Crook, E. M. and Watson, D. J. 1950. Studies on the storage of potatoes II. The temperature conditions inside potato clamps. *The Journal of Agricultural Science.* 40 (3), pp. 199-226.

VOLUME 40 JULY 1950 PART 3

STUDIES ON THE STORAGE OF POTATOES

II. THE TEMPERATURE CONDITIONS INSIDE POTATO CLAMPS

BY E. M. CROOK* AND D. J. WATSON, *Rothamsted Experimental Station, Harpenden, Herts*

(With Thirteen Text-figures)

CONTENTS

	PAGE
Dimensions of clamps and positions of thermograph bulbs	199
Results	201
(1) Temperature in the potatoes	203
(*a*) Seasonal drift	203
(*b*) Variation of temperature with position in the potatoes	206
(*c*) Short period fluctuation of temperature; the effect of wind	207
(2) Temperature in the clamp coverings	215
(*a*) Temperature at the outer surface of the earth cover	215
(*b*) Temperature at the inner surface of the earth cover, and outer surface of the straw cover	217
(*c*) Effect of wind	217
(3) The diurnal temperature wave	220
(4) Temperature variation in the potatoes after removal of the earth cover	222
Discussion	224
Summary	226
References	226

In the autumn of 1942 the Agricultural Research Council called a conference of research workers interested in the potato crop to consider the problems of wastage during storage in clamps. In the course of discussion it became apparent that very little information was available on the conditions that exist inside clamps, and as it seemed probable that temperature was a most important factor affecting wastage, it was decided to make continuous temperature records throughout the storage period in one of the experimental clamps set up for studies of wastage. A number of mercury-in-steel recording thermographs of the type used for recording soil temperatures were available at Rothamsted, and these were installed in a clamp at the end of October 1942. Further records were obtained from three clamps built in October 1943. The data obtained in the two seasons are presented in this paper.

The only previous work published appears to be that of Barker & Wallace (1946), who gave results of an investigation of clamp temperatures made in 1934–5, and 1935–6 in Lincolnshire. They used glass thermometers inserted into wooden tubes built into the clamp during its construction. These were read in the morning at intervals of 3–5 days during the period of 4 months from November to February.

DIMENSIONS OF CLAMPS AND POSITIONS OF THERMOGRAPH BULBS

The clamp used in 1942–3 had been prepared in several sections, separated by wire-mesh and sisal-kraft paper partitions lined with straw, for testing a number of treatments for sprout inhibition. There was a central section about 5 yd. long kept as untreated control, and the thermograph bulbs were inserted at the mid-point of this section.

The dimensions of the clamp in cross-section were: potatoes, width of base 8 ft. 6 in., height 3 ft. 4 in.; straw cover 5 in. thick; earth cover 1 ft. 3 in. thick at base, decreasing to 6 in. on the ridge. The long axis of the clamp lay in the direction W.N.W.–E.S.E. The potatoes were of the variety Arran Banner.

Initially, four thermographs with six bulbs in all were available. These were installed on 29 October 1942 while the clamp was being built. The potatoes were covered only with straw until 7 December; on that date the old straw was removed and replaced by fresh straw and the earth cover was put on. There were no straw vents through the earth cover. Later two more thermographs became available, and were installed on 20 January 1943.

The final positions of the bulbs in the clamp, and symbols used subsequently to refer to them, were as follows (see Fig. 1):

(1) In the potatoes, on the centre line of the clamp, approximately 9 in. from the ground (lower centre, *L*).

(2) In the potatoes, vertically above (1), 2 ft. from the ground (upper centre, *U*).

(3) On the south side of the clamp at the surface of the potatoes, half-way up the face of the heap (south, *S*).

(4) In a corresponding position to (3) on the north side of the clamp (north, *N*).

* Now at University College, London.

(5) At the outer surface of the earth cover, half-way up the south face of the clamp (south outside, *SO*).

(6) In a corresponding position to (5) on the north face (north outside, *NO*).

The bulbs in positions *SO* and *NO* lay with their length running horizontally along the clamp face, with half of their section buried in the soil and the other half exposed to the air. Penman (1943) has shown that bulbs disposed in this fashion on a horizontal soil surface give a good estimate of the true surface temperature.

(7) Just inside the earth layer, at its inner surface on the south side of the clamp, in line with (3) and (5) (south earth inside, *SEI*).

(8) Just inside the straw layer, at its outer surface on the south side, in line with (3) and (5) (south straw outside, *SSO*).

Until 7 December 1942, when the clamp was earthed up, the bulbs at positions *SO* and *NO* had been placed on the outer surface of the straw layer on the south and north sides of the clamp. The bulbs at *SEI* and *SSO* were placed in position on 20 January 1943.

The object of this disposition of the thermograph bulbs was to give information on the vertical and lateral gradients of temperature within the potatoes, and across the earth and straw covers. It was hoped that records at the four points *SO*, *SEI*, *SSO* and *S* would enable the thermal diffusivity of the earth and straw covers to be compared by the method described by Keen (1931), but this turned out to be impossible because the diurnal temperature wave was not distinguishable in the straw layer (Fig. 12).

The clamp collapsed on 27 April 1943, because of the development of soft bacterial rots following blight infection of the tubers, but the records were continued until 19 May 1943, when the clamp was cleared away. Towards the end of the period there were a number of breaks in the records for positions *S* and *SSO* owing to the thermograph clock stopping.

The three clamps used in 1943–4 were constructed in sections, which were removed in succession at intervals to determine the progress of wastage (Crook & Watson, 1948). The thermograph bulbs were installed in the end sections that survived until the last sampling date. Each section was about 5 ft. long and was separated from its neighbours by partitions. The end sections were protected by 'guards' of unused tubers, to ensure that the conditions should be comparable with those in the middle sections. The clamps were slightly smaller than that used in 1942–3; their dimensions were: potatoes, width of base 7 ft. 4 in., height 2 ft. 9 in.; straw cover 5–6 in. thick; earth cover 1 ft. thick at base decreasing to 6 in. on the ridge. The overall length of each clamp was 36 ft. Clamp *A* contained potatoes of the variety Arran Banner, and Clamps *B* and *C* the variety Majestic. The orientation of the clamps was the same as in 1942–3. Three thermograph bulbs were installed in the potatoes in each of clamps *B* and *C* at positions *S* and *N* and at a point on the centre line of the clamp about 15 in. from the ground (*M*, marked with a cross in Fig. 1). In clamp *A* there were only two bulbs, at positions *S* and *M*. There were no records of the temperatures in the clamp covers in 1943–4.

The clamps were built on 4–7 October 1943. Until 10 November they were covered only with straw. On that date the straw cover was renewed, and the clamps were covered with soil to within 2 ft. of the ridge. The earthing up of the ridge was completed on 23 November. Clamps *B* and *C* had a straw vent through the earth cover on the ridge in each section, but clamp *A* had no vents. On 13 April 1944, the whole of the earth cover was removed from clamps *A* and *B*, but the earth on clamp *C* was left undis-

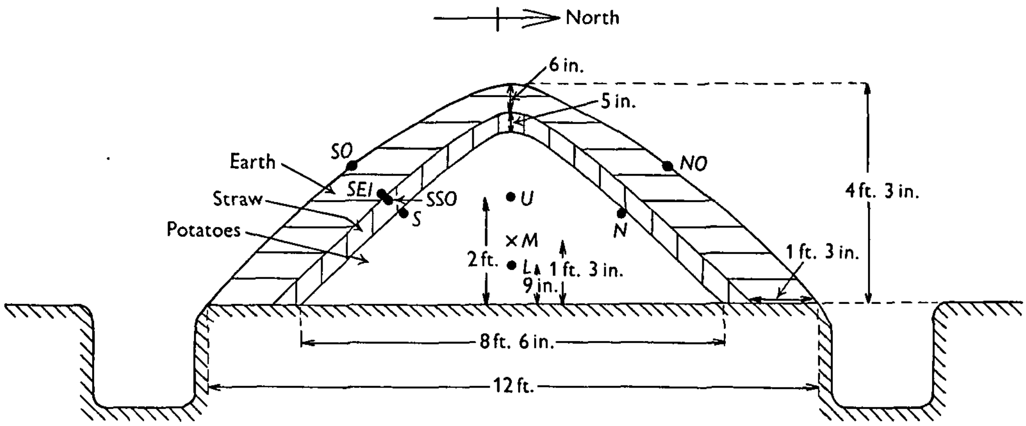

Fig. 1. Diagrammatic cross-section of the 1942–3 clamp showing the positions of the thermograph bulbs. The dimensions of the 1943–4 clamps were slightly smaller.

turbed until the end of the storage period. The records were continued until 3 July 1944.

Records of ambient air temperatures, taken by a thermograph in a standard Stevenson Screen at the Rothamsted meteorological station about three-quarters of a mile distant from the clamping site, were available in both seasons for comparison with the clamp temperatures. All temperatures are expressed in ° C.

RESULTS

Summaries of all the records taken in 1942–3 and 1943–4 are given in Figs. 2 and 3 respectively. In these figures a line is drawn for each day on the

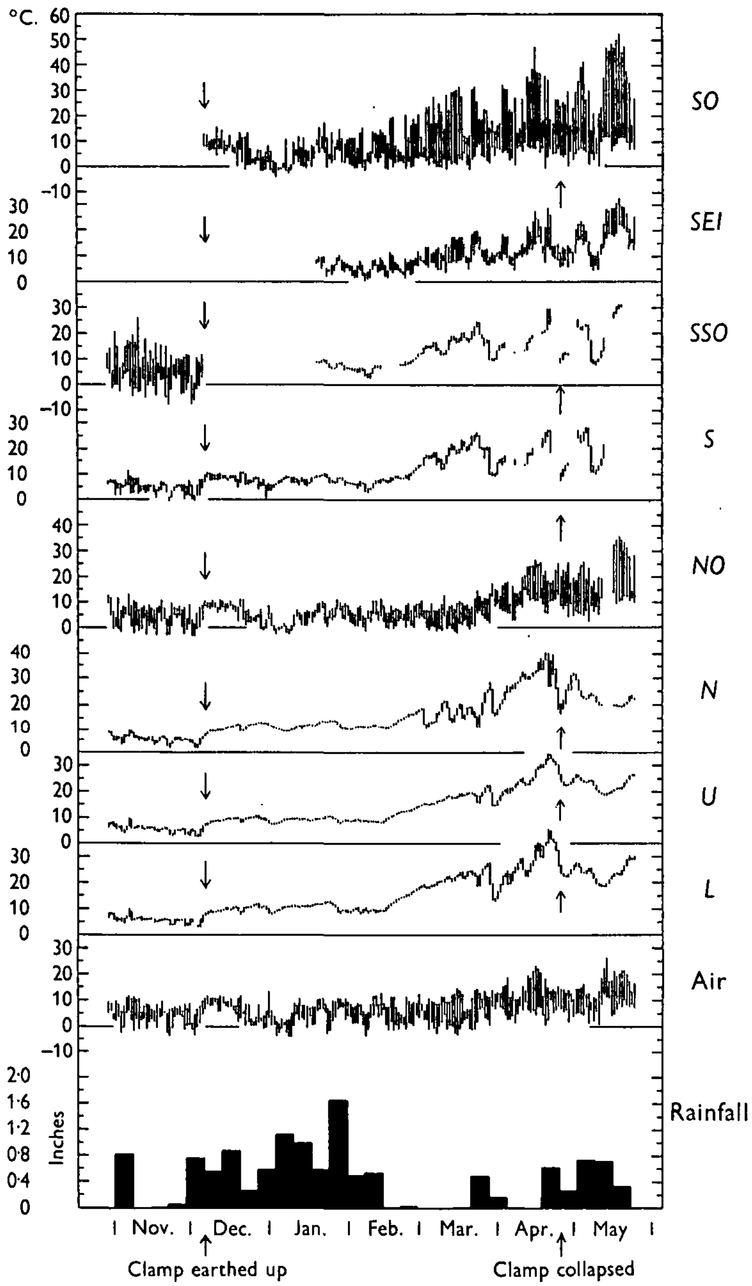

Fig. 2. Daily range of temperature at different positions in the 1942–3 clamp and its coverings, and in the air, and rainfall in successive weeks of the storage period.

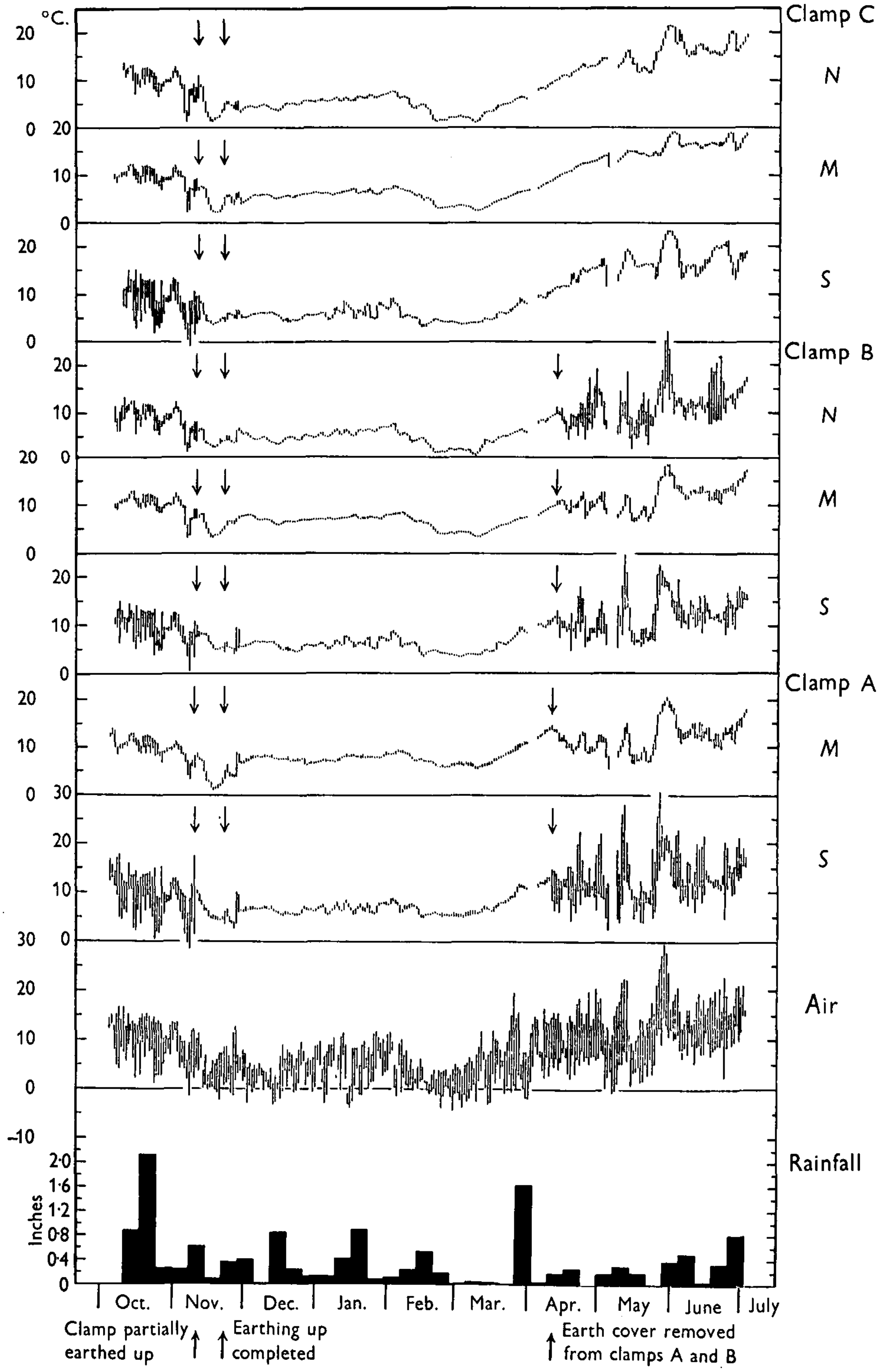

Fig. 3. Daily range of temperature in the potatoes of the 1943–4 clamps and in the air, and rainfall in successive weeks of the storage period.

temperature ordinate, joining the maximum and minimum temperatures recorded on that day. The length of the line thus shows the daily temperature range. At the foot of each figure a histogram gives the weekly rainfall.

Daily mean temperatures, and means taken over longer periods given in subsequent tables and figures to show time drifts, and for comparison between different positions in the clamps, have been estimated from the means of the daily maximum and minimum temperatures. To test whether estimates of mean temperature obtained in this way were biased, 20 days were selected at random from the 1942–3 records, at least one occurring in each week between the earthing-up of the clamp and the end of March, and the true mean temperatures were determined by integrating the thermograph traces for each position in the clamp covers and in the air. It was found (Table 1) that, for positions *SEI*, *SSO* and the air, the mean of maximum and minimum temperatures gave an unbiased estimate of the true mean, and the difference between estimated and true means was independent of the daily temperature range. For positions *NO* and *SO*, the estimate from maximum and minimum temperatures was greater than the true mean, and the difference between them increased with increase in the daily temperature range; the regression coefficient of the difference on daily range (Table 1) was significant and positive. Daily variations of temperature at positions in the potatoes were so small that the mean of daily maximum and minimum can safely be assumed to be very close to the true daily mean, and it was therefore not considered necessary to make a direct comparison of the two.

Little use was, in fact, made of mean temperatures at *NO* and *SO*; the only values quoted, those in Table 6, were calculated from daily maximum and minimum temperatures and corrected for bias by using the regression coefficients on daily range given in Table 1.

Table 1. *Mean temperature for 20 days selected at random*

(*a*) Estimated as the mean of the daily maximum and minimum temperatures, and (*b*) determined by integrating the thermograph trace, at various positions in the coverings of the 1942–3 clamp and in the air, and the regression coefficients of the difference between *a* and *b* on mean daily temperature range, ° C.

Position	*a*	*b*	*a* − *b*	Mean daily range	Regression coefficient of *a* − *b* on daily range
NO	10·04	9·33	0·71 ± 0·14	9·38	0·130 ± 0·023
SO	14·01	11·06	2·95 ± 0·23	17·20	0·111 ± 0·022
SEI	12·34	12·18	0·15 ± 0·08	6·05	0·019 ± 0·021
SSO	14·16	14·11	0·05 ± 0·04	1·36	0·046 ± 0·064
Air	8·54	8·68	−0·13 ± 0·20	7·57	−0·011 ± 0·029

(1) *Temperature in the potatoes*

(*a*) *Seasonal drift.* To eliminate short-period fluctuations and show the general drift of temperature during storage, the mean temperatures at the centre of the potatoes for successive weeks are plotted in Fig. 4 (1942–3, positions *U* and *L*) and Fig. 5 (1943–4, clamps *A*, *B* and *C*, position *M*). The weekly mean air temperatures are also shown.

During November 1942, while the clamp was covered only with straw, the temperature of the potatoes fell slowly, following closely the fall in air temperature (Fig. 4). The mean temperature of the potatoes during this period was about 1° above that of the ambient air (Table 2*a*). Immediately after the clamp was covered with soil, the temperature of the potatoes rose rapidly within 2 weeks from 4·5 to 10°. This rise may be attributed partly to the warmer weather immediately after the soil cover was put on; in the first week the mean air temperature was slightly above that of the potatoes. However, there is no doubt that the rise was mainly due to reduction of heat loss from the respiring tubers by the soil layer, for the rise continued throughout most of December while the air temperature was steadily falling. At the end of December, the very low external temperatures were reflected by a slight fall in the temperature of the potatoes, followed by a rise to the end of January as the air temperature rose, but there was no steady upward or downward trend in the potatoes between mid-December and mid-February. The mean air temperature during this 10-week period was 9° at position *U* and 10° at position *L* (Table 2*a*); the average of the two posiions was approximately 4° above the mean air temperature. The lowest temperature recorded in the potatoes during this period was 7°.

From mid-February onwards, the temperature of the potatoes began to rise rapidly, and the rise continued, with an interruption during one week at the end of March, to a maximum in the second half of April, when the weekly mean temperatures reached 34·8° at position *L* and 31·4° at position *U*, representing a rise of 25° at *L* and 23° at *U* in the course of 10 weeks. The cause of the temporary fall of temperature at the end of March is discussed later (p. 209). The maximum temperature recorded at *L* was 40·5° and at *U* 34·5° on 21 April.

The rapid heating of the potatoes was evidently due to some change inside the clamp, for the external air temperature showed no upward trend, in fact it tended to fall slightly for 5 weeks after the temperature of the potatoes began to increase. By mid-March, there was a difference of about 15° between the temperature of the potatoes and the external air, and the difference remained at approximately the same value during the subsequent period (Table 2*a*) because the air temperature also rose steadily during late March and throughout April and May. temperature fell for some time before the clamp collapsed is obscure; possibly it indicates that all the tubers had become infected, and that the activity and rate of multiplication of the bacteria within individual tubers began to decline through exhaustion of food supplies before the tissues collapsed. The final rise of temperature in the last week of the record was presumably caused by rising external air temperature.

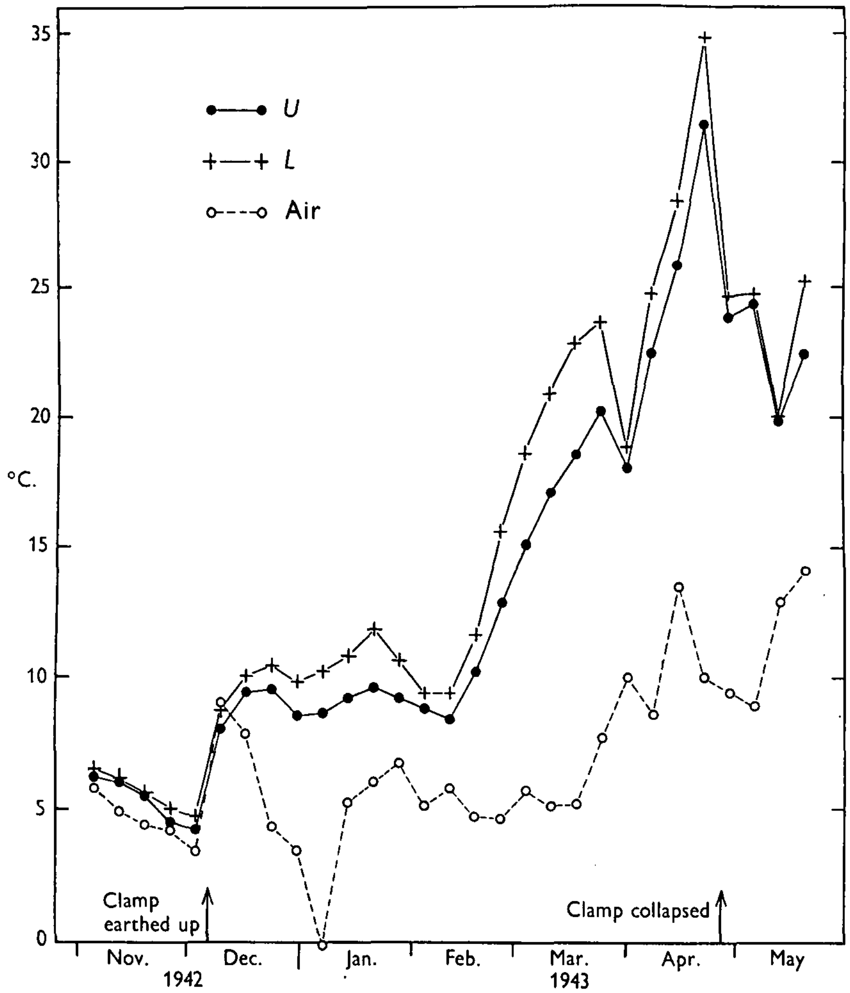

Fig. 4. Change with time in weekly mean temperature at positions *U* and *L* in the potatoes on the centre line of the clamp, and in the air, 1942–3.

From the peak value on 21 April, the temperature of the potatoes fell very suddenly. Six days later the sides of the clamp fell in, and the tubers were found to be almost completely decomposed. It seems certain, therefore, that the rise of temperature beginning in mid-February is to be attributed to a greatly increased respiration rate caused by the development of the bacterial pathogens responsible for the rotting of the tubers. The reason why the

The temperature of the potatoes at the time when they were put into the clamps in October 1943 was about 5° higher than in the previous season. In the preliminary period, when the potatoes were covered only with straw, the temperature at position *M* (Fig. 5) fell steadily, closely following the change in air temperature. The difference in mean temperature between the external air and the middle of the potato heaps was very small (0·2° in *A*, 0·5° in *B*, and 0° in *C*;

Table 2*b*), and less than half the corresponding value in 1942. The temperature of the potatoes continued to fall in the subsequent short period when the clamps were partially covered with soil but the difference ture of the potatoes showed no upward or downward trend. There was a slight depression in clamps *B* and *C* in mid-December, correlated with a fall in air temperature; in clamp *A* there was a similar fall, but it

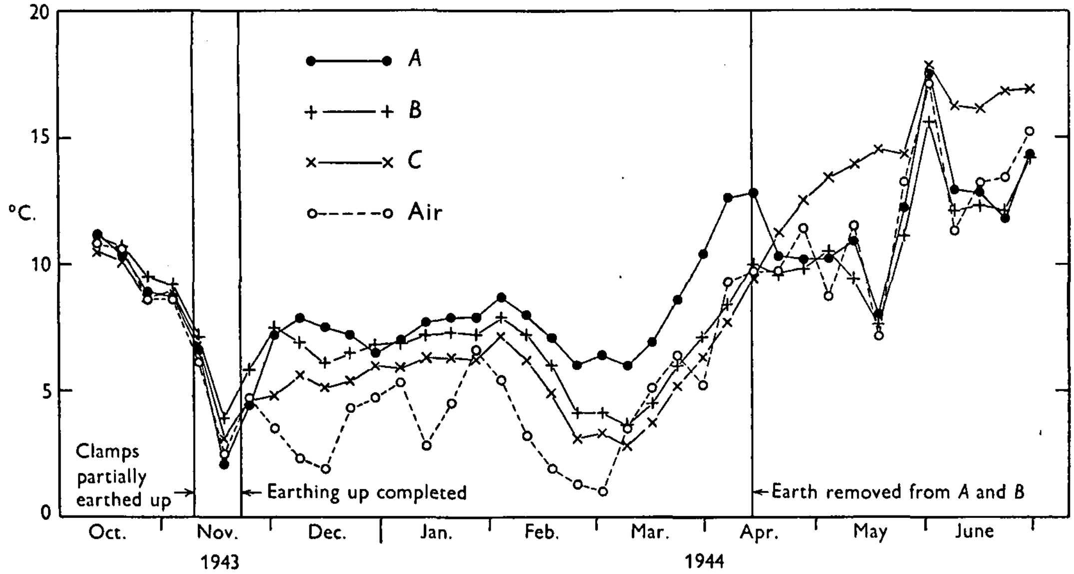

Fig. 5. Change with time in weekly mean temperature at position *M* in the middle of the potatoes in clamps *A*, *B* and *C* and in the air, 1943–4.

Table 2. *Mean temperatures of the air and at different points in the potatoes for successive periods during storage, ° C.*

(*a*) 1942–3

Period	Air	*N*	*U*	*L*	*S*
2 Nov.–6 Dec. 1942*	4·5	5·3	5·3	5·6	4·4
7 Dec. 1942–14 Feb. 1943	5·3	11·3	8·9	10·1	7·3
15 Feb.–21 Mar. 1943	5·1	15·5	14·7	17·9	14·0
22 Mar.–25 Apr. 1943	9·9	26·3	23·4	26·1	18·2
26 Apr.–23 May 1943†	11·3	22·7	22·6	23·6	16·1

(*b*) 1943–4

Period	Air	Clamp *A*		Clamp *B*			Clamp *C*		
		M	*S*	*N*	*M*	*S*	*N*	*M*	*S*
11 Oct.–7 Nov. 1943‡	9·6	9·8	8·4	9·6	10·1	9·4	10·6	9·6	8·7
8 Nov.–21 Nov. 1943§	4·3	4·4	5·9	4·8	5·5	6·7	5·3	5·0	5·1
22 Nov. 1943–30 Jan. 1944	4·1	7·1	5·8	5·7	6·8	5·6	5·7	5·6	5·6
31 Jan.–5 Mar. 1944	2·6	7·2	5·8	3·8	5·8	5·3	4·5	4·9	4·7
6 Mar.–9 Apr. 1944	5·9	8·9	8·4	5·3	5·9	6·9	5·5	5·1	6·4
10 Apr.–2 July 1944‖	11·8	12·0	12·4	11·6	11·2	11·7	15·2	14·4	16·0

* Clamp covered with straw only.
† Clamp collapsed on 27 April 1943.
‡ Clamps covered with straw only.
§ Clamps partially covered with earth.
‖ Earth cover removed from clamps *A* and *B* on 13 April 1944.

between potatoes and external air widened. After the completion of the earthing of the clamps the temperature rose rapidly in the following 2 weeks, but, as in 1942, part of this rise may be attributed to a temporary rise in the external temperature. Throughout December and January the tempera- continued until the end of December, for some time after the air temperature had begun to rise. The fall of air temperature in the middle of January apparently had no effect on the temperature of the potatoes. Throughout this period there were consistent differences between clamps; *A* was the

 https://doi.org/10.1017/S0021859600045871

warmest, and B had a higher temperature than C. The mean temperatures for the 10-week period 22 November 1943–30 January 1944 (A, 7·1°; B, 6·8°; C, 5·6°; Table 2*b*) were all lower than in the 1942–3 clamp for the corresponding dates. The differences in mean temperature in this period between the middle of the potatoes and the external air were only 3·0, 2·7 and 1·5° for A, B and C respectively, compared with 4·6° in 1942–3.

From the last week of January until early March, the mean air temperature fell steadily from 6·6° to 1·0°. A similar fall began in the potatoes a week later, and continued for a week after the air temperature started to rise again. During this period the difference in temperature between B and C was maintained at about the same value as previously, but as the temperature in A decreased by only 2·7°, compared with 6·3° in B and C, the difference between A and the other two clamps increased. At the minimum point in early March the differences in mean temperature were: $A-B$, 2·4°, $B-C$, 0·8°. For at least 4 weeks at the end of February and in early March the tubers in the middle of clamps B and C were exposed to temperatures sufficiently low to cause sweetening, and accumulation of sucrose was observed in samples taken at this time (Crook & Watson, 1948). The temperature in clamp A, however, never fell below 6°, the limit above which sweetening does not occur.

The mean air temperature continued to rise throughout March and April, and the temperature of the potatoes in all three clamps showed a parallel rise until the soil cover was removed from A and B on 13 April. The difference in temperature between A and B tended to increase slightly, while that between B and C remained almost constant (mean differences, 6 March–9 April: $A-B$, 3·0°; $B-C$, 0·8°; Table 2*b*). In this phase of rising temperature, the difference between the mean temperatures of the air and the potatoes was much less than in the early stages, as would be expected if the rise of temperature of the potatoes was induced by the rise in external temperature. In 3 of the 5 weeks the mean air temperature was actually higher than the mean temperature of the potatoes in B and C. This is in striking contrast to the records for 1942–3 (Fig. 4), where the rise in the temperature of the potatoes from mid-February onwards, was associated with an increasing difference between the temperatures of the air and the potatoes, and confirms the conclusion that the 1942–3 rise was due to the onset of rotting. The temporary fall in mean air temperature in the last week of March (Fig. 5) had no detectable effect on the temperature of the potatoes.

After the soil cover was removed from A and B, the mean temperatures of the potatoes in these clamps differed little from that of the air, though the fluctuations from week to week were smaller. Clamp A continued to be slightly warmer than B (mean difference $A-B$, 0·8°; Table 2*b*). In C, which retained its soil cover, the temperature continued to rise, and in June it was about 3° higher than in A and B. The fall and subsequent rapid rise of air temperature in May caused a similar fluctuation in the potatoes of clamp C, and the highest temperature recorded, 19·2°, occurred on 2 June, 4 days after the highest daily mean air temperature. From 26 to 30 May the daily mean air temperature was 2–5° higher than the temperature of the potatoes in C.

The tubers in clamps B and C were taken from the same bulk, and the construction of the two clamps was as nearly as possible identical. The constant difference of nearly 1° between B and C throughout the period when both were covered with soil must therefore be attributed to chance variability of the tubers or to differences in the clamp coverings. It was certainly not due to errors in the thermograph readings, for all the thermographs were checked at the end of the experiment and found to be recording correctly. As the temperatures were measured at only one point in each position, similar variation may have occurred at comparable positions along the length of a single clamp. In the early part of the storage period, the temperature difference between A and B was of similar magnitude to that between B and C. The higher temperature in A than in the other clamps may again have been due to chance variations, but if it was a real effect of some difference in treatment, it could have resulted either from the presence of straw vents through the soil casing in B and C, but not in A, or from the fact that A contained tubers of a variety different from those in B and C. There is no way of distinguishing between these alternatives. The increase in the temperature difference between A and the other clamps that became apparent from the end of February onwards may be explained by greater heat production associated with earlier sprouting of the Arran Banner tubers in A than of the Majestic tubers in B and C. Sprouts were first found on the Arran Banner tubers when a section of clamp A was opened on 22 February 1944; the weight of sprouts then was 0·6% of the initial fresh weight of the tubers. The Majestic tubers did not produce a comparable weight of sprouts until the end of April; on 25 April the weights of sprouts as percentage of initial tuber fresh weight were 0·7 for clamp B and 0·9 for clamp C, compared with 5·9 for clamp A. It might be argued that the earlier sprouting in clamp A was a consequence of the higher temperature during the winter months, but this is not likely because the temperature difference between B and C, which was as great as that between A and B, did not cause any appreciable difference between B and C in the time or amount of sprouting.

(*b*) *Variation of temperature with position in the potatoes.* As the mean air temperature was below

 https://doi.org/10.1017/S0021859600045871

the temperature of the potatoes throughout most of the storage period (Figs. 4, 5), it might be expected that there would be a gradient of temperature within the potatoes falling from the centre to the outer surfaces of the heap. The existence of a temperature gradient in the vertical plane passing through the peak of the clamp is shown by the difference in temperature between positions *L* and *U* in 1942–3; the temperature at *L* was consistently higher than at *U* (Fig. 4). Before the clamp was earthed up, the average difference was only 0·3°, but it increased with the rise in temperature of the potatoes after the earth cover was put on (Table 2*a*). In the period from December to mid-February when the temperature of the potatoes showed no steady rising or falling trend, the mean difference was a little over 1°. In the subsequent phase of rapid temperature rise, attributed to bacterial infection, the gradient became steeper, and the difference between *L* and *U* increased to about 3°. Barker & Wallace (1946) recorded a similar vertical temperature gradient.

It is difficult to make any generalization about the temperature differences between the centre of the potato heap and its outer faces, for they vary widely between clamps and with time. In the 1942–3 clamp the temperature at *N* on the north face was often higher than at *L*, especially in the period from December to mid-February before the rapid temperature rise began, but at *S* on the south face it was always lower than at *L* (Table 2*a*). In clamps *A* and *B* of 1943–4, the surface temperatures (*N* and *S*) were below the temperature at the middle of the heap (*M*) throughout the period when the clamp was earthed-up, and in *B* the temperature at *S* was usually equal to or greater than that at *N* (Table 2*b*). In clamp *C* of 1943–4, the differences between *N*, *M* and *S* were small and variable in sign. At the end of the storage period (Table 2*b*, period 10 April–2 July) the surface temperatures were higher than those at the middle of the potatoes in all three clamps, but to a greater extent in *C*, which retained its earth cover, than in *A* and *B* from which the soil was removed. Such a gradient, falling from the outer surface towards the centre might be expected if the external air temperature exceeded that of the potatoes; this was so for clamp *B*, but for *A* and *C* the reverse was true. Nor can the higher temperatures at the surface be attributed to greater heat production arising from more rapid sprouting at the surface; in clamp *C*, the weight of sprouts percentage of tuber weight was actually slightly less at the surface than in the middle (Crook & Watson, 1948). Barker & Wallace (1946) found a similar variability in the relation between surface and centre temperatures; the mean temperatures over the whole storage period at a position near to the north face and at the centre bottom position were identical in two of their clamps, in the third the north temperature was higher and in the fourth it was lower than that at the centre. In three of the four clamps the north side mean temperature was higher than that at a corresponding position on the south face, while in the fourth clamp the two were equal.

As the temperature record for each position in the cross-section of a clamp was made at only one point and was not replicated along the length of the clamp, the means for each position may be subject to errors arising from temperature variation along the length of the clamp. Such variation might, for example, be caused by differences in the thickness of the clamp covers. Bacterial rotting of the tubers, such as occurred in the 1942–3 clamps, probably spreads from foci of infection, and if a thermometer were by chance installed in or close to one of these, it would give readings higher than the mean for comparable positions in other parts of the clamp. This may account for the high temperatures recorded at position *N* in 1942–3, but there is no independent evidence to support this explanation. Errors of this type may be reduced in the 1943–4 results by averaging the temperatures for comparable positions in the three clamps. The mean temperatures, ° C., over the period when the clamps were completely covered with soil (November–April) were as follows:

	Mean of clamps *A*, *B* and *C*		Mean of clamps *B* and *C*		
Air	*M*	*S*	*N*	*M*	*S*
4·2	6·4	6·0	5·2	5·8	5·7

It may be concluded that the temperature in the potatoes tended to fall from the centre of the heap towards the outside, but that the temperature gradients across the potatoes varied widely with time, and between, and probably within, clamps. One cause of variation with time will be discussed in the next section.

(*c*) *Short period fluctuation of temperature; the effect of wind.* At the beginning of March 1943, the temperature in the potatoes became much more variable both within and between days than in the earlier period (Fig. 2); this is particularly obvious for position *N*. Fig. 2 gives only the range of temperature for each day, but to understand the nature of the increased variability during March it is necessary to examine continuous records of temperature; these are shown Fig. 6 replotted on a reduced scale from the thermograph charts for positions *N*, *L* and *S*. Fig. 6 shows that during January and February the deviations of temperature at *N*, *L* and *S* from smooth trends were small, but that from 3 March onwards they increased greatly in amplitude. The large fluctuations during March did not show a regular periodicity and therefore cannot be attributed to the penetration of the diurnal wave of external temperature through the clamp coverings into the potatoes. Records for positions *NO* and *SO* on the outer surface of the earth cover are included in Fig. 6 to show the diurnal wave, and it is obvious that the fluctuations at *N*, *L* and *S* do not correspond with the daily peaks and troughs of the temperature records for *NO* and *SO*. If the variation in the temperature of the potatoes were caused by changes in temperature outside the clamp, it would be expected that the temperatures at different positions would rise and fall together, but the most striking feature of the records for March in Fig. 6 is that the temperatures at *N* and *S* tended to change in opposite directions. For example, the sharp fall at *N* on 3 March was accompanied by a rise at *S*, and changes of the same sort were repeated on 13, 18 and 23 March. The reverse effect, a rise at *N* occurring simultaneously with a fall at *S*, was apparent on 8, 10 and 25 March. When the thermograph charts were compared with anemobiagraph records, it was found that these abrupt changes of temperature in the potatoes were correlated with the occurrence of windy periods, and that the nature of the temperature change depended on the direction of the wind. This correlation is demonstrated in Fig. 6. The upper curve in this figure shows the change with time in the component of wind velocity normal to the long axis of the clamp, winds incident on the south face being given a positive sign and northerly winds a negative sign. On occasions when the temperature fell at *N* and rose at *S* (e.g. on 3, 13, 18 and 23 March) there were strong winds blowing on the north face of the clamp, while the opposite effect, a rise of temperature at *N* and a fall at *S* (e.g. on 8, 10 and 25 March), occurred when the wind was blowing on the south face. The variation of temperature at *L* in the middle of the potatoes was smaller than at *N* and *S* and not so clearly related to wind. Usually the changes at *N* and *L* were similar but on some occasions (e.g. 10 March) the *N* and *L* temperatures changed in opposite directions.

The inverse relation between the temperatures at *N* and *S* and its dependence on the direction of the wind can be explained by assuming that wind blowing against the face of the clamp caused cold air to flow from outside through the earth and straw covers; this influx of cold air depressed the temperature at the surface of the potatoes on the side of the clamp towards which the wind was blowing, and by displacing warm air from the middle of the potato heap, raised the temperature at the opposite surface. Evidence in support of this hypothesis that wind caused a flow of air through the clamp covers, obtained from a study of the composition of the atmosphere inside a clamp, will be published in a later paper.

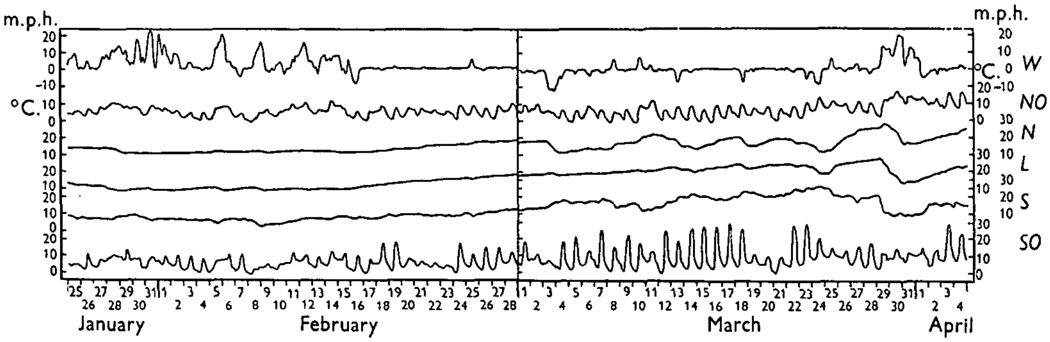

Fig. 6. The effect of wind on the temperature of the potatoes. The figure shows the variation with time of temperature at positions *N*, *L* and *S* in the potatoes and at *NO* and *SO* on the outer surface of the earth cover of the 1942–3 clamp, and of the component of wind velocity normal to the south face of the clamp (*W*), for the period January–April 1943.

Fourteen examples of changes of this type, occurring at the transition from a calm to a windy period, or more rarely at times when the wind changed in velocity or direction, were distinguishable from the thermograph charts between 3 March and 8 April. In all but three of them the wind persisted for less than 24 hr., and the temperature changes were completed within the period. On 29 March to 1 April a different type of variation was found (Fig. 6). After a period of calm, a southerly gale began to blow on 29 March, and continued until the morning of 1 April. At first, changes of temperature similar to those described above were observed: the temperature at *S* began to fall, there was also a slow fall at *L*, and at *N* there was a rise which continued for 6 hr. After that time the temperatures at all three positions fell rapidly to low values which were maintained throughout 31 March. With the cessation of the southerly wind on 1 April, the temperatures at all three positions began to rise. The rise continued until 4 April at *N* and *L*, but at *S* it was completed more rapidly. During the recovery period there were intermittent northerly winds.

The explanation of this sequence of changes appears to be that the strong southerly wind continued for so long that the warm air present in the potato heap was all displaced beyond the north surface, and a cooling of the whole mass of the potatoes followed. The temperature fell more rapidly at S than at L or N, and this can be attributed to the air-stream becoming warmed by passage through the potato heap. After the transition from calm conditions to the period of continuous high wind, about 2 days elapsed before the temperature throughout the heap of potatoes reached approximate equilibrium. The reason for this slow equilibration is, presumably, that the heat capacity of the tubers was very high compared with that of the air flowing through them.

Incidentally, the depression of the temperature of the potatoes during the period 29 March–1 April, which has been shown above to be related to persistent high wind, accounts for the low value of mean temperature for the week beginning 29 March (Fig. 4).

period of the change determined from anemobiagraph records. On this basis of calculation the normal component of winds blowing towards the north face of the clamp had a negative sign. As the long axis of the clamp lay in the direction W.N.W.–E.S.E., the direction normal to the clamp faces along which the wind velocities were resolved was S.S.W.–N.N.E.

Linear and quadratic regression coefficients of rate of temperature change on the normal component of wind velocity are given in Table 3. The linear coefficients for positions N and S were highly significant showing that, in accordance with expectation, the rate of temperature change was closely dependent on the magnitude of the normal wind component. The quadratic coefficients just failed to reach the 5% level of significance; they had the same sign as the linear coefficients for both positions. The fitted regression lines plotted in Fig. 7 passed close to the origin, since no temperature change occurred in the absence of wind, and the signs of the linear regressions therefore indicate that southerly winds depressed the temperature at S and raised it at N, while northerly winds, having a negative normal component, caused a fall of temperature at

Table 3. *Regression coefficients of rate of change of temperature, °C. per hour, at positions N, L and S in the 1942–3 clamp, on the component of wind velocity normal to the south face of the clamp in miles per hour*

Position	Regression coefficients ($\times 10^3$) Linear	Quadratic	Reduction of variance (%)
N	49.5 ± 7.1	0.79 ± 0.40	77
L	-3.8 ± 10.1	-0.30 ± 0.57	0
S	-73.1 ± 13.9	-1.58 ± 0.78	61

So far, it has been shown that the fluctuations of temperature in the potatoes during March 1943 were caused by wind, and that the direction of the wind determined the direction of temperature change. If the hypothesis that the fluctuations of temperature were caused by movement of air into the clamp is correct, the rate of temperature change over a short period after the beginning of a windy period should increase with increase in the air pressure at the clamp surface. The appropriate measure of this air pressure, in terms of wind velocity and direction, is the component of wind velocity normal to the clamp face, for obviously any component tangential to the clamp face cannot be effective in moving air into the clamp. For each of the fifteen examples of rapid temperature change in the period 3 March–8 April (including only the first 6 hr. of the change on 29 March–4 April) the duration of the changes and their magnitudes at N, L and S were read off from the thermograph charts and the mean rates of change were calculated. The normal component of wind velocity ($V \cos \theta$, where V = wind velocity and θ = angle between a line perpendicular to the south face of the clamp and the direction of the wind) was computed from the mean velocity and the direction of the wind during the

S and a rise at N. Within each quadrant of Fig. 7, the magnitude of the rate of change, whether positive or negative, increased with increase in the magnitude

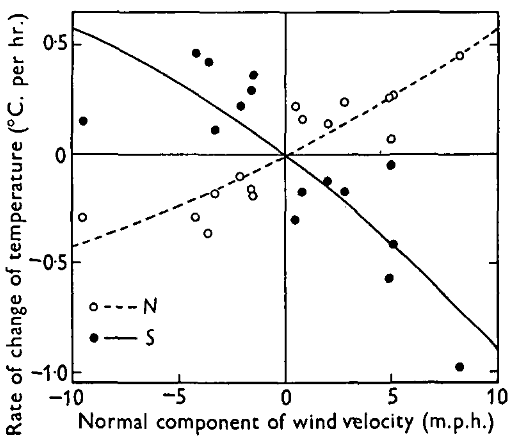

Fig. 7. Rate of change of temperature at positions N and S plotted against the component of wind velocity normal to the south face of the clamp, for fifteen cases of rapid temperature change observed between 3 March and 8 April 1943, and the fitted regression lines (full line, position S; broken line, position N).

of the normal wind component. The difference in the magnitude of the linear coefficients for N and S shows that the effect of wind was not symmetrical on the two sides of the clamp; it had a greater effect on the temperature at S than at N. The curvature of the regression lines, represented by the quadratic coefficients, was such that the magnitude of the rate of temperature change at both N and S varied less rapidly with change in the normal wind component when the latter was negative than when it was positive. This implies that the effect of southerly winds was greater than that of northerly winds at both N and S, but this result is not fully established since the quadratic coefficients were barely significant. As both coefficients for position L (Table 3) were smaller than their standard errors, there is no evidence that the rate of change of temperature at L was dependent on wind velocity.

Although the fluctuations of temperature at N and S during January and February 1943 were much smaller than those in March (Fig. 6) there are indications that they were related to wind in a similar way. For example, the southerly winds on 5 and 8 February were accompanied by a temperature fall at S and a slight rise at N. However, the deviations from smooth trends were too small, especially at N, to allow the time of onset and the duration of the temperature changes associated with a windy period to be determined with any confidence, and consequently it was not possible to compute rates of temperature change and to relate them to wind velocity by the method used for the March–April period.

The discussion has, so far, been based on an examination of the more conspicuous fluctuations of temperature in the potatoes during March and April. In another investigation, which made use of the whole of the temperature records instead of selected parts of them, an attempt was made to account for the deviations of daily mean temperatures at N, L and S from smooth trends by correlation with the wind factor. The daily means of the normal component of wind velocity were determined by making eye estimates of the mean velocity over 3 hr. periods from the anemobiagraph chart, averaging the eight estimates of velocity for the day, and then calculating the mean normal component from mean velocity and mean direction. The latter could usually be read off easily from the chart, because changes in direction within most days were small. For some days on which wide changes of direction occurred, the mean normal component was estimated separately for parts of the day before and after the change, and subsequently averaged. Multiple regressions of daily mean temperature at N, L or S on the daily mean normal wind component and its square, and on the mean temperature of the previous day were then fitted. The regressions on previous day's temperature served merely to eliminate smooth time trends, and need not be discussed here; they were all highly significant and accounted for 50–70 % of the variance of daily mean temperature. Table 4*a* shows that, for positions L and S, the regression on the wind factor accounted for over 50 % of the variance of daily mean temperature remaining after the elimination of trend. For position N the fit was not so good; the regression accounted for only 15 % of the residual variance. The quadratic coefficient for S was small and not significant.

Table 4. *Regression coefficients of deviations from smooth trend of daily mean temperature, in ° C., in the potatoes on daily mean component of wind velocity normal to the south face of the clamp, in miles per hour*

Position	Regression coefficients ($\times 10^3$) Linear	Quadratic	Reduction of variance (%)
	(*a*) 1 March–4 Apr. 1943		
N	223 ± 136	−50 ± 20	15
L	−119 ± 74	−49 ± 10	56
S	−397 ± 73	−17 ± 10	59
	(*b*) 16 May–3 July 1944		
N	31 ± 27	−2·9 ± 2·9	4
M	−39 ± 16	−5·8 ± 1·8	18
S	−83 ± 32	−5·0 ± 3·5	10

The fitted regression lines, showing the effect of change in the normal component of wind velocity when the previous day's mean temperature was held constant at its mean value, are plotted in Fig. 8. At position S on the south face of the potato heap, the temperature increased with increase in northerly wind and decreased with increase in southerly wind over the whole range of the normal component. The temperature at L in the middle of the heap was depressed by both northerly and southerly winds. At N on the north surface, the temperature fell with increasing northerly wind, and rose with increasing southerly wind to a maximum when the normal component was 2·5 m.p.h., but subsequently fell again when the normal component increased to higher values. This fall of the regression line for N at high positive values of the normal wind component was determined by the changes which occurred on 29–31 March, when the persistent southerly wind eventually caused a depression of temperature at N as well as L and S, after an initial rise at N. There was no comparable instance during the period of a northerly wind persisting long enough to cause a reversal of the change of temperature at S. The more uniform effects of northerly wind on the temperature at S than of southerly wind on the temperature at N accounts both for the better fit of the regression on wind velocity, and for the smaller curvature of the regression line, for S than for N.

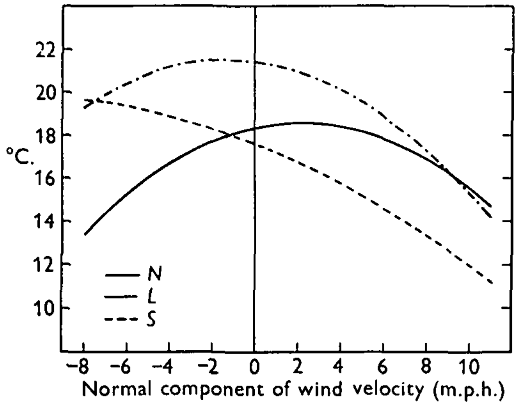

Fig. 8. Regression lines relating daily mean temperature at positions N, L and S in the potatoes of the 1942–3 clamp to the daily mean component of wind velocity normal to the south face of the clamp, for the period 1 March–4 April 1943. (The temperature of the previous day is held constant at its mean value.)

A similar analysis was done on mean daily temperature during January and February 1943, but the regresssion coefficients on the wind factor were not significant.

Having established that the large fluctuations of temperature in the potatoes during March 1943 were caused by variation in the direction and velocity of the wind, it is now necessary to explain why wind effects were absent, or, if they existed, were so much smaller during the earlier part of the storage period. It is clear from Fig. 6 that the absence of large temperature fluctuations during January and February cannot be attributed to lack of variation in the wind factor; on the contrary, the normal component of wind velocity varied widely from day to day during January and early February, and winds of high velocity occurred even more frequently than in March. It follows, therefore, that at some time towards the end of February the sensitivity of the temperature of the potatoes to wind was greatly increased. The time when this change took place cannot be fixed precisely, because there was a long period of calm weather between 17 February and 3 March. As the short spell of southerly wind on 25 February (Fig. 6) caused a much smaller temperature disturbance than comparable winds in March (e.g. on 8 and 10 March), it seems likely that the change in sensitivity occurred between 25 February and 3 March. The magnitude and direction of the temperature changes has been shown to agree with the hypothesis that wind affected the temperature of the potatoes by causing a flow of air through the clamp coverings. If this is true, the effect of wind should depend on the resistance of the coverings to the movement of air through them, and the increase after the end of February in the sensitivity of temperature to wind may have been due to a decrease in the resistance. Support for this explanation and a clue to its cause is provided by the weekly rainfall record in Fig. 2. There was heavy rainfall throughout December, January and the first 2 weeks of February, but the 5 weeks beginning on 15 February onwards were almost rainless. The soil cover of the clamp was probably saturated with water until the middle of February, but afterwards it must have lost water rapidly. It is reasonable to suppose that the saturated soil was almost impermeable to the passage of air through it, but that a large decrease in resistance to air flow occurred abruptly when the drying of the soil had proceeded so far that the larger pore spaces were emptied of water sufficiently to create continuous air channels through the soil. Apparently the critical water content was reached at the end of February. It is possible that the critical stage was determined by the formation of cracks in the drying soil, rather than by the emptying of the pore spaces. No cracks were seen at the end of February, but small ones may have been present though they escaped observation; no special search was made for them as their possible importance was not appreciated until later. During the fortnight beginning on 22 March, 0·7 in. of rain fell (Fig. 2), but apparently this did not wet the soil sufficiently to cause a detectable decrease in the effect of wind.

It has been assumed that wind affected the temperature of the potatoes by causing air to flow through the clamp coverings, and consequently that the component of wind velocity tangential to the clamp face had no effect. An attempt was made to test this for the period 1 March–4 April, by fitting multiple regressions on the tangential component in addition to the normal component. Unfortunately it was inconclusive, because the distribution of winds was such that the normal and tangential components were correlated.

A survey of the 1943–4 records showed no obvious dependence of the fluctuations of temperature in the potatoes on wind until very late in the storage period. Between November and mid-April, while all three clamps were covered with soil, the deviations from smooth trends were small. In clamp *C* which continued to retain its soil cover, they became larger in May and June and showed a relation to wind similar to that found during March 1943. In 1943, the change in sensitivity to wind occurred suddenly at and July was obscured by the diurnal temperature wave that developed after the soil cover was removed.

The changes in temperature at positions *N*, *M* and *S* in clamp *C* and in the component of wind velocity normal to the south face of the clamp during

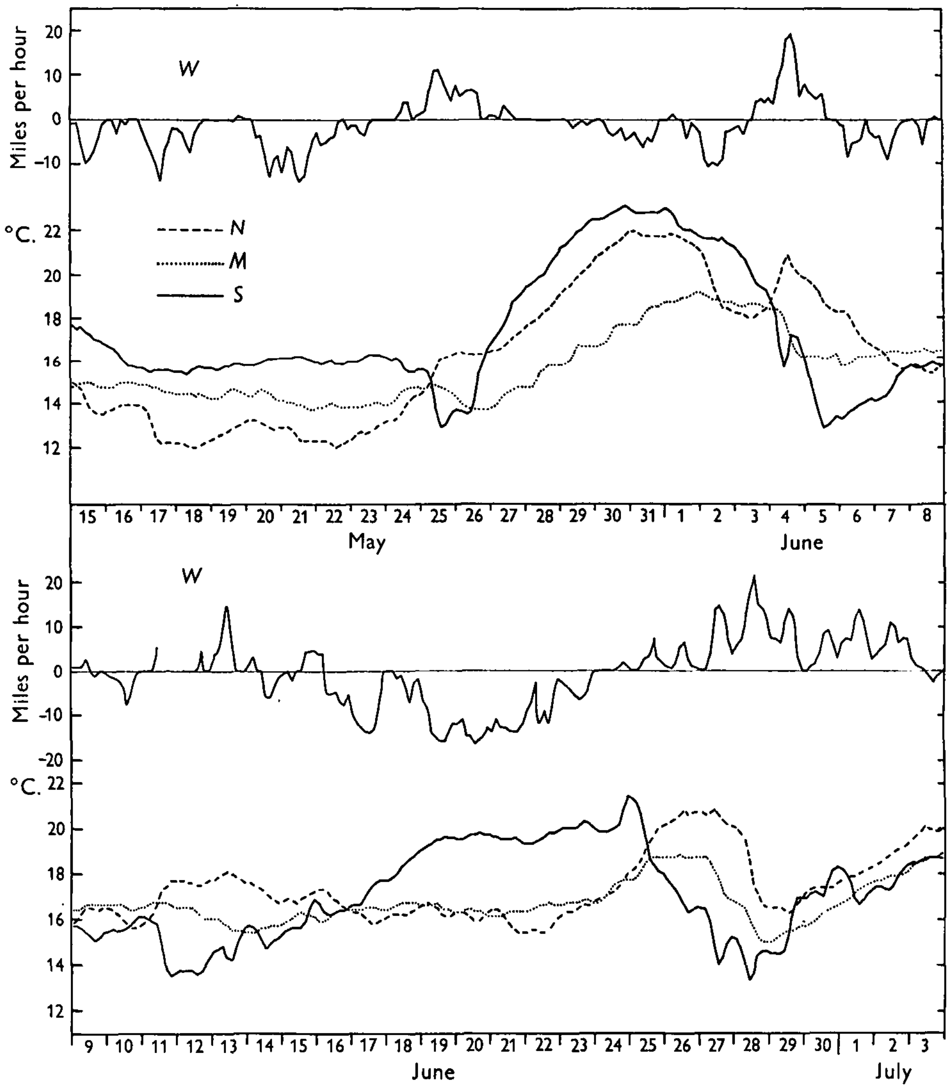

Fig. 9. The effect of wind on the temperature of the potatoes. The figure shows the variation with time of temperature at positions *N*, *M* and *S* in the potatoes of clamp *C*, 1943–4, and of the component of wind velocity normal to the south face of the clamp (*W*), for the period 15 May–3 July 1944.

the end of February, and this has been attributed to the drying of the soil cover during the period of very low rainfall beginning in the middle of February. There was a similar, though shorter, dry period in March 1944 (Fig. 3), but there was no evidence that this caused an abrupt change in sensitivity to wind. Any effect that wind may have had on the temperature of the potatoes in clamps *A* and *B* between mid-April the last 7 weeks of the storage period in 1944 are shown in Fig. 9. With the onset of a southerly wind (e.g. on 25 May, and on 3, 11 and 27 June) the temperature at *S* began to fall, while at *N* there was a rise. Northerly winds (e.g. on 17 and 20 May, and on 2, 10 and 16 June) had the reverse effect, depressing the temperature at *N* and raising it at *S*, but the effect of northerly wind at *S* was small compared with that of southerly wind at N. The changes at M were not consistent, but usually there was a fall with both northerly and southerly winds. In general, the relation between temperature and wind was the same as in March 1943, but the magnitude of the temperature changes was smaller, and the temperature at S was much less affected by northerly wind than in 1943. The effects of the prolonged southerly wind observed in 1943 between 29 March and 1 April (p. 208) were matched in 1944 between 24 and 29 June. The initial rise of temperature at N beginning on 24 June was reversed after the southerly wind had continued intermittently for 3 days, and during 28 and 29 June there was a rapid fall of temperature throughout the potatoes.

The most conspicuous temperature change in Fig. 9, the rise and fall between 26 May and 3 June, was not attributable to wind, for the temperatures at all three positions were affected similarly, though the change was smaller and reached its maximum later at M than at N and S. It was caused by a sudden temporary increase in external air temperature (Fig. 5). During this period the temperatures at N and S were both much in excess of that at M. This also occurred on 30 June and 1 July at the beginning of another period of rising temperature, and the reverse effect, with a higher temperature at M than at N or S, was apparent between 7 and 11 June after a fall in external air temperature to a minimum on 6 June. At other times during the period covered by Fig. 9, the temperature at M was intermediate between those at N and S. The point to be noted here is that the whole of the variation in the temperature differences between N, M and S cannot be attributed to changes in wind; part of it was the result of the greater effect of rapid change in external air temperature on the temperatures at the outer surfaces of the potatoes than in the middle of the heap.

Regression coefficients of daily mean temperature at N, M and S on the daily mean normal component of wind velocity and its square, after eliminating trend by a regression on mean temperature of the previous day, were calculated for the period 16 May–3 July 1944 (Table 4*b*). The coefficients had the same signs as the corresponding ones for March 1943 (Table 4*a*), but all were smaller, and the regressions accounted for a smaller fraction of the variance remaining after the elimination of trend. For position N, neither the linear nor the quadratic coefficient was significant. Regressions calculated in a similar way for earlier periods in 1943–4 were not significant. These results confirm the conclusion of the previous section, namely that there was the same general relation between temperature and wind in both years, but that the effects found were much greater in 1943 than in 1944.

The difference between the two seasons in the sensitivity of the temperature of the potatoes to wind may be attributed to the much higher temperature of the potatoes in 1943 caused by the rotting of the tubers, and to the greater difference between the temperatures at the middle of the potato heap and the outer surfaces in 1943 than in 1944. The mean temperature at position L in the period 1 March–4 April 1943 exceeded that of the external air by 14·2°; for the period 16 May–3 July 1944, the difference in mean temperature between position M and the external air was only 3·6°. The temperature differences between the middle and the outer surfaces of the potato heap for the same periods were:

1943	$L-S$	3·4°	$L-N$	3·2°
1944	$M-S$	0·9°	$M-N$	0·0°

It follows from these figures that the passage of a given amount of external air into the clamp would be expected to cause a greater fall of temperature in the potatoes at the surface towards which the wind was blowing, and a greater temperature rise at the opposite side, in 1943 than in 1944.

So far it has been shown that the temperature of the potatoes was dependent on wind during the later part of the storage period, but the existence of a similar relation in the early stages of storage has not been demonstrated. As the characteristic feature of the wind effect was that the temperature changes at opposite sides of the clamp were of opposite sign, it seemed probable that the most sensitive test of the existence of wind effects might be obtained by correlating the temperature differences between the various positions in the potatoes with wind variates. Table 5 shows the regression coefficients of differences in daily mean temperature between pairs of positions on the daily mean normal component of wind velocity. Wind velocities normal to the north and south faces of the clamp were treated as separate variates in this analysis; previously the normal component was treated as a single variate by giving components with a northerly direction a negative sign. The regression coefficients on 'north component' in Table 5, therefore, show the change in the daily mean temperature differences associated with an increase of 1 m.p.h. in the normal component for winds blowing from the north, and the coefficients on 'south component' show the changes associated with winds blowing from the south. As temperature changes external to the clamp affected the temperature at all positions in the potatoes similarly, it was not thought necessary to eliminate time trend in comparing the regression coefficients of the temperature differences.

If, as has been suggested, wind affects the temperature of the potatoes by causing cold air to enter the clamp and displace warm air from the centre towards the side remote from that on which the wind was blowing, it would be expected that a southerly wind would lower the temperature at S relative to that at the middle of the potatoes (position L in 1942–3, and M in 1943–4), and at L or M relative to that at N, so that the regression coefficients of the differences L (or M)$-S$ and $N-S$ on the south component of wind velocity would be positive, while that of L (or M)$-N$ would be negative, and the corresponding coefficients on the north component would have the opposite signs. The regression coefficients for clamp C in the period 13 April–3 July 1944 (Table 5) conformed with this pattern; the coefficients of the difference $M-N$ were not individually significant, though together they accounted for a significant fraction of the variance of $M-N$. For clamps A and B in the same period, after the removal of their soil cover, all the coefficients were small compared with their standard errors, and there is no evidence that wind had any effect. The coefficients for the 1942–3 clamp in the period 1 March–4 April were all of the expected sign, except that for $L-N$ on the north component, which was considerably smaller than its standard error; with this exception all the coefficients had a much larger magnitude than the corresponding ones for clamp C in the later period of 1943–4. Though the coefficients of the differences $L-N$, $L-S$ and $N-S$ on the north component, and of $L-S$ on the south component were not individually significant, the multiple regression on north and south components accounted for a significant fraction of the variance of all three temperature differences.

The results for the earlier stages of the storage period were less consistent. The regressions on the south component for the period 23 November 1943–12 April 1944 were significant and of the expected sign for all differences between positions in all three clamps. None of the regression coefficients on the north component were significant, but those for clamps A and B were of the expected sign. It may be concluded that southerly winds affected the temperature in the potatoes, in a manner consistent with the assumption that they caused a flow of air into the clamp, but northerly winds either had no effect or a very much smaller effect.

Table 5. *Regression coefficients of differences in daily mean temperature in ° C. between the middle* (L, 1942–3, M, 1943–4) *and north and south outer surfaces* (N *and* S) *of the potato heap, and between* L *and* U (1942–3) *on the mid-line of the clamp, on daily mean components of wind velocity normal to the north and south faces of the clamp in miles per hour*

		Mean	Regression coefficients (×10³) on: North component	South component	Reduction of variance (%)
		1942–3. 11 Dec. 1942–28 Feb. 1943*			
	$L-N$	−1·10	−137± 73	−149± 33	19
	$L-S$	3·35	−65±116	−220± 53	16
	$N-S$	4·44	72±148	−71± 68	0
	$L-U$	1·37	−47± 51	−119± 23	24
		1 Mar.–4 Apr. 1943†			
	$L-N$	3·16	−64±270	−907±201	36
	$L-S$	3·39	−494±274	355±203	16
	$N-S$	0·23	−429±505	1262±376	27
	$L-U$	3·38	−285±124	−417± 92	35
		1943–4. 23 Nov. 1943–12 Apr. 1944‡			
Clamp A	$M-S$	0·78	−15± 24	49± 22	3
Clamp B	$M-N$	1·95	36± 27	−89± 26	11
	$M-S$	0·43	−7± 32	66± 30	3
	$N-S$	−1·52	−43± 29	154± 28	23
Clamp C	$M-N$	0·58	11± 19	−72± 18	12
	$M-S$	−0·23	15± 30	63± 28	2
	$N-S$	−0·82	4± 29	135± 28	15
		13 Apr.–3 July 1944§			
Clamp A	$M-S$	−0·85	85± 74	51± 94	0
Clamp B	$M-N$	0·30	−43± 57	50± 73	0
	$M-S$	−0·33	65± 60	77± 77	0
	$N-S$	−0·63	108± 84	26±107	0
Clamp C	$M-N$	−0·17	77± 43	−88± 55	9
	$M-S$	−1·47	−113± 57	215± 71	18
	$N-S$	−1·30	−190± 60	303± 76	33

* 80 days.
† 35 days.
‡ 138 days; no records for 1–4 April. All clamps covered with soil.
§ 78 days; no records for 5–8 May. Soil removed from clamps A and B, but retained on clamp C.

The results for the 1942–3 clamp in the early part of the storage period (11 December 1942–28 February 1943) followed a different pattern. As in the corresponding part of the 1943–4 storage period, northerly winds could not be shown to have any effect. None of the regression coefficients of the differences $L-N$, $L-S$ and $N-S$ on the north component were significant, but it should be noted that the first two were negative. The regression coefficients of $L-N$ and $N-S$ on the south component were both significant and negative, while that of $N-S$ was small and far from significance. These results indicate that wind, whether from north or south, lowered the temperature at both surfaces of the potato heap relative to that at the middle, but the effect of southerly winds was greater than that of northerly winds. No satisfactory explanation of these results, and of the difference between them and the results for other periods, has been found. They might be explicable if wind from either north or south depressed the temperature in the soil cover on both sides of the clamp, but it will be shown later that this was not so.

Table 5 also shows that the gradient of temperature in the vertical plane passing through the ridge of the clamp, as measured by the temperature difference between positions L and U in 1942–3, was reduced by wind, southerly winds having a greater effect than northerly winds.

The successive stages of the analysis of wind effects have consistently indicated that southerly winds had a greater effect on the temperature of the potatoes than northerly winds, and this is especially well shown in Table 5. This difference, like that between the early and late stages of storage, may have had its origin in a difference in the permeability of the clamp coverings, and if so it would imply that the soil cover on the north side of the clamp was less permeable to the passage of air than that on the south side. As the south surface of the clamp was exposed directly to solar radiation, while the north side was shaded from the sun and received radiation only from the sky and surrounding objects, evaporation from the soil must have been more rapid on the south side than on the north. It is, therefore, probable that the soil cover on the south face consistently had a lower water content than that on the north face, and was more permeable to air, except immediately after periods of heavy rain.

(2) *Temperature in the clamp coverings*

Temperature changes in the clamp coverings do not affect the storage behaviour of the potatoes directly. They are chiefly of interest because they throw light on the heat exchanges of the clamp, for obviously the temperature of the potatoes depends ultimately on loss or gain of heat through the coverings. Data are available only for 1942–3, for the period between the application of the earth cover on 7 December 1942, and the collapse of the clamp on 27 April 1943. It is clear from Fig. 2 that the diurnal temperature wave was a dominant feature of the records for the earth cover, accounting for a large fraction of the temperature variation. The following discussion is, therefore, based on an examination of the variation in daily maximum and daily minimum temperatures, which takes into account both long-period time-trends of temperature and the diurnal deviations from this trend.

(*a*) *Temperature at the outer surface of the earth cover*. Weekly means of the daily maximum and minimum temperatures at positions NO and SO on the outer surfaces of the earth cover and in the air are given in Fig. 10. The daily maximum at SO was nearly equal to that of the air until mid-January, at which time the weekly means of both were about 8°. Subsequently they diverged, the maximum temperature at SO rising more rapidly than that of the air until, in mid-March, the weekly mean for SO was over 22° while that for the air was only 10°. Later the difference between them narrowed slightly, but in April it increased to 15°. The daily maximum at NO was consistently less than that of the air by about 1° from December until the end of March. At this time the weekly mean for the air was 13°. The daily maximum at NO then rose steadily above that of the air until at the end of April they differed by about 6°.

The daily minimum temperatures at NO and SO and that of the air were nearly equal throughout the period from December to March, and the small differences between them were not consistently of the same sign. In April the daily minimum at NO rose slightly above the others.

A summary of the changes in daily mean temperature and daily temperature range at NO and SO, associated with the time-drifts of daily maximum and minimum temperatures described above, is given in Table 6. The daily means at NO and SO were lower than that of the air except in March and April when the mean at SO rose above that of the air. The daily range at NO was consistently less than that of the air, but at SO it was greater, and the difference in range between SO and the air became very large in March and April.

This sequence of temperature changes is very similar to that which occurs at the surface of a fallow field soil at Rothamsted. Penman (1943) has shown that during the winter months the daily maximum and minimum temperatures at a horizontal soil surface are approximately the same as those of the air. Air temperature is apparently determined by the soil-surface temperature in the same neighbourhood, for the diurnal wave of the latter is in phase with solar radiation, the maximum temperature occurring at mid-day, while maximum air temperature lags behind maximum solar radiation.

When the air and soil surface maxima rise above about 52° F. (11° C.) in spring, the soil-surface maximum begins to increase about twice as rapidly as the air maximum, and the same relation holds for the minimum temperatures. During the summer months, the soil-surface maximum is therefore much above the air maximum, while the soil-surface minimum is only slighly above the air minimum. Thus, the daily mean and daily range at the soil surface are much greater than in the air. The divergence between soil surface and air temperatures is associated with drying of the soil surface. Penman showed that the year can be divided into two periods, a winter period during which the monthly mean maximum air temperature falls below 55° F.,* and a summer period during which it exceeds 55° F., the transitions between the periods occurring in April and October. The winter period, so separated, corresponds to the period during which evaporation form the soil is equal to that from an open water surface, while the summer period corresponds to the

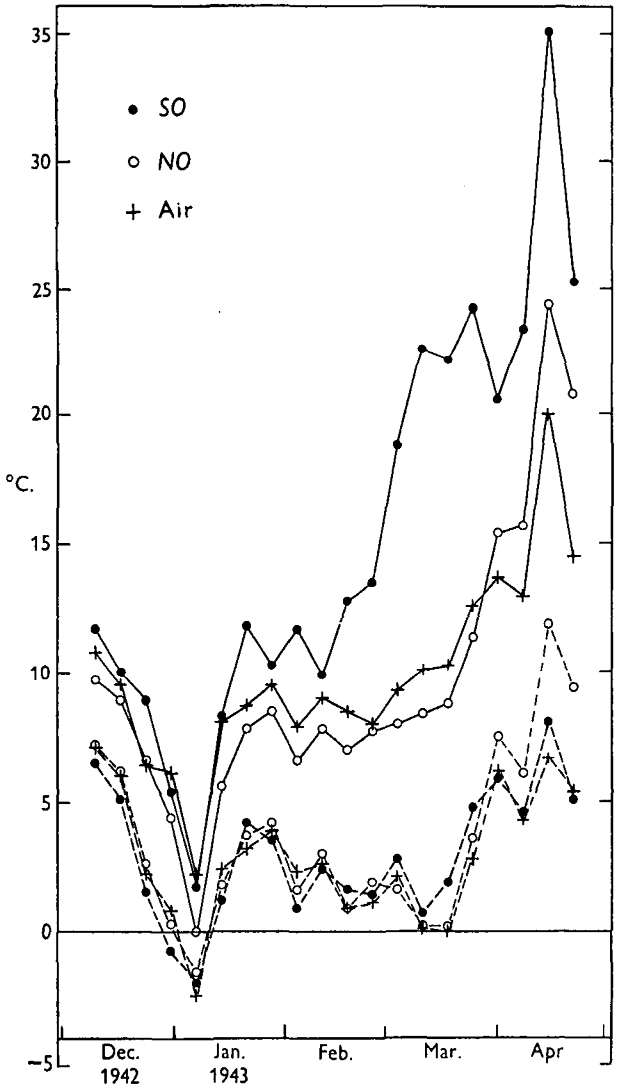

Fig. 10. Change with time in the weekly means of daily maximum temperature (full lines) and of daily minimum temperature (broken lines) at positions *SO* and *NO* on the outer surfaces of the earth cover of the 1942–3 clamp, and of the air.

* Note that the critical temperature used by Penman for the division of the year differs slightly from the threshold for the divergence of air and soil temperatures (52° F.) The reason is not stated in Penman's paper, but presumably it is implied that the threshold is not sharply defined.

period during which evaporation from the soil is less than that from an open water surface because the surface soil is dry except immediately after rain. A much smaller fraction of the radiant energy absorbed at the soil surface is therefore used as latent heat of vaporization of water in summer than in winter, and a larger fraction remains to raise the temperature of the soil. The divergence between air and soil-surface maxima in summer is presumably due to increased convection, that is, the heat transferred from soil to air is distributed over a larger volume of air in summer than in winter, and the rise in air temperature is correspondingly restricted. The apparent discontinuity in the relation between air and soil-surface temperatures occurring at about 11° may be explained by assuming that the transition from stable to less stable air conditions is rather abrupt.

At position *SO*, the divergence of the air and soil-surface maxima occurred earlier in the year and at a lower temperature than at the horizontal soil surface studied by Penman; it began in January instead of April, when the mean maximum temperature was 8° instead of 11°. Presumably the soil on the south face of the clamp tended to dry out earlier than the horizontal surface of a field soil because the angle of incidence of solar radiation at the tilted clamp face was nearer to the normal, so that the energy absorbed per unit area of the clamp surface was greater than at a horizontal surface. The greater exposure and better drainage of the clamp coverings would also encourage more rapid drying.

On the other hand, although the north face of the clamp did not receive any direct radiation from the sun until mid-April, the rise of the soil surface maximum at *NO* above the air maximum began at the end of March, though the threshold temperature at the divergence, 13°, was higher than the threshold found by Penman. The early divergence may have been due to drying of the clamp surface in the almost rainless period between mid-February and the end of March (Fig. 2).

(*b*) *Temperature at the inner surface of the earth cover, and outer surface of the straw cover.* Records for positions *SEI* and *SSO* on the south side of the clamp (Fig. 1) are available for the period from mid-January to April 1943. Weekly means of the daily maximum and minimum temperatures at these positions, and at *SO* and *S* for comparison, are plotted in Fig. 11. Until mid-February the maxima at *SEI*, *SSO* and *S* were very similar, and all about 5° below the maximum at *SO*. Later the maxima steadily increased with time at all positions. The maxima at *S* and *SSO* rose above that at *SEI* except during the short period of very high temperatures in mid-April, but remained below the maximum at *SO*. Thus, in March and April there was a large difference, of the order of 8–10°, between the maxima at the outer and inner surface of the soil cover, and a much smaller difference of 2–3° across the straw cover.

Throughout the whole storage period the minimum temperatures at *S* and *SSO* differed by not more than 3°. Both greatly exceeded the minimum at *SEI*, which in turn was higher than that at *SO*. Daily mean temperature (Table 6) increased slightly across the earth cover from *SO* to *SEI*, rose sharply between *SEI* and *SSO* at the junction between the earth and straw, and showed a further small increase across the straw cover from *SSO* to *S*. The daily temperature range decreased across the earth cover between *SO* and *SEI*, while it differed little between the two sides of the straw cover, being slightly less at *SSO* than at *S*; again there was a sharp discontinuity at the junction of the earth and straw layers. Evidently the temperature conditions were fairly uniform throughout the straw cover, and differed greatly from those at the inner face of the earth cover. The nature of these temperature variations will be made clearer when the diurnal temperature fluctuations are discussed (p. 220).

(*c*) *Effect of wind.* As the temperature of the potatoes has been shown to be dependent on wind, at least in the later stages of storage, an examination was made by the same procedure to see whether the temperatures in the clamp coverings were similarly affected. Multiple regressions of daily mean temperature at positions *SO*, *NO*, *SEI* and *SSO* on the daily mean normal component of wind velocity and its square, after eliminating time trend by a regression on mean temperature of the previous day, were calculated for the period 1 March–4 April 1943 (Table 7).

The regressions on the wind velocity variates for position *SSO* accounted for a significant fraction, over 50 %, of the residual variance remaining after the elimination of trend, and the magnitude and signs of the coefficients were similar to those for position *S* (Table 4*a*). For the other positions, the coefficients were all far from significance except for the quadratic coefficient for position *NO*, and this was opposite in sign to that for position *N* (Table 4*a*). Thus, wind produced similar variations of mean temperature at *SSO* and *S*, but there is little evidence of any wind effects at positions in the earth cover; if they existed they were clearly of a different nature from those at the surface of the potatoes. It is to be noted, particularly, that the coefficients for *SEI* were much smaller than those for *SSO* on the opposite side of the earth/straw interface, and that while highly significant effects were found at *SSO*, no effect of wind on daily mean temperature could be demonstrated at *SEI*. This is a further example of the uniformity of temperature conditions within the straw cover, and of discontinuity at the junction between straw and earth covers.

Regressions of daily temperature range at *NO*, *SO* and *SEI* on the normal component of wind velocity and its square were computed for the same period, and were found to be significant for all three positions. The regression lines had maxima near to zero normal wind component, and were nearly symmetrical about zero, showing that all winds reduced the daily temperature range in the earth cover at both faces of the clamp, and that northerly and southerly winds with numerically equal normal components had effects of about the same magnitude. This result suggested that the effect of wind on the temperature of the earth cover was independent of wind direction. Accordingly, linear regressions of daily mean temperature, and daily temperature range at positions *NO*, *SO* and *SEI* on daily mean wind velocity, ignoring its direction, were computed for two periods in 1943 (Table 8).

In both periods daily mean temperature at *NO* and in the air increased with increase in wind velocity, but at *SO* and *SEI* the coefficients were not significant, and three of the four were negative. All the regression coefficients of daily range were negative, but those for the early period were not significant. The coefficient for *SO* was greater than those for other positions in both periods. The magnitude of all the coefficients was greater in the second period than the first.

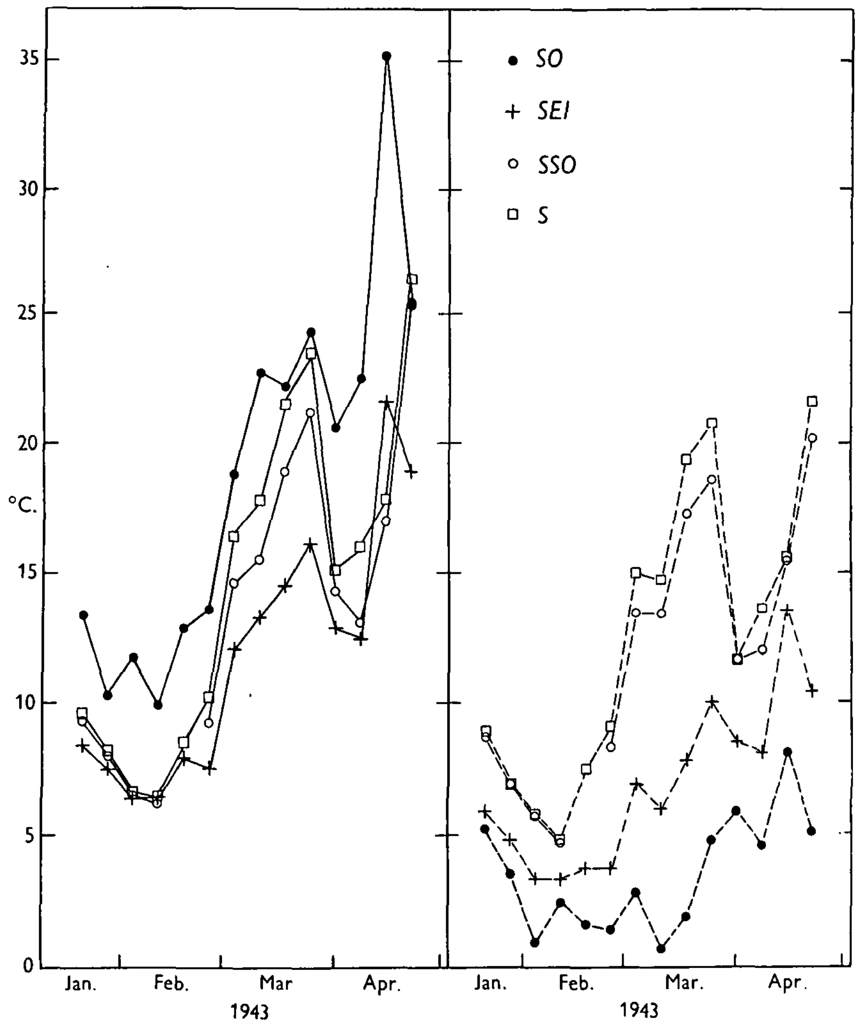

Fig. 11. Change with time in the weekly means of daily maximum temperature (full lines) and of daily minimum temperature (broken lines) at positions *SO*, *SEI*, *SSO* and *S* on the south side of the 1942–3 clamp.

Since daily mean temperature was estimated as the mean of daily maximum and minimum, and daily range is the difference between maximum and minimum, the regression coefficients of daily maximum on wind velocity could be determined by adding half the coefficient of daily range to the coefficient of daily mean. Similarly, the coefficient for daily minimum was obtained by subtracting half the daily range coefficient from the daily mean coefficient. The coefficients for daily maximum and daily range so determined are given in Table 8. Their standard errors cannot be computed from those of the coefficients of daily mean and range, but it was not thought necessary to calculate them directly, as the results were consistent and clear. The daily minimum at all positions in both periods increased with increase in wind velocity. The daily maximum at *NO* and in the air also increased, but to a less extent than the daily minimum. The daily maxima at *SO* and *SEI*, on the other hand, were depressed by increased wind velocity. These effects of wind on temperature at *NO* and *SO* can be recognized in Fig. 6.

The effect of wind on minimum temperature has an obvious explanation. On calm nights there is a temperature inversion in the lower layers of the atmosphere, because the soil surface losses heat by radiation and cools the air overlying it. Wind dissipates the inversion by replacing and mixing the cold air near the soil surface with warmer air from higher levels. This accounts for the rise in minimum air temperature (measured in the standard screen 4 ft. from the ground) with increasing wind. The influx of warm air close to the soil surface supplies part of the heat lost by radiation and so reduces the temperature fall at the soil surface, and this explains the effect of wind in raising the minimum temperature at *SO* and *NO*.

During the day, the south face of the clamp absorps solar radiation, and its temperature rises above that of the air (Fig. 10). It would be expected that air movement would increase the heat exchange between the soil surface and the air, and so reduce the temperature rise at the soil surface. Air movement may also cause an increase in evaporation from the soil surface, and this again would tend to reduce the temperature rise. Both effects may be involved in the depression of maximum temperature at *SO* by

Table 6. *Mean temperatures and mean daily temperature ranges, ° C., of the air and at different positions in the clamp coverings for three periods in* 1942–3

	Mean temperature						Mean daily range					
Period	Air	*NO**	*SO**	*SEI*	*SSO*	*S*	Air	*NO*	*SO*	*SEI*	*SSO*	*S*
7 Dec. 1942–17 Jan. 1943	4·9	4·4	3·1	—	—	7·4	4·5	3·1	5·7	—	—	1·9
18 Jan.–28 Feb. 1943	5·5	5·0	4·9	5·7	7·3	7·6	6·3	5·0	9·3	3·2	1·0	1·1
1 Mar.–11 Apr. 1943	7·0	6·7	9·5	10·7	15·3	17·1	8·9	8·1	18·4	5·6	1·9	2·5

* Estimated from the mean of daily maximum and minimum temperatures and corrected for bias by the regression on daily range given in Table 1.

Table 7. *Regression coefficients of deviations from smooth trends of daily mean temperatures, ° C., at various positions in the clamp coverings, on wind velocity normal to the south face of the clamp in miles per hour, for the period* 1 *March*–4 *April* 1943

	Regression coefficients (× 10³)		Reduction of variance
Position	Linear	Quadratic	(%)
SO	−41 ± 193	−12 ± 27	−5
NO	103 ± 114	37 ± 16	19
SEI	−140 ± 104	1 ± 14	0
SSO	−319 ± 64	−8 ± 9	52

Table 8. *Regression coefficients of daily mean temperature, daily temperature range, daily maximum and minimum temperatures at positions in the earth cover of the clamp, and in the air, on wind velocity. ° C. per m.p.h.* (× 10³)

Position	Mean	Range	Maximum	Minimum
		(*a*) 20 Jan.–28 Feb. 1943		
NO	130 ± 63	−14 ± 54	123	137
SO	−22 ± 87	−268 ± 159	−156	112
SEI	24 ± 60	−53 ± 52	−2	50
Air	186 ± 72	−161 ± 81	106	266
		(*b*) 1 Mar.–4 Apr. 1943		
NO	478 ± 105	−171 ± 79	392	564
SO	−153 ± 145	−952 ± 275	−629	323
SEI	−89 ± 96	−354 ± 105	−266	88
Air	267 ± 87	−324 ± 148	105	429

increased wind velocity. However, it is difficult to understand why the air maximum should be raised by wind, for though more heat is likely to be lost to the air from soil surfaces heated by the sun on windy days than on calm days, the volume of air to which it is transferred is probably much greater, so that the temperature rise of the air would be expected to be less. The most probable explanation of the rise of the air maximum with increasing wind velocity seems to be that the moving air masses that constitute a wind have previously passed over the sea, and during the winter and spring they tend to have a higher temperature than the air overlying the land which they displace. If this explanation is correct, it may also account in part for the rise of the air and soil surface minima with increasing wind. The rise of maximum temperature at *NO* on the north face of the clamp, which received no direct solar radiation in the period under discussion, was presumably a consequence of the rise in the maximum temperature of the ambient air.

The effects of wind on the temperature at position *SEI* may be assumed to be a consequence of the changes at *SO*; they were smaller than at *SO* because the amplitude of the diurnal wave diminished in its passage from the outside to the inside of the soil cover.

(3) *The diurnal temperature wave*

The sequence of temperature change in a clamp during a 24 hr. period is illustrated in Fig. 12. To smooth out the minor fluctuations that occur on individual days the average changes for a period of 7 days have been plotted. The particular days selected, 12–18 March 1943, were near the end of the storage period and were almost continuously sunny throughout the hours of daylight (the mean number of hours of bright sunshine per day was 7·2), so that the amplitude of the diurnal wave was as wide as possible (see Fig. 6). For each recording position, the temperatures at successive hours of the day were read off from the thermograph charts and the seven values for each hour were averaged. Smooth curves were then drawn through the mean values.

The temperature at *SO* began to increase immediately after sunrise, and the rise continued

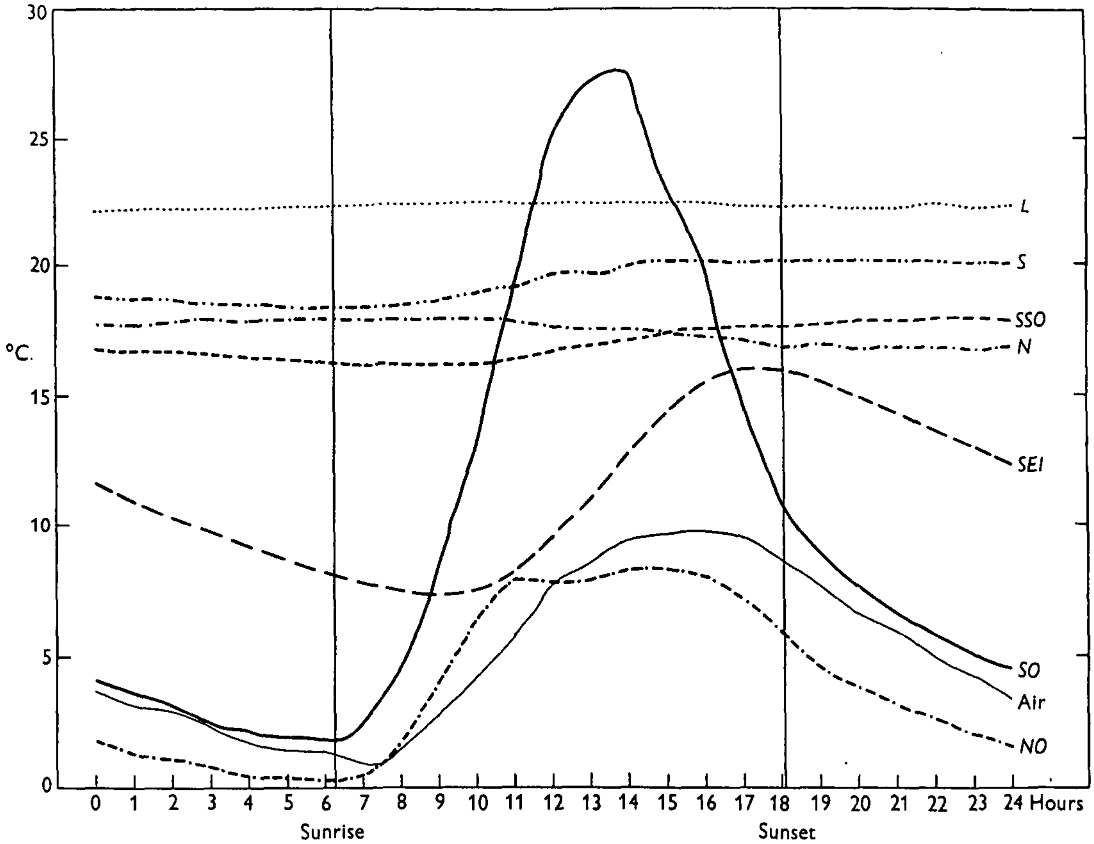

Fig. 12. Diurnal variation of temperature at various positions in the 1942–3 clamp and its coverings, and in the air; average for the 7 days, 12–18 March 1943.

throughout the morning to a maximum at about 14.00 hr. With decreasing solar radiation during the afternoon the temperature began to fall. The fall continued throughout the hours of darkness, but more slowly than in the afternoon; there was a well-marked point of inflexion at sunset. The temperature at *SO* was about 9° higher at sunset than at sunrise.

a rise at *S* and a fall at *N*, was caused by the prevailing northerly winds which increased in velocity during the morning and early afternoon and died away at night on each day of the period averaged in Fig. 12. The mean components of wind velocity normal to the south face of the clamp for successive 3 hr. intervals, averaged for the 7 days 12–18 March were:

Interval ...	01·00–03.00 hr.	03.00–06.00 hr.	06.00–09.00 hr.	09.00–12.00 hr.	12.00–15.00 hr.	15.00–18.00 hr.	18.00–21.00 hr.	21.00–24.00 hr.
Mean normal component, m.p.h.	−0·2	−0·2	−0·3	−1·4	−2·0	−2·5	−0·7	−0·4

Between midnight and sunrise, air temperature was very close to the temperature at *SO*, but it continued to fall for an hour after sunrise. During the morning, the difference between *SO* and the air steadily widened. Air temperature showed a much more flattened peak than the temperature at *SO*, and its maximum occurred about 16.00 hr., 2 hr. later than the maximum at *SO*. After sunset the temperatures at *SO* and in the air again approached each other closely. Air temperature was ½–1° below the temperature at *SO* throughout the hours of darkness.

The form of the diurnal temperature wave at *SO* and its relation to the air wave were similar to those described by Penman (1943) for the horizontal surface of a fallow soil in summer. The occurrence of the minimum at *SO* at sunrise and the maximum soon after noon shows that the temperature rise at *SO* was determined by solar radiation. The lag of the air minimum and maximum behind those of solar radiation is evidence of the dependence of air temperature on soil-surface temperature.

The minimum and maximum temperatures at *NO* occurred slightly later than those at *SO*, but were well in advance of the air minimum and maximum. Also, the morning rise of temperature was more rapid at *NO* than in the air, so that between 08·00 and 12.00 hr. the temperature at *NO* exceeded that of the air. These facts suggest that the heating and cooling of the soil surface on the north side of the clamp, which was shielded from direct solar radiation, was controlled by radiation from surrounding objects and from the sky, and was not determined by the temperature variation in the ambient air.

The temperature wave was greatly damped in its passage across the earth cover of the clamp. At *SEI* on the inner surface the amplitude of the wave was only about one-third as great as at *SO* on the outer surface. There was a lag of about 3 hr. between the minima at *SO* and at *SEI*, and a similar interval between the maxima.

There was no trace of a diurnal wave at the other positions in the clamp—*SSO* at the outside of the straw cover, and *S*, *L* and *N* in the potatoes. The divergence between the temperatures at the north and south surfaces of the potatoes, resulting from

The temperature at *SSO* ran almost parallel to that at *S*, showing the same rise between 09.00 and 18.00 hr. As the temperature at *SSO* was unaffected by the wide diurnal fluctuations at *SEI* on the opposite side of the junction between the earth and straw covers of the clamp, it follows that the interface between earth and straw must be a region of very low thermal conductivity.

The amplitude of the diurnal wave varied widely between days, depending on the amount of solar radiation. As already noted, Fig. 12 refers to a period when the amplitude was large because there was almost continuous bright sunshine during the day. The two following days, 19 and 20 March, were overcast throughout and no bright sunshine was recorded. The range between maximum and minimum temperatures on these days was about 7° at *SO* and 1·5° at *SEI*, compared with 26° and 9°, respectively, in Fig. 12. On 19 March the temperature at *SO* never rose above that at *SEI* and the maximum at *SO* was only 12·5°, compared with 27° on the previous day.

The picture of the heat exchanges of the clamp during a period of 24 hr. which emerges from these results is as follows: after sunrise the surface of the clamp is heated by the sun, directly at the south face and at the north face indirectly, by re-radiation from the sky and surrounding objects. Part of the heat absorbed at the surface of the soil is conducted towards the centre of the clamp, part is lost to the overlying air, and part remains to raise the temperature at the soil surface. After midday, the rate at which radiation is absorbed at the soil surface declines, and the heat intake becomes insufficient to balance that lost to the air and the inner soil layers. The surface temperature then begins to fall. Meanwhile, heat conducted towards the centre of the clamp raises the temperature at the inner layers of the soil, but very little of it passes from the soil into the straw. At about sunset the net gain of heat by the clamp falls to zero, and cooling of the whole earth cover begins; heat accumulated in the inner layers near to the straw is now conducted outwards, and there is a uniform fall of temperature throughout the earth cover during the hours of darkness. Over the whole 24 hr. period, heat flows outwards from the centre of the potatoes towards the outside of the straw cover, but the amount of heat passing must be very small compared with the quantities entering and leaving the earth cover in the same period. When the earth cover is sufficiently dry to permit the passage of air through it, the distribution of temperature within the straw cover and the heap of potatoes may be affected by the entry of air caused by wind, but otherwise the temperature in the potatoes and the straw varies little in the course of a day.

Immediately before sunrise the clamp is approaching an equilibrium condition in which the rate of conduction of heat outwards is constant throughout the straw and earth covers. It is noteworthy that at this time the temperature difference across the earth/straw junction considerably exceeds those across the earth and straw covers, demonstrating once more the importance of this junction as a barrier to the passage of heat. If it is assumed that the equilibrium state is nearly reached at sunrise the temperature difference across unit thickness of earth or straw at this time may be taken as an inverse measure of thermal conductivity. The temperature difference between S and SSO at 06.00 hr. was 2·1°, and between SEI and SO 6·4°. Assuming that the thickness of the straw cover was 6 in. and of the earth cover 12 in., the temperature gradient in the straw was 0·35° per in. and in the earth 0·56° per in. The ratio of the thermal conductivity of the straw to that of the earth was therefore 1·6 : 1. However, the conductivities of the straw and earth covers are not of much practical interest, for they do not measure the relative efficiencies of the earth and straw in insulating the potatoes from external temperature change; this depends on the thermal diffusivities of the two materials, which is a function of both conductivity and specific heat. As mentioned earlier, absence of a detectable diurnal wave through the straw cover makes it impossible to compare the diffusivities of earth and straw.

(4) *Temperature variation in the potatoes after removal of the earth cover*

It has been shown already that, after the earth cover was removed from clamps A and B in April 1944, the mean temperature in the potatoes was almost the same as that of the air (Table 2 and Fig. 5), and was lower than in clamp C which retained its earth cover. It is also obvious from Fig. 3 that removal of the earth cover greatly increased the temperature variation in the course of a day at positions N and S on the outer surface of the potato heap, and to a less extent at M in the middle of the heap. The mean daily ranges of temperature at different positions in the clamps compared with that in the air, for the period 10 April–2 July 1944 were as follows:

Clamp ...	*A*		*B*			*C*			
Position ...	*M*	*S*	*N*	*M*	*S*	*N*	*M*	*S*	Air
Mean daily range (° C.)	1·7	6·6	4·2	1·3	3·6	0·8	0·5	1·2	9·6

Examination of the thermograph charts showed that the increased variation within days at N and S in clamps A and B after the removal of the soil, was due to the appearance of a diurnal temperature wave. There was no regular diurnal periodicity at M in the middle of the potatoes, and the temperature variation within days at this position was the result of trends persisting over longer periods than a day. The magnitude of the diurnal wave at N and S depended on wind in a manner that is made clear by Fig. 13. This shows the temperature variation at N, M and S in clamp B during the 8 days, 20–27 May 1944, and mean values of the component of wind velocity normal to the south face of the clamp determined over successive intervals of 3 hr. are also plotted.

Throughout the first 3 days, 20–22 May, when there was a persistent northerly wind, the temperature at N showed wide diurnal fluctuations, but at S no diurnal wave was apparent and the temperature was close to, and usually slightly above, that at M. The wind died down in the morning of 23 May, and the rest of the day was calm. On this day, the variation at both N and S was small. Early on 24 May a southerly wind began to blow and continued until 27 May. On each of the 4 days, 24–27 May, there was a well-defined diurnal wave at S, but not at N; the temperature at N was slightly below that at M throughout and showed the same changes with time. These and similar results for other periods, when there was a change in the direction of the wind, lead to the conclusion that in calm periods the diurnal wave at N and S was small, but that in windy periods there was a well-marked diurnal wave at the surface of the potatoes on the side of the clamp towards which the wind was blowing, while on the opposite side the diurnal wave was suppressed. Table 9 establishes this relationship on a wider basis. The 78 days covered by the records after the removal of the earth cover from clamp B (13 April–3 July, omitting 5–8 May when one of the thermograph clocks stopped) were divided into nine groups, each group covering a different range of daily mean normal component of wind velocity. The mean daily temperature ranges at positions N, M and S in clamp B and in the air, were then averaged for the days in each group.

With southerly winds, the group means of daily range at N were small and independent of wind velocity, but the daily range at S increased steadily with increase in southerly normal component from 3° at zero velocity to over 5° for normal components greater than 5 m.p.h. The values for the group between 0·1 and 1 m.p.h. deviated from this smooth in the group mean daily range at N from 2·8° at zero velocity to over 7° for normal components greater than 5 m.p.h., while the mean daily range at S remained small, between 1·9 and 3·3°, throughout the range of northerly wind velocity. The mean daily

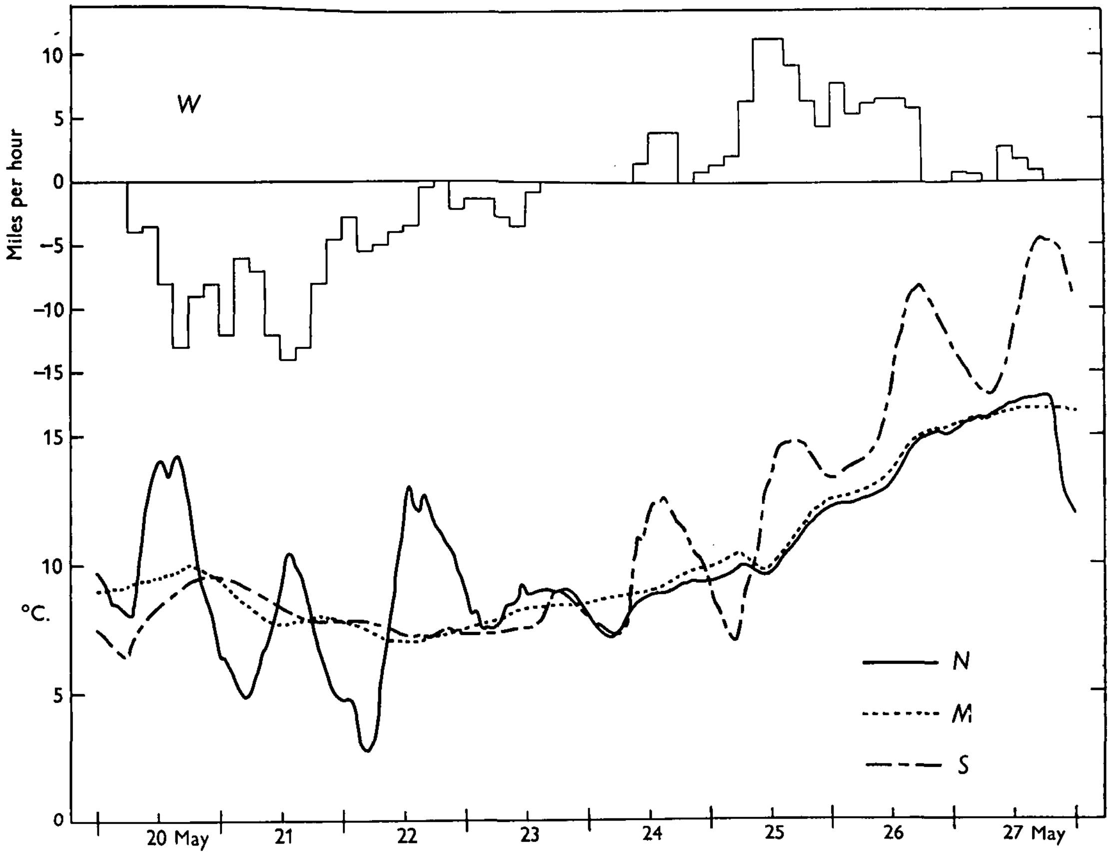

Fig. 13. The effect of wind on the temperature of the potatoes, after removal of the earth cover of the clamp. The figure shows the change with time in the temperature at positions N, M and S in clamp B, 1943–4, and in the component of wind velocity normal to the south face of the clamp (W), during the period 20–27 May, 1944.

Table 9. *The daily temperature range in ° C. at positions N, M and S in the potatoes of clamp B*, 1944, *for days grouped according to the component of wind velocity normal to the clamp faces, in the period* 13 *April*–3 *July after the removal of the earth cover*

		Southerly					Northerly			
Range of normal component, m.p.h.		Over 5	5 to 2·6	2·5 to 1·1	1 to 0·1	0	0·1 to 1	1·1 to 2·5	2·6 to 5	Over 5
Number of days averaged ...		10	6	5	6	9	7	9	12	14
Daily range	N	2·0	1·9	1·3	2·8	2·8	5·0	6·0	5·8	7·3
	M	1·6	1·4	0·9	1·1	0·6	0·9	0·8	1·2	2·2
	S	5·2	5·0	4·1	7·5	3·0	3·3	1·9	2·3	2·8
	Air	9·0	10·1	9·0	14·0	10·2	9·7	8·8	8·2	8·5

trend, and this was due to the fact that the mean range in air temperature for the days included in this group was exceptionally high (14° compared with 8–10° in the other groups). Increasing northerly wind velocity, on the other hand, caused an increase ranges at N and S for the 9 days of zero normal component were both about 3°. The daily range at M tended to increase, and that for the air to decrease, with increase in the normal component, whether northerly or southerly. This effect of wind in reducing the daily range of air temperature has already been noted.

The effects shown in Fig. 13 and Table 9 can be explained as follows: in windless periods, when there is no air movement through the straw cover over the potatoes, heat can be exchanged between the surface of the potatoes and the external environment only by conduction through the straw and radiation through the air spaces. This is a comparatively slow process, and the amplitude of the diurnal temperature wave at the surface of the straw cover is therefor greatly reduced in its passage towards the potatoes. When wind is blowing towards a clamp face, however, air readily passes through the straw, and the entering air heats the surface of the potatoes during the day and cools it at night. The temperature at the surface of the potatoes therefore tends to follow that of the external air, showing a large diurnal fluctuation. Entry of air into the potato heap caused by wind, displaces air from the middle of the potatoes towards the opposite side, and air flows out from the potatoes into the straw cover. The temperature at the surface of the potatoes on this side is therefore controlled by the temperature in the middle of the heap, and so shows no diurnal wave. This explanation is supported by the fact that the maxima and minima of the diurnal waves at the surface of the potatoes on the side of the clamp towards which wind was blowing occurred simultaneously with those in the air. Also the amplitude of the wave at the surface of the potatoes varied with the amplitude of the air wave. On cloudy days, when the daily range in the air was small, there was little variation in temperature at the surface of the potatoes on the side of the clamp facing the wind. An example of the opposite effect—wide daily range at *S* correlated with wide range in the air on days with southerly wind—has already been pointed out in Table 9.

DISCUSSION

The storage of potatoes in clamps is a traditional practice, developed by trial and error and not deliberately designed to satisfy a prescribed set of physical conditions. However, there can be little doubt that one of the most important objects it is intended to achieve is to protect potatoes from harmful effects of wide temperature fluctuations, and especially from injury by frost. The work of Barker & Wallace (1946), and the results described in this paper, show that the control of temperature attained in a clamp is poor, and that the storage conditions are far from ideal. Little information on the effect of temperature of storage on wastage is available, but *a priori* considerations suggest that a constant temperature of about 7° C. (45° F.), the lowest possible without causing sweetening, would be optimal for storage, for it would reduce wastage by respiration and sprouting and by infection with fungi and bacteria to the minimum consistent with maintaining the potatoes in a fit state for human consumption.

It has been shown that when the potatoes were covered only with straw, their average temperature was close to that of the ambient air, though the diurnal range in the air was greater than at the surface of the potato heap, and still more than at the centre. If the straw also were removed and the potatoes were fully exposed to climatic influences their temperature would presumably follow the fluctuations of air temperature still more closely, except that potatoes exposed to bright sunshine would probably show a wider diurnal fluctuation than the air. It is, therefore, reasonable to assess the effect of clamping by comparing the temperature of the potatoes with the air temperature.

The presence of the earth and straw coverings on a clamp has two effects on the temperature of the potatoes. It greatly reduces the penetration of external short-period fluctuations; the diurnal wave is completely suppressed and sudden deviations of air temperature from a smooth trend persisting for about a week have little effect. The clamp coverings also maintain the temperature of the potatoes at about 1–5° above the smooth trend of air temperature. The magnitude of the temperature difference between potatoes and air must depend partly on the thickness and nature of the coverings and partly on the rate of heat production by the potatoes. If the latter is increased by the onset of rotting due to bacterial infection the difference may be much greater than 5°, as in 1942–3. At Rothamsted, a difference of 5° between potatoes and air would be just about sufficient in an average winter to maintain the temperature of the potatoes above the critical value for sweetening, for the mean air temperature in the coldest month is 2·1° (January average for the 10 years, 1940–9). It follows that potatoes in clamps in eastern England must quite frequently be exposed to temperatures sufficiently low to cause sweetening for some part of the period between December and March; examples of this occurred in the experiments of Barker & Wallace and in the 1943–4 clamps.

Although the effect of the clamp coverings in damping short-period temperature fluctuations protects the potatoes against short spells of frosty weather, there is little doubt that continuous frost persisting for many weeks would eventually cause the temperature of the potatoes to fall below freezing-point. It is the comparative rarity of prolonged frosts in this country that makes clamping a practicable method of storage. In countries with more severe winters, where the temperature remains below freezing-point for long periods as in the eastern states of U.S.A., more efficient storage methods involving the construction of special buildings have to be used to prevent the potatoes becoming frozen.

Storage in clamps does not protect potatoes against adverse effects of the seasonal rise of temperature in spring and early summer; on the contrary, the temperature of the potatoes follows, and remains consistently above, the trend of air temperature. From April onwards the temperature in a clamp becomes steadily more unfavourable, and by July it may be 10° above the optimum, even if the tubers are free from bacterial rotting. This is why very serious losses occurred during the war, when stocks of potatoes had to be held in clamps until July or later. There is no obvious way of preventing the rise of temperature in spring and summer. Placing the clamp so that it is shaded from the sun, for example, on the north side of a farm building, would help. If the soil cover could be kept moist the diurnal temperature rise, and hence the mean temperature, at the outer surface would be reduced and this would tend to depress the temperature of the potatoes, but the quantity of water required would probably be prohibitive. The general conclusion is that clamp storage provides reasonably good temperature conditions only in a winter free from prolonged frosts, during the months from November to April when the mean air temperature is below, or only slightly above, the storage optimum of 7°.

It has been shown that the chief barrier to the penetration of temperature fluctuations through the clamp covers lies at the junction of the soil and the straw. It is, therefore, probable that the thickness of the coverings is not very critical. The temperature gradient across the straw cover is so small that fairly wide deviations from the usual thickness of about 6 in. would make little difference to the temperature of the potatoes. The thickness of the earth cover could probably be reduced considerably without permitting the diurnal wave to penetrate. Variations in the thickness of the soil layer would, however, affect the difference in mean temperature between the potatoes and external air, as was shown experimentally by Barker & Wallace (1946). Accordingly, a thick soil covering is desirable in cold periods when the external temperature is well below the storage optimum, but when the temperature rises in spring, a thinner layer would be advantageous. When storage is prolonged into the late spring it is a common practice to remove part of the earth cover, exposing the straw either in a band along the ridge of the clamp or in panels running from the ridge to the base. A better practice might be to remove part of the soil over the whole clamp, so leaving a thinner soil cover, for this would reduce the temperature of the potatoes while avoiding wide diurnal temperature fluctuation and the rapid water loss from the potatoes that occurs when the earth cover is removed (Crook & Watson, 1948). In practice, the thickness of the earth cover is determined partly by considerations of stability; a very thin layer of soil might tend to slide down the clamp face and expose the straw.

The conclusion that the earth/straw interface is the most important insulating region of the clamp coverings, and that the thickness of earth and straw is not critical, may account for the wide differences in clamp construction that are found in different parts of the country. Local opinion often holds strongly that the clamp dimensions and details of construction traditionally used in the district have special advantages, and that any changes would have disastrous consequences. On the contrary, it seems probable that local variations in clamping procedure have arisen merely because the dimensions of the clamp and its coverings can be varied fairly widely without greatly affecting the storage conditions. This is a matter requiring experimental study.

The insulating property of the earth/straw interface probably depends on the separation of earth and straw by a layer of still air, across which heat can pass only very slowly. If this is the correct explanation, the rationale of clamp construction becomes obvious. The function of the straw is to hold a mass of still air around the potatoes, while the earth cover forms a layer that is almost impermeable to air, preventing exchange of heat by convection between the potatoes and the external air and surrounding objects. If the potatoes are insulated from temperature fluctuations mainly by the air held within the straw and between the straw and soil covers, it is obviously important that the straw should be dry; the presence of water films on the straw would allow more rapid passage of heat by conduction between the earth cover and the potatoes. This would explain why, after the period allowed for the surface moisture present on the potatoes when they are dug to distil over into the straw, a process commonly known as 'sweating', the moist straw is usually replaced by a fresh supply before the earth cover is applied.

The temperature of the potatoes in the later part of the storage period has been shown to be affected by wind. This is a surprising and previously unsuspected result, but it is probably of little practical significance. The temperature changes caused by wind involve only a re-distribution of heat within the potatoes with little net gain or loss, except when a wind with a high velocity-component normal to the clamp face continues to blow from the same direction for several days. The wind effect has been attributed to flow of air through the clamp coverings, made possible by drying of the earth cover. This has a bearing on the results of experiments made in 1942–3 on the chemical control of sprouting in potatoes stored in clamps until late in the season. Volatile compounds, that had been shown to inhibit sprouting in laboratory tests, were introduced into clamps in November or April, but when the clamps were opened in June no appreciable reduction of sprouting as a result of the chemical treatment could be detected. The inference from the temperature changes, that air flow through the clamp coverings takes place, makes it probable that escape of the vapour of the inhibitory compounds through the clamp covers prevented the maintenance of an effective concentration inside the clamp.

SUMMARY

Continuous records of the temperature of potatoes stored in clamps were made in 1942–3 (one clamp) and in 1943–4 (three clamps). In the first year, the temperatures at various positions in the clamp coverings were also recorded.

The temperature at the middle of the potato heap showed a drift with time similar to that of mean air temperature. Deviations of mean air temperature from smooth trend, lasting for about a week, had no effect on the temperature of the potatoes; longer-period deviations were reflected in the temperature of the potatoes after a lag of about a week. The difference in weekly mean temperature between potatoes and external air averaged about 1–5° C. in 1943–4. In 1942–3 it was greater, increasing to over 20° C. in April, because bacterial rotting of the potatoes following blight infection increased the rate of heat production and caused the clamp to collapse at the end of April.

In two of the 1943–4 clamps (variety Majestic) the potatoes were exposed to temperatures sufficiently low to cause sweetening for several weeks during February and March. In the third clamp (variety Arran Banner) the temperature of the potatoes never fell below 6° C. This difference may have been due to greater heat production by Arran Banner than by Majestic, associated with earlier sprouting.

The temperature in the potatoes tended to fall from the centre of the heap towards the outside, but the temperature gradients across the clamp varied widely with time and between clamps.

The diurnal temperature wave at the outer surface of the earth cover, caused by absorption of heat from solar radiation during the day and loss of heat during the hours of darkness, penetrated through the earth cover but failed to pass the junction between earth and straw. No diurnal wave was detectable in the straw cover or in the potatoes.

Three effects of wind were distinguished:

(1) Wind depressed the temperature of the potatoes at the surface of the heap towards which it was blowing, and raised the temperature at the opposite surface. This occurred in the late stages of storage and was attributed to the earth cover becoming sufficiently dry to permit the passage of external air through it. Southerly winds had a greater effect than northerly winds of equal velocity, presumably because the earth cover dried more rapidly at the south face of the clamp than at the north face. Temperature within the straw cover was affected in the same way as that of the potatoes.

(2) The daily temperature range throughout the earth cover and in the air was reduced by wind blowing from any direction.

(3) After the earth cover was removed from a clamp, in April 1944, wind greatly increased the diurnal temperature fluctuation at the surface of the potatoes on the side of the clamp towards which the wind was blowing, and suppressed it on the opposite side.

It is concluded that the chief barrier to the penetration of external temperature fluctuation lies at the junction of the earth and straw covers, and that the thickness of the coverings is therefore not very critical.

In general, clamp storage in eastern England provides temperature conditions reasonably close to the optimum only during the months from November to April in winters free from prolonged frosts.

The authors wish to thank Mr J. R. Moffatt for providing the experimental clamps at Rothamsted farm, Mr S. A. W. French for help with the statistical computation and Dr H. L. Penman and Mr G. Samuel for reading and criticizing the manuscript.

REFERENCES

Barker, J. & Wallace, E. R. (1946). *J. Pomol.* **22**, 189–96.

Crook, E. M. & Watson, D. J. (1948). *J. Agric. Sci.* **38**, 440–57.

Keen, B. A. (1931). *Physical Properties of the Soil*, p. 327. London: Longmans, Green and Co.

Penman, H. L. (1943). *Quart. J. R. Met. Soc.* **69**, 1–16.

(*Received* 1 *May* 1950)