Fire Protection in Agricultural Facilities: A Review of Research, Resources and Practices

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ABSTRACT: Agricultural facilities present unique challenges for fire prevention and suppression, as they are often located in remote locations and not continually monitored. Effects of fire can be severe, because of the large quantities of animals, crops and equipment present. In this paper, research and industry practices aimed at improving fire protection in agricultural buildings are reviewed. Sources of fire safety information for building designers and engineers, the fire service and building owners are identified, along with challenges to providing fire safety in these buildings. Areas of future research in this area of fire protection engineering are also identified.

KEY WORDS: fire protection, agriculture, spatial separation, detection, animals, hazardous materials, firefighting.

INTRODUCTION

CONSIDERABLE EFFORT IS being expended in Canada and other countries into developing engineering methods to evaluate the performance of fire protection systems in buildings. Motivation for this work includes the move from current, prescriptive-based building codes to performance/objective-based codes, which are already in place in some countries, and are to be introduced in Canada in 2004. Many of these methods are intended for use in the design of buildings in urban

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environments that are densely populated. Some of the buildings that have been extensively studied include apartment and office buildings, shopping centers, theaters and sports arenas. Industrial buildings have also received considerable attention, because of the presence of flammable materials and the high replacement costs of the assets within these structures.

In Canada and many other countries, there are also large numbers of agricultural buildings. These range from buildings on family farms to grain elevators to livestock barns to food processing facilities. Agricultural facilities present some unique challenges for fire protection system design, and fire prevention and suppression, as they are often located in remote locations and may not be continually monitored. Fuel loads in these buildings may be different from those in offices, homes and most industrial facilities. Although these buildings contain a very small number of people, effects of fire can be severe, because of the large quantities of animals and equipment present. Despite these challenges, there are very few standards aimed specifically at these buildings, and there is little research being conducted into the behavior of fire in these facilities.

Fire safety in agricultural facilities is increasing in importance with other developments in the agriculture industry, such as attempts to increase production. In the province of Saskatchewan, the hog industry hopes to increase its annual production from 1.5 to 5 million hogs by 2005 [1]. This is to compete with other regions in North America that have recently expanded their production, such as North Carolina, which has increased production from 2.5 to 10 million hogs per year over the last decade. One of the ways in which hog production will be increased is through the development of larger facilities for livestock. Besides issues related to fire protection, this has also raised a number of other safety issues, including the management of animal wastes.

In this paper, research and industry practices aimed at improving fire protection in agricultural buildings are reviewed. This review is primarily based on information from the fire science and agricultural engineering literature, and Canadian and American government agencies, design guides, building codes and standards. The paper first discusses fire statistics for agricultural buildings, and identifies sources of fire safety information for building designers and engineers, the fire service and building owners. Challenges to providing fire safety in these buildings are then identified, along with research aimed at addressing each of these challenges. While the intent of this paper is to present the findings of this literature review, rather than to offer specific guidance to fire protection engineers, industry practices used to address these challenges, which have been reported in the literature, are also discussed. Based on the literature search, areas of future research are identified.

FIRE STATISTICS

Accounts of individual fires in agricultural facilities can be found on a regular basis in the local and national media, and in firefighting publications. Two recent examples in Western Canada were a fire in April, 2000 at a flax storage facility in Manitoba and a hog barn fire in Saskatchewan in February, 2001. The Manitoba fire made headlines across Canada – approximately 100,000 bales of flax straw were destroyed and losses were initially estimated at $1.8 million (Canadian) [2]. A "fire funnel" was seen almost 100 km away and one worker was killed. In the Saskatchewan fire, 14,000 pigs were killed and losses were initially estimated at $6.5 million (Canadian) [3]. There have also been many large agricultural fires in the United States in recent years. For example, a fire in July, 2001 in a farm in Utah killed 12,000 hogs and damages were initially estimated at over $1 million (US) for the livestock and $3.3 million for the building [4].

National, provincial and state fire statistics illustrate the larger problem of fires in agricultural buildings. In 1996, there were 941 fires in farm buildings, about 1.6% of the total number of fires in Canada [5]. The number of human injuries and deaths in these fires was relatively small – 25 injuries (0.8% of the total in 1996) and 2 deaths (0.6% of the total). In the Province of Saskatchewan, from 1997 to 2001, large numbers of fires occurred in farm machinery, and animal barns and livestock facilities (Table 1) [6]. There were also significant fire losses in agricultural product storage facilities.

Shutske [7] tracked data on fires in farm machinery in Minnesota and other U.S. states using the National Fire Incident Reporting System (NFIRS), Minnesota newspapers and death certificates. During a ten-year period, there were over 25,000 total documented cases in 44 states of fires on combines, tractors, or other mobile farm machinery. Over 1200 of these fires occurred in Minnesota. The average property damage for each incident was about $7400, not including the effect of downtime when equipment damaged in a fire could not be used.

While fires in agricultural buildings do not result in a large number of human injuries and deaths, economic losses are relatively large when compared to the number of fires that do occur. As mentioned previously, Canadian fire statistics indicate that fires in farm buildings accounted for 1.6% of the total number of fires in Canada in 1996. However, total fire losses in farm buildings were over $56 million in 1996, just under 5% of the total fire losses in Canada that particular year. In Saskatchewan, where agriculture is one of the largest industries, fires in agricultural buildings account for a much larger percentage of the total number of fires and fire losses. As shown in Table 1, fires in agricultural buildings accounted for

Table 1. Average annual numbers of fires and fire losses for selected types of agricultural facilities in Saskatchewan: 1997–2001 [6].

Type of Agricultural Facility	Average Annual Number of Fires	% of Provincial Total	Average Annual Total Fire Losses (thousands of Dollars)	% of Provincial Total
Farm machinery	264.2	6.2	4007	8.3
Crops, including hay stacks or bales	71.2	1.7	319	0.7
Animal barns and other animal and livestock facilities	55.0	1.3	3973	8.3
Agricultural Product storage	26.6	0.6	1745	3.6
Single family dwellings on farms	19.0	0.4	721	1.5
Slaughter, and preparation and preservation of meat and poultry	3.8	0.1	87	0.2
Other agricultural buildings	13.4	0.3	129	0.3
Total for agricultural buildings	**453.2**	**10.6**	**$10,980**	**22.9**
Provincial totals	**4292.2**	**100.0**	**$48,035**	**100.0**

approximately 11% of the total number of fires in Saskatchewan from 1997 to 2001, and approximately 23% of the total fire losses. These figures are five-year averages–in 2001, 37% of the total fire losses in the province were from fires in agricultural buildings.

It should be noted that this paper deals with agricultural production facilities, rather than residential buildings on farms and in rural communities. The reader who is interested in information on fire protection and statistics for residential buildings in rural communities is referred to reports by the US Fire Administration [8] and NFPA's annual fire statistics (e.g., [9]). Many of the challenges to fire protection discussed in this paper, such as the location of agricultural buildings relative to firefighting resources, will of course also be pertinent to the study of fire protection in residential buildings in these communities.

FIRE PROTECTION RESOURCES

To help address the challenges to fire protection in agricultural buildings, a number of resources are available to building designers, engineers, the fire service and building owners. Many of the design guides and handbooks that can be used for the design of fire protection systems in agricultural buildings are the same as those used by designers for other occupancies. These guides and handbooks include the SFPE Handbook of Fire Protection Engineering [10] and the NFPA Fire Protection Handbook [11]. Building and fire code regulations may also pertain to these buildings (e.g., [12]). Currently, in Canada, there is also a Farm Building Code [13], which can be used in fire protection design for "farm buildings of low human occupancy."

Besides these codes and handbooks, many textbooks and design guides for agricultural buildings contain a section or chapter on fire protection measures. For example, Phillips [14] provides information to help make designers aware of the importance of considering fire safety in design. Fire stops, flame spread ratings, protective coverings, fire retardant treatments, methods to protect metal frame buildings and fire extinguishers are discussed. Bengtsson and Whitaker [15] discuss many of the same topics, as well as spatial separation, evacuation and the use of firebreaks to protect buildings from bushfires.

There has been limited research focused specifically on fire protection in agricultural facilities. While some of this research can be found in the fire science literature, much of it has been published in the agricultural engineering literature. Therefore, codes, and conference and journal publications from technical societies such as the American and Canadian Societies for Agricultural Engineers can be sources of fire protection information for designers of agricultural buildings.

Publications dealing with firefighting contain information on strategies for dealing with fires in these types of buildings. Examples of information from firefighting periodicals will be given throughout this article. Two reports that specifically discuss firefighting in agricultural buildings have been published by the Natural Resource, Agriculture, and Engineering Service (NRAES). One deals with a number of different incidents that firefighters may respond to in agricultural buildings, including fire, chemical exposures and injuries caused by agricultural equipment [16], while the other deals specifically with fire incidents in these buildings [17].

A number of other resources are available in print, videotape, and/or on the internet, which provide information to building owners on fire behavior, fire prevention, suppression, and other fire safety topics. The National Agricultural Safety Database [18] is a database of general interest articles maintained by the National Institute for Occupational Safety and Health (NIOSH) in the US. Many of the publications in the database were written to summarize research findings or the requirements of fire safety standards. The NRAES [19] also maintains a website and has a catalogue of publications, many of which deal with fire protection.

Many of the articles on these websites have been published by university engineering colleges, or agricultural safety or extension departments. These schools also publish reports, fact sheets and other resources geared specifically for the agricultural industry, or individual farmers and their families (e.g., [20]). As will be discussed later in this paper, fire prevention is particularly important in these buildings because of the relatively long times required for fire department intervention. Therefore, much of the information provided by these agencies is aimed at educating building owners about the dangers of fire, and how fires can be prevented in agricultural buildings.

CHALLENGES FOR FIRE PROTECTION

Designing fire protection systems for agricultural buildings presents a number of challenges. Some of these challenges are the same as in other types of buildings. For example, agricultural buildings may not be continually monitored, and may contain materials that exhibit very rapid fire growth. Other challenges may be quite different. For example, these buildings may contain a significant number of animals. Distances from fire halls to agricultural buildings may be longer than typical distances to urban buildings. Many fire departments that respond to agricultural buildings are volunteer organizations. Fire department operations may also be more challenging because of the nature of agricultural buildings, and the materials and animals within these buildings.

This paper examines the following challenges to providing fire protection in agricultural buildings:

- the characteristics of materials found in agricultural facilities,
- the detection of fires in agricultural buildings,
- the characteristics of agricultural buildings themselves,
- the locations of agricultural buildings,
- the presence of animals in these buildings, and
- the economic impact of fire on surrounding communities.

It should be noted that while this paper is concerned with agricultural buildings, some of these challenges (and the methods used to address them) are not unique to agricultural buildings, but are described here for the sake of completeness. Each of the challenges listed above is described in the following sections of this paper, along with research and fire protection practices reported in the literature, which are aimed at addressing these challenges.

In these subsequent sections, challenges to fire protection will be demonstrated using heat release rate curves of four common design fires –

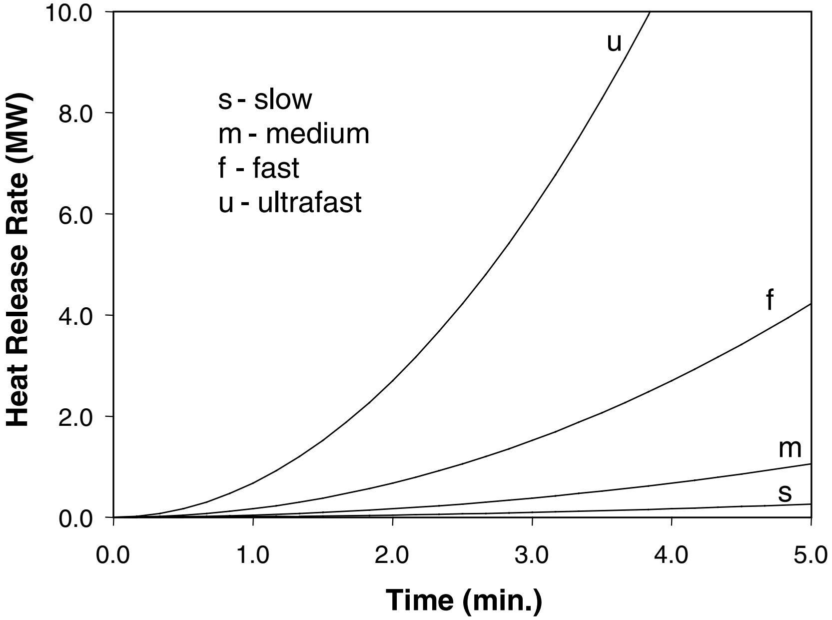

Figure 1. *Heat release rates of t^2 design fires.*

slow, medium, fast and ultrafast t^2 fires, which are shown in Figure 1 [21]. The rate at which the heat release rate increases will have an important effect on the rate at which other important quantities, such as temperature, increase. This will, in turn, influence when fire detection and suppression systems activate, and the effects of fire on buildings and occupants.

The rate at which the heat release rate increases will also have an important effect on firefighting operations. For example, an ultrafast t^2 fire will have a significantly larger heat release rate at the time when firefighters begin suppression operations, than a slow t^2 fire that has been burning for the same length of time. The fire department intervention time, which is defined as the time between the start of the fire and when the fire department begins to suppress the fire, will also significantly affect the heat release rate of the fire at the time suppression operations begin. The intervention time can be calculated as the sum of the times required for detection, notification of the fire department, dispatch and travel, and setup on the fire ground.

The heat release rate of the fire at the time suppression begins will affect the amount of water necessary for fire suppression, and ultimately whether a particular fire can be suppressed. As water can theoretically absorb approximately 2600 kW/L/s of flow as it is heated to 100°C and converted to steam, one method of estimating the required water flow rate to extinguish a particular fire, is that the required water flow rate (RFR) will be proportional to the heat release rate (Q) [22]:

$$\mathrm{RFR} = \frac{Q}{\eta(2600)} \tag{1}$$

where η is the efficiency of the application of water by the fire department. Hence, in this method, the required water flow rate will be directly proportional to the square of the elapsed time since the beginning of the fire for a particular t^2 design fire. The amount of water required for suppression will directly affect the equipment and number of firefighters, which must respond to an individual fire, and hence the strategy used by the fire department once they get to a fire. Firefighting operations in agricultural buildings will be discussed in greater detail later in this paper.

CHARACTERISTICS OF MATERIALS

As in other occupancies, some materials in agricultural buildings may exhibit rapid fire growth, such as chemicals (e.g., pesticides) and unprotected insulating materials. As noted above, rapid fire growth will have an impact on the ability of the fire department to extinguish the fire, failure times of structural members and walls, and human and animal life safety. For example, the heat release rate in a medium t^2 fire would be 1.1 MW after five minutes, while the heat release rate in an ultrafast t^2 fire would be 16.9 MW after the same length of time. If the application of water by the fire department is assumed to be 20% efficient, then Equation (1) predicts that, after 5 min, 122 L/min of water would be required to suppress a medium t^2 fire, while 1948 L/min of water would be required to suppress an ultrafast t^2 fire.

Agricultural facilities can also contain hazardous materials, or materials with toxic products of combustion. Hazardous materials are a threat to occupants, firefighters, and animals, and can also contaminate runoff from water used by firefighters. Dusts that are encountered in many agricultural buildings are also an explosion hazard [11]. Some materials in agricultural facilities can also undergo spontaneous ignition.

Fire Protection and Prevention Strategies

Many strategies used to prevent rapid fire growth in agricultural buildings are similar to those in other occupancies. These strategies include fire stops between ceilings and the roof, specifying minimum fire resistance ratings and maximum flame spread ratings, treating wood with fire retardants, protecting metal frames and allowing adequate spatial separation between buildings (which will be discussed in more detail in the section dealing with the challenges associated with the locations of agricultural buildings). This section provides examples of discussions from fire protection resources of some of these and other strategies.

Phillips [14] provides information to help make designers aware of the importance of considering fire safety when selecting building materials and discusses the importance of including fire stops to slow the progress of a fire. Strategies outlined include using gypsum boards as fire stops in the area between ceilings and the roof, placing walls with an appropriate fire resistance rating between areas with different levels of fire risk, specifying maximum flame spread ratings for building materials in certain occupancies and using protective coverings for materials such as insulations that have high flame spread ratings. Fire retardant treatments for wood, methods of protecting metal frames, and methods of extinguishing different classes of fires are also discussed. Arble and Murphy [20] provide information on fire retardant materials for use in agricultural buildings, and how to specify these materials. Fire walls and fire curtains are also discussed. These authors discuss fire tests of insulating materials in another publication, the results of which illustrate the importance of protective coverings for these materials [23]. Suggestions of specific materials that can be used to cover insulation in agricultural buildings are also provided.

Margentino and Malinowski [24] provide building owners and designers with examples of combustible materials and accelerants, and discuss barn construction practices that can help to improve fire safety. These construction practices include the addition of fire walls between areas used for hay and bedding storage and areas used for livestock, the use of fire retardant latex paint, and the use and monitoring of detectors, alarms and sprinklers. Other practices, such as the installation of emergency lighting to aid in evacuation of people and animals, and the provision of sufficient on-site water supply for firefighting are also discussed, along with fire safety precautions which should be included in building operating procedures.

Besides materials stored in agricultural buildings and materials used in their construction, machinery used and stored in these buildings is also an important consideration in fire protection. For example, as shown earlier in Table 1, 6.2% of the total number of fires in Saskatchewan from 1997 to 2001 involved farm machinery. One potential location for fire is a grain drier. Fire safety resources recommend that farmers point driers into the wind so that airborne fibers are blown away from the drier, rather than into the drier intake where they can be ignited, possibly causing a fire to develop [25]. It is also recommended that driers should be cleaned at least once a day, and that it is very important to constantly monitor the drier and to have an appropriate extinguisher in close proximity. Shutske [26] has prepared a fact sheet on methods to prevent combine and tractor fires, and what to do if such a fire does break out. Fire safety resources remind farmers to keep their equipment clean, and to eliminate possible sources of ignition. They should be prepared for fire by carrying one or two extinguishers on board, in locations that are easily accessible if they are inside or outside the machinery, as well as a cellular phone or two-way radio, in case they require help. Besides machinery, electrical systems can also be potential sources of ignition. Margentino and Malinowski [24] discuss the importance of providing adequate clearance for motors, and encasing wires in metal conduit. Electrical systems will be discussed further in the section dealing with the characteristics of agricultural buildings.

Besides these methods of reducing the effects of fire, fire prevention is also emphasized in public education campaigns. For example, the importance of housekeeping and frequent inspections of electrical systems is stressed. Some of the resources available to building owners were discussed earlier. Other resources include fact sheets, such as one published by Oklahoma State University [27], which outlines the fire triangle, the importance of preventing fire by preventing ignition and appropriate extinguishing agents for different classes of fires. Particular emphasis is placed on making fire prevention part of the daily routine for farmers – specific advice includes keeping work areas, machinery and engines clean, not storing fuels inside buildings and incorporating fire safety into the design of new buildings (e.g., spatial separation and using fire resistant building materials). Other resources suggest inviting fire departments to make regular inspections of farms, developing and conducting fire inspections, conducting regular fire drills, testing detectors regularly and not smoking within buildings [28].

Fire Testing

As in other occupancies, fire testing has also been used to gather information on the fire behavior of materials used in agricultural buildings. Besides discussions of the use of standard tests to determine fire resistance and flame spread ratings, there have been some other examples of full-scale fire tests in the literature. Kelly [29] reports on a series of fire tests in two 12 m long × 8 m wide × 2.75 m high buildings used to simulate hog production facilities. Two test buildings were constructed, one with a flat ceiling and the other with a pitched roof lined with cellular plastic board insulation. Wood cribs and hay bales were used as ignition sources, and temperatures at ceiling level were monitored using thermocouples. These tests were used to evaluate the fire performance of insulating materials used in agricultural buildings.

Some full-scale testing has been conducted to specifically examine the fire behavior of materials that are commonly stored in agricultural buildings. Nelson reviews research aimed at better understanding the fire behavior of toxic materials, such as pesticides, insecticides and poisonous plants, and provides examples of fires involving some of these materials [30]. Two large European research programs (TOXFIRE and the COMBUSTION Project), are described, in which experiments were conducted in facilities, which ranged in size from cone calorimeters, to medium- and large-scale test rooms (e.g., the ISO 9705 test room [31]), to large-scale outdoor facilities. Various quantities, including the composition and toxicity of combustion products, and heat release rates of fires, were measured. Information on how results of small-scale tests compare with larger-scale tests is particularly important, because of the fact that full-scale tests of some materials that are stored in agricultural buildings may be dangerous to perform because of the toxicity of their combustion products. A comparison of results generated in different sizes of test rooms for particular materials can be found in Markert's review of the TOXFIRE project [32]. Information gathered from the TOXFIRE project was also used to develop guidelines for fire protection engineers designing warehouses, and firefighters responding to fires in these facilities.

Computer Models

As with other types of buildings, full-scale testing of materials used in agricultural buildings is very expensive. As mentioned previously, the products of combustion of these materials can also be very toxic [32]. Therefore, as with other types of buildings, computer fire models can be very useful in the design of fire protection systems in agricultural buildings. However, unlike other types of buildings, there have been few published examples of the application of computer fire models in agricultural buildings.

One exception to this is the work of Shutske et al. [33] who discuss possible applications of computer fire models, including determining appropriate temperature settings for detectors, public education, spatial separation and fire testing. Their paper reviews equations commonly used by fire protection engineers, such as those used to estimate temperatures in NIST's ASET-B computer model [34] and those developed by McCaffrey et al. [35]. The paper then describes a computer model based on the ASET-B and McCaffrey equations, which was used to predict the temperatures and flame heights during fire tests in small enclosures used to simulate fires in the engine compartments of combines. For a 108 kW fire test, conducted using a pan of diesel fuel, the model did a reasonably good job of predicting temperatures above the fuel pan, up until the point suppression began. The authors state that the model did not predict the temperatures during the initial portion of a diesel fuel spray fire test, where the heat release rate increased from 0 to 450 kW in a few seconds, nearly as well. While no details are provided as to how the heat release rate for these latter fires was modeled (steady-state or as a function of time), the authors suggest that one source of error was the fact that their model did not account for the very rapid increase in heat release rate in the diesel fuel spray fire test.

As part of the TOXFIRE project, software was developed to assist fire departments responding to chemical warehouse fires [36]. Possible strategies can be evaluated based on information from the fireground about the rate of fire growth, presence of automatic detection and suppression equipment, and the fire department intervention time. A database of chemical properties is included in the software, along with a module that provides information on the consequences of different chemicals reacting with suppression agents and/or each other.

Spontaneous Ignition

An additional consideration when dealing with materials in agricultural facilities is the risk of spontaneous ignition, caused by heating of materials due to microbiological and other thermal chemical processes. The theory of spontaneous ignition is discussed by Beever in the SFPE Handbook of Fire Protection Engineering [37]. A review of early research in this area, from the ancient Greeks (who believed, for example, that forest fires were caused by the friction between branches of trees rubbing together in the wind) to the early twentieth century was published by Browne [38] in 1929. Examples of more recent research in this area include Nelson [39], and Currie and Festenstein [40]. Nelson studied the effects of moisture content and age of alfalfa hay at the time it was baled on nutrient retention, and heating and possible spontaneous combustion of high-density hay bales. Currie and Festenstein studied the heating of hay from a temperature of 70°C to ignition, including the effects of aeration and moisture movement within the hay. More recently, Miao and Yoshizaka [41] studied the chemical reactions necessary to generate the heat required for spontaneous ignition to occur using methods such as thermal gravimetric analysis and differential thermal analysis.

Research has also been conducted in spontaneous ignition of other materials. Beever and Crowhurst [42] discuss self-ignition of milk powders, which can occur during milk spray drying. Milk powder contains components, which can be oxidized in exothermic reactions. These reactions can generate enough heat, especially at the elevated temperatures found in drying, to cause self-ignition. Beever and Crowhurst discuss regions in spray driers where milk powder can build up, and the critical thickness of powder for self-ignition. Self-ignition can also occur at low temperatures when large quantities of milk powders are processed or stored. The authors also discuss other sources of ignition for milk powder, such as friction between moving parts and electrical sparks, as well as methods to avoid self-ignition through the design of operating procedures and equipment so as to reduce the thickness of build-up of powder in driers.

The risk of spontaneous ignition has resulted in recommendations for the processing and storage of products such as vegetable and animal oils, wool, flax, hay and milk powder. Examples of these recommendations can be found in the NFPA Fire Protection Handbook [11]. Guidance of interest to designers and owners of agricultural buildings can also be found in reports and fact sheets from extension departments of universities. For example, Prather [43] describes the cause of hay fires and provides recommendations for the conditions under which hay should be stored. He describes a method of using a temperature probe to monitor bales of hay in order to determine if a fire is imminent. Guidance is also provided as to the procedures, which should be used for suppressing hay fires. Cyr and Johnson [44] emphasize the need to harvest loose or chopped hay at low enough moisture content to prevent molding. The causes of spontaneous ignition and methods of extinguishing hay fires are also discussed by Murphy and Arble [17].

Fire Department Operations

Due to the possible threat posed by the materials in these facilities, fire department resources stress the importance of being aware of materials that are stored in the particular facilities that fire departments may respond to, so that they can take appropriate precautions in the case of fire. Besides the danger posed by the burning of hazardous materials, the threat of contamination of firefighting water will also affect firefighting strategies. Specific advice on these and other important issues to fire departments can be found in many sources, including the NFPA Fire Protection Handbook [11], Field et al. [16], Nelson [30], Linn [45] and Baker [46]. Fire department issues will also be discussed in more detail in a later section on the challenges presented by the characteristics of agricultural buildings themselves.

FIRE DETECTION IN AGRICULTURAL BUILDINGS

As agricultural buildings often have high ceilings, it may take a relatively long time for temperatures or smoke concentrations at the ceiling to be

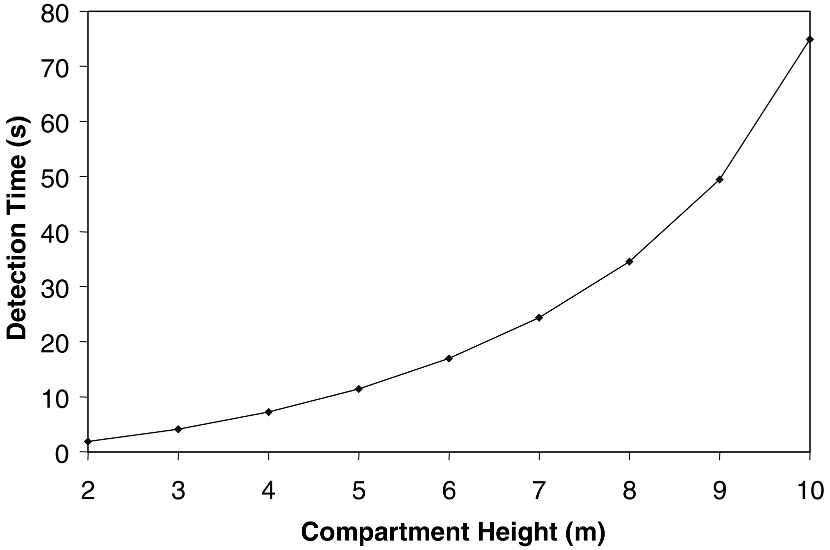

Figure 2. *Detection times predicted for a detector located directly above a 1 MW fire for various compartment heights (RTI = 100 $m^{1/2}s^{1/2}$, activation temperature of 68°C, ambient temperature of 20°C) [47].*

high enough to activate detectors. For example, Figure 2 shows detector activation times for compartment heights from 2 to 10 m, predicted using correlations in the NFPA Fire Protection Handbook [47]. This particular detector has an RTI of 100 $m^{1/2}\,s^{1/2}$ and an activation temperature of 68°C, and is located directly above a 1.0 MW fire (with an ambient temperature of 20°C). As shown in Figure 2, the compartment height will have a significant effect on the detection time, and hence the time required for notification of occupants and the fire department. It should also be noted that, in this case, the predicted temperature of the hot gases in the ceiling jet did not exceed the activation temperature of this particular detector for compartment heights above approximately 11 m.

In addition to the ceiling height, the amount of dust in some agricultural buildings can also affect the operation of detectors. As many of these buildings are not densely populated and/or not continually occupied, detection by human occupants is not as likely as in buildings which are more densely populated and/or occupied a larger percentage of the day. This is evident when reading accounts of many fires in these facilities, which were not detected until a passerby noticed that the building was almost completely on fire.

Some research has been conducted into detection in agricultural buildings. Shutske and Field [48] discuss the results of a survey of agricultural machinery fires. Information is presented on the number of fires involving tractors and combines from 1979–1981, including ignition and fuel sources. The authors also note that it may be more difficult for farmers to detect fires themselves, as they are in a more enclosed environment in modern farm machinery and may have to monitor a number of processes at the same time. Therefore, a fire may not be detected soon enough to allow the farmer to suppress it manually using a hand-held extinguisher. The authors advocate the use of detection devices that are commonly used in other industries, such as mining, where it is difficult for operators to detect and suppress fires. The principles of operation and the limitations of a number of detection devices are described, including temperature and rate of rise detectors, flame detectors, and smoke detectors. Fire detection systems are also discussed by Arble and Murphy [20], along with recommendations for the maintenance of these devices.

Some methods being used in practice to address concerns with detection are first of all, to ensure that detection devices are installed in these buildings. New detection technology from other occupancies can sometimes be applied to these occupancies. Monitoring of buildings can be increased by modifying building operating procedures or through the use of technology. Notification time for fire departments can be reduced by using alarm monitoring companies or automatically notifying the fire service when an alarm is activated. However, this also increases the importance of using and/or developing detection technology that minimizes the possibility of false alarms.

CHARACTERISTICS OF AGRICULTURAL BUILDINGS

Agricultural buildings are often quite different from other buildings, which can provide challenges to fire protection. Environmental conditions within these buildings can affect the integrity of electrical wiring. Compartment sizes may be very large, which will affect the speed at which a fire can grow and spread. These buildings may also pose challenges to fire service personnel as they may be difficult to locate, and their floor plans and contents may be quite different from other types of buildings that individual fire departments respond to on a more frequent basis. Fires in silos can also present special hazards to fire service personnel.

Electrical Systems

Besides affecting the operation of detection and suppression systems, environmental conditions can affect the electrical system. For example, weather conditions, chemical action and moisture can cause degradation of electrical wiring [49]. Overheating of motors and power tools due to excessive dirt and other materials can also ignite combustibles. These buildings contain a large amount of equipment, much of which requires electrical power to operate. Overloading of electrical circuits will also increase the fire hazard. Rodents and other animals may chew through electrical wiring [24]. Therefore, recommendations in the literature include running wire in metal conduit, and using electrical panels that are corrosion and weather resistant.

Compartment and Door Sizes

Other features, such as the large doors necessary for the movement of machinery and livestock into and out of these buildings will increase the amount of oxygen available to support a fire [50]. This can ultimately increase the maximum possible heat release rate of a fire, and hence the effects of the fire on occupants and the building. Air movement through these doors can also affect fire plumes, which in turn affects detection. For example, a wind may affect the structure of a fire plume, which in turn affects the time required for detection of a fire.

Fire Department Operations

Agricultural buildings can also pose challenges to fire service personnel. Minor [51] discusses some of these challenges, including unfamiliarity with farm facilities, the fact that equipment for automobile extrication is not designed for agricultural equipment, the presence of hazardous materials, and the possibility that confined spaces may be oxygen deficient. Steps that can be undertaken in preplanning are outlined in the article. In a separate article, Minor [52] discusses other issues that need to be considered in fire department operations including the fact that the location of some agricultural buildings can be difficult to find from their address. Farm accidents can occur some distance away from the main road, which may create difficulties for vehicle access. Incidents are also more likely during planting and harvesting seasons, and farm animals may present “crowd control” issues, as will be discussed in a later section.

Wieder [50] discusses how building features of hay barns can impact on fire growth and the ability of the structure to withstand fire. For example, as discussed previously, the large doors that are necessary for tractors and trucks can supply large amounts of oxygen to the fire. Assuming that these facilities only contain animal feed, and not dairy or other operations, Wieder advocates that fire departments take a defensive approach, concentrating on providing exposure protection to fixed installations and moving any equipment or livestock that may be endangered by the fire, rather than attacking the fire directly. This opinion is based on his observations that many of these fires have grown very large by the time the fire service begins their operations, fires involving tightly packed hay are difficult to extinguish, and the structural integrity of these buildings may be damaged. These factors increase the level of risk to firefighters and environmental concerns. If it is necessary to mount an offensive attack, Wieder provides suggestions as to how to control large hay barn fires.

A fair amount of information has been published on firefighting operations in silos. These include resources mentioned earlier ([16,17]), as well as a special report by the US Fire Administration [53]. Articles in firefighting publications include those by Halpin and Shattuck [54], and Maloney [55], who stress the importance of preplanning, and emphasize that the firefighting techniques that should be used will depend on whether a silo is of conventional construction, or is an oxygen-limiting silo. The latter type is particularly dangerous, as the possibility exists for explosions, which in the past have killed firefighters. Exposure protection for other buildings on the farm is also important when combating silo fires, as will be discussed in the section on the location of agricultural buildings.

LOCATION OF AGRICULTURAL BUILDINGS

Once a fire department is notified, the remote location of many agricultural facilities can cause an additional delay before the fire department begins to suppress the fire. In addition, fire departments that service these buildings may be volunteer departments, which can further increase the fire department intervention time. These increases are in addition to the extra time that is often required to detect fires in these buildings, which was discussed earlier. Increases in fire department intervention time can affect both the water requirements needed for firefighting, and the spatial separation distances required between buildings.

Water Requirements for Firefighting

The long distances between many agricultural buildings and fire departments will increase the travel, and hence the fire department intervention time. Even a delay of a few minutes can have a large effect on the heat release rate of a fire, and hence the water and equipment required for firefighting, and the ability of a fire department to suppress the fire. For example, the use of a t^2 fire and Equation (1) predict that the required flow rate of water quadruples if the fire department intervention time doubles. In addition, a remote location may make it more difficult to provide the required amount of water for suppression of these fires, because of the available infrastructure. Some suggest that the effects of location on fire department intervention time and the amount of water available for firefighting are important reasons that economic losses from rural fires are relatively large, in proportion to the number of rural fires that occur [56].

To address the water requirements for agricultural buildings, design guides and standards specify the amount of water, which should be readily available for firefighters to use in suppression and/or protection of adjacent structures. For example, NFPA 1142 [57] specifically deals with firefighting water requirements for rural and suburban areas where water must be transported to the scene of the fire from rivers, lakes, wells, cisterns or similar bodies of water. Some have also suggested specific ways that small rural departments can access water for firefighting, such as how to equip individual pieces of apparatus so that they can be used as a water shuttle [58]. Other suggestions made include using firefighting chemicals, such as foams, along with water, if appropriate [50].

Spatial Separation

In addition to the effects of increased fire department intervention times on water requirements, the fact that a fire may be larger when the fire department begins suppression operations will also impact the heat fluxes from the fire to adjacent buildings, and hence the risk of fire spread to these adjacent buildings. Therefore, just as minimum spatial separations between buildings are important in urban areas, it is important to specify minimum distances between agricultural buildings in order to prevent the spread of fire. In specifying these minimum distances, the nature and location of agricultural buildings should be taken into account.

Methods to determine the required spatial separation distances between buildings can be found in building codes (e.g., National Building Code of Canada [12]) and in other standards or guidelines (e.g., NFPA 80A [59]). Some design guides also discuss the importance of spatial separation and provide specific recommendations. Bengtsson and Whitaker [15] state that a minimum separation of 6–8 m may be adequate, but 15–20 m is preferable, especially where "buildings are large or contain special fire hazards". Another fact sheet states that there should be a minimum of 15.2 m (50 ft) between buildings, while fuel storage buildings and farm shops should be located at least 30.5 m (100 ft) apart [60].

Most building codes are based on the principle of limiting incident heat fluxes to adjacent buildings to below the critical heat flux for piloted ignition of cellulosic materials, $q''_{cr} = 12.5\,\mathrm{kW/m^2}$. This is typically done using a method developed by McGuire and Williams-Leir, researchers in the Division of Building Research at the National Research Council of Canada, based on data from the St. Lawrence Burns [61]. Eight abandoned buildings (six houses, a school and a community hall) were burned in the Village of Aultsville, Ontario, which was to be flooded as a result of construction of the St. Lawrence Seaway. To study the spread of fire by thermal radiation, investigators measured thermal radiation heat fluxes at the window of the room of fire origin in the building and at various distances from the buildings. The horizontal projection of flames outside of the windows of the buildings was measured using motion picture images of the fires.

It was assumed that the thermal radiation from the fire could be represented by an effective heat flux value (q''_o) based on only the window area, which was calculated using the heat fluxes measured at various distances from the buildings and radiation view factors (F) from the windows to the locations of these measurements. The ratio of the maximum effective thermal radiation heat flux to view factor (q''_o/F) was found to be a useful means of comparing the thermal radiation from different buildings. Assuming a view factor of unity, maximum values of the effective thermal radiation heat flux at the windows of the burning building were of the order of 1680 kW/m^2 (40 cal/cm^2 s) and 840 kW/m^2 (20 cal/cm^2 s) for buildings with highly flammable and noncombustible linings, respectively [62]. These effective heat flux values are larger than the heat fluxes from blackbodies at typical fire temperatures (e.g., a 1000°C blackbody emits a heat flux of approximately 150 kW/m^2), as they represent the fact that at later times, the area of the fire will be much greater than the area of the unprotected openings.

However, these large effective heat flux levels were not recorded for at least 16 min after any of the St. Lawrence Burns fire tests began. Heat fluxes earlier in the exposure were of the order of one-fifth of these maximum values. As it was thought that the fire department should reach a burning building within 16 min, critical view factors were selected based on the lower heat flux values and a critical heat flux of 12.5 kW/m^2 to adjacent buildings (i.e., $F''_{cr} = q''_{cr}/q''_o$). Two values of the critical view factor were suggested for spatial separation calculations: 0.07 for an occupancy that can be considered a normal hazard and 0.035 for an occupancy that is particularly hazardous.

All unprotected openings in a particular exterior wall can be represented using a single unprotected opening that has the same total area as the sum of the areas of the individual openings. The view factor can be calculated from this single unprotected opening to a point on the exposed face of the adjacent building that is directly opposite the middle of the single unprotected opening. The following equation is used [63]:

$$F_u = \frac{2u}{\pi}\left[\sqrt{\frac{C/S}{C/S+4}}\arctan\sqrt{\frac{CS}{C/S+4}} + \sqrt{\frac{CS}{CS+4}}\arctan\sqrt{\frac{C/S}{CS+4}}\right] \quad (2)$$

where:
u is the fraction of unprotected openings ($0 \leq u \leq 1$),

$$\mathrm{C} = \frac{\mathrm{hw}}{\mathrm{d}^2} \quad (3)$$

h is the height of face of the burning building (m); w is the width of the face of the burning building (m); d is the "effective" distance (see below) between the burning and adjacent buildings (m), and

$$S = \frac{h}{w}\left(\text{or } \frac{w}{h} \quad \text{if } w > h\right) \quad (\text{i.e., } S > 1) \quad (4)$$

Either the maximum value of the fraction of unprotected openings, or the minimum distance between buildings can be calculated using the above equations and the appropriate value of the critical view factor.

McGuire also suggested that a distance, d_f, of 1.5 m (5 ft) (normal case) or 2.1 m (7 ft) (hazardous case) should be added to separation distances to account for the horizontal projection of flames from windows. The effective distance, d, for use in calculations is then the actual distance between the buildings (d_a) minus d_f.

$$d = d_a - d_f \quad (5)$$

McGuire also stated that these two distances could probably be adjusted by 0.6–0.9 m (2–3 ft), so as not to be overly conservative.

In addition to research based on the St. Lawrence Burns, there has been some additional research into spatial separation requirements for agricultural buildings. In the 1960s, Moysey and two of his graduate students at the University of Saskatchewan developed methods for estimating the spatial separation required between farm buildings. At the time, Moysey [64] stated that recommendations for spatial separation distances ranged between 30.5 and 45.7 m (100 and 150 ft), which may not always be practical. Moysey used a maximum heat flux from a burning building of 150 kW/m^2 (3.6 cal/cm^2 s), based on the assumption that building fires can be represented by a flame temperature of 1000°C and an emissivity of 1.0, which is consistent with the data from the St. Lawrence Burns and other experiments. He also assumed that the critical heat flux required for the ignition of wood is 12.5 kW/m^2 (0.3 cal/cm^2 s), which means that the view factor between the burning and adjacent building must be kept below 0.08 (12.5/150). He further reduced this critical view factor to 0.05 for lower hazard buildings, such as insulated vegetable storage facilities and 0.03 for higher hazard buildings, such as hay storage facilities covered with a single ply of lumber, in order to account for the fact that the area radiating energy would be larger than the actual area of the burning building, once the structure was completely on fire.

Scott [65], one of Moysey's graduate students, measured heat fluxes from three farm buildings, with floor areas between 14 and 18.6 m^2 (150 and 200 ft^2) and heights between 2.1 and 2.7 m (7 and 9 ft), which were burned in order to determine typical heat fluxes from fires in these buildings and to investigate the effect of cladding on these heat flux levels. Peak heat fluxes were measured between 12 and 30 min after ignition in the various tests. Scott found that heat flux measurements at a distance could be predicted by assuming a heat flux of 150 kW/m^2 (3.6 cal/cm^2 s) from the fire. For a building without steel cladding, an effective area of 150% of the actual area of the building was used to account for the fact that the area radiating energy may be larger than the area of the building, while for a building with steel cladding, the actual area of the building was used as the effective area for view factor calculations. Scott also conducted laboratory tests with a gas-fired radiant panel in order to determine the heat fluxes necessary to ignite various cladding materials, such as asphalt shingles, and wood and metal cladding. These minimum heat flux levels for ignition were then used along with a heat flux of 150 kW/m^2 (3.6 cal/cm^2 s) from the burning building in order to calculate critical values of the view factor. A flame projection of 3.0 m (10 ft) was also added to the calculated spatial separation distances.

Muir, another of Moysey's graduate students, studied the effects of building geometry and ventilation openings on the burning rate of fires, and the effects of the burning rate on flame heights and thermal radiation heat fluxes to adjacent buildings [66]. Small-scale structures (between 10 cm × 10 cm × 15 and 30 cm × 30 cm by 45 cm) were used in the laboratory. These structures had no roofs, as Scott [65] had found that the maximum heat fluxes occurred after the roofs of the farm buildings in his experiments had collapsed. Measured heat fluxes were less than 150 kW/m^2 (3.6 cal/cm^2 s), although it was noted that this was likely due to the fact that the smaller flames that projected from these small-scale structures had an emissivity less than 1.0, as was assumed in other studies. Therefore, Muir continued to use a value of 150 kW/m^2 (3.6 cal/cm^2 s) for the heat flux from the burning building. He also developed an equation, which could be used to calculate the flame height based on the dimensions of a structure and the burning rate. This flame height could then be used along with the width of the building to determine the effective area of the fire, and hence the view factor. Muir also used a gas-fired radiant panel to further study the piloted ignition of building materials, including the effects of wind, and the effectiveness of different paints and sheet metal and asbestos cement in preventing ignition. Minimum heat fluxes for ignition were tabulated and used along with an incident heat flux value of 150 kW/m^2 (3.6 cal/cm^2 s) to calculate the critical view factors for buildings with various materials on their exterior walls.

Muir also compared the recommended spatial separation distances calculated using his method with those calculated using other published methods – the 1965 supplement to the National Building Code of Canada for farm buildings [67], McGuire [62] and Williams-Leir's [63] method, and Moysey's method [64]. For the later two methods, occupancies classified as normal and high hazard were considered (using $F_{cr} = 0.07$ and 0.035, respectively). For example, a 9.1 m × 6.1 m high (30 ft × 20 ft high) wall was considered. Muir assumed that the wall of the adjacent building was made of wood, and, based on his research, recommended using a minimum heat flux for ignition of 15.9 kW/m^2 (0.38 cal/cm^2 s). In this case, the various methods gave the following results:

• Muir	18.3 m (60 ft);
• NBC Supplement	21.3 m (70 ft);
• McGuire and Williams-Leir	15.2 m (50 ft) (normal hazard); 21.9 m (72 ft) (high hazard);
• Moysey	19.8 m (65 ft) (normal hazard); and 24.4 m (80 ft) (high hazard).

Muir and Moysey later used Muir's method to develop a series of tables of recommended spatial separation based on the building dimensions, construction type, cladding material, and area of unprotected openings [68]. The tables in this last reference were also included in the National Farm Building Code of Canada for a number of years (e.g., [69]).

While spatial separation regulations are typically based on limiting building-to-building fire spread, in some locations, there is also a risk of wildfire spread from surrounding forests and grasslands to agricultural buildings and farmhouses. Dennis [70] provides guidance as to the requirements for vegetation and fuel storage around a house, in order to provide an adequate amount of space for firefighters to operate. Besides thermal radiation, flying brands can also be a cause of fire spread between buildings. In order to reduce the risk of fire caused by flying brands it is recommended that designers avoid roof openings and low roof slopes [15]. The latter reference also provides information on constructing firebreaks, which can be placed around farms to protect them from bushfires. A review of Australian research, standards and practices aimed at protecting houses from flying brands from wildland fires can be found in [71]. Suggested ways in which buildings can be protected from flying brands include placing metal shutters on windows and protecting exterior walls.

EVACUATION OF ANIMALS

Another issue that must be addressed in many agricultural buildings facilities is the evacuation of animals in case of fire. As shown earlier in Table 1, although only 1.3% of the total fires that occurred in Saskatchewan from 1997 to 2001 were in facilities that housed animals, over 8% of the total fire losses during this period occurred in these buildings. Building codes are concerned with human safety versus animal safety [72]. Therefore, human egress is a major concern of these codes. However, unlike humans, animals typically cannot evacuate from agricultural buildings by themselves, as they will be in cages, pens or stalls. They will need to be guided out of the building should a fire occur, and to be taken to a safe area outside the facility. If there are a large number of animals in a facility, some planning will need to be done so that there is a large enough area for these animals to go to once they have been evacuated. One source of information on protecting animals in agricultural buildings from fire is NFPA 150, which deals with fire safety in stables at racetracks [73].

The Royal Society for the Prevention of Cruelty to Animals (RSPCA) in the UK organized a one-day session in 1991, which dealt with topics such as sprinklers, building materials and research results related to fire protection in livestock buildings [74]. One novel fire protection idea was described by individuals from Denmark where a portion of the exterior wall of a farm building was designed so that it could be pulled out by a tractor, thus providing a large opening for animals to escape in the case of a fire. Recommendations from the RSPCA arising from this session included improving the design of heating equipment, increasing the awareness of fire safety and prevention among workers in the livestock industry and encouraging research in detection technology specifically designed for farm buildings. A brochure was also published by the Ministry of Agriculture, Fisheries and Food in the UK (now part of the Department for Environment, Food and Rural Affairs) [75] to provide information to farmers about fire protection.

One example of how concerns over animal evacuation are addressed is the development of escape plans for horse barns [76]. Plans include identifying escape routes for each stall in the barn, and marking these routes with exit signs and lines on the floor. Plans also include a safe place of refuge, which is large enough to accommodate all of the animals in the barn. Proper equipment for leading the horses out of the barn must also be placed in an easily accessible location. It is important to provide training for firefighters, who may not be used to handling horses, as well as for horses, who otherwise would not be used to smoke and firefighters. Therefore, regular fire drills are important. Some barns have even included the use of simulated smoke in fire drills, in order to help horses get used to conditions they may encounter in an actual fire, and to give firefighters experience in handling horses under these conditions. Another example of a fire department planning for animal evacuation is an operating guideline for large animal rescue developed by the Langley, BC Fire Department [77]. All firefighters are made aware of issues during training, while some receive specialized training, such as barn evacuation, and horse rescue and handling techniques.

ECONOMIC IMPACT

As mentioned earlier, although the number of human casualties may be small in these fires, the number of animals that die in these fires can be very large. Facilities may be very large, and contain a great deal of equipment. Therefore, economic losses can be very large if fire occurs. As discussed earlier, fire losses for fires that occur in agricultural buildings are disproportionate to the number of fires that occur in these buildings. Table 1 showed that about one-quarter of all fire losses in Saskatchewan from 1997 to 2001 occurred in agricultural buildings. To put this in perspective, the average annual fire losses in this five-year period ($11 million) are approximately 0.2% of the total farm cash receipts in 2001 [78]. In 2001, the year with the highest total fire losses in agricultural buildings ($20.9 million), these losses were approximately 0.3% of the total farm cash receipts.

However, fire loss statistics only tell part of the story. As many agricultural facilities are located in smaller communities, the effect of a fire on a major employer or a family farm can be devastating. Even if there are only partial losses, damage to key equipment or facilities can make operations difficult, especially if fire occurs during harvest or another busy part of the year. For example, Shutske [7] discusses the economic effect of farm machinery fires, including downtime. He has also developed a method to estimate downtime losses. Clearly, due to the large economic impact of fires in agricultural buildings, addressing the challenges to fire protection listed in this paper for agricultural buildings is very important.

CONCLUSIONS AND FUTURE WORK

Some of the challenges in providing fire protection to agricultural buildings have been outlined. These challenges can be a result of the materials in these buildings, the characteristics and locations of the buildings themselves, issues related to detection systems, the presence of animals, and/or the economic impact of fire in these buildings. There are a number of resources in print or on the world wide web dealing with fire protection in agricultural buildings. These resources typically describe fire protection principles, current practices and/or firefighting issues, and have been developed for building designers and engineers, the fire service and building owners.

Future work that will help to improve fire protection in agricultural buildings includes increasing the use of existing fire protection strategies in these buildings. As demonstrated by the results of this literature search, there are already a number of resources available to designers and building owners that discuss these strategies. Increasing the implementation of existing technology and fire protection practices, such as detection and suppression systems, passive fire protection and animal evacuation plans, will help to reduce the relatively large numbers of fires and fire losses in these buildings. While some of these fire protection strategies may already be used in the agriculture industry, other strategies that have been used successfully in other types of buildings could also be adapted to agricultural buildings (e.g., detection systems used in other buildings with high ceilings).

Although the fire science literature contains a growing number of examples of the use of performance-based fire protection design in buildings, this literature search indicates that performance-based fire protection design does not appear to be extensively used in the design of agricultural buildings. While fire protection in these buildings is sometimes discussed in the agricultural engineering literature, much of this discussion involves code requirements or other prescriptive-based designs. While engineers may not be involved in the design of some smaller agricultural buildings, such as those on family farms, performance-based design should be explored for agricultural buildings, such as production facilities, which engineers do design. Performance-based design may also be useful in developing guidelines that can be used in the construction of smaller buildings, which may not be typically designed by engineers.

There has been a relatively small amount of research in both the fire science and the agricultural engineering areas specifically dealing with fire protection in agricultural buildings. Areas of future research, which could help to improve fire protection in agricultural buildings, include the following.

- Improved models of the growth of fire in agricultural buildings and the effects of fire on people, animals and building materials are needed. Models developed should take into consideration the unique features of agricultural buildings and the materials contained within them. These models will allow designers to improve the safety of buildings, reduce the need for full-scale fire testing of building materials and support building codes and test standards. Besides detailed fire models, design fires for different types of agricultural buildings should also be developed, which can be used in performance-based design.
- Along with the development of fire models, small- and full-scale fire testing is necessary to provide information on the fire behavior of a larger number of materials used and stored in these buildings. For example, Nelson [30] states that information is needed on the fire behavior of a larger number of chemicals found in these buildings. Information on the fire behavior of specific chemicals will allow fire service personnel to make decisions as to which strategy to use at a particular fire, taking into account the effect of water on the toxicity of the combustion products and the effects of contamination to nearby water supplies caused by the run-off of water from the fire. Fourier Transform Infrared Spectroscopy (FTIR), which is becoming more commonly used in fire science, could prove useful in this research.
- Researchers continue to study heat and moisture transfer in fibrous materials such as hay, in order to learn more about the degradation of these materials during storage. Along with this research, there is a need to continue to improve the understanding of spontaneous ignition in agricultural materials. This research can be applied through the development of fire safety procedures for the storage, shipping and handling of these materials.
- Besides increasing the use of existing detection technology in these buildings, further research is needed to develop new cost-effective fire detection equipment and strategies for agricultural buildings. As noted above, in some cases this may simply involve the application of detection technology that was originally developed for other occupancies.
- As new technologies, such as geographic information systems, become more cost-effective, these can be used to assist smaller fire departments in locating agricultural buildings in rural locations more quickly. Other research results in the area of fire department deployment in urban settings, such as water requirements and resource planning models, could

also find application in rural settings, either in their present form, or with some modifications.

- As discussed in the section on spatial separation calculations, requirements in many building codes and standards for spatial separation are based on an assumption that the fire department will begin suppression operations within 16 min after the start of a fire. In many rural settings, this may not be the case. As measured heat fluxes in the St. Lawrence Burns after 16 min were up to five times greater than the values used to develop most building code requirements, it may be appropriate to significantly increase spatial separation distances between agricultural buildings. As some organizations are re-examining spatial separation requirements [79], it may be an opportune time to determine whether separate requirements are needed for rural buildings, or if requirements can be developed that will be able to address both urban and rural buildings where there is a wide range of fire department intervention times.

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NOMENCLATURE

Symbol

C = ratio of area of exterior wall of building to square of distance to adjacent building
d = distance to adjacent building
F = radiation view factor
h = height of exterior wall of building (m)
Q = heat release rate (kW)
q'' = heat flux (kW/m^2)
RFR = required flow rate of water (L/s)
RTI = response time index (m$^{1/2}$s$^{1/2}$)
S = ratio of area of height to width of exterior wall of building (or inverse if less than unity)

$t =$ time (s)
$u =$ fraction of unprotected openings
$w =$ width of exterior wall of building (m)
$\eta =$ efficiency of application of water

Subscripts

$a =$ actual
$cr =$ critical
$f =$ flame
$o =$ effective
$u =$ unprotected openings

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