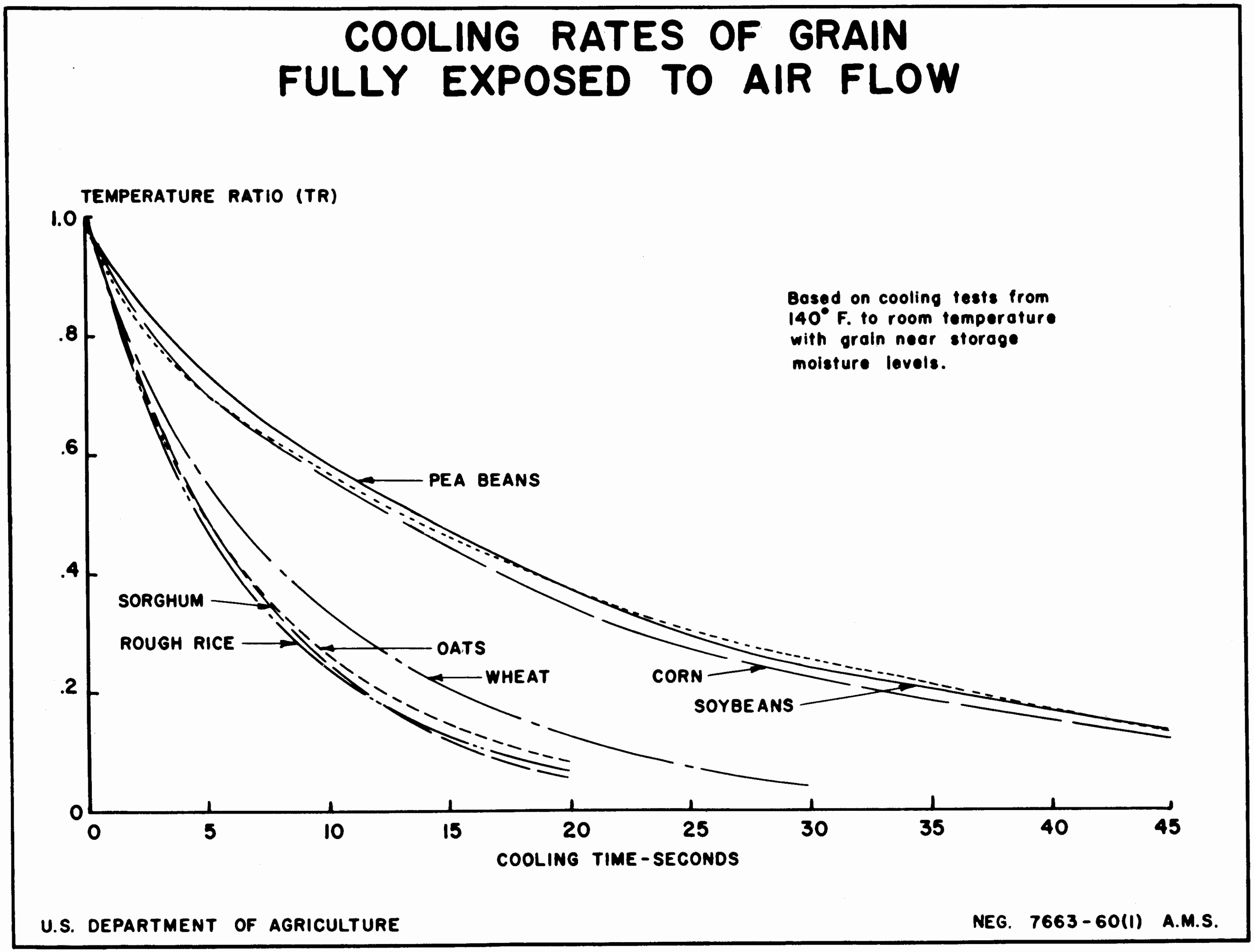
COOLING RATES OF GRAIN
FULLY EXPOSED TO AIR FLOW
TEMPERATURE RATIO (TR)
1.0
.8
.6
.4
.2
0
Based on cooling tests from
140° F. to room temperature
with grain near storage
moisture levels.
PEA BEANS
SORGHUM
ROUGH RICE
OATS
WHEAT
CORN
SOYBEANS
0
5
10
15
20
25
30
35
40
45
COOLING TIME-SECONDS
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Figure 3

The times required to cool the grain to a temperature ratio of 1/2 and 1/10 were determined graphically and compared to those determined from the least squares analysis. The mean differences between the two values for the six tests with each of the seven grains ranged from -0.28 seconds to +0.27 seconds. None of the differences was statistically significant at the 5 percent level.

When the least squares method was applied to the data, the resulting curve of the equation $TR = ae^{-k\theta}$ had an intercept of less than unity. The fact that the curve went through a point less than unity at zero time indicates (1) that the half-response theory is not entirely valid for describing this process, or (2) that there were losses between the time the initial temperature was taken and the time the measured cooling was started. It should be recognized that some of the smaller seeds were cooled more than halfway to equilibrium before the first measurement of cooling was made after 5 seconds' exposure. Thus some of the cooling curves were determined from data representing less than half of the total cooling done.

Heat losses and heat gains occurring during the tests were major factors affecting the accuracy of this work. The tests were set up so that any unaccounted-for heat transfer would be a heat loss from the grain samples. This was done merely for consistency. The handling time for each operation was kept as short as possible although unaccounted-for heat losses certainly must have occurred, particularly when pouring the grain from the thermal box to the sieve pan and from the sieve pan to the second thermal box.

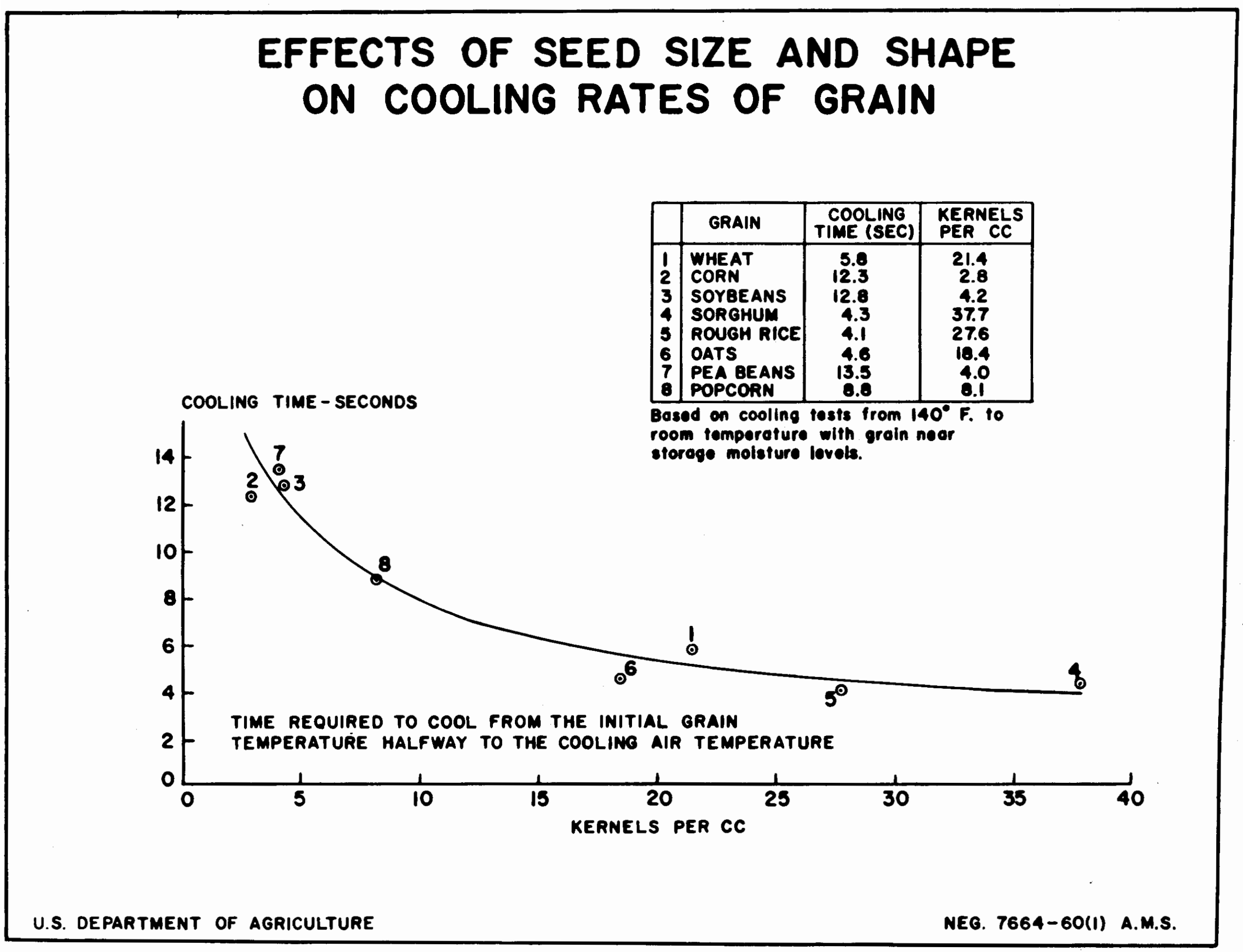
The following example, using data recorded for test 101-2 (wheat), shows the effect of these heat losses:

Sample weight	50 grams
Moisture content	below 2%
Exposure time.	5 seconds
Initial cooling air temperature.	84° F.
Final cooling air temperature.	84° F.
Initial grain temperature.	200.5° F.
Final grain temperature.	140.5° F.

These data yielded a temperature ratio of $\frac{140.5-84}{200.5-84} = .485$. Assuming that the initial temperature of the grain was actually 198.5° F. and the final temperature 142.5° F., the temperature ratio then would be $\frac{142.5-84}{198.5-84} = .511$. This example shows how an error of 2° in determining both the initial and final temperature of the grain could affect the temperature ratios. If the error were always in the direction assumed in the example, the cooling times reported would be somewhat low.

The difficulty of obtaining full exposure--particularly during the early part of the exposure period--was evident from the results of these tests. Full exposure demands that the ratio of cooling air to grain is such that the heat will be removed from the grain with a negligible rise in the temperature of the cooling air. This was not the case in all tests, although the air supplied to the wheat was equivalent to an aeration rate of 91,800 c.f.m. per bushel. However, any failure to obtain full exposure made the cooling times reported somewhat high, and tended to offset any error from unmeasured heat losses which reduced the cooling time.

The relation of cooling time to selected physical factors of the test grains and seeds was investigated as a basis for predicting the cooling rates for fully exposed grains and seeds not included in the tests. Evaluation of cooling time vs. kernel volume, and of cooling time vs. the least dimension of the kernel, showed that each of these factors had an effect on cooling time. The number of kernels per cubic centimeter (cc.) was selected as a practical physical measure which included to some extent both the size and shape factors of the kernels. The relation of cooling time to the number of kernels per cc. is shown in figure 4. Cooling time data for an eighth grain, popcorn, with a kernel volume between that of the small grains and the larger seeds tested, were added to determine this relationship more accurately.



	GRAIN	COOLING TIME (SEC)	KERNELS PER CC
1	WHEAT	5.8	21.4
2	CORN	12.3	2.8
3	SOYBEANS	12.8	4.2
4	SORGHUM	4.3	37.7
5	ROUGH RICE	4.1	27.6
6	OATS	4.6	18.4
7	PEA BEANS	13.5	4.0
8	POPCORN	8.8	8.1

Figure 4

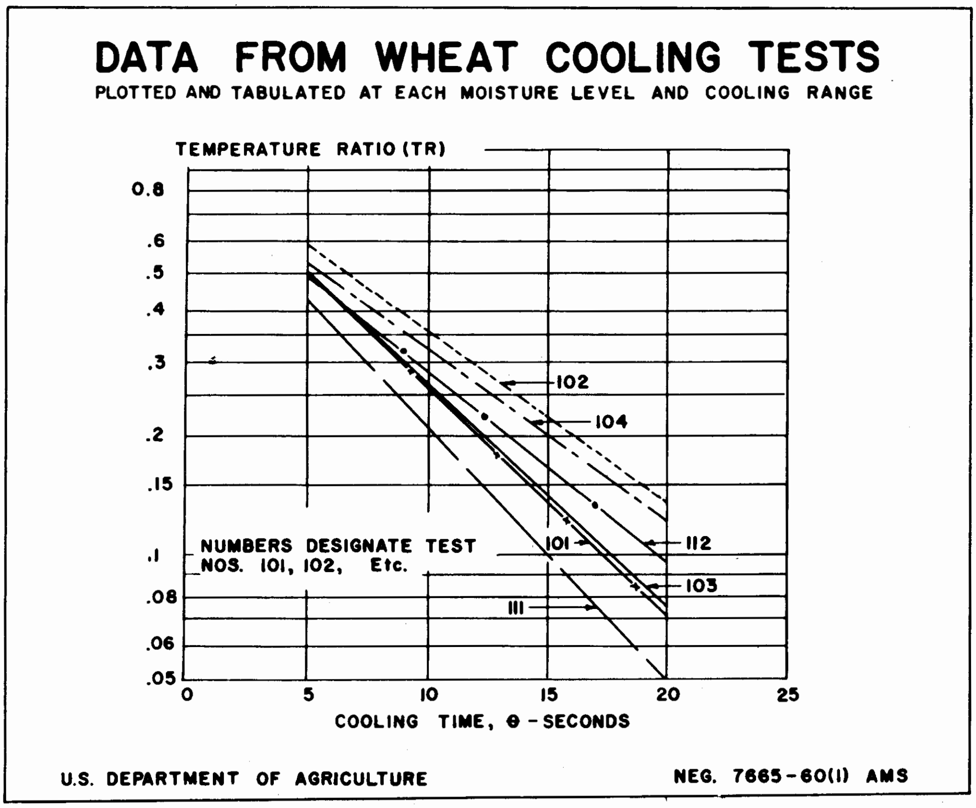


Figure 5

Test No.	Cooling range °F	Moisture content %	a 1/	k 1/	s 2/
101	200-room	below 2	0.9971	0.1310	0.50
102	200-room	11.7	0.9827	0.0998	0.38
103	140-room	below 2	0.9827	0.1286	0.84
104	140-room	11.7	0.8882	0.0995	0.77
111	Room-40	below 2	0.9127	0.1460	0.45
112	Room-40	11.7	0.8777	0.1104	0.30

1/ Experimental constants for the general equation $TR = ae^{-k\theta}$.
2/ Standard deviation, in seconds, from the regression line of cooling time versus ln TR.

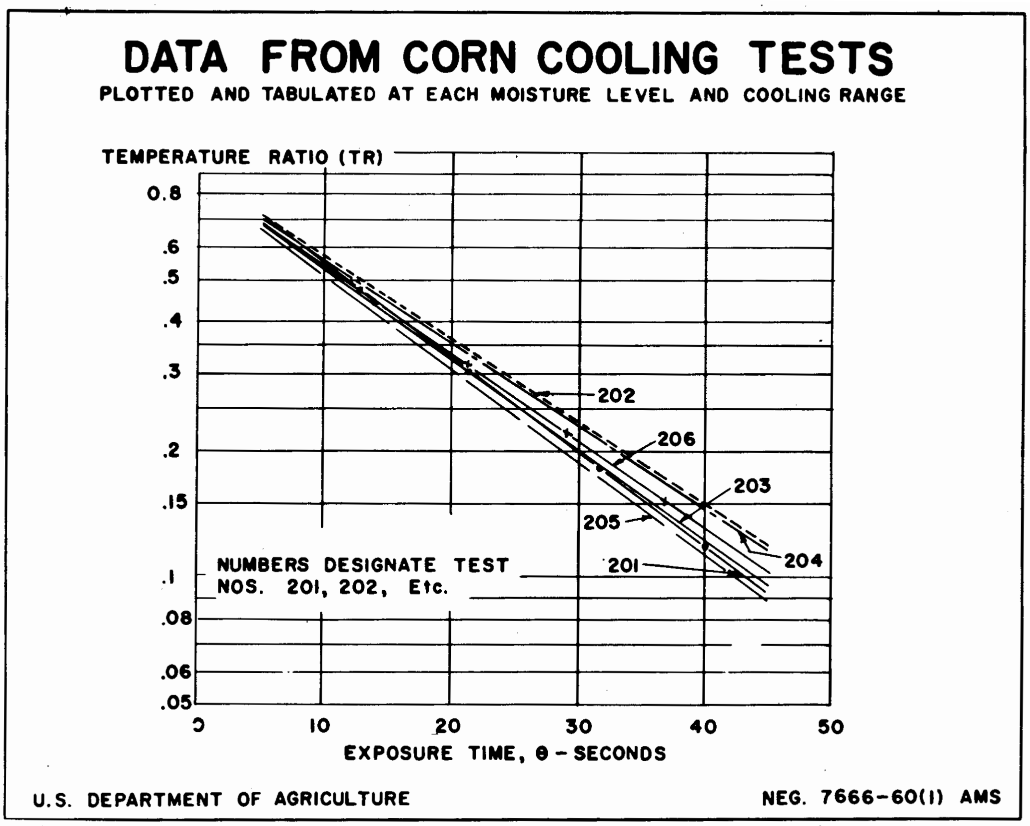


Figure 6

Test No.	Cooling range °F	Moisture content %	a 1/	k 1/	s 2/
201	200-room	below 2	0.9003	0.0505	0.79
202	200-room	9.6	0.8839	0.0449	0.58
203	140-room	below 2	0.8863	0.0500	0.60
204	140-room	9.6	0.8707	0.0448	0.66
205	Room-40	below 2	0.8436	0.0507	0.71
206	Room-40	9.6	0.8704	0.0479	0.78

1/ Experimental constants for the general equation $TR = ae^{-k\theta}$.

2/ Standard deviation, in seconds, from the regression line of cooling time versus ln TR.

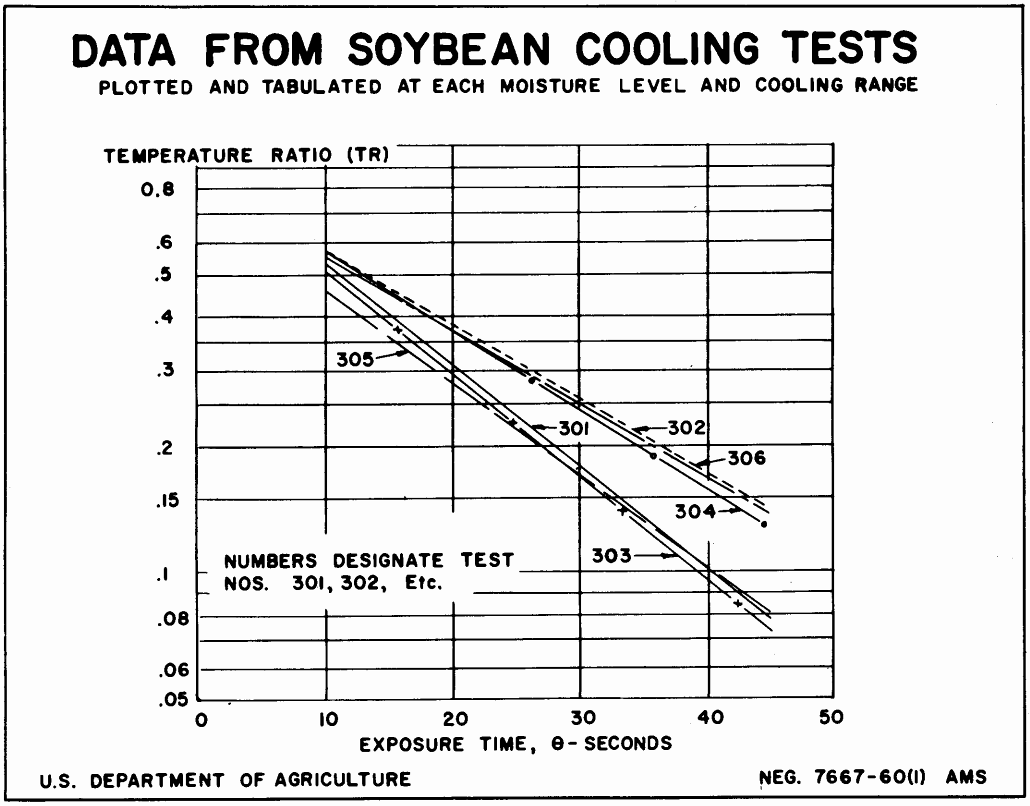


Figure 7

Test No.	Cooling range °F	Moisture content %	a 1/	k 1/	s 2/
301	200-room	below 2	0.9187	0.0555	0.69
302	200-room	11	0.8580	0.0405	0.90
303	140-room	below 2	0.8743	0.0550	0.75
304	140-room	11	0.8733	0.0433	1.03
305	Room-40	below 2	0.7753	0.0511	0.58
306	Room-40	11	0.8383	0.0412	0.58

1/ Experimental constants for the general equation $TR = ae^{-k\theta}$

2/ Standard deviation, in seconds, from the regression line of cooling time versus ln TR.

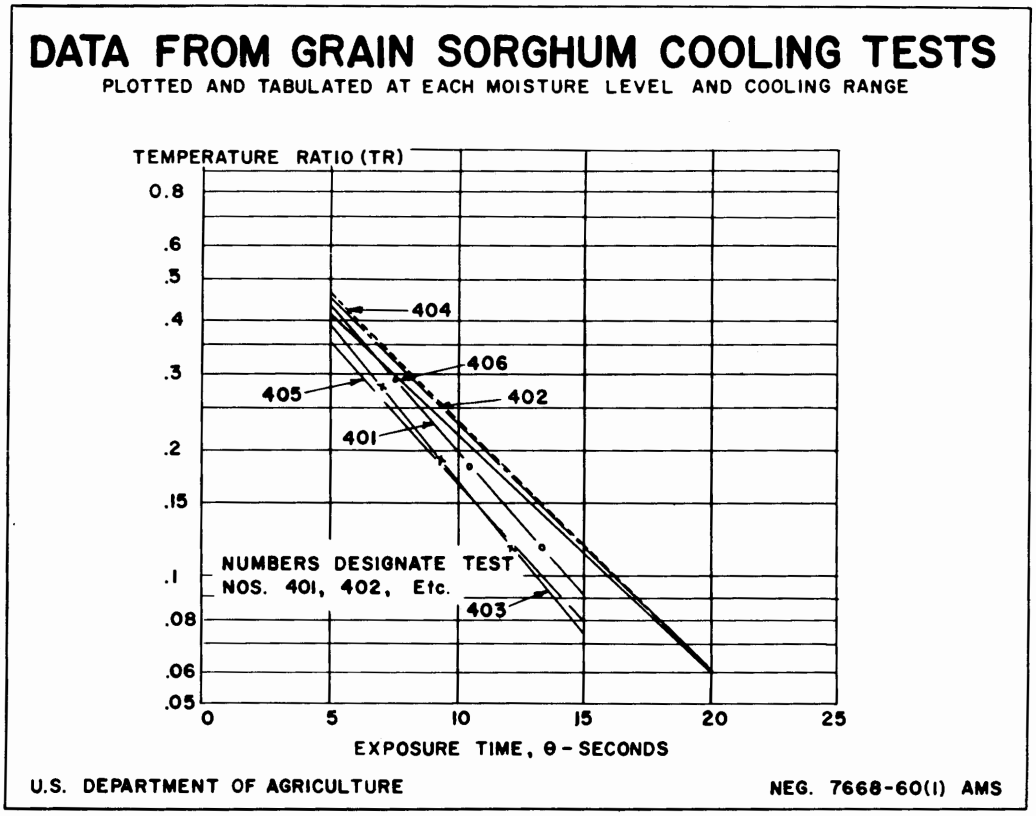


Figure 8

Test No.	Cooling range °F	Moisture content %	a 1/	k 1/	s 2/
401	200-room	below 2	0.9588	0.1575	0.32
402	200-room	11.4	0.9177	0.1375	0.75
403	140-room	below 2	0.9198	0.1693	0.39
404	140-room	11.4	0.9021	0.1361	0.35
405	Room-40	below 2	0.7747	0.1534	0.46
406	Room-40	11.4	0.7965	0.1291	0.38

1/ Experimental constants for the general equation $TR = ae^{-k\theta}$.

2/ Standard deviation, in seconds, from the regression line of cooling time versus ln TR.

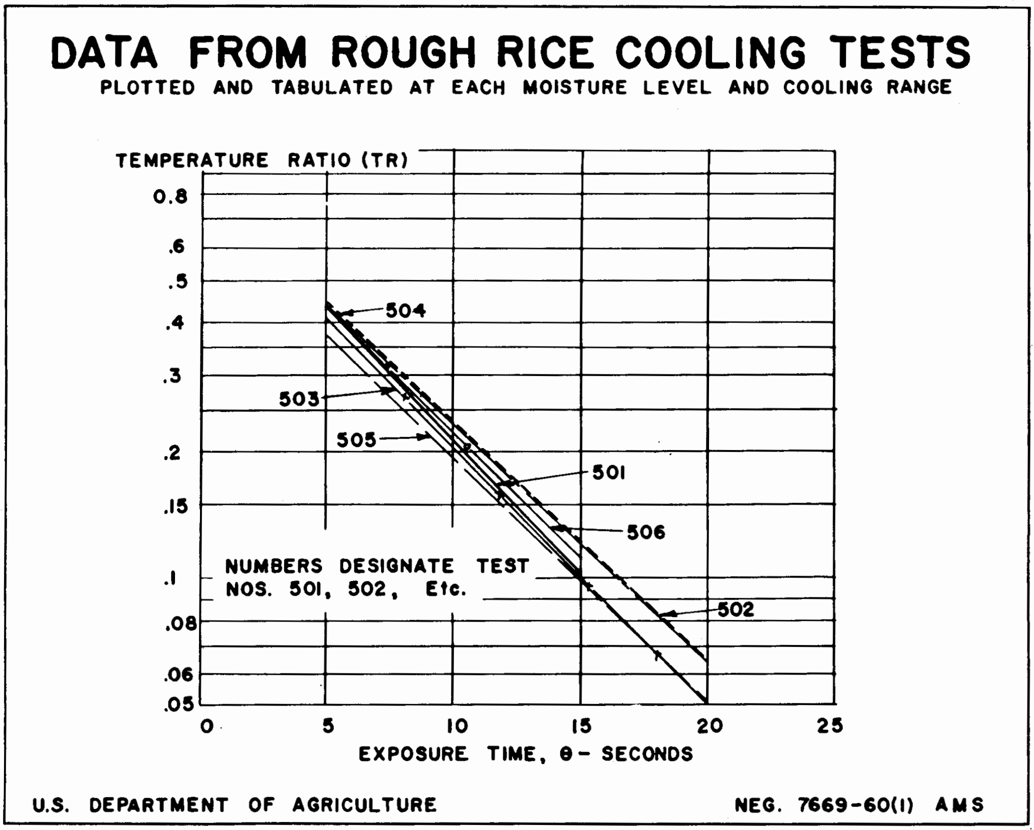


Figure 9

Test No.	Cooling range ^{o}F	Moisture content %	a 1/	k 1/	s 2/
501	200-room	below 2	0.8544	0.1427	0.32
502	200-room	10.1	0.8305	0.1298	0.26
503	140-room	below 2	0.8180	0.1410	0.37
504	140-room	10.1	0.8534	0.1310	0.21
505	Room-40	below 2	0.7243	0.1335	0.41
506	Room-40	10.1	0.8275	0.1341	0.41

1/ Experimental constants for the general equation $TR = ae^{-k\theta}$.

2/ Standard deviation, in seconds, from the regression line of cooling time versus ln TR.

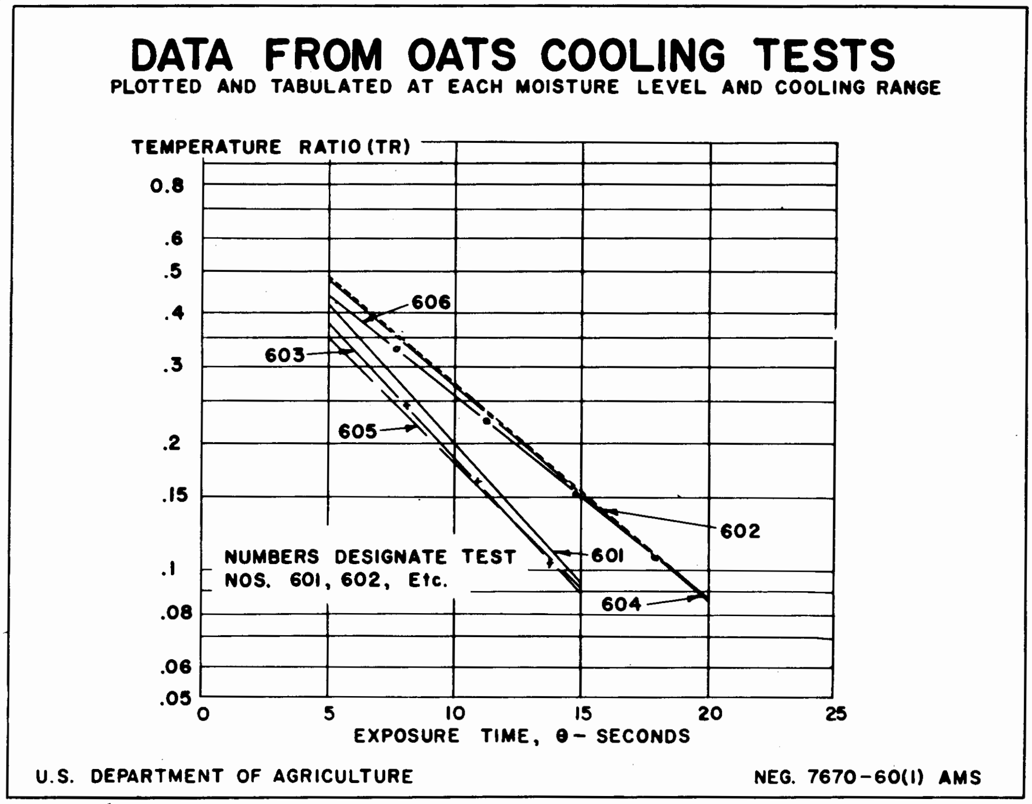


Figure 10

Test No.	Cooling range °F	Moisture content %	a 1/	k 1/	s 2/
601	200-room	below 2	0.8592	0.1489	0.32
602	200-room	12	0.8304	0.1148	0.53
603	140-room	below 2	0.7730	0.1465	0.43
604	140-room	12	0.8555	0.1177	0.44
605	Room-40	below 2	0.6787	0.1359	0.29
606	Room-40	12	0.7363	0.1082	0.50

1/ Experimental constants for the general equation $TR = ae^{-k\theta}$.

2/ Standard devistion, in seconds, from the regression line of cooling time versus ln TR.

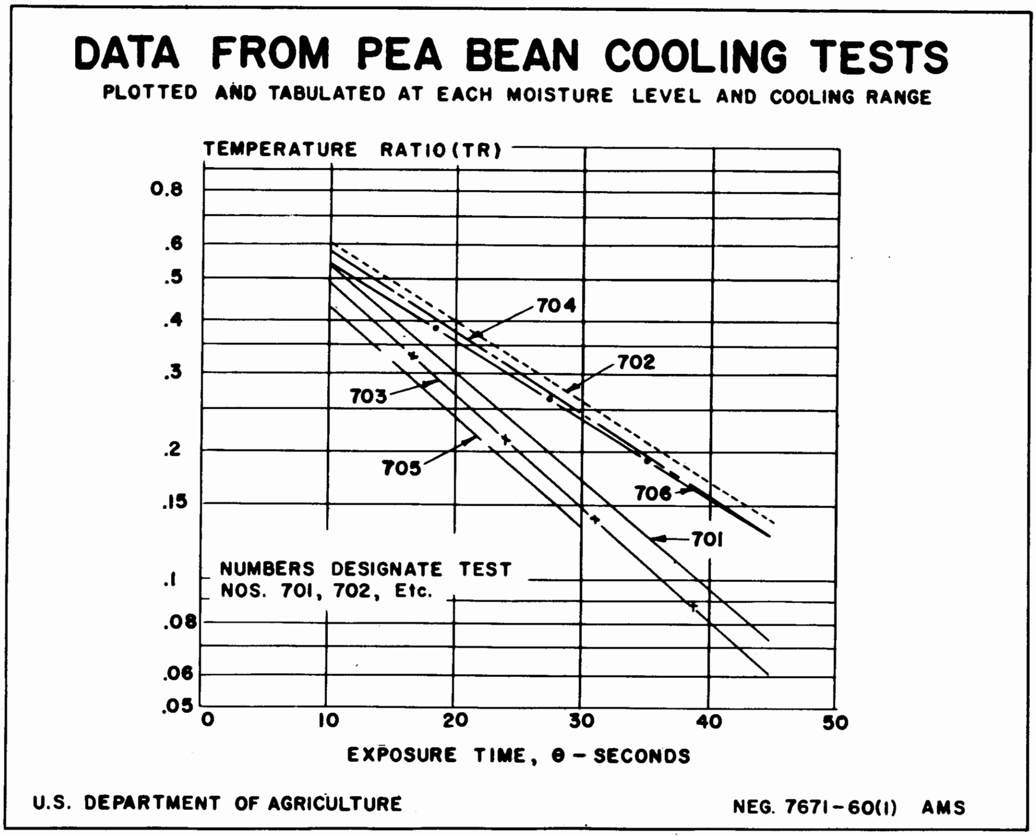


Figure 11

Test No.	Cooling range °F	Moisture content %	a 1/	k 1/	s 2/
701	200-room	below 2	0.9450	0.0578	0.32
702	200-room	13.6	0.9199	0.0422	0.53
703	140-room	below 2	0.8870	0.0598	0.43
704	140-room	13.6	0.8971	0.0434	0.44
705	Room-40	below 2	0.8520	0.0638	0.29
706	Room-40	13.6	0.8296	0.0423	0.50

1/ Experimental constants for the general equation $TR = ae^{-k\theta}$.

2/ Standard deviation, in seconds, from the regression line of cooling time versus ln TR.