Executive Summary

Europe uses approximately 1,000 t of methyl bromide annually for structural pest control. The southern countries, Spain, France, Italy and Greece, are the major consumers. The purpose of this paper is to give some concrete examples of methyl bromide alternatives being tested under industrial conditions in Europe today, the addresses of the people who carried out the work, and how these methods could be adapted for use in Canada.

Carbon dioxide has been studied as a fumigant for decades in the laboratory, and there are now several examples of it being used to control insects in the food industry. However it still remains slower-acting and more expensive than phosphine or methyl bromide. To address these problems, the Stored-Product Laboratory at Bordeaux investigated the use of high pressure and carbon dioxide. After extensive testing in the laboratory, a high pressure fumigation chamber was designed and built in collaboration with MG SIAC (France). The chamber can hold 32 palettes, or the equivalent of the contents of one transport trailer. The unit is designed to recuperate at least 85% of the carbon dioxide used. The pressure rises to 19 atmospheres in 90 minutes, is held there for 60 minutes and takes about 30 minutes to release the pressure. With loading, fumigation and unloading, a full cycle takes approximately four hours. To verify the effectiveness of the unit, red flour beetle adults and Indian meal moth larvae were placed in bags of pet food, the commodity to be fumigated, and the bags placed throughout the chamber. None of the 3200 red flour beetles or the 1600 Indian meal moth survived the fumigation. The unit cost approximately $850,000 CAN to build, and it costs $300 CAN per fumigation. This is the first example of high pressure carbon dioxide fumigation at an industrial scale.

In Germany since 1993, MeBr can only be used in special circumstances, so there has been an active search for alternatives. As a partial replacement for MeBr, sulfuryl fluoride (SO₂F₂, tradename Altarion® Vikane, DowElanco) has been recently registered for use in Germany as a space fumigation in non-food areas (eg. museums, churches, artifacts). To minimize the amount of sulfuryl fluoride used, a hand-held calculator has been designed to determine the amount of sulfuryl fluoride needed. It takes into consideration: target insect, stage of development, volume to be fumigated, duration of fumigation, temperature, airtightness of the building, and wind velocity. Carbon dioxide has also been used to fumigate entire churches. The church is covered with a tarpaulin, the fumigation takes several weeks and requires several tonnes of CO₂. This method is successful at controlling wood boring pests, but is considerably more expensive than traditional fumigations.

A group in Scandinavia has shown that spot heat treatment controls insects in roller stands in flour.

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1 Presented at Workshop on Alternatives to Methyl Bromide, Toronto Canada, May 30-31, 1996, pp 83-90
mills. Roller stands were covered with a tarpaulin and flexible ducts were used to direct heat into the machinery. High temperatures ranged from 60 to 80°C, and all test insects placed in the machinery were killed. The heating took only four hours and the technique is proposed as a method to control insects in high risk areas, without stopping production for several days, as is necessary for a MeBr fumigation.

Flour mills in Italy have used mass trapping or attracticide to reduce by half the number MeBr fumigations. The main insect pest in Italian flour mills is the Mediterranean flour moth (*Ephestia kuehniella*). By placing several high capacity pheromone traps throughout a flour mill (one every 260-280 m³), Mediterranean flour moths were reduced over a three year period. Another method, attracticide, was also able to significantly reduce moth populations. Pheromone dispensers are treated with an insecticide, cypermethrin. Male moths are attracted to the lure, and receive a lethal dose of insecticide when they land on the lure. These methods have yet to be attempted against insects that have aggregation pheromones, such as the red flour beetle (*Tribolium castaneum*) or the confused flour beetle (*T. confusum*), insects that are the major pests of flour mills and other food processing plants in Canada.
INTRODUCTION

Before methyl bromide, which began to be used extensively in Europe after World War II, there were several techniques used to control insects in food processing plants. As early as the 16th century heat was used to control the moth *Sitotroga cerealella* in flour mills in France (Oosthuizen 1935). Underground grain storage was one of the main methods of long-term preservation of large grain bulks in most cereal growing societies. Underground grain stores are known to have existed from pre-neolithic times in the Middle East (9000 to 7000 BC) and in Europe (4500 BC) (Sigaut 1980).

In 1991, there were 18,521 t of methyl bromide sold in Europe (excluding former U.S.S.R.). Most of this was for soil fumigation (80%), the rest was used for structural fumigation or commodity fumigation. In 1992, the approximate amount of methyl bromide used for structural pest control was: Spain 397 t, France 176 t, Italy 150 t, Greece 90 t, Germany 70 t, United Kingdom 55 t, Belgium 30 t, Netherlands 27 t, Eire 18 t, Sweden 17 t, Norway 11 t, Finland 7 t, Denmark 5 t (Banks 1995). For comparison purposes in the same year Canada used 130 t for structural fumigation (Figure 1.). All the major users of methyl bromide in Europe are signatories to the Montreal Protocol, and therefore will have to reduce MeBr consumption by 25% in 2001, by 50% in 2005 and full elimination by 2010. There may be some "critical uses" retained, such as quarantine or other uses for which viable alternatives have not been found. Some countries in Europe intend to phase out methyl bromide before 2010.

The purpose of this paper is give some concrete examples of methyl bromide alternatives being tested under industrial conditions in Europe today, the addresses of the people who carried out the work, and how these methods could be adapted for use in Canada.

HIGH PRESSURE CARBON DIOXIDE: FRANCE

The insecticidal properties of carbon dioxide (CO$_2$) at atmospheric pressure, under tarpaulins or in fumigation chambers are well known, and there are numerous applications against stored-product insects (Banks and Fields 1995). Nevertheless, the use of CO$_2$ fumigation at atmospheric pressure is used much less than the traditional fumigants, methyl bromide (CH$_3$Br) and phosphine (PH$_3$). The two main inconveniences of CO$_2$ fumigation that render it more expensive than traditional fumigants are the longer durations and higher gas concentrations necessary for a successful CO$_2$ fumigation. A CO$_2$ fumigation can take from three days to several weeks, depending upon the temperature and target insect, and requires concentrations above 60% or the equivalent of 2000 g/m$^3$. Methyl bromide fumigations generally take 1-2 days and need only 32-48 g/m$^3$. 
As MeBr is slated to be greatly reduced in the near future, we (Fleurat-Lessard and Le Torc'h) at the same time as the Germany stored-product group (Christoph Reichmuth, Federal Biological Research Centre for Agriculture and Forestry, Königin-Luise-Strasse 19, 14195 Berlin, Germany, telephone: +49 30 8304 261, Fax: +49 30 8304 284, Reichmuth and Wohlgemuth 1994) investigated the use of high pressure (10-20 atmospheres) CO₂ fumigation as a viable alternative to MeBr fumigation. As it is necessary to carry out the fumigation in a pressurized container, this method is aimed at the control of insects in processed food and animal feed in non gas tight packaging, as well as artifacts.

Laboratory Trials.

The first trials in the laboratory showed that raising the CO₂ pressure from 1 to 20 atmospheres reduced the time to control the granary weevil (Sitophilus granarius) larvae from 18 days to 4 hours (Le Torc'h and Fleurat-Lessard 1990, Prozell and Reichmuth 1990). Given the success of these first tests, the study was expanded to insects that are more common in processed foods, the likely commodity for this procedure. Eggs, larvae, and adults of the red flour beetle (Tribolium castaneum), the hide beetle (Dermestes maculatus) and the Indian meal moth (Plodia interpunctella) were placed in a pressurized chamber and subsamples were removed at various times to check for survival. Pupae were not used, as in a pretest they were shown to be more susceptible than the other stages.

Table 1 gives the minimum times needed to control insects. For the red flour beetle the eggs were the most resistant stage, requiring just over four h at 10 atmospheres and one h at 19 atmospheres. Other insects at other stages were more susceptible than red flour beetle eggs. Trials were also conducted with air in place of CO₂. Hide beetles adults had 93% and Indian meal moth adults had 100% mortality at 19 atmospheres.

<table>
<thead>
<tr>
<th>Insect</th>
<th>Stage</th>
<th>Duration (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CO₂ Pressure (atmospheres)</td>
</tr>
<tr>
<td>Red Flour Beetle</td>
<td>egg</td>
<td>&gt;240</td>
</tr>
<tr>
<td></td>
<td>larva</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>adult</td>
<td>240</td>
</tr>
<tr>
<td>Hide Beetle</td>
<td>egg</td>
<td>&gt;240</td>
</tr>
<tr>
<td></td>
<td>larva</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>adult</td>
<td>240</td>
</tr>
<tr>
<td>Indian Meal Moth</td>
<td>egg</td>
<td>&gt;240</td>
</tr>
<tr>
<td></td>
<td>larva</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>adult</td>
<td>120</td>
</tr>
</tbody>
</table>
atmospheres after two h, but all three larval and egg stages were unaffected after two h at 19 atmospheres.

Pre-industrial Pilot Trials.

A pre-industrial pilot pressure chamber with a capacity of 0.75 m³ and the ability to simulate the complete pressure treatment with a rapid rise in pressure to 11 or 16 atmospheres, with a final stable pressure of 19 atmospheres was built and tested. The pressure chamber was attached to a suite of 11 cylinders with 160 atmospheres of CO₂ and a heat exchanger for the injection of the gas into the chamber. The CO₂ was injected into the lower part of the chamber and the bags of insect-infested pet food placed at different levels in the chamber to estimate the degree of gas stratification. The chamber was not purged of air before the injection of CO₂, causing a slight reduction in CO₂ concentration (approximately 1/19th). This may be the reason there were a few red flour beetle eggs that survived in the topmost level. To avoid this, the industrial scale chamber was designed to be purged with one volume of CO₂ before pressurization, and gas is introduced at several points in the chamber.

The pilot trials also determined the rates of pressurization and depressurization that the packaging could tolerate. The initial pet food packaging was too gas tight and often tore during the rapid changes in pressure. Replacing the packaging with a more porous material, and the reducing the rates of pressure change solved this problem.

Industrial Scale Trials.

The full scale pressure chamber has a working capacity of 80 m³, enough space to treat 32 palettes of pet food or the equivalent of the contents of one transport trailer (Figure 2). The industrial unit was designed and built by MG SIAC (contact Mr. C. Henry, MG-AIRGAZ, 84, rue Charles-Michels, 93206 Saint-Denis, France, telephone: +33 1 49 33 70 00, Fax: +33 1 48 20 35 81). In a normal treatment cycle, palettes are loaded into the chamber, the chamber is sealed and purged with one volume of CO₂ (Figure 3). The CO₂ is injected into the chamber, and it takes 90 minutes to obtain 19 atmospheres. This pressure is maintained for 60 minutes and it takes 30 minutes to depressurize the chamber. The entire cycle with loading, fumigation and unloading takes approximately four hours. The operation of pressurizing and depressurizing is complicated by the desire to minimize the amount of CO₂ lost during each fumigation. This is obtained by a patented system using two CO₂ holding tanks and a compressor.

To verify the effectiveness of the unit, red flour beetle adults and Indian meal moth larvae were placed in bags of pet food, the commodity to be fumigated, and placed throughout the chamber. None of the 3200 red flour beetles or the 1600 Indian meal moth survived the fumigation.

Currently the unit does six fumigations a day, at a cost of approximately $300 CAN to cover the electricity and 300-400 kg of CO₂ needed for each fumigation. The unit cost approximately $850,000 CAN (one million FF) in 1995 to build, and the pet food company, Royal Canin, intends to build another two units, which will enable them to treat 15 truck loads of product a day. The one pressurized unit replaces eight fumigation units that used phosphine and took three days per fumigation. This system is appropriate for any packaged food or animal feed product that has a non airtight packaging, is a high value product, the manufacturer needs a rapid treatment and a high assurance that the product is free from infestation.

SULFURYL FLUORIDE AND CARBON DIOXIDE FUMIGATION: GERMANY

In Germany since 1993, MeBr can only be used in special circumstances, so there has been an active search for alternatives. As a partial replacement for MeBr, sulfuryl fluoride (SO₂F₂, tradename Altarion® Vikane, DowElanco) has been recently registered for use in Germany as a space fumigation in non-food areas. In the USA, sulfuryl fluoride has been used for many years, mainly for fumigation against termites in houses. In Germany it is used for fumigation of artifacts in museums and churches (Figure 4). The
main pests in these situations are wood boring insects (eg *Hylotrupes bajulus*) or dermestids (*Dermestes maculatus*, *Anthrenus* spp.) which can feed on a wide range of organic material (skins, leather, stuffed animals, wool, etc. . . .). Sulfuryl fluoride has several advantages compared with MeBr for fumigation of wood boring pests in cultural artifacts. It does not damage the ozone, is non carcinogenic, does not penetrate via the skin, is 2-3 times less toxic to mammals, has low solubility in water, is inert, does not react with paint or gilding, has good penetration in wood, and desorbs quickly. The disadvantages are that as any fumigant, it is very toxic to humans and must be used with extreme caution, while less toxic to insect eggs than MeBr.

To minimize the amount of sulfuryl fluoride used, a hand-held calculator has been designed to determine the amount of sulfuryl fluoride needed. It takes into consideration: target insect, stage of development, volume to be fumigated, duration of fumigation, temperature, airtightness of the building and wind velocity. The fumigator has some control over these variables. The building can be made more airtight with more extensive sealing, the temperature can be increased (though with art work this is not recommended because of the cracking caused by dehydration), the fumigation can be prolonged, or postponed if there are high winds, or volume can be decreased using balloons inside the structure to reduce the effective volume.

Nitrogen or CO$_2$ have also been used to fumigate whole artifacts or entire churches (Gerhard Binker, Binker Materialschutz GmbH, AM Vogelherd 6, Schwaig, Beyern, D-90571, Germany, telephone: + 49 911 507 5011, Fax: +49 911 507 6782). These gases are inert, but have the disadvantage that they require much longer exposure times than MeBr or sulfuryl fluoride, and higher gas concentrations, rendering fumigations with these gases considerably more expensive than with the traditional fumigants. For artifacts that can be moved, fumigation chambers are the simplest method of fumigation. For artifacts that cannot be moved, portable fumigation chambers can be installed around the artifact. These chambers can be flexible (greater loss of gas) or rigid (more difficult to transport and to install). It is essential when doing partial fumigations to verify that there are no other insect infestations in the same building that will reinfect the artifact after fumigation. Entire churches have been fumigated using CO$_2$ (Figure 5 et 6). The church is sealed as for a normal fumigation, covered with a multi-sectioned form-fitting tarpaulin, the CO$_2$ is supplied from truck tanks, heat exchangers bring the liquid CO$_2$ up to the temperature in the church, the CO$_2$ is humidified and pumped into the church and maintained at 60% for 2-6 weeks. Temperature, relative humidity, CO$_2$ and oxygen concentrations are measured to determine how much CO$_2$ and water vapour must be pumped in at a given time. The effective volume in the church is reduced by filling the church with balloons. The tarpaulin serves to reduce CO$_2$ and water vapour leakage. Despite the extensive sealing and volume reduction, church fumigation requires several tonnes of CO$_2$. One reason for the long durations needed to carry out the fumigations is that the CO$_2$ or nitrogen must diffuse into the wood. In food-handling facilities this would be less of a problem, and times could be substantially reduced.

**SPOT HEAT TREATMENT IN FLOUR MILLS: SWEDEN AND NORWAY**

The Nordic countries (Finland, Sweden, Norway, Iceland and Denmark) have committed themselves to a complete phase out of MeBr by 1 January 1998, with the exception of preshipment and quarantine uses (Banks 1995). Hence in March 1995 a group (project leader: Stein Norstein, Anticimex AS, Postboks 56, Abelsø, 1105, Norway, telephone: +47 22 29 50 10, Fax: +47 22 29 50 20) was formed to investigate the use of heat treatment as an alternative to MeBr for treating food processing facilities.

In addition to conducting preliminary trials on heat treatment of entire floors, they have developed a method for spot heat treating roller stands (Norstein 1996) (Figure 7). Roller stands are the site of many insect infestations in flour mills because there are numerous cracks and crevices that are difficult to clean, and as they are in contact with the grain they cannot be treated with contact insecticides. A row containing
six roller stands was fitted with flexible ducts, one duct for each roller. The entire row was covered with a tarpaulin to maintain the heat in the machinery. An oil burner with a capacity of 427 kW with a fan capacity of 10,000 m³/h was used as a heat source. It was kept outside the mill, and the heated air was moved into the mill with flexible ducts. Temperatures in the roller stands reached a minimum of 60°C for at least one hour and a maximum of 80°C for at least one hour. The heater ran for a total of four hours. All the insects (Tribolium destructor, larvae and adults, Trogoderma spp. larvae and Oryzaephilus surinamensis larvae and adults) placed inside the roller stands were dead after the treatment. Four months after the heat treatment, the mill has not had any technical problems with the heat-treated roller stands, and has noted fewer insects in the treated stands compared to untreated stands.

They recommend that the surfaces not exceed 70°C, as this is maximum temperature approved for PVC electrical wire insulation. This translated into an output temperature of 130°C at the heater with the length of duct work they used. Cleaning before heat treatment is essential because flour and food residues are very good heat insulators. In general they estimate that the heat treatment of an entire mill will initially cost twice what a treatment with MeBr would cost, though they feel that this cost will drop as they gain experience with the technique.

The advantage of the spot treatment is that it is rapid, treats high risk areas, minimizes the amount of heat needed for a treatment. The main disadvantages are that it does not control all insects at once in the mill, allowing the treated equipment to become reinfested after treatment, and requires the installation of heat tarpaulins over the equipment to be treated.

CONTROL OF MOTHS USING PHEROMONES IN FLOUR MILLS: ITALY

Many stored-product insects have pheromones, volatile substances that emitted by an insect cause a change in the behaviour in another insect (Burkholder and Ma 1985). In general, the stored-product beetles have aggregation pheromones, produced by the adult male which attract both male and female adults. The stored-product moths do not have aggregation pheromones, but female adults have a sexual pheromone that attracts males. Many of these pheromones have been identified, and are available commercially (Phero Tech Inc., 7572 Progress Way, R R #5, Delta, BC V4G 1E9, Canada, telephone: 604-940-9944, Fax: 604-940-9433, Insects Limited, 10540 Jessup Blvd., P.O. Box 40641, Indianapolis, IN, 46280-1451, USA, telephone: 317-846-5444, Fax: 317-846-9799). Pheromones combined with traps are a powerful tool for finding hidden infestations and tracking pest populations. Pheromones have been used to a lesser extent to actually control populations in forests, orchards and vegetable fields, either by mating disruption; males cannot find females, mass trapping; males are removed by trapping, or attracticide; males are lured to a dispenser that contains a lethal dose of a contact insecticide.

Pasquale Trematerra (Dipartimento di Scienze Animali, Vegetali e dell' Ambiente, Universita degli Studi del Molise, Via Cavour 50, Campobasso, Italy, telephone/Fax: +39 874 98743) has lead a team that has demonstrated that the Mediterranean flour moth, Ephestia kuehniella, can be reduced using either mass trapping or attracticide (lure and kill) with a thorough sanitation program (Trematerra 1994).

From April 1987 to November 1989 a large flour mill (four stories high, 20,000 m³, production of 125 t of flour/day) used mass trapping to reduce Mediterranean flour moth populations (Figure 8). Sixty-seven (one trap/260-280 m³) high capacity funnel traps baited with 2 mg of TDA (Z9E12-14Ac, major component of Mediterranean flour moth pheromone, Figure 9) were placed in the flour mill. Traps were emptied every two weeks and the pheromone lures changed every 2.5-3 months. In addition to the mass trapping, the mill was fumigated with methyl bromide each April, instead of the two fumigations annually, and a special effort was made to clean-up flour residues. A flour mill, situated in the same area, served as a control. It had the usual two methyl bromide fumigations a year, one in April and the second in August or September.
Table 2. THE CONTROL OF THE MEDITERRANEAN FLOUR MOTH USING MASS TRAPPING AND ONE FUMIGATION A YEAR.

<table>
<thead>
<tr>
<th>Year</th>
<th>Moths in Traps (#/trap/year)</th>
<th>Residual Moths (%)</th>
<th>Filth Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>240</td>
<td>3.4</td>
<td>under the limits</td>
</tr>
<tr>
<td>1988</td>
<td>62</td>
<td>2.3</td>
<td>under the limits</td>
</tr>
<tr>
<td>1989</td>
<td>39</td>
<td>2.3</td>
<td>under the limits</td>
</tr>
</tbody>
</table>

Taken from Trematerra (1990), as well as Trematerra unpublished data

The mill that used the combination of mass trapping, sanitation and one fumigation saw a consistent drop in the number of insects in the traps, resting on walls and machinery (residual moths) and insect fragments in flour (Table 2). This control was as good or better than the mill that used two MeBr fumigations/year.

As mass trapping alone could not eliminate the need for fumigations, attracticide was investigated by Trematerra (1994). Attracticide is achieved by placing on one side of a laminar dispenser 2 mg of pheromone (TDA) and on the other side 10 mg of cypermethrin, a pyrethroid contact insecticide. Dispensers are placed on the walls about two m from the floor, with one dispenser for every 220-280 m³. Males are attracted to the pheromone, land on the dispenser and receive a lethal dose of the insecticide. Moths in the untreated mill reached peaks of 400 males trapped over two wks, whereas in the mill using attracticide there were never more than 20 males caught over two wks.

With the success of these trials several mills in Italy have adopted these methods of control. Mass trapping and attracticide have the disadvantage that they target only one species. To date these methods have only been tested with the Mediterranean meal moth (Trematerra 1994), Indian meal moth (*Plodia interpunctella*, Pierce 1994) and the cigarette beetle (*Lasioderma serricorne*, Pierce 1994). For all these insects the sex pheromone was used. These methods have yet to be attempted against insects that have aggregation pheromones, such as the red flour beetle (*Tribolium castaneum*) or the confused flour beetle (*T. confusum*), insects that are the major pests of flour mills and other food processing plants.

Acknowledgements: We would like to thank, Gerhard Binker, Patrick Ducom, Hakan Kjellberg, Stein Norstein and Pasquale Termaterra, who provided us with information on very short notice.

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Figure 1. Tonnes of methyl bromide used for space treatment in 1991.
Figure 2. High pressure CO₂ fumigation with tanks for recycling gas.

Figure 3. Palettes of pet food being placed in the fumigation chamber.
Figure 4. The inside of a German church susceptible to wood boring insects.

Figure 5. A German church.                             Figure 6. A tarped church
Figure 7. A roller mill treated with localized heat.

Figure 8. An Italian flour mill.
Figure 9. A high capacity bucket trap.