GRAIN REFRIGERATION TRIALS IN AUSTRALIA

W.B. Elder, T.F. Ghaly and G.R. Thorpe

Division of Chemical and Wood Technology, Commonwealth Scientific and Industrial Research Organisation, Highett, Victoria, AUSTRALIA.

ABSTRACT

A summary of the results of trials commencing in 1967 using mainly wheat in bulk grain storages ranging in capacity from 500 to 15 000 tonnes shows the feasibility of various refrigeration strategies and their costs and effectiveness against grain infesting insects. Air flow through the bulk in an upwards direction brought insects to the surface where they could be treated readily with an insecticide if and when necessary. Partial filling of horizontal storages is seen to have an important influence on duct layout design. Insulation with rigid polyurethan foam, spray-applied to the outside of storages and protected with an appropriate coating, has to date been satisfactory, apart from easily repairable minor damage by birds and rodents. The refrigeration plant developed on a unit module concept is shown to have other applications in the industry. These will assist in the gradual introduction of the technology.

INTRODUCTION

The motivation for conducting trials using refrigerated air to cool bulk stored grain in Australia arose form the industry's recognition that total reliance on chemical control of insect infestation is vulnerable to insect resistance, objections by markets and industrial bans, and the belief that cooling with untreated atmospheric air would not provide an adequate degree of insect control. Overviews of the role of various complementary physical methods of insect control in Australia have been given by Elder (1978) and Evans (1981). As part of an overall strategy, a research programme on refrigeration of grain commenced in the CSIRO Division of Mechanical Engineering in 1967 with fundamental studies of heat and mass transfer in porous hygroscopic materials (Sutherland *et al.*, 1971), computer simulation of cooling system performance and a field trial in Queensland involving non-insulated silos and non-recirculation of cooling air. Subsequently a series of trials was conducted in insulated silos with recirculation, the objective being to develop a commercial prototype system for shed type storages which account for over 60% of Australia's storage capacity. It became evident that there could be a number of different applications for refrigeration in the industry, and that it would be possible to design the plant with a high degree of standardization to meet the various specifications and criteria.

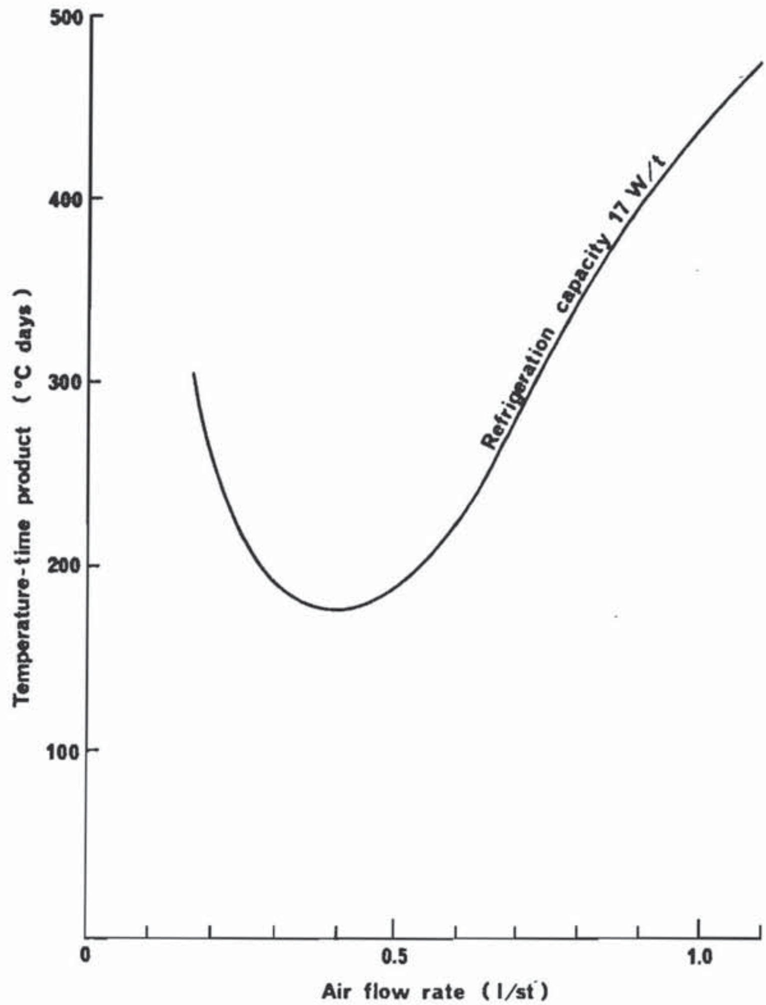

Fig. 1 Variation of insect population growth potental (^{o}C days above threshold) with refrigerated air flow rate showing existence of an optimum air flow for a given cooling capacity in a sub-tropical climate (Brisbane).

REFRIGERATED AERATION WITHOUT RECIRCULATION IN NON-INSULATED SILOS

Initial trials involved the placement of a refrigeration coil upstream of the aeration fan blowing atmospheric air into the silo.

Computer simulation of an aerated vertical silo of wheat with a refrigeration coil of fixed capacity revealed there was an optimum air flow per unit mass of grain under given climatic conditions. As a measure of the potential for the growth of grain infesting insect populations, the temperature-time product above a nominal breeding threshold temperature based on the data published by Howe (1965) was used as a criterion for cooling performance. Low air flow rates resulted in high temperature-time products in the grain last to be traversed by the cooling wave (or front). Higher air flow rates increased the speed of the cooling wave but at the expense of higher grain temperatures behind the wave some times above the breeding threshold. Excessively high air flow rates therefore also led to high temperature-time products as shown in Fig. 1. The optimum air flow rate was taken as that which minimized the temperature-time product. This value was used as a basis for design.

The plant used for the first trial at Dalby, Queensland in collaboration with the State Wheat Board was described by Sutherland *et al.*, (1970). It incorporated an automatically adjusting damper to vary the air flow to keep the temperature of the air entering the grain just low enough to arrest population growth behind the cooling wave.

The results of three trials at Dalby are summarized in Table 1. The effect of the air flow being too low is clearly shown by the much larger infestation level at the end of Trial 2. The low air flow and consequent inadequate cooling at the walls of the silo was concluded to have supported insect population growth after the initial cooling. Although insect control performance was good in the other two trials, it was concluded that insulation or direct cooling of the walls would be necessary to render all parts of the bulk inhospitable to insects and to achieve the very high level of hygiene demanded by export regulations.

REFRIGERATED AERATION WITH RECIRCULATION IN INSULATED SILOS

Trials at Brookstead, Queensland

A 5400 tonne capacity wheat silo at Brookstead, Queensland was insulated externally with 50 mm thickness of spray-applied rigid polyurethane foam, with the object of maintaining all parts of the bulk of stored grain to be refrigerated below 15°C, the insect population growth threshold.

TABLE 1

SUMMARY OF RESULTS OF THREE REFRIGERATED AERATION TRIALS WITH WHEAT IN 580 TONNE VERTICAL CONCRETE SILOS 6.4 m DIAMETER AND 23 m HIGH AT DALBY, QUEENSLAND

Trial No. Year	1 1967/68	2 1967/68	3 1968/69
Average air flow rate (L/s per tonne of silo capacity)	0.45	0.15	0.6
Compressor rating (shaft W/tonne of silo capacity)	3.8*	1.3*	5.1
Quantity of Wheat (t)	594	594	570
Initial grain moisture (% wet basis)	10.8	10.7	11.1
Final grain moisture (% wet basis)	12.5	10.9	10.9
Storage period (months)	10	10	10
Initial grain temperature (°C)	26.4	33.0	28.3
Initial cooling to 15°C (months)	0.6	2.1	0.6
Final grain temperature (°C)	10.4	12.1	15.5
Total operating time (hours)	5600	5600	1900
Energy used (kWh/tonne of silo capacity)	34	11	18
No. of live insects at inloading	0	0	0
Quantity of grain sieved (kg)	76	72	82
No. of live insects at outloading	0	35	3
Quantity of grain sieved (kg)	214	94	91

*Proportioned in accordance with air flow rate

A series of trials began at Brookstead in 1973. In the first, the existing aeration system was used to blow air throught the grain via conventionally laid out perforated distribution ducting. Return ducts were connected from the headspace to the two aeration fans to recirculate the air. The headspace air was cooled via a separate recirculation system comprising a fan and chilled brine cooling coil connected to a commercial chiller set at 70 kW nominal capcaity. The plant is described in more detail by Elder *et al.*, (1975). The results revealed that the air flow through the grain at the bottom of the concrete wall was insufficient for removing heat penetrating the wall insulation and the silo floor to maintain temperatures below 15°C.

The duct layout was modified for the second trial at Brookstead to concentrate air flow at the base of the silo wall after the initial cooling. The peripheral duct system showed that, over the full height of the wall, grain temperatures could be maintained below 15°C. Other features of the system are described by Elder *et al.*, (1976) and the results given are summarised in Table 2.

TABLE 2

SUMMARY OF RESULTS OF THREE GRAIN REFRIGERATION TRIALS IN AN INSULATED 5400 TONNE CONCRETE WALLED SILO 28 m DIAMETER, 9.6 m WALL HEIGHT AT BROOKSTEAD, QUEENSLAND

Trial No. Year	1 1973/74	2 1974/75	3 1975/76
Air flow rate (L/s per tonne of silo capacity)	0.8	0.8	0.9
Compressor rating (shaft W/tonne of silo capacity)	4.2	4.2	4.2
Quantity of grain (t)	2390	5230	2230
Initial grain moisture (% wet basis)	11.0	11.2	11.3
Final grain moisture (% wet basis)	11.4	11.6	11.7
Storage period (months)	6	9	10
Initial grain temperature (°C)	29	27	26
Initial cooling to 15°C (months)	1.7	1.2	1.4
Final grain temperature (°C)	6	5	8
Total operating time (hours)	Continuous operation		
Energy used (kWh/tonne of silo capacity)	22	30	28
No. of live insects at inloading	17	1	6
Quantity of grain sieved (kg)	384	543	255
No. of live insects at outloading	1	0	0
Quantity of grain sieved (kg)	490	863	429

The third trial at Brookstead was conducted using barley, and the enhanced germination and malt yield resulting from storing in a refrigerated silo has led to continued use of the system.

Trials at Lah, Victoria

Mathematical modelling of refrigerated grain silos had progressed to a stage where a design could be specified for a 1700 t steel silo in northern Victoria. Details of the model and results of optimization studies are given by Thorpe (1976). The significant conclusion of the work was that recirculation systems gave much lower annual costs than systems like that at Dalby in which the air from the silo is exhausted to atmosphere. These studies were based on maintaining wall temperature below 15°C and took account of the drying effect of heat flowing through the wall on grain moisture content and the consequent effects on insect behavior. The eco-system modelling of the complete process is barely within the capabilities of modern computers; but Thorpe *et al.*, (1982) have initiated procedures compatible with both the physical and biological aspects.

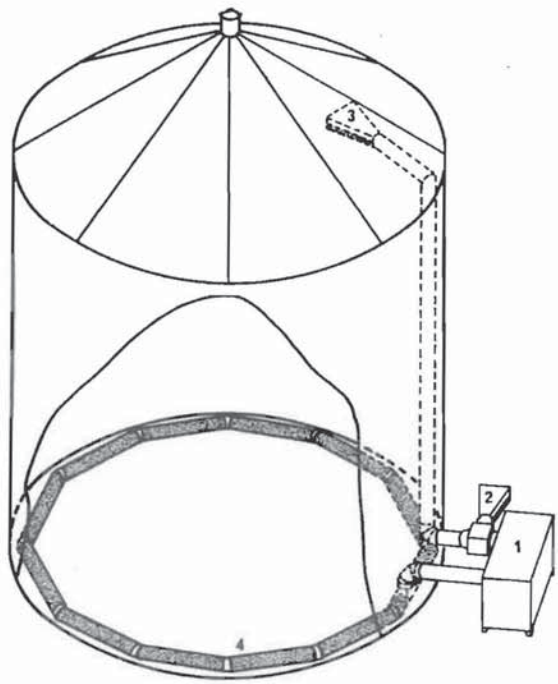

Fig. 2. Layout of ducting in 1700 t capacity insulated silo for grain refrigeration trials at Lah, Victoria.

1. Refrigeration Unit; 2. Atmospheric Air Intake;
3. Return Air Intake: 4. Perforated Air Distribution Duct.

The system at Lah is described by Hunter and Taylor (1980) and comprises a self-contained refrigeration unit with direct-expansion air cooling coil connected to distribution ducting around the periphery of the silo floor and recirculation duct from the headspace as shown in Fig. 2. The insulation thickness on roof and wall, the air flow rate and the refrigeration capacity were all specified in accordance with the optimized model. The results of the two trials at Lah, summarized in Table 3, indicated that adequate insect control temperatures were achievable, that energy cost was comparable with that of new protectant insecticides, and that the peripheral duct satisfactorily cooled the central grain and peak of the bulk in addition to the grain at the silo wall.

TABLE 3
SUMMARY OF RESULTS OF TWO GRAIN REFRIGERATION TRIALS WITH WHEAT IN AN INSULATED 1700 TONNE STEEL SILO 14.5 m DIAMETER AND 13.1 m WALL HEIGHT AT LAH, VICTORIA

Trial No. Year	1 1976/77	2 1977/78
Air flow rate (L/s per tonne of silo capacity)	1.5	1.5
Compressor rating (shaft W/tonne of silo capacity)	4.4	4.4
Quantity of wheat (t)	1650	1750
Initial grain moisture (% wet basis)	8.8	8.3
Final grain moisture (% wet basis)	9.2	8.8
Storage period (months)	9	5
Inital grain temperature (°C)	34	30
Initial cooling to 15°C (months)	1.2	1.4
Final grain temperature (°C)	9	9
Total operating time (hours)	–	–
Energy used (kWh/tonne of silo capacity)	24	22
No. of live insects at inloading	0	0
Quantity of grain sieved (kg)	276	271
No. of live insects at outloading	0	0
Quantity of grain sieved (kg)	204	210

Trials at Gravesend, NSW

The ability of the direct-expansion refrigeration system and continuous air flow through the grain at the silo wall to provide adequate cooling performance led to a concept of modular cooling units of a standard design to suit all types of grain storages (Elder, 1980). Six such units were installed on a 15 000 tonne capacity horizontal shed storage at Gravesend in the northern wheat belt of New South Wales. Each unit recirculated refrigerated air through individual sections of the bulk thus enabling positive cooling of the first loads of grain entering the storage. A description of the system and some preliminary results were given by Thorpe and Elder (1978).

Unlike previous trials where filling of the storage was completed in only a few days, the 15 000 tonne shed took many weeks to fill. In the first trial, cooling was not commenced until the grain at the temperature monitoring position was alsmost at its full height. The objective of this was to observe the development of cooling patterns from the peripheral air distribution ducts towards the central regions of the bulk, and confirm model predictions that central ducting in sheds even as wide as 24 m was not necessary. The patterns developed after 17 and 39 days of plant operation are shown in Fig. 3 and clearly demonstrate that the centre of the bulk is being cooled progressively.

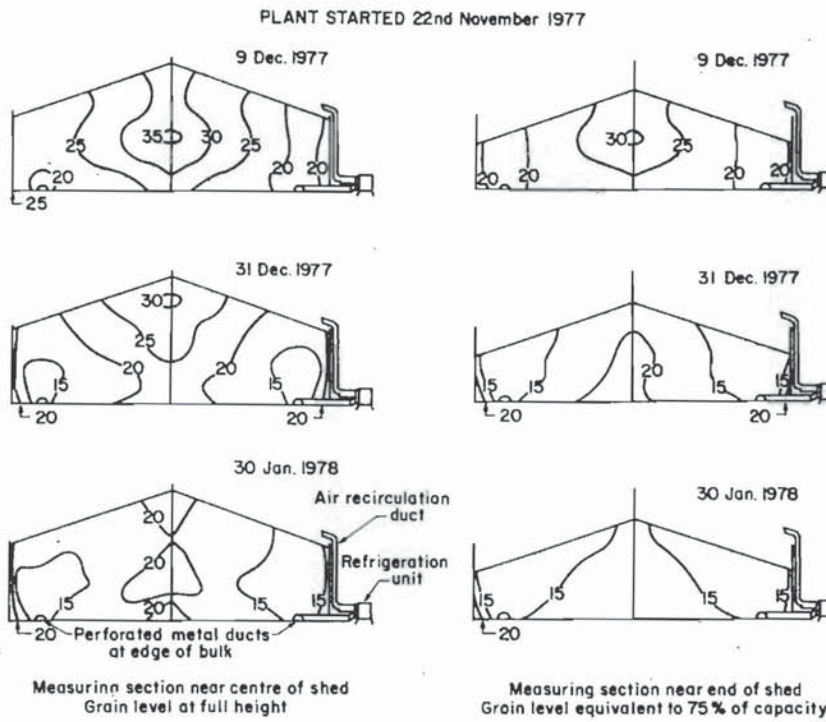

Fig. 3 Grain temperature contours at two measuring sections of 15 000 t capacity insulated horizontal storage at Gravesend, NSW showing progressive cooling from ducts on floor near walls to centre. Note: Air flow of 0.7 L/st only two-thirds of specified rate.

During the trial, the air flow rate was found to be substantially less than the specified value and consequently the cooling performance was not as good as it should have been. However, very good control of infestation was achieved as shown in Table 4. In a subsequent trial when the air flow had been brought up to specification, the cooling of the centre of the bulk was proportionally more rapid as shown in Fig. 4.

The initial cooling performance of the system as shown in Table 4 was never as good as in previous trials, even though the refrigeration capacity was greater. After exhaustive measurements and testing, it was found that outside atmospheric air was leaking into the air recirculation circuit of the refrigeration units downstream of the cooling coil. This leakage amounted to about 12% of the air flow. In the hot summer period following the filling of the storage, this admixture of outside air with the refrigerated air off the cooling coil almost annulled the cooling effect before the air could reach the grain. Consequently, the average grain temperature could not be brought below 15°C until the onset of consistently cooler atmospheric conditions. This is illustrated in Fig. 5 by cooling performance in the third season at Gravesend which is compared with that at Brookstead in the same climatic zone.

TABLE 4

SUMMARY OF RESULTS OF TWO GRAIN REFRIGERATION TRIALS WITH WHEAT IN 15000 TONNE HORIZONTAL STORAGE 96 m LONG, 24 m WIDE AND 6 m WALL HEIGHT AT GRAVESEND, NSW

Trial No. Year	1 1977/78	2+ 1980/81
Air flow rate (L/s per tonne of silo capacity)	0.7	1.0
Compressor rating (shaft W/tonne of silo capacity)	6.5	6.5
Quantity of grain (t)	12160	4335
Initial grain moisture (% wet basis)	9.9	10.9
Final grain moisture (% wet basis)	11.0	11.8
Storage period (months)	10	10
Initial grain temperature (°C)	32	28
Initial cooling to 15°C (months)	2.9	4.5*
Final grain temperature (°C)	9	12*
Total operating time (hours)	-	-
Energy used (kWh/tonne of silo capacity)	26	29
No. of live insects at inloading	0	5
Quantity of grain sieved (kg)	968	404
No. of live insects at outloading	5	19
Quantity of grain sieved (kg)	1016	340

* Weighted mean for three separate heaps of cooled grain

\+ Drought season

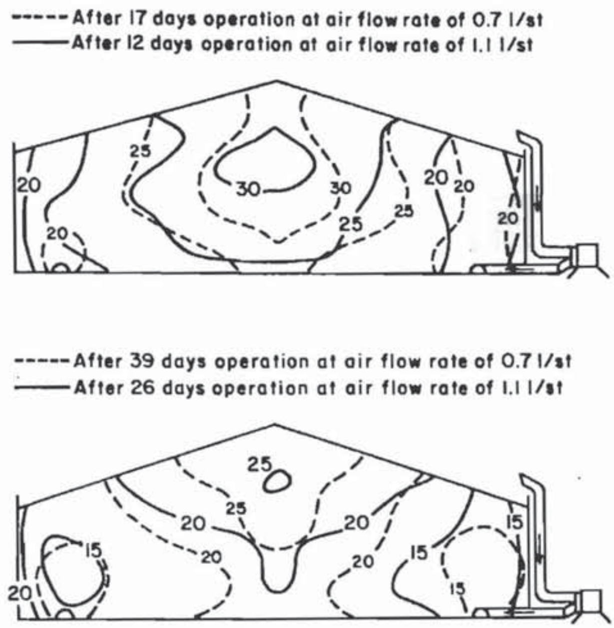

Fig. 4 Grain temperature contours at central measuring section of 15 000 t capacity insulated horizontal storage at Gravesend, NSW showing effect of increased air flow on cooling rate at centre of bulk.

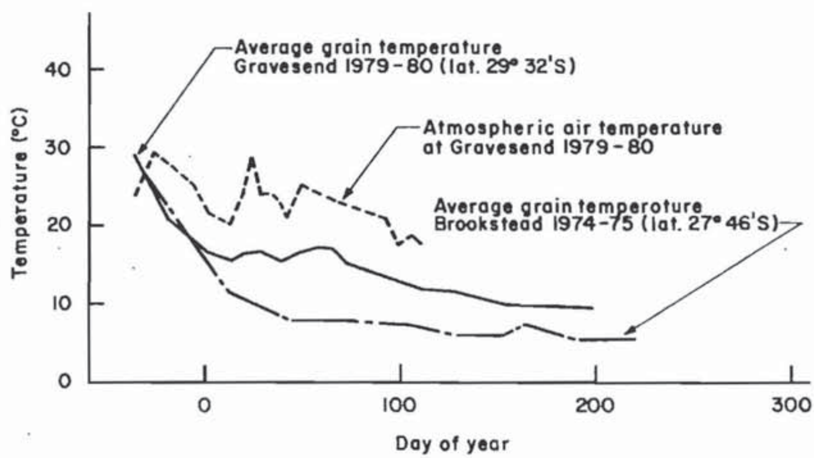

Fig. 5 Comparison of cooling performance between the grain refrigeration systems at Brookstead, Queensland and at Gravesend, NSW showing the dwell in the initial cooling at Gravesend resulting from 12% leakage of atmospheric air into the recirculating air downstream of the cooling coil.

A few live insects were occasionally found at the peaks of the grain throughout most of the storage period. At the conclusion of the first season's storage, grain temperatures were monitored in the railway wagons transporting the refrigerated grain to the port, a distance of some 600 km over four days. The average grain temperature increased from 10 to 12°C during the journey. The grain was not treated with insecticide at any time and passed inspection for export several weeks later.

During the second season, part of the bulk become infested before one of the refrigeration units (being modified for increased air flow) could be re-installed. A surface spray and subsequent cooling arrested the infestation. At the end of the season it was necessary to carryover this grain and it was transferred without the usual insecticide treatment to the emptied end of the shed for continued cooling. The new season's grain was then received and cooled as indicated in Fig. 4. Although it would have been most informative to have sieved the grain from the two seasons at outloading to determine the level of insect activity, the cost of the exercise precluded a rigorous sieving programme similar to that conducted for the first season.

The dynamics of insect activity at the peaks of the bulk throughout the second and third season is shown in Fig. 6. It must be remembered that with cool air flowing up to the surface, insects will migrate as shown by Navarro *et al.*,(1981) to the warmer zones such as the peaks. Therefore the infestation that may be found by inspectors is not representative of the general condition of the grain as in typical storages, but gives a biased result suggesting that the grain needs to be treated to meet export inspection criteria. Although it would be prudent, and in some States of Australia legally mandatory, to treat the surface infestation prior to outloading, the grain may still meet export inspection requirements as was demonstrated in the first season. The concentration of any infestation that may be present at the readily accessible surface, facilitates very effective insecticide treatment and will lead to exceptionally low residual insect populations.

A severe drought in the northern wheat belt of NSW resulted in very little grain being available for the fourth and final trial at Gravesend. The performance of the refrigeration system with separate heaps of grain and no central ducting was observed, and the overall results are summarized in Table 4. The effectiveness of the cooling from the peripheral ducts was related directly to the height of grain. With the grain level at the equivalent of 75% full capacity, cooling was satisfactory and no live insects were found at outloading. However, at the 50% full level, insufficient air was passing up through the central regions of the bulk to cool the peak and live insects could be found easily by sieving. One of the heaps of grain did not flow over any of the perforated ducting near the walls. It did not cool by conduction to the surrounding refrigerated air and, later in the storage period, a hot spot and heavy infestation was detected at the floor near the centre of the heap. To prevent contamination by this infestation of the cooled grain to be sieved during outloading, the uncooled heap was sheeted and fumigated with phosphine. The calculated quantity of gas dispersed in the headspace air would have been well below lethal levels determined by Hole *et al.*, (1976) and would not have affected live insects in the cooled heaps. The insect numbers given in Table 4 are for the live adults found in the cooled grain.

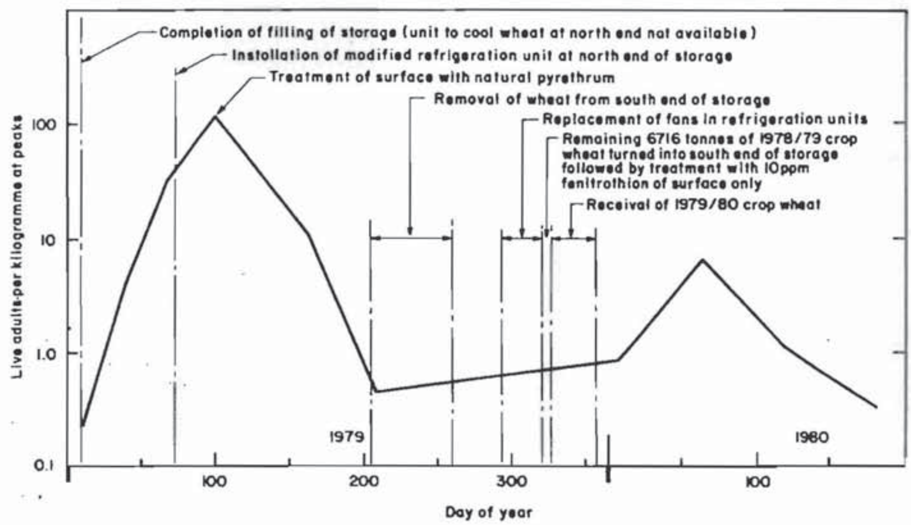

Fig. 6 Overall insect population desities at the peaks of the surface of wheat held over two seasons in 15 000 t insulated horizontal storage at Gravesend, NSW.

Central ducting, although not necessary if the storage is at least 75% full, should be considered to cater for poor seasons or small quantities of grain in separate heaps. The air flow may be changed-over from the central to peripheral ducting at the end of the initial cooling period as at Brookstead, or for simplicity, flow into both duct systems continuously. A central system will also hasten the initial cooling of the peaks of the bulk, but will detract from cooling at the walls for the majority of the storage period.

Performance of insulation

The insulation was applied to the outside of the storages for a number of reasons concerned mainly with hygiene and operational matters. The uptake of moisture by the insulation under the vapour pressure gradient imposed by the Queensland climate was monitored for several years at Brookstead and shown by Elder *et al.*, (1975) to stabilize after an initial increase. The moisture uptake was too small to have any noticeable effect either on the thermal conductivity, or on the roof load.

Various coatings to protect the insulation from ultra violet (u.v.) degradation have been tried. Low cost aluminium paint did not adhere satisfactorily in the long term; but the most disturbing feature of this coating was that it highlighted irregularities in the spray application of the insulation foam, and consequently attracted considerable criticism from the industry. Subsequently, PVA white paint was applied which improved the appearance of the silo at Brookstead considerably. At Lah, a white elastomeric hypalon coating was applied which has proved satisfactory but very expensive. Likewise at Gravesend, a white hypalon mastic coating was applied. The costs of various coatings have been analysed and a panel of a number of these is undergoing long term tests at Gravesend.

Damage to the insulation and coating has resulted from a number of environmental factors. At Brookstead, rodents found the 50 mm thickness of insulation on the roof to be sufficient to form nests. Furthermore, the burrows collected rain water, and this was a major cause of local wetting of the insulation. The subsequent mathematical modelling by Thorpe and Elder (1977) showed the optimum roof insulation thickness to be about 15 mm which would be insufficient to enable burrowing by rodents. At Lah, the insulation was attacked by birds and it appears that this attack is continuing. Pieces of the elastomeric coating could also be peeled off the insulation leaving the exposed yellow surface vulnerable to u.v. degradation as well as, perhaps, making it more attractive to birds. Being an isolated site remote from housing, some vandalism of the insulation has occurred but this was not as serious nor as persistent as bird damage. At Gravesend vandalism was limited to embedding of stones and other missiles in the wall insulation. After the first season, birds appeared to lose interest in attacking the insulation. Rodents have burrowed into the wall insulation at fillets where structural members contact the grain retaining wall. Considering that the total area of insulation is over half a hectare, the proportion of damage is extremely small; however the blemishes in the surface give the impression of a serious shortcoming.

Fears that heavy hail storms will tear the insulation of the storages have to date been proved groundless, although at Gravesend there is evidence that hail has fallen on the storage and caused a crazed cracking of the mastic coating.

Cost

One of the objectives of conducting full scale field trials in collaboration with the industry was to positively indentify the real commercial costs of grain refrigeration. These have been used in various studies by the Bureau of Agricultural Economics and others as well as in our own cost optimization modelling work. Connell and Johnston (1981) have shown that the annual costs are similar to those for controlled atmosphere storage, and of the order of 2% of the value of the grain stored.

Too concentrated a focus on the cost of applying refrigeration can lead to an unbalanced perspective of the role of the treatment in the overall grain storage and handling system. This is perhaps best illustrated by an example. The 5400 tonne silo at Brookstead had a history of uncontrollable insect problems and at the time we chose it for the first trial of full scale refrigeration, it was being used only for short term storage of grain sorghum when absolutely necessary. For less than one tenth the cost of replacing the storage, refrigeration redeemed it as a most valuable facility for long term storage of malting grade barley. The thrust of CSIRO's research programme on grain refrigeration has been towards similar storages such as the shed type. It was thought that shed storages may prove totally unsatisfactory if chemical protectant insecticides could no longer be used to control infestation because of resistance or commercial or industrial factors.

The capital costs for the three refrigeration systems are summarized in Table 5. Using the Consumer Price Index (a measure of inflation) to normalize costs, it will be seen that the cost of insulation per tonne of storage capacity is very closely related to the surface area to capacity ratio of the storage. A generalized graph showing a range of typical grain storages is shown in Fig. 7 with the trial storages plotted. Clearly, the larger the storage capacity, the lower the cost per tonne. For example, the cost of insulating CBH's No. 1 shed at Kwinana, Western Australia, also shown in Fig. 7, is about one third of the cost of insulating the shed at Gravesend.

TABLE 5
CAPITAL COST OF RETRO-FITTED GRAIN REFRIGERATION SYSTEMS IN AUSTRALIA

	Brookstead Queensland	Lah Victoria	Gravsend N.S.W
Year of installation	1973-74	1976-77	1977-78
Consumer Price Index	46.7	70.1	76.7
Capacity of storage (t)	5400	1700	15 000
Total capital cost ($/t)	8.1	18.4	14.2
Insulation cost - ($/t)	3.0	7.6	5.8
- ($/m^2)	10.1	15.6	15.5

Note: Tabulated costs in Australian dollars
A$1.00 in June 1973 = US$1.42
1976 = US$1.24
1977 = US$1.12

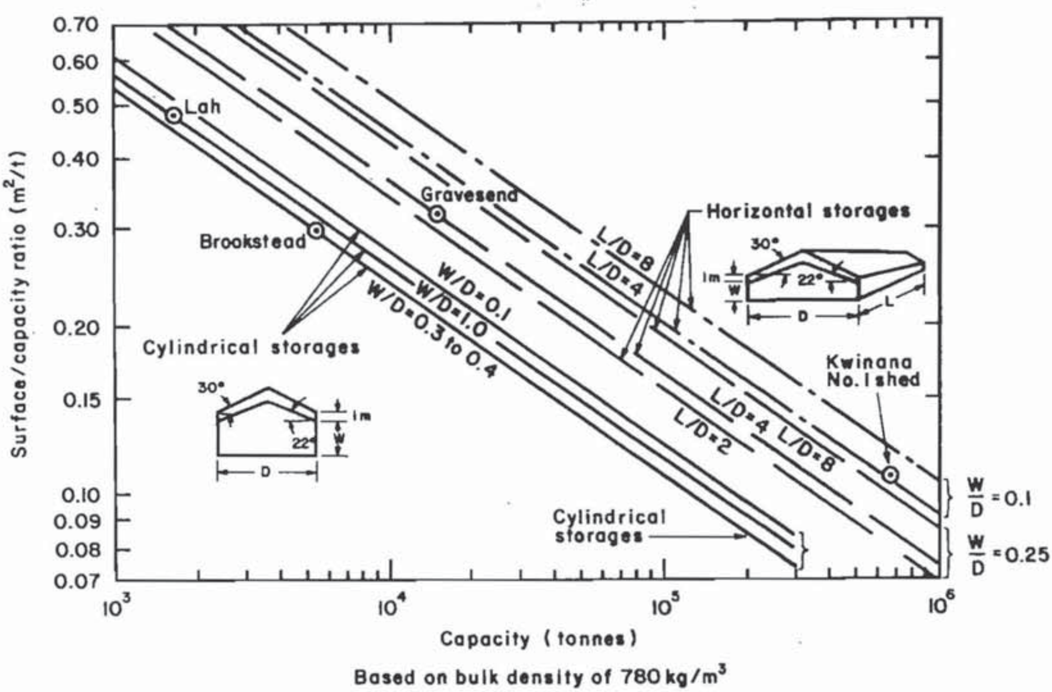

Fig. 7 Chart for surface area to capacity ratio representing capital cost for insulation per tonne for grain storages of various capacities and configurations.

Operating costs are indicated by the electrical energy consumption in Tables 1 to 4. Maintenance and servicing costs vary considerably but do not appear to exceed 4¢/t p.a. (Connell and Johnston, 1981).

Repair costs for insulation are governed by the degree of deterioration tolerated before refurbishing is implemented. No repairs have been carried out at Lah even though a total of approximately 5 m^2 has been attacked by birds. A quotation of $600 was obtained in 1980 for abour 2 m^2 repair. The cost per unit will obviously be higher than that quoted in Table 5 because of relatively high establishment costs, the additional cost of frequent movement of scaffolding to reach isolated damaged regions and difficulties in spraying the foam into depressions. The cost of repair plus application of additional insulation for experimentation purposes at Gravesend was 11c/t after three years.

MOBILE GRAIN REFRIGERATION UNITS

The modular refrigeration unit concept permits the use of the treatment for other applications in the grain storage industry, by mounting units on trailers for transportation to a number of sites involving a wide variety of storage types and stored commodities.

Cooling of protectant treated grain was shown by Bengston *et al.*, (1980), Desmarchelier *et al.*, (1979) and Thorpe and Elder (1980) to prolong the effectiveness of the insecticide, and a trial was conducted at Murtoa, Victoria in collaboration with the Stored Grain Research Laboratory and the Grain Elevators Board using a mobile refrigeration unit. On the basis of the results, an economic analysis has been presented by Hunter (1981).

Mobile refrigeration units of similar capacity as used at Lah, Gravesend and Murtoa are being used by the State Wheat Board in Queensland for cooling high moisture grain sorghum, and by Co-operative Bulk Handling Limited for cooling wheat in Western Australia.

These and other applications facilitate the gradual introduction of the technology into the industry as relatively modest amounts of money are made available.

CONCLUSIONS

Trials using refrigerated air to cool grain stored in large bulks have shown that the treatment is feasible and effective as an insect control measure, and that the cost is reasonable. Early work showed that insulation was necessary to maintain all of the grain below 15°C, the insect population growth threshold adopted for design. Adequate control of grain temperatures near the wall was achieved by using peripheral air distribution ducting. In sheds, ducts placed close to the wall provide adequate cooling of the central regions of the bulk only if the storage is substantially full. An additional central duct system would cater for small heaps of grain particularly in drought seasons, and also enhance the initial cooling of the peaks of the bulk.

Although live insects may be detected at the peaks of refrigerated grain bulks, their prescence does not necessarily indicate that the grain will not pass export inspection. The movement of cold waves up to the warmer peaks concentrates live insects at the surface where they can be treated appropriately. During transportation, the temperature of refrigerated grain remains low thus providing a residual protection from insect problems.

Spray-applied closed cell rigid polyurethane insulation can be put successfully on the outside of the structure without including long term moisture accumulation from the adverse water vapour pressure gradients. The thickness must be such that rodents cannot form burrows, and care must be exercised in ensuring that fillets of insulation against structural members are avoided. Minor repairs to the insulation resulting from damage by birds will be necessary in most circumstances. The best coatings are in general the most expensive. A mastic is preferred to an elastomeric coating which can be peeled off the insulation. However, the long-term effects of crazed cracking of mastic by hail, on the degradation of the insulation under the cracks is yet to be observed. Hail has not caused any damage of a serious nature to date.

The capital cost of retro-fitting refrigeration systems to existing silos is a noticeable proportion of the cost of the storage facility and cannot compete with alternative insect control measures. It can however be justified if the alternatives are banned, or unsatisfactory facilities can, by becoming refrigerated, be upgraded to an acceptable standard. In the future, refrigeration may be regarded as an integral part of new storage facilities and its additional cost would then be a small proportion of the overall project budget. Operation and maintenance costs will then become the most noticeable feature of the system. It appears this is presently of the order of $1 per tonne per annum. Refrigeration cost is lower the larger the storage structure, and therefore this treatment is more worthwhile for the large horizontal storages common in Australia which may not otherwise provide satisfactory protection against insects.

The plant for grain refrigeration has been developed on a unit module for cooling about 2000 t of grain. This has been shown to facilitate the use of these cooling units for a number of pseudo-refrigeration applications involving various criteria other than direct insect control. this will lead to the gradual acceptance by the industry of the technology and in due course will enable a smoother transition to full scale refrigeration when necessary.

ACKNOWLEDGEMENTS

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