RESISTANCE OF WINTER WHEAT TO ARTIFICIALLY PRODUCED LOW AND HIGH TEMPERATURES

by

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TABLE OF CONTENTS

INTRODUCTION

Hard red winter wheat is the most important grain crop of the Great Plains region. In recent years the annual acreage devoted to this crop in Kansas, Oklahoma, Nebraska, Minnesota, Montana, Colorado, Iowa, Texas, New Mexico, South Dakota, and Wyoming has amounted to approximately 32,749,000 acres with an annual average production of 527 million bushels (30). Estimating a market price of $2.00 a bushel, it will be seen that this is an industry having an annual value of one billion dollars. The importance of wheat in this region has stimulated much interest and effort to improve the crop. A research program is needed to gain a better understanding of the fundamental nature of cold, heat and drought hardiness and to develop better means of testing for hardiness to weather extremes.

A greater acreage of hard red winter wheat is abandoned because of drought, or drought associated with other factors, than for any other cause. Drought may be considered to be either edaphic or atmospheric. Edaphic drought is characterized by a deficiency of soil moisture for the normal development and growth of the plants. Atmospheric drought is the result of high temperature and low humidity accompanied with dry winds so that the plants are injured and severe desiccation may result. A study of the resistance of plants to high temperatures is a means of studying the adaptability of plants to drought conditions.

Cold and conditions associated with cold are estimated to account for the abandonment before harvest of about 3.5 percent of the acres sown in the United States. In surviving fields the plants may be damaged, thereby reducing the yield in many fields which are harvested. The average annual loss caused by cold and associated conditions in the hard winter wheat region is estimated at 15,000,000 bushels.

The problem of winter-killing has been intensified by crossing winter and spring varieties, since the resulting hybrids may lack winter hardiness. To be winter hardy, a variety should have a high degree of midwinter cold resistance, a high degree of fall and spring cold resistance, and should be able to withstand dry winters.

A study of resistance of plants to artificially produced low and high temperatures offers possibility for estimating their winter and drought hardiness. The use of mechanical refrigeration has been suggested by a number of investigators and use of a drought chamber is becoming very popular for testing relative resistance of plants. This equipment is of great help in plant research because extremely high and low temperatures do not occur every year which makes it impossible in many years to test the strains for their resistance to these extreme temperatures. Shirley and Meuli (36) stated the following three advantages of a drought machine: (a) it is free from biotic influence which often disturbs tests in the field; (b) the machine is available for test any time whereas field tests can be made only during certain periods; (c) possible control over environmental factors in the machine reduces variability to a great extent and consequently it increases the reliability of the results. These advantages might well be applied to the use of artificial freezing machines also.

This investigation involved the study of resistance in wheat to artificially produced high and low temperatures and of the correlation which might exist between resistance to cold and to heat. Also, a study was made, using information that was available from Uniform Winter Hardiness Nurseries, of the correlation between laboratory results and winter survival in the field for several of the entries.

REVIEW OF LITERATURE

Use of Low Temperature Chamber

The general subject of the effect of low temperature on plant tissue has been thoroughly reviewed by many authors. It is only within the last 30 to 35 years that mechanical refrigeration has been extensively used in studies of this kind. Early investigators were obliged to depend on naturally occurring low temperatures or on mixtures of ice or snow and salt or similar devices, with the attendant difficulties in reaching the desired temperatures and in controlling and maintaining them for any length of time. The advent of mechanical refrigeration has removed, or so greatly lessened, these difficulties that the investigator of today may well consider the possibilities in a new light.

Harvey (9) was, perhaps, the first of the modern investigators to see the possibilities in, and to make use of, mechanical refrigeration. He was closely followed by Akerman, et al. (2), who made an extensive study of the relative winter hardiness of varieties of wheat in Sweden and of their resistance to controlled low temperature. They found this method to be the most promising for determining the relative hardiness of new strains.

Hildreth (12) found a close correlation between the results of artificial refrigeration of twigs from 17 varieties of apples and their winter hardiness as determined by field experience.

Maximov (24), apparently on the basis of observations in his own laboratory as well as in other European laboratories equipped with mechanical refrigeration, points out:

> The application of such equipment, besides yielding purely practical results, such as the possibility of rapidly and exactly determining frost resistance of different varieties of crop plants, puts into the hands of investigators a powerful means for the further study of the problem of the physiological factors of resistance, thus bringing us nearer to the final aim of work in this field of investigation.

Tumanov and Borodin (40) exposed a considerable number of varieties of Russian winter wheat to low temperatures produced by mechanical refrigeration. In the majority of cases the resistance to low temperature, as determined by the direct-freezing method, correlated well with the relative hardiness of the same varieties under field conditions and the method was considered satisfactory for determining varietal resistance to frost.

Quisenberry (29) subjected the parents and F_3 segregates of a cross between Minhardi winter and H-44 spring wheats to artificially produced low temperatures and grew the same lines at

St. Paul, Minnesota, and Moccasin, Montana, for comparison. The relative hardiness for each place or condition was expressed as a hardiness index, which took into consideration not only the percentage of plants killed, but also those which were badly injured or weakened. The correlation coefficients between the hardiness indices for the artificial-freezing test on the one hand and the field results on the other were 0.582 for St. Paul, Minnesota, 0.629 for Moccasin, Montana, and 0.713 for the average of the two stations. The coefficient between indices for the field results at St. Paul and at Moccasin was 0.416. Quisenberry concluded that the rather limited data seemed to show that "artificial freezing offers considerable promise in eliminating hybrid lines susceptible to cold."

Foster Martin (22) froze 12 varieties of spring wheat commonly grown in Eastern Oregon, ranked them according to injury, and correlated these ranks with those of the same varieties arranged according to their survival under field conditions. The correlation coefficient was -0.762.

Low Temperature Injury

There are many possible causes of winter-killing, most of which relate directly or indirectly to low temperatures. Salmon (31) lists them as follows: (a) heaving, caused by alternate freezing and thawing; (b) smothering, in which frozen snow or an ice covering keeps out the air; (c) physiological drought, where the plants cannot obtain moisture because of the frozen soil; and (d) freezing of the plant tissue due to the direct effects of low temperature.

The last factor is of the most concern when subjecting plants to low temperatures in an artificial refrigeration room. Numerous explanations have been devised to explain the cause of death due to low temperatures. One of the oldest and most commonly accepted is that advanced by Muller-Thurgau is 1886, quoted by Chandler (5). He decided, after careful study, that ice usually formed in the intercellular spaces and within the cells only in the case of rapid freezing or in exceptionally large cells. He also proved that in some cases the formation of ice was the cause of death, since plants when supercooled were not injured, but were killed if ice formed at higher temperatures. He believed that death was due to the withdrawal of water from the cells to form ice.

Wiegand (43) holds that death from freezing is usually, if not always, caused by the drying out of protoplasm beyond its critical water content. In the opinion of Maximov (24), however, there is a mechanical deformation of the protoplasm as a result of being compressed by ice. Martin (23) believed that the plant was killed because low temperatures coagulate and dehydrate the protoplasm to such an extent that it cannot take up water.

Newton and Brown (25) explained the phenomena of freezing in plants in this manner:

> The sap adhering to the external surface of the cell walls is necessarily more dilute than the vacuolar sap, else plasmolysis would exist. When the cells are exposed to frost, the more dilute sap freezes first, and ice forms in the intercellular spaces. These abstract water from the cell walls in considerable force, disturbing the equilibrium of the whole system, to restore which there is set up a streaming of water out of the cells.

Wiegand (43) found that hardy tissue, upon thawing, draws water back into the cells while less hardy tissue is not capable of regaining the water lost and thus death results.

Other external factors are believed to enter into the effects which low temperatures have on plants. Klages (15) grew wheat seedlings in different soil types and moisture contents and found that a low percent of moisture had a protective influence during the first part of exposure. When killing on the low moisture soil set in, however, it progressed rapidly and almost completely. This phenomenon was explained on the basis of relative activity of the plants grown on soils differing in moisture content and also upon the relation of specific heat of water to that of soil particles.

The general consensus of opinion seems to have been summed up by Salmon (31) when he stated that desiccation of the protoplasm, mechanical injury caused by ice, and suspension of metabolism are all direct effects of low temperatures.

Hardening

As the material which was subjected to low temperature stresses was planted and grown outside in pots and allowed to harden under winter conditions, a brief review of literature concerning the hardening process will follow.

A plant is said to be hardened when its resistance to adverse conditions has been increased by external influences. According to MacDougal (21), plants may be hardened by exposure to cold, restricting the water supply, growing in poor soils for a period, by root pruning, or by watering with a weak salt solution. These conditions tend to create a stunted type of growth, cause a concentration of the cell sap, and a high proportion of dry matter in the plant.

Wiegand (43) assumed that the basis of frost resistance lies in the capacity of the protoplasm to withstand the dehydrating influence of a direct or indirect deprivation of water. It appears, then, that in order for a plant to become resistant, some mechanism is needed to absorb and retain within the cells as much water as possible.

Salmon (31) described hardening of winter grains as involving: (a) a slight though not always consistent decrease in moisture content, (b) a marked decrease in the amount of sap that can be extracted from living tissue by pressure, (c) an increase in the sugar content, and (d) a decrease in free water, i.e., the water in the tissue from which ice will be formed at any given temperature.

After extensive trials, Hill (13) showed that hardening is very important in a winter hardiness test by artificial freezing. He induced hardening by subjecting the plants to temperatures near the freezing point, and found periods of from six to ten days to be satisfactory. Chandler (5) found that resistance to frost is increased by previous exposure to low temperatures.

Salmon (32), working with 23 varieties of winter wheat, reported it would appear that very little dependence can be placed in the results of artificial freezing of unhardened plants of the very hardy varieties as a means of estimating relative winter survival. For fully hardened plants, however, the agreement may be regarded as very good, as shown by the correlation coefficients which ranged from 0.65 to 0.84 when the results of the freezing tests were correlated with the average survival in all of the winter-hardiness nurseries. Thus it would seem that the relative injury produced by exposure of hardened plants to freezing temperatures agrees reasonably well with winter-killing under field conditions.

Martin (23) summed up the effects of hardening. He stated that during the hardening of wheats there was a decrease in moisture content, and an increase in total solids in the sap, freezing point depression of the sap, and imbibition pressure of the cell colloids. He added that there are not always observable differences between varieties, as all the points mentioned fluctuate widely during the fall and winter.

Use of a Drought Chamber

Several investigators have emphasized the importance of artificial heat tests for studying varietal differences to determine their relative drought resistance. Shirley and Meuli (36) pointed out several advantages of drought machines over field testing. Many of the workers have shown the possibility of using controlled high temperatures to select the strains which are drought resistant under field conditions. Hunter, et al. (14), subjected corn seedlings to 140° F. temperature for 6.5 hours with a relative humidity of about 30 percent and found a close relationship between the results obtained by the drought machine and the performance of the same strains under field conditions. Bayles, et al. (3), when testing eight spring wheat varieties in a drought machine reported similar success. Pots of each variety were placed on a revolving table in a current of hot air. A close relationship between the performance in the field and under artificial hot winds was apparent.

Aamodt (1) constructed a drought machine consisting of a glass enclosed tunnel through which heated air blows at a velocity of about six miles per hour. He noted a high correlation between the results obtained with this apparatus and the findings of field test plots.

Heyne and Laude (11) and Heyne and Brunson (10), while conducting a genetic study of drought resistance in inbred lines of corn, reported that high temperature tests of seedling plants could be a valuable aid in the breeding of strains resistant to heat and drought. The former reported that the results obtained when testing seedlings for heat resistance could be relied upon for distinguishing genetic differences in the drought tolerance of larger plants of different strains of maize. Platt and Darroch (28) stated that artificial drought tests would be very useful in eliminating low yielding lines of plants from a hybrid population.

Shirley (35) devised a drought chamber for testing drought resistance of seedling conifers. This drought machine consisted of an illuminated chamber with a revolving table through which hot, dry air was forced. He found that results in the drought machine correlated well with those obtained in the field.

Schultz and Hayes (33) compared the resistance of plants in both seedling and sod stage in a drought machine with behavior under field conditions. Very good agreement was obtained with artificial drought trials as compared with field data. They concluded that artificial tests of drought resistance may be used to indicate those species or varieties of forage which can best be expected to survive under natural atmospheric drought.

High Temperature Injury

High temperature injury to plants has been found to be closely related to injury caused by drought. Chen (6) stated that injury due to either soil drought or to atmospheric drought, which usually involves high temperature, is through desiccation and dehydration of the cells.

It was found by Tumanov (39), in his work with drought resistance of different species, that those plants survived whose protoplasm remained more stable and were more capable of enduring dehydration. When drying protoplasm is coagulated in such a manner the change is irreversible and death occurs.

Vassiliev (41) reported that work done in Russia with Canadian wheats indicated that in drought conditions wheat varieties unadapted to drought suffer more from a high intensity of atmospheric factors, including high temperature, which promote increased transpiration, than from a deficiency of water, as is generally accepted. Being highly depressed by the atmospheric factors the yields of the non-resistant wheat suffer but little or not at all from soil drought.

Berkley and Berkley (4) studied the maximum limit of high temperature under which plants could survive. They concluded that the normal death point, i.e., that temperature which will kill protoplasm immediately at a given relative humidity, seemed to depend upon the age of the plant, the duration and the conditions of exposure.

Vassiliev (42) believed that the mobile fraction of carbohydrates in the plant regulates the life processes of the plant. He further stated that the accumulation of soluble carbohydrates by a plant is a means of increasing its drought resistance. In later experiments he concluded that carbohydrates aid markedly in regulating the osmotic pressure of the plant cell. Carbohydrates also play the role of protector in preventing coagulation of the protoplasm when influenced by harmful factors. Also, an accumulation of hemicellulose during the stage of water loss is a means of resistance and is a natural reaction of the wheat plant toward drought.

Kondo (16) found that conditions of growth previous to the experiment determines to a large extent the degree of resistance the plant has in withstanding dehydration. He also believed that the stage of development may play an important role in a plant's ability to resist drought.

Shantz (34), in a summary, stated that plants which succeed in a country subject to drought: (a) escape by a short rapid growth period; (b) evade drought by conserving moisture supply because of small size, restricted growth, wide spacing, or low water requirements; (c) endure drought by storing up a supply of water in the plant; and (d) resist drought by passing into a dormant condition.

Tumanov (38) believed that the ability of a plant to resist drought depends upon many morphological and physiological characteristics which investigators have failed to separate into their component parts. Studies of drought resistance must be considered not only from the standpoint of a plant's reaction to high temperature, low humidity, and other atmospheric factors but also from the standpoint of soil factors and the plant's own physiological and morphological adaptation to adverse conditions. The means that a plant uses to avoid intensive loss of water are different for the various species.

Levitt (20) stated that frost, drought (i.e., desiccation), and heat resistance are all basically similar, and that any resistance to one of these factors carries with it a resistance to the others.

MATERIALS AND METHODS

Cold Hardened Plants

The material used for cold resistance investigations was planted in four inch unglazed pots. The pots were located north of the greenhouses at Kansas State College and, before being placed on the ground, a two inch layer of sand was spread out to keep them from freezing in place and being difficult to remove when needed for testing in December, 1956 and January, 1957.

Material that had hardened under outside winter conditions was used for artificial freezing tests because, as pointed out by Salmon (32), very little dependence can be placed on the results of artificial freezing of unhardened wheat plants. But, for fully hardened plants, the relative injury produced by exposure to freezing temperatures in a low temperature chamber agrees reasonably well with winter-killing under field conditions. Dexter (8) also stated that varieties of winter wheat were found to be tender until subjected to hardening at low temperatures and varietal differences were not clear in unhardened plants.

The soil used was brought in from the Kansas State Agronomy Farm in September, 1956 and was run through a soil pulverizer to give a more homogeneous mixture. No additional fertilizers or organic matter were added.

One hundred thirty-nine entries, consisting of different varieties and strains of winter wheats, were planted in pots with essentially the same amount of soil in each on October 8, 1956. Seven kernels were planted in each pot and three pots used per entry, giving approximately 20 plants to each replication. Twenty plants per replication were used so as to be similar to the entries planted in the greenhouse which were used in the drought hardiness studies.

Five replications of each entry were desired, which necessitated planting 17 pots for each entry to ensure there being five groups of three pots each with approximately 20 plants. This gave a total of 2,363 pots which were arranged in two plots about 30 feet by 18 feet. One plot contained Entries 1 through

89 and the second plot Entries 90 through 139. The second plot also contained several pots of Pawnee which were used in preliminary trials in the freezer to establish the proper temperature and length of exposure necessary to injure the plants. A border of pots around both plots was used to minimize adverse environmental effects on the outermost pots. All the pots were watered soon as planted and were watered thereafter to maintain optimum soil moisture conditions until cooler weather arrived about the middle of November. Table 1 denotes the daily maximum and minimum temperatures as well as daily precipitation from October 1, 1956 to January 16, 1957 when all the pots had been taken in for testing in the freezing room. As can be noted from Table 1, temperatures throughout October were fairly high which was conducive to rapid growth and the plants had reached a rank stage before winter dormancy. There were no appreciable high temperatures during the period of treatment from December 26, 1956 to January 16, 1957, which would indicate any difference in the degree of hardening among the entries before time of exposure to low temperatures in the freezing chamber.

Unhardened Plants

The plants used in the high temperature tests were grown in the greenhouse in soil the same as outside material. But instead of pots, 14 inch by 20 inch by 3-3/4 inch metal flats were used. Each flat had several drainage holes in the bottom to allow even soil moisture distribution. Similar amounts of soil were used in all the flats.

Table 1. Daily maximum and minimum temperatures and precipitation for Manhattan, Kansas, October 1, 1956 to January 16, 1957.

Date	October Max	October Min	October P	November Max	November Min	November P	December Max	December Min	December P	January Max	January Min	January P
1	95	52		69	47	T	61	21	.04	37	24	
2	88	49		66	51		68	29	.77	46	19	
3	92	44		57	36		69	26	T	54	33	
4	82	59		50	41		62	28		35	27	
5	94	42		56	43	.01	44	30	.12	37	24	
6	79	51		58	35	.04	32	20		45	30	.10
7	80	33		56	36		27	13	T	47	21	
8	85	56		47	26		22	19	T	44	33	
9	69	47		60	23		46	12	1.63	39	5	T
10	83	47		72	33		57	27	1.02	18	-1	T
11	89	63		76	37		46	29	.35	38	15	
12	90	68		60	33		33	19	.10	39	16	
13	85	72		72	34		30	15	T	17	10	
14	76	56	1.33	74	52	T	34	20	T	26	4	
15	73	55	T	52	28	T	34	27		22	8	T
16	82	49		49	20		55	23		19	4	T
17	82	52		55	26		47	21	.07			
18	81	53		57	35		45	10	T			
19	77	48		51	33		45	34	T			
20	65	54	.01	43	28		51	27	T			
21	75	43	T	38	22		58	31				
22	79	42		43	17	.01	45	30				
23	77	39		45	31		38	25				
24	80	55		61	28		37	17				
25	73	43		53	34		49	16	T			
26	74	31		40	21		58	28				
27	74	49		55	20		59	30				
28	75	50		44	22		50	37				
29	74	58		45	13		60	30	T			
30	72	49	.65	58	22	T	63	24				
31	61	36	.12				48	25	T			
Av. Temp.	79.4	49.8		55.3	30.9		47.5	24.0		35.2	17.0	
Total Precip.			2.11			.06			4.10			.10

A randomized planting plan was devised for use in planting the 139 entries. Ten entries, plus Pawnee and a Pawnee guard row at each end, were included in each flat. The Pawnee entry was included in every flat to act as a check with which the ten entries could be compared. The Pawnee guard rows at each end were not included when taking survival notes unless one end showed more severe treatment than the other, as was the case in several instances. Approximately 20 kernels were planted in each row which represented one entry. Fourteen metal flats were needed to give one replication of the 139 entries but only 11 flats could be placed end to end on the greenhouse tables so three replications of the first 109 entries were planted at one time, giving a total of 33 flats per table. Similar plantings were made once a week until all 139 entries had been replicated six times. The first table was planted October 19, 1956, the second table October 26, and the third table November 2. Immediately after planting, the flats were watered and thereafter water was applied to maintain optimum soil moisture conditions. Sprouts were usually showing three days after planting. The greenhouse temperature ranged from a low of 55° F. at night to a high of 75°-80° F. during the day, which gave very good vegetative growth.

When the outside temperature was low enough to necessitate turning on steam heat in the greenhouse, it was observed that the plants in the flats nearest the steam pipes grew more rapidly than did plants in flats further away from the influence of the heat. To remedy this situation, cardboard baffles were constructed and secured to the ends of the tables, thus decreasing the temperature effect on the plants nearest the steam pipes, and a fairly uniform temperature was observed throughout the greenhouse. A hygrothermograph was placed in the greenhouse which recorded daily temperatures and humidity on seven-day charts.

Low Temperature Tests

The freezing chamber was a room 6 feet by 8 feet by 8 feet with walls insulated by a six-inch layer of cork. Refrigeration was by a Freon system with the heat exchanger and fan located inside the room at a point along the rear wall near the ceiling. Any desired temperature in the range -30° to 70° F. could be obtained with only $\pm 0.5^{\circ}$ F. fluctuation. The temperature was maintained by a Minneapolis-Honeywell electro-thermostatic control unit. A three-shelf wooden rack with open sides was used to hold the pots and the air circulation was such that no differences in injury were noticeable among the three levels. The 139 entries were divided into two groups--one with Entries 1 through 80 and the second with Entries 81 through 139. The same entries were in the freezer at the same time for all five replications. As there were three pots per entry, one pot was put on each shelf of the rack and the entries were randomized on the shelves.

Preliminary trials were made beginning December 12, 1956 using six pots of Pawnee, two to a shelf in the freezer, in order to determine the proper temperature and length of exposure which would produce differential injury. 4° F. was used for 16, 20, and 24 hours and, after recovering in the greenhouse for ten days, it was decided that the time of exposure should be between 20 and 24 hours.

The first group of 80 entries was brought in from outside and placed in the freezer December 26, 1956. The last of the five replications was tested January 17, 1957 and all 2,085 pots were then in the greenhouse recovering from the low temperature exposure.

High Temperature Tests

The chamber used to simulate drought conditions was a room 5 feet by 5 feet by 8 feet through which hot air was circulated and the temperature controlled by a Johnson thermostatic control unit. Any temperature desired could be obtained in the range 90° to 150° F. with ±1° fluctuations. The hot air entered through the ceiling and left through a conduit in the lower right wall. A rotating table five feet in diameter was located in the center of the room which rotated approximately 1.5 revolutions per minute. It was possible for six flats to be placed on the table at once but five were more convenient so this number was usually placed in the chamber at one time. The level of humidity could not be accurately controlled but it remained constant throughout each trial. Light, when desired, was provided by four light bulbs about three feet above the plants.

Before placing the flats in the drought chamber, the plants were watered thoroughly about one hour prior to the heat treatment as suggested by Salmon (32), who indicated that this prevented undue variations in injury due to fluctuations in soil moisture content.

The first group of flats was placed in the drought chamber November 7, 1956, approximately three weeks after date of planting and this interval between planting and treatment was maintained throughout the testing period. The last flats of the sixth replication were treated December 4, 1956. A temperature of 120° F. was used for 19 to 21 hours on all the trials with the relative humidity ranging from 25 to 30 percent. The flats were usually placed in the drought chamber about 4:00 p.m. and removed around noon the next day. An effort was made to remove the flats from the drought chamber as soon as good differential injury to the plants was observed. Upon cooling to the greenhouse temperature, usually five to six hours, the flats were thoroughly watered again to establish an optimum soil moisture content during the period of recovery.

Checks were made throughout the experiment to determine if the soil temperature varied from one part of the flat to another. The center portion of each flat usually was 2° to 3° F. cooler than the outside portions by the end of the test but this difference was not thought great enough to cause differential root damage. The soil temperature was within 6° to 8° F. of the room temperature by the time the flats were removed from the room after exposure of 19 to 21 hours.

The soil moisture content was checked before and after exposure to the high temperatures to determine whether the injury to the plants was due only to atmospheric drought or whether it was a combination of both atmospheric and edaphic drought as discussed previously. In one particular instance the soil moisture content of a flat was 37 percent before being placed in the drought chamber. Upon removal, after exposure to 120° F. for 20 hours, the moisture content of the soil was again determined and found to be 18 percent, which did not approach the wilting coefficient of the soil, so it was assumed that the injury sustained by the plants was due principally to atmospheric drought.

Recording of Observations

Each of the 139 entries which was exposed to low temperatures in the freezing room was represented by three pots in each of the five replications. The number of plants per pot ranged from five to seven, giving 15 to 20 plants per entry. Observations were made by three different individuals about ten days after treatment. Each estimated the amount of leaf injury that had occurred so that a range of zero to 100 percent injury in increments of ten was possible. The three readings were averaged and the resulting value was used to indicate the hardiness of the plant. The plants with high injury values were the least hardy. There was good injury differentiation among the entries as some were completely killed while others showed only a slight amount of injury. A spot check was made on some of the entries the succeeding day and these readings corresponded very closely to the previous ones suggesting that this method of determining hardiness was reasonably precise.

A somewhat different approach was used for determining the hardiness scores of the entries that were tested in the drought chamber. Observations were made about three weeks after treatment in order to determine which plants were dead. Then after the percent mortality had been computed, the condition of the surviving plants was considered in terms of "strong" growth or "weak" growth as indicated by their vigor. A scale of zero to 1.0 by tenths was used and if the vigor of growth was "strong" a value of zero to 0.5 was used but if the recovery was poor a value of 0.5 to 1.0 was assigned. This value was multiplied by the percent mortality and the product used as a hardiness score. The larger the score the less hardy was the plant. This method is somewhat similar to the one used by Quisenberry (29) to arrive at a hardiness score.

A statistical analysis of the data from the cold resistance experiment was made using formulae as outlined by Paterson (26). The individual readings for each replication were used in determining the standard error. The mean hardiness score for each entry was used in computing the correlation for cold and heat resistance.

More difficulties were encountered with the data from the heat resistance experiment due to several uncontrollable factors. It was observed that flats in the drought chamber at the same time did not always show equal severity of treatment over the entire flat. By using a rotating table the air temperature was uniform but a possible explanation for the variation was that the entries were planted too close together in the flats and future improvement of technique might be gained by planting only seven or eight entries per flat instead of ten. Also, only five flats per trial seemed to give the most satisfactory results.

To compensate for differences among flats in the same trial it was decided to analyse the 139 entries in 14 groups of ten entries, plus Pawnee, as they appeared in the planting plan. This analysis was in accordance with Cochran and Cox (7) and Snedecor (37). After an error variance was computed for each of the 14 groups, Bartlett's test for homogeneity of variances was used to determine which of the group entries could be compared directly. Then an adjusted mean hardiness score was calculated for all 139 entries on the basis of how the Pawnee entry included in each group compared with the overall mean of the 14 Pawnee entries. Thus the Pawnee control in each group served to correct for the differences observed within and among trials in the drought chamber. The variance was twice as great for the difference between two entries that were in different groups as for two entries in the same group.

EXPERIMENTAL RESULTS

In Table 2 are listed the 139 winter wheat entries which were tested for cold and heat resistance in this study. Data in Table 3 are presented principally to show the top 20 entries of the first group of 80 that were subjected to low temperature tests. This is of interest because most of the standard varieties now grown in this region fall into this range as might be

Table 2. One hundred thirty-nine winter wheat varieties and strains tested for winter and drought hardiness.

Entry No.	Variety or Cross[1]	Identification No.[2]	Source of Seed
1	Kiowa x Marquillo-Oro	49H635	Hays
2	Apache x Bison	53H579	"
3	Pawnee x PI 94587-1	52382	"
4	Apache x Com-Oro-Ten 46-52	53H592	"
5	Triumph x Marq-Oro-Com	52277	"
6	Quiv-Ten x Kaw-Med-Kaw-Ten	52286	"
7	Kaw-Med-Kaw-Ten x Apache	52H3010	"
8	Paw-Med-Hope x Com-Oro-Turk-Flor	53423	"
9	Chey- E Blk x Kaw-Med-Kaw-Ten	53438	"
10	Com-Marq-Oro x Red Chief-Nebred	53465	"
11	Paw-Marq-Oro x Chk-E Blk-Ten	53502	"
12	Com x Lo Prevision	53482	"
13	Com x Lo Prevision	53483	"
14	Paw-Med-Hope x Com-Oro-Turk-Flor	53415	"
15	Paw-Med-Hope x Com-Oro-Turk-Flor	53422	"
16	Red Chief x Pawnee	53569	"
17	Red Chief x Pawnee	53584	"
18	Chey-Red Chief x Paw-Marq-Oro	55613	"
19	Nebred-Marq-Oro x Chk-Paw	55637	"
20	Med-Hope-Paw x Kaw-Med-Kaw-Ten	52321	"
21	Timstein x Med-Oro-Kaw-Ten	52223	"
22	Med-Hope-Paw x Oro-Ill #1-Com	49413	"
23	Apache x Kiowa	53H544	"
24	Kiowa x Marq-Oro	49H634	"
25	Marq-Oro x E Blk Hybrid	49H619	"
26	Crockett	CI 12702B	KIN
27	Improved Bluejacket x Comache	CI 13185	"
28	Improved Bluejacket x Comache	CI 13186	"
29	Pawnee Selection	138	"
30	Quivira Hybrid	CI 13285	"
31	Kaw-Med-Kaw-Ten x Apache	52H3011	"
32	Quivira Hybrid	53428	"
33	McM-Exchange-Redin[3] x Cheyenne	56152	Nebraska
34	McM-Exchange-Redin[3] x Cheyenne	56156	"
35	McM-Exchange-Redin[3] x Cheyenne	56157	"

[1]Explanation of abbreviations appears at the end of the table.
[2]CI designates Cereal Investigations number. The other numbers are selection and nursery numbers.

Table 2 (cont.)

Entry No.	Variety or Cross	Identification No.	Source of Seed
36	McM-Exchange-Redin^3 x Cheyenne	56158	Nebraska
37	McM-Exchange-Redin^3 x Cheyenne	56159	"
38	McM-Exchange-Redin^3 x Cheyenne	56165	"
39	McM-Exchange-Redin^3 x Cheyenne	56166	"
40	McM-Exchange-Redin^3 x Cheyenne	56168	"
41	Turkey x Cheyenne	CI 12711	Manhattan
42	Med-Hope-Paw x Oro-Ill #1-Com	CI 12804	"
43	E Blackhull-Ten x Oro-Med-Hope	CI 12871	"
44	Cheyenne	CI 8885	"
45	Concho	CI 12517	"
46	KanKing	CI 12719	"
47	Ponca	CI 12128	"
48	Kiowa	CI 12133	"
49	Pawnee	CI 11669	"
50	Comanche	CI 11673	"
51	Bison	CI 12518	"
52	Wichita	CI 11952	"
53	Pawnee Selection	541	Pauli
54	Pawnee Selection	5424	"
55	Pawnee Selection	5512	"
56	Pawnee Selection	5522	"
57	Ponca Selection	549	"
58	Ponca Selection	5414	"
59	Ponca Selection	5514	"
60	Ponca Selection	5517	"
61	CI 12804 Selection	5425	"
62	CI 12804 Selection	557	"
63	CI 12804 Selection	558	"
64	CI 12804 Selection	559	"
65	CI 12804 Selection	5510	"
66	Turkey	CI 1558	"
67	Bison Selection	551	"
68	Bison Selection	552	"
69	Bison Selection	553	"
70	Bison Selection	5516	"
71	Bison Selection	5518	"
72	CI 12871 Selection	554	"
73	CI 12871 Selection	555	"
74	CI 12871 Selection	556	"
75	Paw x (Iowin-T. timoph-Wisc. 5)	CI 13279	Nebraska

Table 2 (cont.)

Entry No.	Variety or Cross	Identification No.	Source of Seed
76	Blackhull-Oro x Pawnee	CI 13187	Nebraska
77	Chey-Chiefkan x H44-Minter^2	CI 13115	"
78	Pawnee x Cheyenne	483251	"
79	Pawnee x Cheyenne	521672	"
80	Pawnee x Nebred	531522	"
81	Wichita x Nebred	531538	"
82	Wichita x Nebred	531548	"
83	Wichita x Nebred	52NP1672	"
84	Red Chief x Pawnee	521366	"
85	Cheyenne x Ponca	502442	"
86	Cheyenne x Ponca	523848	"
87	Cheyenne x Ponca	523850	"
88	Ponca x Cheyenne	531683	"
89	Ponca x Cheyenne	531687	"
90	Nebred x Red Chief	533561	"
91	Nebred x Red Chief	533570	"
92	Nebred x Red Chief	533576	"
93	Nebred x Red Chief	53A863	"
94	Seu Seun x CI 12500	533321	"
95	Norin 16 x CI 12500	551147	"
96	Kharkof	CI 1442	"
97	Kharkof M.C. 22	CI 6938	"
98	Nebred	CI 10094	"
99	Minturki	CI 6155	"
100	Minter	CI 12138	"
101	Yogo	CI 8033	"
102	Pawnee x Cheyenne	483310	"
103	Cheyenne Selection (Wyoming)	WS432	"
104	TAES#6-234-53-3		Texas
105	TAES#6-218-49-1		"
106	TAES#6-218-53-13		"
107	TAES#6-394-52-26		"
108	TAES#6-274-52-A15		"
109	TAES#6-274-52-A110		"
110	TAES#6-256-52-A47		"
111	TAES#6-218-49-11		"
112	TAES#6-218-50-2		"
113	TAES#6-273-53-23		"
114	TAES#6-240-51-A19		"
115	TAES#6-274-50-21		"

Table 2 (concl.)

Entry No.	Variety or Cross	Identification No.	Source of Seed
116	TAES#6-255-48-9		Texas
117	TAES#6-240-48-10		"
118	TAES#6-218-53-15		"
119	TAES#6-240-50-15		"
120	TAES#6-273-53-15		"
121	TAES#6-256-52-16		"
122	TAES#6-396-53-39		"
123	Improved Bluejacket x Comache	CI 13185	Oklahoma
124	Improved Bluejacket x Comache	CI 13186	"
125	Blackhull-Oro x Pawnee	CI 13187	"
126	Rye x Wheat	Wd. 4444-9	"
127	(Timstein x Com_{F1}) x Ponca	Stw.536968	"
128	Concho x Triumph	536633	"
129	Concho x Triumph	536653	"
130	Concho x Triumph	536937	"
131	Concho x Triumph	536664	"
132	Triumph x Concho	Stw.536671	"
133	Kelo		"
134	World Collection 18	4088	Turkestan
135	Kanred	CI 5146	Kansas
136	No. 816	5489	USSR
137	Minturki	CI 6155	Minnesota
138	Nebraska #6	6249	Nebraska
139	Turkey Selection	7366	Oregon

KEY TO ABBREVIATIONS

Chey - Cheyenne
Chk - Chiefkan
Com - Comanche
E Blk - Early Blackhull
Flor - Florence
Ill #1 - Illinois No. 1
Kaw - Kawvale
KIN - Kansas Intrastate Nursery
Marq - Marquillo
McM - McMurachy
Med - Mediterranean
Paw - Pawnee
PI - Plant Introduction
Quiv - Quivira
TAES#6 - Texas Agricultural Experiment Station No. 6
Ten - Tenmarq
T. Timoph - Triticum timopheevi
Turk - Turkey
Wisc. 5 - Wisconsin No. 5

Table 3. Rankings of the top 20 in the first group of 80 entries in the winter hardened condition subjected to 4° F. for 22 hours.

Rank	Entry No.	Variety or Cross	Mean Hardiness Score
1	80	Pawnee x Nebred	25.8
2	49	Pawnee	27.2
3	44	Cheyenne	27.4
4	55	Pawnee Selection	28.2
5	53	Pawnee Selection	30.0
6	29	Pawnee Selection	30.6
7	41	Turkey x Cheyenne	31.4
8	54	Pawnee Selection	31.8
9	48	Kiowa	32.4
10	77	CI 13115	33.6
11	46	KanKing	33.8
12	45	Concho	34.4
13	63	CI 12804 Selection	35.4
14	52	Wichita	35.6
15	50	Comanche	36.2
16	42	CI 12804	36.4
17	75	CI 13279	37.0
18	56	Pawnee Selection	37.4
19	59	Ponca Selection	37.8
20	66	Turkey	38.4

expected. Pawnee and Pawnee selections were particularly resistant to low temperatures in this experiment. However, all of the entries were considered relatively hardy to normal winter conditions and adapted to this region.

Other entries were selected at time of planting for special study and their resistance to cold and heat will be considered in some detail.

Hardiness of Hays Entries

The seed of the first 25 entries was secured from Dr. John Miller of the Hays Branch Experiment Station. The winter hardened entries were subjected to a low temperature treatment of 4° F. for 22 hours and replicated five times. For the high temperature treatment, six replications of the entries planted in the greenhouse were used. A temperature of 120° F. for 20 hours was found to give differential injury. Table 4 gives the mean hardiness scores of the five replications for the 25 entries subjected to low temperature. Table 5 shows the adjusted mean hardiness scores of the six replications for the drought chamber test. The hardiness scores were computed in the manner previously described.

The hardiness scores of the entries in the cold test ranged from 49.4 for Entry No. 25, the most hardy, to 71.0 for Entry No. 4, the most susceptible to low temperatures. Statistical analysis of the data showed that a difference of 18.6 between the means was needed for significance at the five percent level.

Table 4. Mean hardiness scores based on percent injury of 25 entries in the winter hardened condition subjected to 4° F. for 22 hours.

Rank	Entry No.	Variety or Cross	Mean Hardiness Score
1	25	Marq-Oro x E Blk Hybrid	49.4
2	23	Apache x Kiowa	51.0
3	16	Red Chief x Pawnee	52.6
4	11	Paw-Marq-Oro x Chk-E Blk-Ten	54.4
5	20	Med-Hope-Paw x Kaw-Med-Kaw-Ten	55.0
6	21	Timstein x Med-Oro-Kaw-Ten	55.2
7	24	Kiowa x Marq-Oro	55.6
8	22	Med-Hope-Paw x Oro-Ill #1-Com	58.0
9	15	Paw-Med-Hope x Com-Oro-Turk-Flor	59.8
10	18	Chey-Red Chief x Paw-Marq-Oro	61.4
11	13	Com x Lo Prevision	61.6
12	17	Red Chief x Pawnee	63.4
13	7	Kaw-Med-Kaw-Ten x Apache	64.0
14	19	Nebred-Marq-Oro x Chk-Paw	64.6
15	14	Paw-Med-Hope x Com-Oro-Turk-Flor	64.8
16	8	Paw-Med-Hope x Com-Oro-Turk-Flor	64.8
17	3	Pawnee x PI 94587-1	65.4
18	10	Com-Marq-Oro x Red Chief-Nebred	65.6
19	2	Apache x Bison	66.0
20	1	Kiowa x Marquillo-Oro	66.6
21	12	Com x Lo Prevision	68.0
22	9	Chey-E Blk x Kaw-Med-Kaw-Ten	68.8
23	5	Triumph x Marq-Oro-Com	70.4
24	6	Quiv-Ten x Kaw-Med-Kaw-Ten	70.6
25	4	Apache x Com-Oro-Ten 46-52	71.0
		Pawnee	27.2

Pawnee was included in this study to indicate the relative cold resistance of these 25 entries in comparison with it. Pawnee appeared to be highly significantly more resistant than any of the other entries.

Table 5. Adjusted mean hardiness scores based on percent mortality and condition of the plants of 25 entries grown in the greenhouse subjected to 120° F. for 20 hours.

Rank	Entry No.	Variety or Cross	Mean Hardiness Score
13	1	Kiowa x Marquillo-Oro	61.3
23	2	Apache x Bison	70.8
20	3	Pawnee x PI 94587-1	68.6
8	4	Apache x Com-Oro-Ten 46-52	53.6
18	5	Triumph x Marq-Oro-Com	65.4
25	6	Quiv-Ten x Kaw-Med-Kaw-Ten	76.9
11	7	Kaw-Med-Kaw-Ten x Apache	59.2
6	8	Paw-Med-Hope x Com-Oro-Turk-Flor	52.7
16	9	Chey-E Blk x Kaw-Med-Kaw-Ten	62.7
21	10	Com-Marq-Oro x Red Chief-Nebred	68.7
5	11	Paw-Marq-Oro x Chk-E Blk-Ten	52.5
22	12	Com x Lo Prevision	69.5
24	13	Com x Lo Prevision	71.3
17	14	Paw-Med-Hope x Com-Oro-Turk-Flor	63.1
19	15	Paw-Med-Hope x Com-Oro-Turk-Flor	66.0
12	16	Red Chief x Pawnee	60.1
15	17	Red Chief x Pawnee	62.5
7	18	Chey-Red Chief x Paw-Marq-Oro	53.3
10	19	Nebred-Marq-Oro x Chk-Paw	58.4
14	20	Med-Hope-Paw x Kaw-Med-Kaw-Ten	62.3
4	21	Timstein x Med-Oro-Kaw-Ten	51.6
3	22	Med-Hope-Paw x Oro-Ill #1-Com	49.8
1	23	Apache x Kiowa	38.8
9	24	Kiowa x Marq-Oro	56.5
2	25	Marq-Oro x E Blk Hybrid	44.3
		Pawnee	59.2

Entry No. 25 was significantly more resistant to low temperatures than Entries 12, 9, 5, 6, and 4. Entry No. 23 appeared to be significantly more resistant than Entries 5, 6, and 4. No significance among the other entries could be shown and this might be expected as all of the entries were previously screened through field observations to eliminate the extremely weak ones.

The data from the high temperature treatment were handled in a manner previously described. The entries were treated in groups of ten, with the third group containing Entries 21 to 25. The hardiness scores were adjusted to whatever level the Pawnee entry indicated. Within the first ten entries, a difference of 13.2 between any two means was necessary to show significance at the five percent level. The sensitivity of the experiment was such that no significance could be shown among Entries 11 to 20 nor 21 to 25 after the data were analysed. For comparing Entries 1 to 10 with any of Entries 11 to 20, a difference of 19.0 was needed for significance at the five percent level. A difference of 20.2 was necessary to be significant at the five percent level when comparing any of Entries 1 to 10 with Entries 21 to 25. To compare Entries 21 to 25 with Entries 11 to 20, a difference of 20.5 was needed for significance at the five percent level.

Entries 23 and 25 were the top two in the heat resistance experiment as was the case in the cold resistance test but they had switched positions. Entry No. 23 was significantly better than all other entries except 4, 8, 11, 18, 19, 20, 21, 22, 24, and 25. Entry No. 25 was significantly more resistant to heat than all other entries except for the above mentioned, plus Entries 1, 7, 9, 14, 16, 17, and 20. Pawnee did not show the advantages over the other entries in the drought test as it had in the cold test. Entry No. 6 was the most susceptible to high temperature injury and was next to last in the low temperature test.

In order to compare the entries with respect to both high temperature and low temperature resistance, the correlation coefficient was computed, using the mean hardiness scores obtained for each entry in both tests. The resulting figure was 0.638, a highly significant correlation coefficient. None of the entries remained in the same relative position in both experiments but at most varied only three or four positions and, with this many entries, this was within the limits of chance fluctuation. This suggests that in the situation under which these tests were conducted physiological conditions occurring within the plant to give low temperature resistance also provide protection to the plant from abnormally high temperatures. This is a fact that has been corroborated by several investigators. It is not probable, of course, that temperatures during midwinter would ever rise to a point where the plants would be subject to injury by extremely high temperature.

The plants subjected to high and low temperatures were small, as the ones grown in the greenhouse were treated three to four weeks after planting while the hardened plants grown outside had just reached the tillering stage. It is possible that the comparative resistance might have differed somewhat had older or larger plants been used in the trials. Laude and Nauheim (18) reported information which indicated that plants emerging early in the autumn and showing vigorous growth were more capable of withstanding adverse winter conditions than those which came up later. Pauli (27) demonstrated that extremely low temperatures seriously injured the crown tissue, perhaps severing the vascular connections between tops and roots of the plants. It would be plausible to assume that a plant with a larger crown could more nearly protect at least part of the tissue from injury, both from high and low temperatures. Worf (44) verified this assumption by subjecting different sized plants in both hardened and unhardened conditions to high and low temperatures and found that more resistance was shown by plants with greater development of crown tissue.

After exposure to low temperature, many of the more susceptible plants failed to recover. Injury to the surviving plants occurred primarily within the leaves while those plants that were killed appeared to suffer severe crown or basal injury. Almost no regrowth was noted in those plants dying early.

High temperature injury was also primarily leaf injury, most of those plants surviving showed no injury around the basal portion of the stems. More regrowth was noted in plants injured by high temperature than was seen in plants that were injured by low temperature.

In an attempt to improve the technique of evaluating the hardiness scores which were assigned to each entry in the low temperature test, the percent mortality for each entry was recorded separately. The average percent mortality and average hardiness scores of the five replications for each entry were correlated, the resulting coefficient being 0.931. This was significant at the one percent level. It could be said that approximately 86 percent of the variation in the hardiness scores was contributed by the variation in the percent mortality figures. This appeared to indicate that the method used to describe the injury due to low temperatures was better than just using the percent mortality because even though a plant survived it might have considerable leaf injury. Using the value which took this into account seemed to give more information about the entries than percent mortality figures alone.

Kansas Intrastate Nursery Entries

Another group of entries that was of interest were from the Kansas Intrastate Nursery. Table 6 lists those entries along with the average cold and heat resistance scores for each. The entries subjected to the low temperature treatment were in the freezing chamber for 22 hours at 4° F. The high temperature entries were subjected to 120° F. for 20 hours.

The range of scores was from 30.6 for a Pawnee selection, the most hardy, to 60.6 for a Quivira hybrid which appeared to be the most susceptible to low temperature injury. After an analysis of the data for five replications was completed it was found that a difference of 19.0 between entry means was needed for significance at the five percent level.

The Pawnee selection was significantly more resistant to low temperature injury than either Entry 26 or 32, while Entries 28 and 27 showed significantly less injury than did Entry 32. As far as statistical significance was concerned, it appeared that Entries 29, 28, 27, 30, and 31 possessed factors which

Table 6. Average hardiness scores of Kansas Intrastate Nursery entries subjected to temperature treatments.

Entry No.	Variety or Cross	Average Hardiness Score
	4° Fahrenheit for 22 hours	
29	Pawnee Selection	30.6
28	Improved Bluejacket x Com (CI 13185)	39.4
27	Improved Bluejacket x Com (CI 13186)	41.0
30	Quivira Hybrid (CI 13285)	43.0
31	Kaw-Med-Kaw-Ten x Apache	46.6
26	Crockett	50.6
32	Quivira Hybrid	60.6
	120° Fahrenheit for 20 hours	
28	Improved Bluejacket x Com (CI 13185)	44.1
29	Pawnee Selection	47.6
27	Improved Bluejacket x Com (CI 13186)	50.1
30	Quivira Hybrid (CI 13285)	51.4
31	Kaw-Med-Kaw-Ten x Apache	55.2
26	Crockett	56.3
32	Quivira Hybrid	63.0

produced similar resistance to low temperatures.

The data from the high temperature treatment were analysed. The range of scores was not quite as great as with the low temperature test but there was a spread of 18.9. The average hardiness score for each entry was adjusted to the level indicated by the Pawnee checks and could then be directly compared as the error variances were checked and found to be homogeneous. It was necessary to have a difference of 18.6 between entry means for significance at the five percent level.

There was a reversal of positions in the top two entries showing the most resistance to high temperature injury as compared with the low temperature test. In the latter test the Pawnee selection had shown a little more resistance than did CI 13185 but results of the high temperature test indicated CI 13185 was somewhat more resistant to heat injury than was the Pawnee selection but by no means significantly so. The remainder of the entries retained the same ranking as was shown in the low temperature treatment. CI 13185 was significantly more resistant to heat injury than was Entry 32, a Quivira hybrid. No significant differences among the other entries could be shown statistically. It might be hypothesized that Entries 28, 29, 27, 30, 31, and 26 were of similar genetic constitution for resistance to high temperature injury, at least judging by results of the experiment.

When a correlation of the average hardiness scores of the high and low temperature treatments was computed, a highly significant coefficient of 0.903 was obtained. This figure further illustrated the apparent similarity in high temperature and low temperature resistance of plants.

A Study of Several Standard Varieties

The next group of entries was subjected to low and high temperature treatments in the manner previously described. Entries 96 through 101 were treated together so a good statistical analysis of the results was possible. Table 7 lists those entries by variety name and indicates their average hardiness scores after they were subjected to 4° F. for 22 hours during the cold resistance test and 120° F. for 20 hours during the heat resistance test. All six entries were known to be very winter hardy from past results produced in the field so no great differences among the varieties were expected.

A statistical analysis was made of the low temperature data and a difference between variety means of 16.0 was needed to be significant at the five percent level. The range of scores was from 22.0 for Yogo to 47.4 for Kharkof. Yogo appeared to be significantly better in resistance to low temperature injury than Minturki, Nebred, and Kharkof. Minter was significantly more resistant than was Kharkof to low temperatures. The varieties Kharkof M.C. 22, Minturki, Nebred, and Kharkof showed no significant differences. On this basis it could be said that Yogo, Minter, and Kharkof M.C. 22 showed similar resistance to low temperature injury while Minturki, Nebred, and Kharkof showed similar resistance.

Analysis of the results of the high temperature test showed a range of hardiness scores from 45.0 for Yogo to 58.7 for Kharkof. Significant differences between variety means at the five percent level were approached but never exceeded as a difference of 14.0 was necessary. Yogo was very close to being significant over Minturki and Kharkof. On the basis of this

Table 7. Average hardiness scores of six standard varieties subjected to temperature treatments.

Entry No.	Variety or Cross	Average Hardiness Score
	4° Fahrenheit for 22 hours	
101	Yogo	22.0
100	Minter	29.6
97	Kharkof M.C. 22	37.6
98	Nebred	39.2
99	Minturki	39.4
96	Kharkof	47.4
	120° Fahrenheit for 20 hours	
101	Yogo	45.0
97	Kharkof M.C. 22	50.9
98	Nebred	52.7
100	Minter	54.1
99	Minturki	58.4
96	Kharkof	58.7

experiment where no clear-cut differences could be shown, all six varieties might be said to show a similar level of resistance to high temperature injury.

A correlation of the average hardiness scores was made and a significant coefficient of 0.814 was obtained. Yogo, Minturki, and Kharkof ranked first, fifth, and sixth, respectively, in both high and low temperature tests. The other varieties showed minor variations in comparative rank. Minter shifted from the second position in resistance to low temperature where it was significantly better than Kharkof to the fourth position in resistance to high temperature injury and was significant over no other variety. Nebred also changed positions as it ranked fourth in resistance to low temperature but went to third in high temperature resistance. The significant correlation coefficient of 0.814 again indicated that whatever mechanism is responsible for cold resistance in wheat is closely linked to the factor or factors controlling heat resistance.

These six standard varieties were also selected for particular study because some information was available concerning their hardiness in the field. Table 8 presents data showing the relationship of the laboratory cold resistance scores and percent mortality observed in 1953 in the Uniform Winter Hardiness Nursery at Waseca, Minnesota. A correlation coefficient of 0.863 was obtained from the two sets of data which was significant at the five percent level. Yogo, Minter, and Kharkof retained their relative positions in both the laboratory and field results. Minturki showed the most variation in changing from a standing of fifth in the laboratory tests to the third position in the field. The significant correlation coefficient was an indication that some dependence could be placed in the results of artificial freezing of hardened plants as a means of estimating relative winter survival. Quisenberry (29), it may be remembered, secured a coefficient of 0.713 for artificial freezing at St. Paul, Minnesota, and the average for two field plantings,

Table 8. Average cold hardiness scores as determined in the laboratory and the percent mortality as observed in the field.

Low temperature treatment in the laboratory

Entry No.	Variety	Average Hardiness Score
101	Yogo	22.0
100	Minter	29.6
97	Kharkof M.C. 22	37.6
98	Nebred	39.2
99	Minturki	39.4
96	Kharkof	47.4

Uniform Winter Hardiness Nursery at Waseca, Minn.

Entry No.	Variety	Percent Mortality
101	Yogo	62
100	Minter	62
99	Minturki	72
97	Kharkof M.C. 22	73
98	Nebred	75
96	Kharkof	77

one at St. Paul and one at Moccasin, Montana. Martin (22) also secured a coefficient of 0.762 for artificial freezing of 12 spring wheats at Manhattan, Kansas, and winter survival in the field in the Pacific Northwest.

In comparing the laboratory results with field observations taken in the Uniform Winter Hardiness Nurseries for the six varieties over a period of several years, a significant correlation could not always be obtained. It appeared, though, that the correlation obtained was as good as the one obtained between the nurseries and different years. A correlation of field nursery results between the years 1951, 1952, 1953, and 1955 was computed considering the six varieties and the coefficients ranged from 0.402 to 0.733, none of which approached significance at the five percent level. This suggests that over a period of years using laboratory results to estimate relative winter survival of several varieties would be a dependable method plus the fact that data accumulated in the laboratory are more easily acquired than from field observations.

Salmon (32) also found high correlations between the results of artificial freezing of hardened varieties of wheat and survival under field conditions. In three separate trials involving varieties from the winter hardiness nurseries the correlation coefficients for estimated injury in laboratory tests and winter survival in the field were -0.65, -0.84, and -0.78. Salmon compared the accuracy of the artificial freezing trials with that of single winter hardiness nurseries under field conditions by determining the intra-class correlation coefficients for the latter each year, and also by determining the correlation between the survival at all stations taken individually and the average at all other stations in the same year. The coefficients in all cases were materially lower than those secured for the artificial freezing trials. It appeared that a single artificial freezing test could be expected to furnish a more reliable prediction of relative winter hardiness in the Great Plains region than would the survival of a single winter hardiness nursery selected at random but less reliable than the average of all winter hardiness nurseries for a single season.

Another point in favor of using laboratory data to estimate winter survival in the field was brought out when a study was made of the correlation between the heat resistance scores found in the high temperature tests and the percent mortality in the field for the six varieties appearing in Table 8. The correlation coefficient was 0.540 which was not significant but nevertheless for such a small sample does suggest a degree of association for the two factors.

Table 9 lists another group of standard varieties for which field observations were available from the Supplementary Uniform Winter Hardiness Nurseries located at Brookings, South Dakota; Moccasin, Montana; St. Paul, Minnesota; and Dickinson, North Dakota. The percent mortality figure for each variety is an average for the years 1955 and 1956. The laboratory hardiness scores were obtained as previously described.

A mathematical correlation was computed using the average hardiness scores obtained from the laboratory low temperature tests and the percent mortality figures as observed in nursery plots. The resulting coefficient was 0.902 which was significant at the one percent level. The highly significant coefficient agrees quite well with the conclusions expressed by Salmon

Table 9. Average cold hardiness scores as determined in the laboratory and the percent mortality as observed in the field.

Low temperature treatment in the laboratory

Entry No.	Variety	Average Hardiness Score
123	CI 13185	24.8
124	CI 13186	25.4
49	Pawnee	27.2
46	KanKing	33.8
45	Concho	34.4
50	Comanche	36.2
42	CI 12804	36.4
43	CI 12871	39.2

Supplementary Uniform Winter Hardiness Nurseries

Entry No.	Variety	Percent Mortality
123	CI 13185	29
124	CI 13186	36
49	Pawnee	48
46	KanKing	49
50	Comanche	54
45	Concho	63
42	CI 12804	63
43	CI 12871	70

(32) who stated that the correlation obtained between laboratory artificial freezing data and winter survival information from several winter hardiness nurseries was greater than that obtained between laboratory data and only one nursery selected at random.

There was only one variation in the ranking of the eight varieties when laboratory data were compared with the field observations. Concho ranked fifth and Comanche sixth in the laboratory while in the nursery plots Comanche was fifth and Concho sixth but the difference was very minor and not significant. All of the six remaining varieties retained their respective rankings in both the laboratory and nursery.

It was of interest to note Entries 123 and 124 were the top two in both sets of data. These entries were selections that were made at the Oklahoma station from the same parentage, Improved Bluejacket x Comanche. They both showed more cold resistance than did Comanche itself.

A correlation coefficient of 0.660 was found when percent mortality in the nursery plots and high temperature hardiness scores secured in the laboratory experiment were compared. The degree of association expressed by this coefficient is as great as that found among the different Uniform Winter Hardiness Nurseries. It appears that future research work should be directed toward obtaining correlations between laboratory and field results for larger samples. The possibility of using laboratory data as a criterion for estimating field survival appears to be good, judging from the limited information gained in past experiments.

SUMMARY

Plantings were made of 139 varieties and strains of winter wheat both outside, so as to harden under winter conditions, and in the greenhouse. The hardened material was used for low temperature treatments while the unhardened plants were subjected to high temperatures. The purposes of the experiment were to determine the comparative resistance of these entries to low temperature and to high temperature, whether a correlation existed between high and low temperature resistance, and if results obtained in laboratory artificial freezing tests were dependable for estimating winter survival in the field.

Low temperatures were produced by means of an electrothermostatically controlled refrigeration unit placed in a cork insulated room. High temperatures were provided by hot air which was circulated through a similarly insulated room and a thermostatically controlled steam heating unit.

The hardened plants were subjected to a temperature of 4° F. for 22 hours in groups of 80 and 59 entries each. Five replications were used in the low temperature tests of the 139 entries. The freezing tests of all the hardened plants were made over a period of three weeks but it was believed there was no difference in the degree of hardening between the time the first and the last entries were treated.

The entries subjected to high temperatures were planted at regular intervals in the greenhouse and all treated at about the

same age, that being three to four weeks after date of planting. The plants were in the drought chamber for about 20 hours at 120° F. The entries were treated in groups of ten and Pawnee was included with each group to serve as a check with which to compare the other entries.

Several of the entries were of particular interest and a detailed study of their cold and heat resistance was made. One group of entries included the first 25 for which the seed was supplied by Dr. John Miller of the Hays Branch Experiment Station. A highly significant positive correlation coefficient of 0.638 was found to exist between cold resistance and heat resistance of those entries. Differential injury was found among the entries with respect to low temperature and to high temperature exposure. Entry 23, Apache x Kiowa, and Entry 25, Marquillo-Oro x Early Blackhull Hybrid, were both significantly more resistant to high and low temperatures than were some of the other entries. It appeared that the entries did not differ widely in their resistance as non-hardy strains had been previously screened out. Entry 6, Quivira-Tenmarq x Kawvale-Mediterranean-Kawvale-Tenmarq, was thought to be more susceptible to both high and low temperature injury than were several of the other entries.

Seven entries from the Kansas Intrastate Nursery were tested for resistance to low and high temperatures using treatments similar to that for the Hays entries. A highly significant correlation coefficient of 0.903 was obtained when comparing cold resistance and heat resistance of the entries which further illustrated the apparent similarity in high temperature and low temperature resistance of plants. Entries 29 and 28, a Pawnee selection and CI 13185, respectively, seemed to show significantly more resistance to injury from low and high temperatures. Entry 32, a Quivira hybrid, was the most susceptible to both low and high temperatures. The remaining entries, CI 13186, CI 13285, Kawvale-Mediterranean-Kawvale-Tenmarq x Apache, and Crockett retained their relative positions in both tests and ranked third, fourth, fifth, and sixth, respectively.

Several widely grown standard varieties were tested for resistance. The first group consisted of Yogo, Minter, Kharkof M.C. 22, Nebred, Minturki, and Kharkof. There was a significant correlation coefficient of 0.814 between low and high temperature resistance. Yogo was significantly more resistant to low temperatures than others and very nearly approached that level in the high temperature tests. Kharkof and Minturki were the most susceptible to injury in both tests. A correlation coefficient was computed for the relationship of the laboratory cold resistance scores and the percent mortality observed in 1953 in the Uniform Winter Hardiness Nursery at Waseca, Minnesota. A significant coefficient of 0.863 was obtained. That seemed to indicate that some dependence could be placed in the results of artificial freezing of hardened plants as a means of estimating relative winter survival.

The second group of standard varieties included CI 13185, CI 13186, Pawnee, KanKing, Concho, Comanche, CI 12804, and CI 12871. A study was made of the correlation existing between percent mortality in the field and results produced by artificial freezing in the laboratory. The coefficient obtained was 0.902 which was significant at the one percent level. CI 13185 and CI 13186 were the most resistant to cold injury in both the laboratory and field while CI 12804 and CI 12871 were the most susceptible to injury in both cases. This study furnished more evidence in favor of using laboratory low temperature data as an estimate of actual winter survival in the field.

CONCLUSIONS

Significant differences were obtained in the laboratory through careful control of the temperature and the length of time of exposure. It was thought that most of the entries would be capable of surviving winter temperatures under ordinary Kansas weather conditions. There were several spring wheats in the pedigrees of some of the entries and those could conceivably not survive during a normal winter.

The cold tests were made with plants in a hardened condition and it is possible the relative ratings of resistance obtained might change in later stages of maturity for Laude (17) and Worf (44) both found that the superiority or inferiority of varieties to extreme temperatures in the hardened condition could not serve as an index to their temperature reactions in later stages of growth. However, the resistance to cold as found in the laboratory agreed quite well with data for winter survival in the field for the entries on which this information was available. This investigation did illustrate that the correlation obtained between laboratory artificial freezing data and winter survival figures from several winter hardiness nurseries was greater than that obtained between laboratory data and only one nursery selected at random.

The fact that resistance to low temperature was found to be correlated with high temperature resistance is of practical importance to successful wheat production. Those strains that showed resistance to low temperatures generally showed resistance to high temperatures and therefore it may be assumed that the changes which occur within a plant to increase low temperature resistance are similar to changes which occur to increase high temperature resistance. As injury from both low and high temperatures have been known to occur after spring growth has begun, the value of having resistance to both temperature extremes within the same variety is obvious. The correlation obtained suggests at least two hypotheses: (a) the inheritance of spring hardiness to low and high temperatures is closely linked, and (b) the conditions protecting a wheat plant from low temperatures are the same as those needed for protection from high temperatures.

It would appear that laboratory testing for cold resistance and heat and drought resistance offers possibilities for future use. The problem of winter-killing has been intensified by crossing winter and spring varieties and the resulting hybrids may lack winter hardiness. With laboratory testing, more of the segregates from a cross can be tested for cold and drought hardiness. Obviously there would be a greater chance of finding superior winter and drought hardy strains among the selections.

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RESISTANCE OF WINTER WHEAT TO ARTIFICIALLY PRODUCED LOW AND HIGH TEMPERATURES

by

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Hard red winter wheat is the most important grain crop of the Great Plains region. This importance has stimulated much interest and effort to improve the crop. A study of resistance of plants to artificially produced low and high temperatures offers possibility for estimating their winter and drought hardiness. A research program is needed to gain a better understanding of the fundamental nature of cold, heat, and drought hardiness and to develop better means of testing for hardiness to weather extremes. This investigation involved the study of resistance in wheat to artificially produced high and low temperatures and of the correlation which might exist between resistance to cold and to heat. Also, a study was made of the correlation between laboratory results and winter survival in the field for several of the entries.

One hundred thirty nine entries, consisting of different varieties and strains of winter wheat, were planted in pots outside to harden under normal winter conditions. These entries were used in testing for resistance to low temperatures. The same entries were planted in metal flats and grown in the greenhouse for testing their resistance to high temperatures. A thermostatically controlled refrigerator located in an insulated room provided cold temperatures, and steam-heated air circulated into a similar room provided high temperatures. Five replications containing three pot samples of each entry were made for the cold resistance test and six replications per entry were made for heat resistance. Winter survival data from several of the Uniform Winter Hardiness Nurseries were used to determine the correlation between cold and heat resistance obtained in the laboratory with survival in the field. Four groups of entries were selected at time of planting for special study and their resistance to cold and heat was considered in some detail.

One group of entries included the first 25 for which the seed was secured from the Hays Branch Experiment Station. A highly significant positive correlation coefficient of 0.638 was found to exist between cold resistance and heat resistance of those entries. Entry 23, Apache x Kiowa, and Entry 25, Marquillo-Oro x Early Blackhull Hybrid, were both significantly more resistant to high and low temperatures than were some of the other entries. Entry 6, Quivira-Tenmarq x Kawvale-Mediterranean-Kawvale-Tenmarq, was thought to be more susceptible to both high and low temperature injury than were several of the other entries.

Seven entries from the Kansas Intrastate Nursery were tested for resistance to low and high temperatures. A highly significant correlation coefficient of 0.903 was obtained when comparing cold resistance and heat resistance of the entries, which further illustrated the apparent similarity in high temperature and low temperature resistance of plants. A Pawnee selection and CI 13185 seemed to show significantly more resistance to injury from low and high temperatures.

Several widely grown standard varieties were tested for resistance. The first group consisted of Yogo, Minter, Kharkof M.C. 22, Nebred, Minturki, and Kharkof. There was a significant correlation coefficient of 0.814 between low and high temperature resistance. Yogo was significantly more resistant to low temperatures than others and very nearly approached that level in the high temperature tests. Kharkof and Minturki were the most susceptible to injury in both tests. A significant correlation coefficient of 0.863 was obtained for the relationship of the laboratory cold resistance scores and percent mortality observed in a nursery plot at Waseca, Minnesota. This was an indication that some dependence could be placed in the results of artificial freezing of hardened plants as a means of estimating relative winter survival.

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