THE ROLE OF LOW TEMPERATURE TO CONTROL STORED FOOD PESTS[1]

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Temperature has been recognized as an important regulator of biological processes for a long time. It is not surprising that temperature regulation has been used as a means of controlling pests in stored food. Both high and low temperatures have been used to control pests but this paper will be confined to a discussion of the use of low temperature.

Certain definitions will be made at the beginning to clarify the discussion that is to follow. Stored food is taken to mean any cereal seed or oilseed, or product made from these seeds, that is held in storage before being consumed. Some examples are wheat, rice, peanuts, flax, coconut, barley, corn (maize), oats. Pests of stored food are the organisms that live in and feed on the stored food and produce losses in the quality or quantity of the product before it is used for human or domestic animal consumption. The examples to be used in this paper are in the classes of fungi, mites, insects. Low temperature is taken to refer to any temperature at which growth and reproduction of the pest organisms is less than optimal, usually sufficiently low to prevent reproduction.

RESPONSES OF STORED FOOD PESTS TO LOW TEMPERATURE: Since the temperatures that generally inhibit growth and reproduction are different for the different classes of pests, the responses of each class will be discussed separately.

Fungi - More than 100 species of fungi have been found in stored cereal grains[1]. These species have been grouped into two (or three) main classes (1) field fungi (and intermediate) and (2) storage fungi[2,3]. Field fungi infect the seeds at the time the crop is ripening in the field and usually disappear during the storage period[2,4]. The important species as far as damage to stored food is concerned are storage fungi.

The most important storage fungi are in the genera *Aspergillus* and *Penicillium*. The optimum temperature range for growth of these fungi is 30 to 45°C for *Aspergillus* spp., and 20 to 25°C for *Penicillium* spp.[5]. The minimum temperatures for growth range from 0 to 25°C for *Aspergillus* spp. and from -5 to 0°C for *Penicillium* spp. (Table 1). To prevent extensive growth of fungi in stored food by using temperature alone, the product would have to be cooled to 0°C or lower, depending on the moisture content of the fungus[6].

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[1] Contribution No. 640 from the Research Station, Agriculture Canada.

TABLE I. Minimum temperature and moisture content for growth of some species of storage fungi.

Species	Temperature °C	Moisture Content %
Aspergillus restrictus	5-10	13.5-14.5
A. glaucus	0- 5	13.5-14.5
A. candidus	10-15	15.5-16.5
A. flavus	10-15	18.0-18.5
Penicillium spp.	-5- 0	15.5-18.5

However, temperature is not the most effective factor for the control of fungi. Most fungi do not grow at relative humidities below 65% which is equivalent to about 12.5% moisture content for cereals and 8.5% moisture content for oilseeds. Thus, it is more practical to use temperature and moisture content in combination for the control of fungi rather than to rely only on low temperature.

Mites - The species of mites found in stored food grow and reproduce most rapidly between 20 to 30°C. The major species that feed on stored products are *Acarus siro* L., *Glycyphagus domesticus* DeGeer and *Tyrophagus putrescentiae* Schrank. A large number of species found in stored food are predators on the species mentioned, on other mites of lesser importance or on immature stages of insects. Some important species are *Cheyletus eruditus* (Schrank), *Blattisocius keegani* (Fox), *Androlaelaps casalis* (Berlese). Generally, the optimum temperatures for their growth and reproduction are about 5°C higher than those for the species that feed on whole or broken grain[7,8].

The temperatures that prevent growth of mites vary from species to species but generally are in the range of 0 to 10°C (Table II). Thus temperatures that inhibit the growth of mites are higher than those that inhibit the growth of fungi.

TABLE II. Minimum temperatures for development of some stored product mites.

Species	Temperature °C
Acarus siro L.	0
Glycyphagus domesticus (De Geer)	0 to 5
Tyrophagus putrescentiae (Schrank)	8
Cheyletus eruditus (Schrank)	10

Mites will be killed at temperatures below the lower threshold for development of their immature stages but the time required to achieve death becomes shorter as the temperature becomes lower. Mites have developed at least two mechanisms to increase their survival at low temperatures. One is to enter a hypopus stage which is a resting stage where growth is minimal; the second is to acclimate to low temperature. Acclimation is achieved by changes in the physiology of the mite produced at slowly declining temperatures that diminish the lethal effects of low temperatures.

Acclimation is obligatory in the large number of species without hypopus stage in their development. *Acarus siro* reared at 6°C temperatures for 2 years exhibited higher survival at -18°C than mites reared at 21°C [9]. This effect has also been shown for eggs of *Acarus siro*, adults of *Glycyphagus domesticus* [10] and *Dermatophagoides farinae* [11].

Mites are killed at relative humidities below 60% (equivalent to about 12% moisture content). As with fungi, it is more effective to use a combination of temperature and moisture content to control mite populations rather than rely on temperature alone.

Insects - The optimum temperatures for a large number of stored food insects fall between 25 and 35°C [12]. The minimum temperatures for growth range from 10 to 25°C. Of 25 species that I selected as important pests of stored food, 13 had a lower threshold temperature for development of 20°C, 8 had a threshold of 15°C and 4 had a threshold of 10°C (Table III).

TABLE III. Selected stored product insects classified according to their minimum temperature for development. [12]

Minimum temp. for development	Species
20°C	*Araecerus fasciculatus* Deg.
	Callosobruchus maculatus (F.)
	Cryptolestes ferrugineus (Steph.)
	" *pusillus* (Schön.)
	Lasioderma serricorne (F.)
	Latheticus oryzae Waterh.
	Mecrobia rufipes (Deg.)
	Oryzaephilus mercator (Fauv.)
	Oryzaephilus surinamensis (L.)
	Rhyzopertha dominica (F.)
	Tribolium castaneum (Hbst.)
	Tribolium confusum (Duv.)
	Trogoderma granarium Everts
15°C	*Acanthoscelides obtectus* (Say)
	Corcyra cephalonica (Stnt.)
	Ephestia cautella Wlker.
	Plodia interpunctella (Hbn.)
	Sitophilus granarius (L.)
	Sitophilus oryzae (L.)
	Sitotroga cerealella (Ol.)
	Stegobium paniceum (L.)
10°C	*Anagasta kuhniella* (Zell.)
	Endrosis sarcitrella
	Ephestia eleutella (Hb.)
	Ptinus tectus Boield.

Some species enter a diapause stage at low temperature, particularly species of Lepidoptera that have a diapause in the larval stage e.g. *Plodia interpunctella* (Hubner), *Ephestia elutella* (Hubner), *Anagasta kuhniella* (Zeller) and *Sitotroga cerealella* (Olivier). Species of beetles in the genus *Ptinus* have a diapause in the pupal stage [13]. During diapause, an insect is able to survive temperatures considerably below 0°C.

The mortality of insects below 0°C increases as the period of continuous exposure to a particular temperature increase or as the temperature becomes lower. An example that illustrates this relationship is *Cryptolestes ferrugineus* (Stephens). After 15.6 days exposure at 2°C mortality of adults was 50%, and by extrapolation after 44 days 90% and after 85.8 days 95% [14].

Some insects that infest stored food can survive at low temperatures by acclimating to the low temperatures. As their exposure to low temperatures is slowly increased, their survival at temperatures below 0°C increases. This is illustrated in *Cryptolestes ferrugineus* and *Tribolium castaneum* (Herbst) (Tables IV, V). When adults of *C. ferrugineus* are exposed to -12°C their survival is 0 after 72 hours when no acclimation is given at intermediate temperatures but is 60.8% after 4 weeks when 4 weeks of acclimation at 15°C was provided[14].

TABLE IV. Survival of adult *Cryptolestes ferrugineus* (Stephens) at -12°C after acclimation at 15°C (%).

Acclimation at 15°C (days)	Exposure at -12°C (days)					
	3	5	9	14	22	28
0	0	0	0			
7		33.3	30.8	19.2		
14		79.5	41.4	40.5		
20				76.3	76.5	50.8
28				74.6	73.3	60.8

T. castaneum does not acclimate to the same extent as *C. ferrugineus* and adults are killed by exposure of 3 to 4 weeks at 3.3°C. Mature larvae have not survived longer than 3 weeks at 3.3°C in my experiments. Strains of *T. confusum* and *T. castaneum* have been determined on the basis of survival at subzero temperatures but the differences found in the LT 50's were measured in minutes [15]. It seems doubtful that such small differences would be significant in granaries exposed to seasonal variations in temperature. In the past 20 years *T. castaneum* has become widely distributed in stored grain in the Prairie Provinces of Canada. The reasons for the increasing frequency of occurrence of this species are not clear yet but it appears that an increase in the size of farm storages has been an important factor. The average size of granary was thought to be about 30 tonnes in the mid-50's but now it seems to be 2 to 3 times as large. Grain temperature would normally remain higher in large granaries than in small granaries.

TABLE V. Survival of adults and mature larvae of *Tribolium castaneum* (Herbst) at 3°C after acclimation*.

Weeks at 3°C	% Mortality		
	Adults		Large Larvae
	Test 1	Test 2	Test 2
1 Week	14	45	66
2 Weeks	75	100	98
3 Weeks	95	-	100
4 Weeks	100	-	-

* Acclimation of 1 week at 21.1°C + 1 week at 15.6°C + 1 week at 10°C.

A large number of species of stored food insects were exposed to English winter temperatures in several unheated buildings[16]. Of the 25 species selected previously in this paper, 16 were used in these tests. Of the 7 species that cannot develop below 20°C, 4 were classified in that study as cold susceptible and 3 as cold hardy; of the 6 species that cannot develop below 15°C, 3 were classified as cold susceptible and 3 as cold hardy; of the 3 species that cannot develop below 10°C, all were classified as cold hardy (Table VI). The cold hardiness of these insects does not appear to be related to the minimum temperatures required for development.

TABLE VI. Relationship between minimum temperature for development of certain species of stored products insects and their ability to survive an English winter in unheated buildings [12,16]

Minimum temp. for development	Species	
	Cold susceptible	Cold hardy
20°C	*Araecerus fasciculatus* *Oryzaephilus mercator* *Tribolium castaneum* *Tribolium confusum*	*Cryptolestes ferrugineus* *Oryzaephilus surinamensis* *Trogoderma granarium*
15°C	*Ephestia cautella* *Sitophilus granarius* *Sitophilus oryzae*	*Plodia interpunctella* *Sitotroga cerealella* *Stegobium paniceum*
10°C		*Anagasta kuhniella* *Ephestia eleutella* *Ptinus tectus*

Adaptation to Low Temperatures - The mechanisms that insects have evolved to reduce injury at low temperatures have been studied intensively [17,18]. At temperatures above 0°C some insects experience sufficient injury to result in their death whereas many others undergo cold-acclimation, or as it is sometimes called, chill-hardening. This change enables them to survive longer periods at temperatures below 0°C than insects that are not chill-hardened. Other insects can withstand being frozen and are classed as frost hardened or freezing-tolerant. Other insects are induced to enter a state of diapause when the temperature falls or when some other seasonal stimulus occurs. A period at low temperature is required to end the state of diapause.

Most stored food insects experience cold-injury of the first two types i.e. when the temperature is to low for development and when chill-hardening occurs. A few species enter diapause at low temperatures.

The examples of chill-hardening in *C. ferrugineus* and *T. castaneum* have been described. In unheated grain in Manitoba, live *C. ferrugineus* adults have been found in winter in the central portion of a granary near the floor. The temperature in this part of the grain mass rarely reaches -10°C in the middle of winter and is usually -5 to -8°C during the coldest period.

T. castaneum has not been found alive in unheated grain in granaries in Manitoba in the middle of winter. Occasionally populations are found in the autumn in farm granaries but only when heated grain is present in winter does the population persist until spring. Evidently, this species cannot survive 2°C or lower if the exposure period is at least one month.

The mechanism of cold-acclimation is not well understood. Salt[17] discussed the work on freezing-tolerance and the role of glycerol and sorbitol in protecting insects from cold injury. Well-known examples of insects that form glycerol at low temperatures are the European corn borer, *Pyrausta* (= Ostrinia) *nubilalis* (Hubner), the Saturniid moths, *Hyalophora cecropia* (L.), and *Antheraea polyphemus* (Cramer). However, no glycerol was found in cold-acclimated *C. ferrugineus* adults (Smith, unpublished) and none has been reported in any stored food insect.

The changes in chill-coma temperature, respiration rate and levels of a muscle enzyme, Mg^{2+} -activated ATPase has been investigated in two insects, *Tribolium confusum* (Duval) and *Musca domestica* (L.) [19]. It was found that *M. domestica* acclimated more quickly near the chill coma temperature than *T. confusum*, leading to the conclusion that the change in ATPase activity was not important. It was suggested that other mechanisms might be more important. Furthermore, it was suggested that the rate of acclimation is related to the insect's environment. Insects that live in a relatively stable thermal environment appear to acclimate slowly, e.g. *T. confusum*, whereas insects that live in an unstable thermal environment appear to acclimate more rapidly, e.g. *M. domestica*.

The majority of stored product insects live in relatively stable thermal environments and would be expected to respond as *T. confusum* did. Nevertheless, the mechanism responsible for low temperature acclimation is unknown.

Supercooling points, the temperatures at which insects freeze, were determined on acclimated and nonacclimated adult *C. ferrugineus* (Smith 1970). The differences were not large, ranging from -16.7°C for adults with no acclimation to -20°C for adults acclimated for 4 weeks at 15°C and -21°C for adults acclimated 1 week at 15°C, followed by 4 weeks at 4°C. The supercooling points were not a useful indicator of the ability of adults to survive at temperatures below 0°C.

In a steel granary at Winnipeg containing 20 tonnes of wheat, adults migrated through the grain according to the season. In late May they moved to the wall of the granary where the grain was warm and moist. In early September, the adults moved toward the centre of the granary and spent the winter from 1 to 2 m. (3 to 6 ft.) from the outside wall (Smith, unpublished).

PRINCIPLES OF PEST CONTROL BY LOW TEMPERATURE: The kinds of pests that occur in stored food can be changed by changing the temperature of the stored product. Assuming relative humidity is constant at 70%, fungi, mites and insects will be able to grow and reproduce at temperatures above 20°C; only fungi and mites will grow and reproduce above 10°C; virtually all growth of fungi and mites will be arrested at 0°C to -5°C. Therefore, if temperature is the only variable to be altered the product must be held below 0°C to prevent losses from all pests.

However, by lowering the relative humidity below 60%, the growth of fungi and mites will be prevented at all temperatures and insects can be relatively easily controlled by lowering the temperature.

PRACTICAL PEST CONTROL USING LOW TEMPERATURE: The conditions required to maintain stored food free of pests have been well known for a long time. As a result, strenous efforts are made to ensure that food in storage is kept dry and cool in some countries. These efforts are usually successful in small amounts of stored food but become increasingly difficult as the amounts become larger. New technology must be found to achieve the goal of protecting stored food from damage by biological organisms.

Grain stored in small granaries in temperate climates become cool enough to prevent pest development; in tropical climates small amounts of grain can be dried relatively easily.

Other simple methods that can be used in cold climates are moving the grain in winter from one granary to another or from one bin to another. This method is known as turning the grain. The principal cooling effect here does not appear to be achieved by moving the grain through cold air but rather by mixing cold grain from the outside of the granary with warmer grain from the centre of the granary and finishing with an average temperature close to the original wall temperature [20].

In some flour mills in Canada and the United States, freeze-outs are still used in winter to control insects. The procedure is to close the mill operations for several days in the coldest part of the winter. During this time, the heat for the building is shut off and all the windows and doors are opened. Flour from the boots is spread thinly on the floor and a-l covers are opened on the machinery such as sifters and rolls. The water must be drained from the pipes in the building. Results are said to be satisfactory if a three-day period with minimum temperatures of about -35°C is selected. This procedure is usually undertaken once a year. A disadvantage is that the power plant section must be kept heated and may be a source of re-infestation. Another disadvantage is the loss of production time.

In small granaries of about 30 tonnes capacity in temperate regions, the important factors for safe storage are moisture content, prevention of the entry of rain or snow, size of granary and preferably separation from sources of heat such as animal barns. The moisture content at storage time should be below 14.5%. The roof, walls and floor should be sealed to prevent moisture from entering the granary. A granary painted white will reflect heat and keep cooler than a dark granary. Steel granaries will cool more rapidly than wooden granaries of comparable size [21].

The advantages of turning grain in Canada are that cold air is readily available in winter and equipment for moving grain is available. The disadvantages to the method are that an empty bin must be available for temporary storage of the grain; there is some weight loss in grain each time grain is moved, and it takes time for the farmer or the elevator staff to make the transfer.

AERATION: In regions where there is a cool season, grain quality can be maintained by aeration of the grain mass. The technique is to mount perforated ducts of suitable diameter on the floor of the granary and attach a fan to the end of the duct [22,23,24]. The fan can be fitted either to blow cool air into the grain or to pull cool air down through the mass. Various modifications have been made to automate the technique such as controlling the operation of the fan with a thermostat, or a humidistat, or operating the fan intermittently to cool the grain in stages.

In Sweden, studies have been made of the comparison of drying grain alone or drying grain in combination with aeration[25]. No advantage was found using aeration.

In Australia, trials are being conducted to use aeration to dry grain by operating the fan when dry air is present in the atmosphere[26].

Advantages - The main advantage is to increase the rate of cooling by accelerating the air flow through the grain. Aeration has also been used to preserve damp grain up to 20% moisture content in Europe[27]. The aeration can be combined with an insecticide treatment[28]. The cost of the equipment is relatively high but operating costs are low. Overall the cost of aeration is similar to the cost of treatment with a fumigant[22].

Disadvantages - The use of aeration is limited to regions that have a cool season or at least where outside temperatures fall low enough to prevent insect reproduction. A serious problem is condensation of moisture where cold air meets warm grain [29,30].

This can usually be controlled by reducing the air flow, or by drawing cold air through the grain before it is exhausted by the fan. To use aeration, bins or granaries must be fitted with perforated pipes. Usually, one fan is used to aerate several bins. Therefore, there must be a small expenditure of time and labor to move the fan from one bin to another.

REFRIGERATION: A modification of aeration that has been used in several parts of the world has been to refrigerate the air that is blown into the grain. This technique has been described in detail recently by Burrell [6] under the title of chilling. The air used in refrigeration must not only be chilled but must be dried after it has been cooled to prevent condensation of moisture where the cool air enters the grain.

Refrigeration of grain has been studied in temperate regions and sub-tropical regions. Three examples will be described briefly to illustrate the results that may be achieved and provide an indication of the cost of the method of treatment. (Tables VII, VIII). Trials using refrigeration on wheat and barley in metal rectangular bins have been conducted in England [30]. Damp grain was cooled after harvest to prevent damage before the grain was used. The moisture content in one bin of wheat ranged from 15.7 to 17.6% and the initial temperature was 20 to 23°C. The temperature was lowered to 5°C in 60 hours, which is a cooling rate of 1.7 tonnes/hr. The energy consumption was not given. The second bin contained wheat with a higher moisture content, 16.6 to 22.4%, and was cooled more quickly, reaching 5.6°C in 36 hr. The cooling rate was 2.8 tonnes per hour, approximately 65% faster than the drier wheat.

In Australia, wheat was cooled using refrigeration to prevent insect damage in the summer months [31]. The wheat was dry, 11% moisture content, and warm 28.4 to 33.3°C. The wheat was cooled to about 15°C, sufficiently low to prevent development. The temperature decrease was achieved in 17 to 18 days in one bin when the air flow was 3/4 of the total air flow but was achieved in 63 days in a bin which received 1/4 of the total air flow from the fan. The cooling rate appeared to be 1.4 to 1.2 tonnes per hour at maximum flow which is slightly less than the rate achieved in England [30]. The energy required to lower the initial temperature to 15°C was 4 KW hr. per tonne. However, it was pointed out that 14 KW hr per tonne were required to maintain that temperature for the remainder of the ten month storage period [31]. It was concluded that cooling must be achieved in less than 3 weeks to inhibit insect development.

The third example is a trial conducted in Israel in 2 bins of wheat, one containing 699 tonnes, the other 863 tonnes [32]. The moisture content of the grain in both bins was relatively low, about 11% in the smaller mass and about 12% in the larger mass. The grain was cooled following harvest. The smaller mass was cooled from about 37°C to about 19°C; the larger from a range of 33° to 42°C to a range of 15 to 21.5°C. The total cooling time in each

TABLE VII. Selected examples of cooling trials using refrigeration

Country	Storage Structure	Months	Authors	Year
		Barley		
United Kingdom	rectangular metal silo	Aug.-Oct.	Burrell & Laundon	1967
		Wheat		
United Kingdom	rectangular metal silo	Aug.-Oct.	Burrell & Laundon	1967
Australia	circular concrete silo	Nov.-Sept.	Sutherland, Pescod & Griffiths	1970
Israel	circular & octagonal concrete silos	Sept.-Nov.	Donahaye, Navarro & Calderon	1974

TABLE VIII. Characteristics of cooling trials using refrigeration

Amount (tonnes)	Moisture Content (%)	Temperature (°C)		Cooling Rate (tonnes/hr)	Cooling Time	Energy kWhr/tonnes
		Initial	Final			
		United Kingdom				
100	15.7-17.6	20-23	5	1.7	60 hr	unknown
100	16.6-22.4	20-22	5.6	2.8	36 hr	unknown
		Australia				
560	11	33.3	14.5	1.4	17 da	3
560	11	32.8	15.6	0.33	63 da	1
560	11	28.4	13.9	1.2	18 da	4
		Israel				
699	10.4-11.1	36-37	18-19	4.0	160 hr	4.65
863	11.1-13.2	33.5-42	15-21.5	3.7	236 hr	4.7

bin was 160 hr and 236 hr. Therefore, the cooling rates were 4.0 and 3.7 which were 43 to 118% slower than the rates obtained in England [30]. The higher initial temperature and the lower moisture content undoubtedly contributed to the difference in cooling rate. Nevertheless, the energy consumption was similar to that calculated in the Australian trial, 4.65 and 4.7 kW hours per tonne [31].

Advantages - The use of refrigeration appears to have advantages for use in damp or moist grain up to 20% m.c. It can be used in warm climates to prevent insect growth but would probably be more effective in underground storages than above-ground silos.

Disadvantages - The disadvantages are that the capital cost of the equipment is high and operation costs are higher than for aeration alone. The air must be dried sufficiently after cooling to prevent condensation at the point where the duct enters the grain. Otherwise fungi and mites will grow and damage the grain. The problem of uniform distribution of the cool air will determine the effectiveness of this method as it does in aeration with ambient air. In warm climates it will be difficult to cool the grain sufficiently at the walls and surface of the mass to prevent insect growth without a large amount of insulation.

SUMMARY ON CONTROL OF STORED FOOD PESTS WITH LOW TEMPERATURES:

The use of low temperature to maintain quality of stored food will vary from one part of the world to another. In temperate regions where fungi and mites are the main pests, low temperatures occur naturally but the benefits will be enhanced by drying the grain in storage or accelerating the cooling in the first weeks of storage. In tropical regions, where insects will be the main pests, low temperature can only be achieved by refrigeration. The use of grain drying techniques alone or in combination with low temperatures are effective tactics for the control of pests.

A major consideration in the use of aeration or refrigeration to cool grain will be the cost of power. The method used to generate power in a country will determine the economics of these methods.

The amount of loss that is anticipated will also determine the method of low temperature control to be used. It appears that long term storage is not being considered as a problem in grain storage since the world's production is nearly equal to the world's consumption each year. Carryovers seem to be more the result of disruption of transportation from producer to consumer than a result of overproduction.

The size of the storage structure to be protected from damage will also determine if and when low temperature control of pests will be used. The larger the structure the more difficult it is to detect pests and the more likely ecological controls such as low temperature will be considered. The problem of non-uniform cooling will have to be overcome.

Provided that a relatively uniform low temperature can be achieved in a stored food structure, the product will probably maintain its quality longer at low temperature than it will when treated by other pest control measures. Nevertheless, the most economical methods of control will still be combinations of two or more methods of pest control. The time of application of each particular method will be critical for success.

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