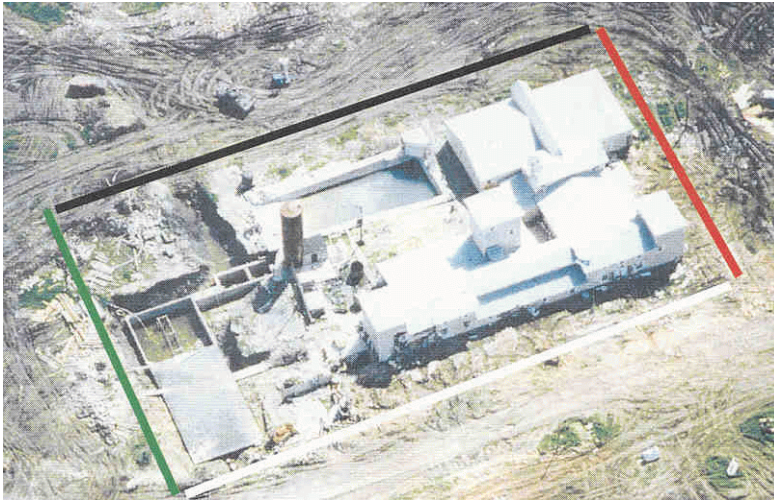


**ANALYSIS OF FLAMMABILITY HAZARDS
ASSOCIATED WITH THE USE OF TEAR GAS AT THE
BRANCH DAVIDIAN COMPLEX
WACO, TEXAS
APRIL 19, 1993**



PREPARED FOR

**THE OFFICE OF SPECIAL COUNSEL
JOHN C. DANFORTH**

BY

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**Fayetteville, Arkansas
September 12, 2000**

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1. EXECUTIVE SUMMARY

1.1 Background

In September 1999, the Attorney General of the United States of America appointed Former United States Senator John Danforth to investigate the events that occurred at the Branch Davidian Complex located at Mount Carmel, near Waco, Texas, on April 19, 1993. Senator Danforth established the Office of Special Counsel (OSC) to carry out the investigation, and in December, 1999 the OSC engaged me (Dr. Jerry Havens) to investigate the following questions:

- ! Did the tear gas cause the fire which destroyed the Complex?
- ! Did the tear gas contribute to the fire spread throughout the Complex?
- ! What caused the explosion/fireball observed during the fire in the Complex?

1.2 Tear Gas Concentrations in the Complex

Using data provided me by the Office of Special Counsel regarding the amounts, schedule, and location of all of the tear gas placed in the Complex on April 19, 1993, I calculated the concentrations of the tear gas components orthochlorobenzylidenemalononitrile (CS) and methylene chloride which could have occurred throughout the complex.

1.3 Flammability Hazards Assessment

Using information regarding the physical states (vapor, liquid, solid) of the tear gas components, and the concentrations of the components which could have occurred in the Complex, I determined the flammability hazards posed in the Complex by the tear gas.

1.3.1 Contribution of Tear Gas to Cause of Fire

Based upon my review and analysis, I conclude that the tear gas, which contained CS and methylene chloride, as used in the Branch Davidian Complex, did not cause the fire.

1.3.2 Contribution of Tear Gas to Spread of Fire

Based upon my review and analysis, I conclude that the tear gas, which contained CS and methylene chloride, as used in the Branch Davidian Complex, did not materially contribute to the spread of the fire.

1.4 The BLEVE Observed in the Vicinity of the Bunker

Based upon my review and analysis, I conclude that the explosion/fireball observed during the destruction by fire of the Complex was a boiling liquid expanding vapor explosion (BLEVE) which resulted from the rupture, due to fire exposure, of a liquefied petroleum gas (LPG) tank.

I further conclude that the size and shape of the fireball created by the BLEVE is consistent with the quantity of propane that could have been contained in the tank whose remnants were found in the immediate vicinity of the location of the fireball.

2 INTRODUCTION

2.1 Report Preparation

I, Dr. Jerry Havens, Distinguished Professor of Chemical Engineering and Director of the Chemical Hazards Research Center, University of Arkansas, Fayetteville, compiled this report. I prepared the report acting as a private consultant to the Office of Special Counsel. The statements made here are my responsibility; no responsibility therefor attaches to the University of Arkansas. Scientific and computational support was provided by Dr. Tom Spicer, Professor of Chemical Engineering, University of Arkansas, Fayetteville. The examination of evidence provided me by the Office of Special Counsel was conducted at my home office in Fayetteville, Arkansas, and by Dr. Spicer at his home office in Fayetteville, Arkansas. Biographical sketches for me and for Dr. Spicer are attached hereto as Appendix A.

2.2 Purpose

On September 9, 1999, the Attorney General of the United States appointed Former United States Senator John C. Danforth to investigate certain events that occurred at the Branch Davidian Complex near Waco, Texas, on April 19, 1993. Senator Danforth established the Office of Special Counsel to carry out the investigation. In early December 1999, I was retained by the Office of Special Counsel to investigate the use of tear gas at the Branch Davidian Complex on April 19, 1993. My specific charges were to provide an analysis of the hazards that were presented to the occupants of the Complex on April 19, 1993, sufficient to answer the following questions:

- ! Did the tear gas cause the fire which destroyed the Complex?
- ! Did the tear gas contribute to the fire spread throughout the Complex?
- ! What caused the explosion/fireball observed during the fire in the Complex?

2.3 Disclosure of Interests

Neither I nor Dr. Spicer have any conflicts of interest with any of the parties, witnesses, or experts involved in this matter.

2.4 Methodology

In order to determine the flammability hazards associated with tear gas introduction into the Branch Davidian Complex, I required specification of the following attributes of the tear gas components CS and methylene chloride in all of the individual enclosed spaces in the Complex:

- ! The physical state (i.e. solid, liquid, or gas).
- ! The highest temperatures which might have been achieved.
- ! The concentration (mass per unit volume) as a function of time.

I carefully considered all of the pertinent reports (provided me by the Office of Special Counsel) by several experts regarding the flammability aspects of the events at the Branch Davidian Complex on April 19, 1993. I immediately identified the primary need to determine as accurately as possible the concentration levels of the tear gas (components) inside the Complex. My careful review of all of the materials provided me revealed that prior analyses had never considered the effects (on the tear gas concentrations) of the ventilation of the complex that resulted from the strong wind that was blowing during the entire morning before the fire started. It followed that a first requirement of my analysis would be to identify an appropriate method to estimate the effect of the wind driven ventilation on the tear gas concentrations inside the Complex.

To estimate the tear gas concentrations inside the Complex, I utilized the COMIS computer model, with input data (provided me by the Office of Special Counsel) specifying the amounts and the time schedule of placement of the tear gas in the Complex, to estimate the (time varying) concentrations of the tear gas in all of the rooms, halls, and stairwells in the Complex during the period beginning at 6 a.m. and ending at the time of the fire shortly after noon on April 19, 1993. The COMIS results were provided to the Office of Special Council and its designated toxicology experts for further (toxicological) analyses. I utilized the COMIS results to estimate the concentrations of both tear gas components (CS and methylene chloride) in order to determine whether either could burn under the prevailing conditions (of concentration and temperature). Finally, I considered whether it was possible for sufficient amounts of either of the components to accumulate on the surfaces in the enclosed spaces of the building (either due to direct impact (splashing) or settling in areas that might have not been as effectively ventilated) to cause or contribute to the spread of the fire.

I performed additional computer modeling to determine the size and extent of any potentially flammable zone which might have occurred during the period(s) of injection of tear gas by the Model 5 Protectojet dispensers mounted on the combat engineering vehicles. I undertook this investigation to determine whether the tear gas sprayed into the Complex (by the Protectojets) could have been ignited had it come into contact with an open flame (or other sufficiently energetic) ignition source (such as a lighted gas lantern).

Finally, I analyzed video recordings of the explosion/fireball observed in the vicinity of the bunker to determine the fireball's size and duration. I also studied photographs and dimensions of the ruptured LPG tank that was found in the vicinity of the location where the explosion/fireball was observed. I utilized combustion and fluid mechanics theory and data from the scientific literature to develop an opinion regarding the cause and origin of the explosion/fireball.

3 DESCRIPTION OF TEAR GAS

The common designation for the tear gas used at the Branch Davidian Complex is CS. The identifier CS is derived from the names of the two persons who are identified with its synthesis in 1928 - Carson and Stoughton.

CS is used in several forms, both pure and mixed with other materials, depending on the application and the associated desired effects. There are four basic forms which have been widely utilized; CS, CS1, CS2, and CSX. CS (referring to the first form), is normally dispersed as a dry powder, either thermally as a solid aerosol (utilizing a small explosive device), or as a liquid aerosol by dissolving it in a carrier material such as methylene chloride. CS1 and CS2 are blends of CS and secondary materials which are primarily designed to increase the persistence of the material's irritating characteristics. CSX is a specific mixture of CS with trioctylphosphite which was developed for dissemination as a liquid. It is important to distinguish the different forms, because there are different degrees and types of hazards which might result from their use.

There has been considerable confusion about the type of CS, as well as the types of delivery systems, used at the Branch Davidian Complex. The Office of Special Counsel has determined that only CS (the first of the four designations above) was used, and there were (only) three different delivery systems used:

- ! Model 5 Protectojet - The Protectojets were essentially steel cylinders (canisters), containing CS dissolved in methylene chloride and pressurized with carbon dioxide, which were mounted on a boom extending from a combat engineering vehicle. The boom was used to breach the building siding (or window), after which the entire contents of the canister were ejected (as a liquid aerosol) during a period of about 15 seconds. A canister contained 1070 grams methylene chloride and 30 grams CS.
- ! Ferret - Ferret rounds were launched through windows (or other openings) into the Complex. Upon impact on hard surfaces in the Complex, the Ferret rounds burst and released the CS (dissolved in methylene chloride) in the form of a liquid aerosol. The introduction of the tear gas by this method was essentially instantaneous. A single Ferret round contained 33.25 grams methylene chloride and 3.7 grams CS.
- ! M651 - The Office of Special Counsel has determined that three M651 rounds were fired at the tornado shelter, which is outside the Complex. The M651 rounds contained pyrotechnic components. However, M651 rounds were not used inside the Complex, and they had no material effect on either tear gas concentrations in the complex or the initiation or course of the fire.

It is important to emphasize that for the tear gas insertions inside the Complex, the CS, which is a solid (powder) at the temperatures experienced (at Waco), was dissolved in methylene chloride to enable delivery as an aerosol cloud, and it is important to reemphasize that the delivery systems used to insert tear gas into the Complex did not contain pyrotechnic components. With

both delivery systems used inside the Complex (Model 5 Protectojets and Ferrets), the tear gas (aerosol) was released into the air where the methylene chloride rapidly evaporated leaving small solid CS particles suspended.

Because the method used to deliver CS to a targeted area results in substantial reduction of the concentration (through forced mixing with air), and because further dilution follows in outdoor applications (due to additional mixing with air), it is unlikely that outdoor applications of CS will result in severe health effects because the required concentrations (and persistence of exposure) are highly unlikely. However, if CS is inserted into semi-closed spaces, the ensuing dilution (by mixing with air), and consequent exposure to persons therein, will depend on the ventilation conditions present in the targeted space.

This investigation was directed to the determination of the acute (i.e., immediate as opposed to chronic) hazards to which occupants of the Branch Davidian Complex were exposed due to the use of tear gas inside the Complex. The primary purpose of my investigation was to identify the flammability hazards posed in the Complex by the tear gas. Identification of the flammability hazards required the estimation of the concentration of the tear gas components throughout the complex. My estimates of tear gas concentration in the Complex were also provided to the Official of Special Counsel's designated experts for their analyses of the toxicity hazards to which the occupants of the Complex were exposed. The following summaries of information regarding the tear gas components orthochlorobenzylidenemalononitrile (CS) and methylene chloride are presented here because this (selected) information pertains directly or indirectly to the determination of the concentrations which could have resulted at any location in the Complex, and to the hazards thereby imposed.

3.1 Orthochlorobenzylidenemalononitrile (CS)

<u>Chemical Name</u>	<u>Chemical Formula</u>
orthochlorobenzylidenemalononitrile	C ₁₀ H ₅ ClN ₂
or	
2-chlorophenylmethylenepropanedinitrile	
or	
2-chlorobenzalmalononitrile	

Pure CS is a white crystalline solid material adopted by the U.S. Army in the late fifties and early sixties for use as an incapacitating agent. Although military (war) use of CS is prohibited by the Chemical Weapons Convention, its use by law enforcement officials for riot and/or crowd control is not, and its use for such purposes has been widespread.

Physical Properties

Molecular Weight	188.62
Density	1.04 g/cc crystalline density; ~0.25 g/cc bulk (powder) density
Melting Point	93 - 95 C
Boiling Point	310 - 315 C (accompanied by thermal decomposition)

Vapor Pressure	0.00034 mm Hg at 20 C
Solubility	Soluble in a variety of solvents, including methylene chloride
Flash Point	197 C

In very small quantities, CS has an irritating, pepper-like odor. Relatively low concentrations can cause involuntary eye closure due to burning sensation and profuse tearing, heavy nasal drainage, and stinging sensation to the skin. Higher concentrations can cause severe coughing and tightness of the chest and throat, dizziness, and pulmonary edema which can lead to permanent injury or death.

3.2 Methylene Chloride

<u>Chemical Name</u>	<u>Chemical Formula</u>
methylene chloride or dichloromethane	CH ₂ Cl ₂

Methylene chloride is a clear colorless liquid which has many uses as a solvent and degreasing agent. It was used as the solvent to dissolve solid CS for loading into the delivery systems used at the Branch Davidian Complex.

Physical Properties

Molecular Weight	84.93
Density	~1.3 g/cc liquid density; vapor density ~ 2.9 times that of air
Boiling Point	39.8 C
Vapor Pressure	355 mm Hg at 20 C
Flash Point	None
Lower Flammable Limit	12% - 14% (at 25 C)

Methylene chloride has a penetrating, ether-like, odor which is irritating at high concentrations. Inhalation of air containing methylene chloride in the range 500 - 1000 ppm can cause minimal anesthetic or narcotic effects. Progressively higher levels can cause dizziness and drunkenness, and still higher concentrations can cause cardiac arrhythmia, unconsciousness, and death.

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4 AMOUNTS, SCHEDULE, AND LOCATIONS OF TEAR GAS PLACEMENT IN THE COMPLEX

The Office of Special Counsel provided the amounts, locations (in the Complex), and time of insertion of all tear gas in the Complex on April 19, 1993. This insertion schedule was based on a careful and detailed review of the FLIR tapes, FBI Event Logs, statements of Branch Davidians, statements of the Hostage Rescue Team tear gas gunners, review of the photographic record, and other eyewitness statements.

Tear gas was introduced by two methods:

! Dispensed from a pressurized canister (Model 5 Protectojet) mounted on a boom extending from a combat engineering vehicle (CEV). The boom was used to breach the building siding (or window), after which the entire contents of the cylinder were ejected during a period of about 15 seconds. A canister contained 1070 grams methylene chloride and 30 grams CS. At the outset of this investigation there was some uncertainty about the location of placement of two canisters in the Complex (at approximately 11:49 and 11:50). Although we were highly confident that two canisters were discharged during this period in the area encompassing Rooms 8, 27, and 30 (See Figure 4.1), there was some uncertainty about the depth of penetration of the CEV and the angle of its boom in the Complex at the time of discharge. Consequently, the following (alternate) scenarios were investigated with COMIS:

- " Case 1 - Two canisters in room 30.
- " Case 2 - Two canisters in room 8.
- " Case 3 - One canister in room 8 and one in room 27.
- " Case 4 - Two canisters in room 27.
- " Case 5 - One-half canister in room 27 and one and one-half canisters in room 30.

In due course, the Office of Special Counsel obtained more precise information about the CEV boom penetration depth and angle. The performance specification for the Protectojet states that the dispersion pattern of the gas is "1 yard in width for every 3 yards in distance." At 11:49 the first canister was discharged into the complex when it was approximately 17 feet from the center of Room 27's front wall. Assuming a complete and unimpeded dispersion, the gas would have struck the center of Room 27's front wall in a stream less than 2 yards wide, missing Room 27's doorway situated on the far left of the front wall. At 11:50 the second canister was discharged into the complex when it was approximately 28 feet from the center of Room 27's front wall. Assuming a complete and unimpeded dispersion, the gas would have struck the center of Room 27's front wall in a stream approximately 3 yards wide, with the left most periphery of that dispersion passing through Room 27's only doorway. Even in the unlikely event that the concentration of the gas at the plume's periphery was equal to that of its center, the amount of gas that entered Room 27 could not have exceeded ½ canister under

these measured conditions. Consequently, I focused on this most likely worst case scenario (½ canister in Room 27 and 1 ½ canister in Room 30) in my subsequent investigation. Although Case 5 is the most likely worst case scenario, some of the other cases indicated higher concentrations in some of the rooms (8, 27, or 30). However, my conclusions regarding flammability hazards in the Complex are not changed by the adoption of any of these (less likely) scenarios.

- ! Ferret rounds launched through windows (or other openings) into the Complex. Upon impact, the plastic Ferret rounds burst and released the tear gas in the form of a liquid aerosol. The introduction of the tear gas by this method was essentially instantaneous. A single Ferret round contained 33.25 grams methylene chloride and 3.7 grams CS. For purposes of my analysis, I assumed that every Ferret hit its target room and deployed as intended. The actual success rate was something less than perfect, because some of the Ferret rounds were observed to hit the side of the Complex (discharging their contents only outside). In my investigation, I assumed a total of 386 (see Figure 4.1). In my opinion, a 5% uncertainty (i.e., plus or minus 20 Ferret rounds) does not affect the conclusions which I reached based on my assumption of 386 rounds.

Table 4.1 shows the schedule of insertion of all of the Ferret rounds and tear gas canisters, and Figures 4.1 - 4.4 show the floor plans for the four levels of the Complex with the total number of Ferret rounds and Model 5 tear gas canisters discharged in each room (subspace).

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Table 4.1. Location and Time Schedule of Placement of Ferrets and Model 5 Canisters

Zone	Time	Ferret Rounds	Canisters	CS (grams)	MC (grams)
Room 1	06:03		1	30	1070
	07:49	2		7.4	66.5
	09:05		1	30	1070
	11:35	2		7.4	66.5
Room 2					
Room 3					
Room 4					
Room 5	06:05		1	30	1070
	07:46	2		7.4	66.5
	09:07		1	30	1070
	11:33	2		7.4	66.5
Room 6	07:43	2		7.4	66.5
	09:09		1	30	1070
	11:31	2		7.4	66.5
Room 7	07:40	2		7.4	66.5
	09:11		1	30	1070
	11:29	2		7.4	66.5
Room 8					
Room 9					
Room 10					
Room 11					
Room 12	07:19	2		7.4	66.5
	11:15	2		7.4	66.5
Room 13	07:16	2		7.4	66.5
	11:13	2		7.4	66.5
Room 14	07:13	2		7.4	66.5
	11:11	2		7.4	66.5
Room 15	07:10	2		7.4	66.5
	11:09	2		7.4	66.5
Room 16					
Room 17					
Room 18	06:13	2		7.4	66.5
	06:55	2		7.4	66.5
	08:06	2		7.4	66.5
	11:10	1		3.7	33.25
	12:05		1	30	1070
Room 19	06:13	2		7.4	66.5
	06:54	2		7.4	66.5
	07:19		1	30	1070
	08:02	2		7.4	66.5
	11:10	1		3.7	33.25
Room 20	06:13	2		7.4	66.5

Table 4.1. Location and Time Schedule of Placement of Ferrets and Model 5 Canisters

Zone	Time	Ferret Rounds	Canisters	CS (grams)	MC (grams)
	06:56	2		7.4	66.5
	08:10	2		7.4	66.5
	11:10	1		3.7	33.25
	06:13	2		7.4	66.5
	06:30		1	30	1070
	06:57	2		7.4	66.5
	07:34		2	60	2140
	08:14	2		7.4	66.5
	11:10	1		3.7	33.25
	06:13	2		7.4	66.5
	06:58	2		7.4	66.5
	08:18	2		7.4	66.5
	11:10	1		3.7	33.25
Room 21					
Room 22	06:13	2		7.4	66.5
	06:59	2		7.4	66.5
	08:22	2		7.4	66.5
	11:10	1		3.7	33.25
Room 23					
Room 24	06:11		1	30	1070
	06:14	24		88.8	798
	06:58	12		44.4	399
	07:35		1	30	1070
	06:13	2		7.4	66.5
	07:00	2		7.4	66.5
	08:26	2		7.4	66.5
Room 25					
Room 26	06:11	6		22.2	199.5
	06:56	3		11.1	99.75
	11:33	2		7.4	66.5
	11:40	8		29.6	266
	06:25	2		7.4	66.5
	06:59	2		7.4	66.5
	08:14	2		7.4	66.5
	11:38	2		7.4	66.5
	12:05	3		11.1	99.75
Room 27	11:49		0.5	15	535
Room 28					
Room 29					
Room 30	11:49		0.5	15	535
	11:50		1	30	1070

Table 4.1. Location and Time Schedule of Placement of Ferrets and Model 5 Canisters

Zone	Time	Ferret Rounds	Canisters	CS (grams)	MC (grams)
Room 31	06:23	2		7.4	66.5
	06:58	2		7.4	66.5
	08:15	2		7.4	66.5
	11:33	2		7.4	66.5
Room 32	07:53		1	30	1070
	08:01	2		7.4	66.5
	11:43	2		7.4	66.5
Room 33	07:55		1	30	1070
	07:58	2		7.4	66.5
	08:20	2		7.4	66.5
	11:41	2		7.4	66.5
	11:45	3		11.1	99.75
Room 34	07:55	2		7.4	66.5
	11:39	2		7.4	66.5
Room 35	07:52	2		7.4	66.5
	11:37	2		7.4	66.5
Room 36	06:21	2		7.4	66.5
	06:57	2		7.4	66.5
	08:14	2		7.4	66.5
	11:28	2		7.4	66.5
Room 37	06:26	3		11.1	99.75
	07:03	1		3.7	33.25
Room 38	06:27	1		3.7	33.25
	07:04	1		3.7	33.25
Room 39	06:28	1		3.7	33.25
	07:04	1		3.7	33.25
Room 40	06:29	1		3.7	33.25
	07:05	1		3.7	33.25
Room 41	07:37	2		7.4	66.5
	11:27	2		7.4	66.5
Room 42	07:34	2		7.4	66.5
	11:25	2		7.4	66.5
Room 43	07:31	2		7.4	66.5
	11:23	2		7.4	66.5
	11:50	1		3.7	33.25
Room 44	07:28	2		7.4	66.5
	11:21	2		7.4	66.5
	11:46	1		3.7	33.25
	11:50	1		3.7	33.25
Room 45	07:25	2		7.4	66.5
	11:19	2		7.4	66.5
Room 46	07:22	2		7.4	66.5

Table 4.1. Location and Time Schedule of Placement of Ferrets and Model 5 Canisters

Zone	Time	Ferret Rounds	Canisters	CS (grams)	MC (grams)
	11:17	2		7.4	66.5
Room 47					
Room 48	07:04	2		7.4	66.5
	11:05	2		7.4	66.5
Room 49	07:01	2		7.4	66.5
	11:03	2		7.4	66.5
Room 50	06:08		1	30	1070
	06:12	2		7.4	66.5
	06:51	2		7.4	66.5
	07:50	2		7.4	66.5
Room 51	06:58	2		7.4	66.5
	11:01	2		7.4	66.5
	06:12	2		7.4	66.5
	06:50	2		7.4	66.5
	07:46	2		7.4	66.5
Room 52	06:11	2		7.4	66.5
	06:52	2		7.4	66.5
	08:09	2		7.4	66.5
	09:40	1		3.7	33.25
	11:03	2		7.4	66.5
Room 53	06:10	2		7.4	66.5
	06:55	1		3.7	33.25
Room 54	06:13	2		7.4	66.5
	06:53	2		7.4	66.5
	08:10	2		7.4	66.5
	09:41	1		3.7	33.25
	11:08	2		7.4	66.5
Room 55	06:07		1	30	1070
	06:12	2		7.4	66.5
	06:52	2		7.4	66.5
	07:54	2		7.4	66.5
	06:12	2		7.4	66.5
	06:53	2		7.4	66.5
	07:58	2		7.4	66.5
Room 56	06:07	3		11.1	99.75
	06:54	1		3.7	33.25
Room 57	06:15	2		7.4	66.5
	06:54	2		7.4	66.5
	08:11	2		7.4	66.5
	09:42	1		3.7	33.25

Table 4.1. Location and Time Schedule of Placement of Ferrets and Model 5 Canisters

Zone	Time	Ferret Rounds	Canisters	CS (grams)	MC (grams)
	11:13	2		7.4	66.5
	06:17	2		7.4	66.5
	06:55	2		7.4	66.5
	08:12	2		7.4	66.5
	09:43	1		3.7	33.25
	11:18	2		7.4	66.5
Room 58	06:12	2		7.4	66.5
	06:48	2		7.4	66.5
	07:38	2		7.4	66.5
	06:12	2		7.4	66.5
	06:49	2		7.4	66.5
	07:42	2		7.4	66.5
Room 59	06:12	2		7.4	66.5
	06:49	2		7.4	66.5
	10:55	2		7.4	66.5
	06:12	2		7.4	66.5
	06:47	2		7.4	66.5
	07:34	2		7.4	66.5
	06:09	2		7.4	66.5
	06:55	1		3.7	33.25
	06:09	2		7.4	66.5
	06:51	2		7.4	66.5
	08:08	2		7.4	66.5
	09:39	1		3.7	33.25
	10:58	2		7.4	66.5
Room 60	06:07	2		7.4	66.5
	06:46	2		7.4	66.5
	10:53	2		7.4	66.5
	06:12	2		7.4	66.5
	06:46	2		7.4	66.5
	07:30	2		7.4	66.5
	06:08	2		7.4	66.5
	06:54	1		3.7	33.25
	06:07	2		7.4	66.5
	06:50	2		7.4	66.5
	08:07	2		7.4	66.5
	09:38	1		3.7	33.25
	10:53	2		7.4	66.5
Foyer	06:17	2		7.4	66.5
	06:52	2		7.4	66.5
	10:57	2		7.4	66.5
	11:55		1	30	1070

Table 4.1. Location and Time Schedule of Placement of Ferrets and Model 5 Canisters

Zone	Time	Ferret Rounds	Canisters	CS (grams)	MC (grams)
	06:22	2		7.4	66.5
	06:55	2		7.4	66.5
	10:59	2		7.4	66.5
Café stairs	06:30	1		3.7	33.25
	07:05	1		3.7	33.25
Foyer stairs	07:07	2		7.4	66.5
	11:07	2		7.4	66.5
Hall 53	06:19	2		7.4	66.5
	06:56	2		7.4	66.5
	08:13	2		7.4	66.5
	09:44	1		3.7	33.25
	11:23	2		7.4	66.5
	Total	386	20	2028.2	34234.5

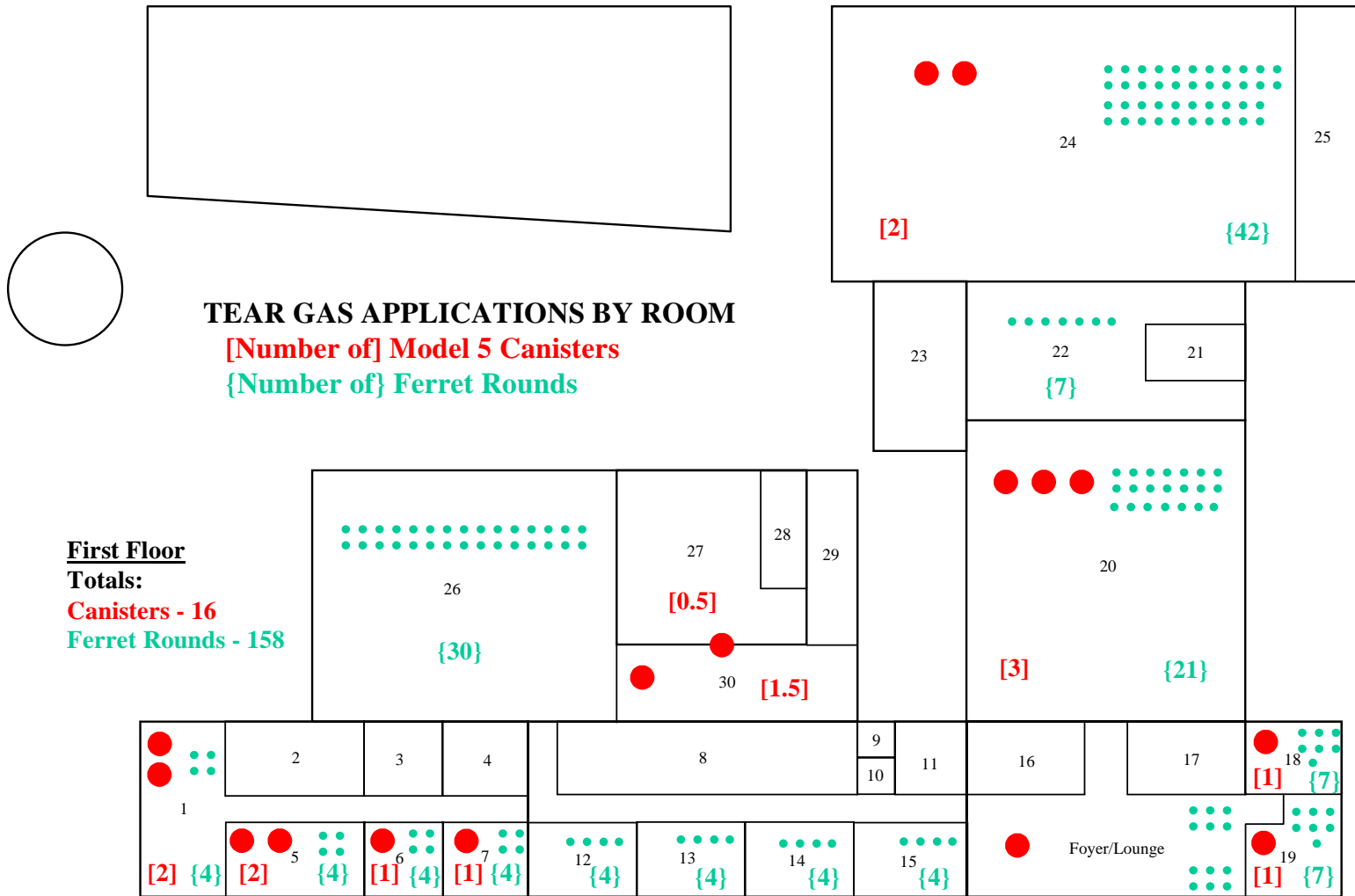


Figure 4.1. Placement of Model 5 Canisters and Ferrets on the First Floor

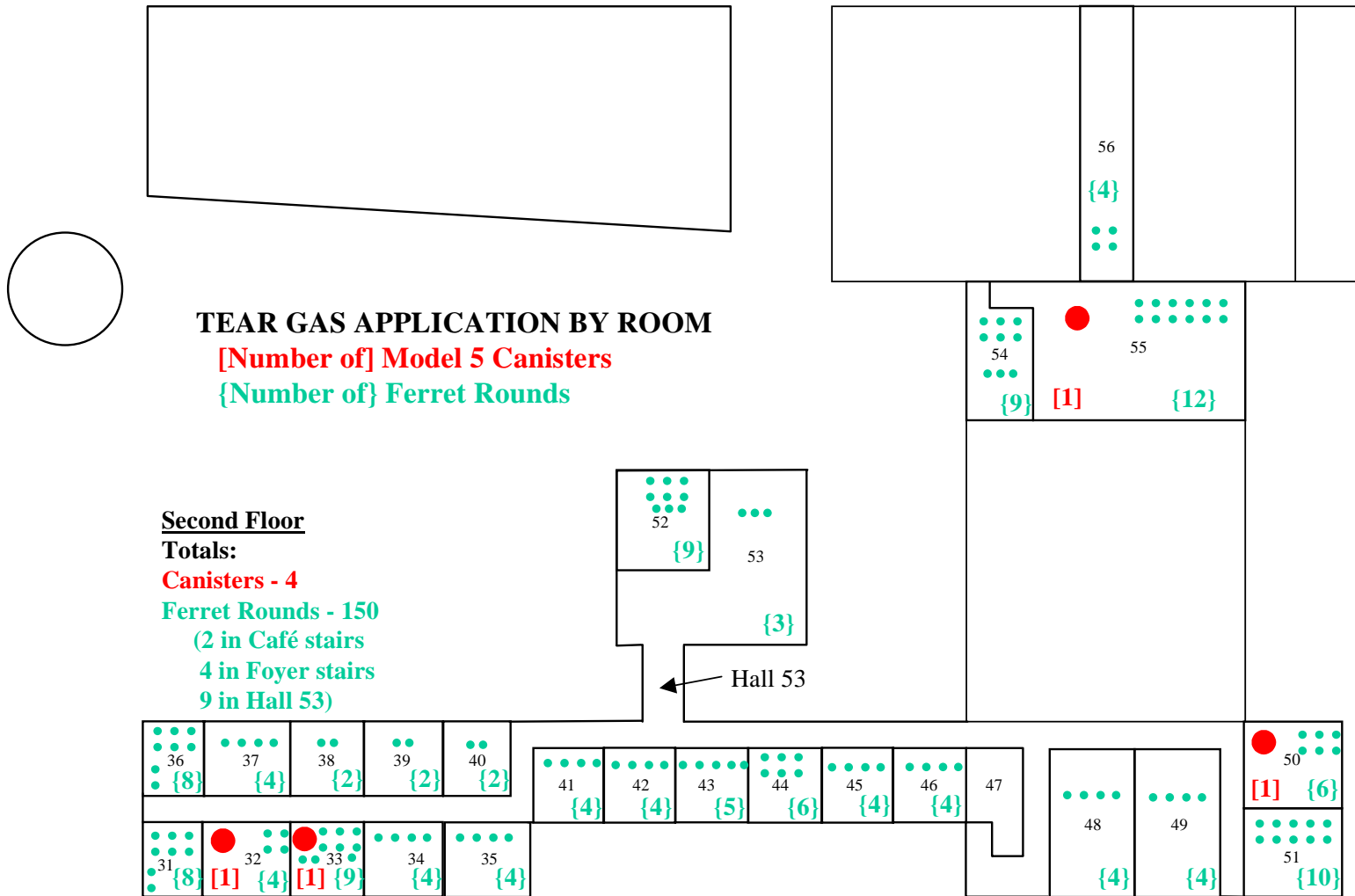


Figure 4.2. Placement of Model 5 Canisters and Ferrets on the Second Floor

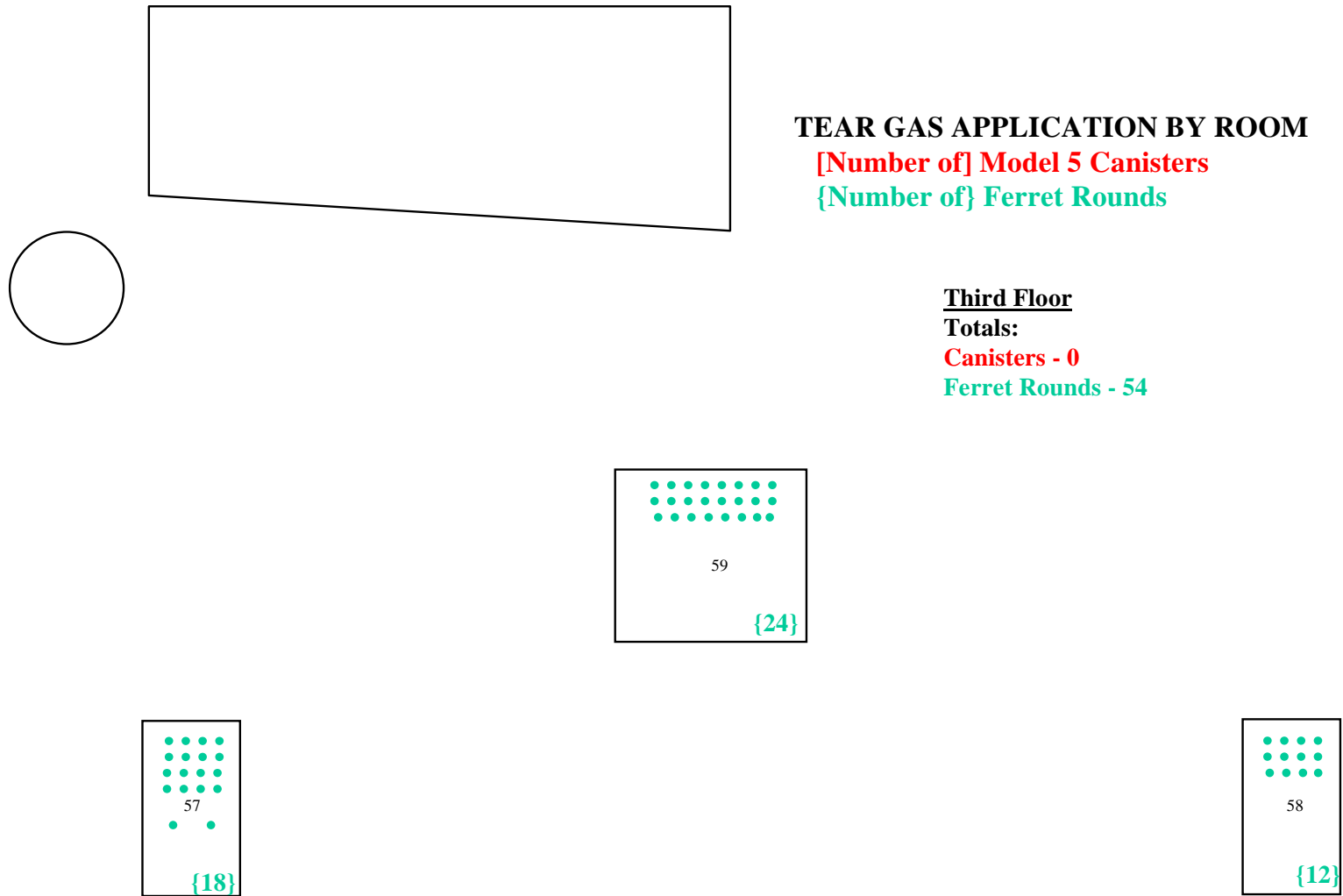


Figure 4.3. Placement of Model 5 Canisters and Ferrets on the Third Floor

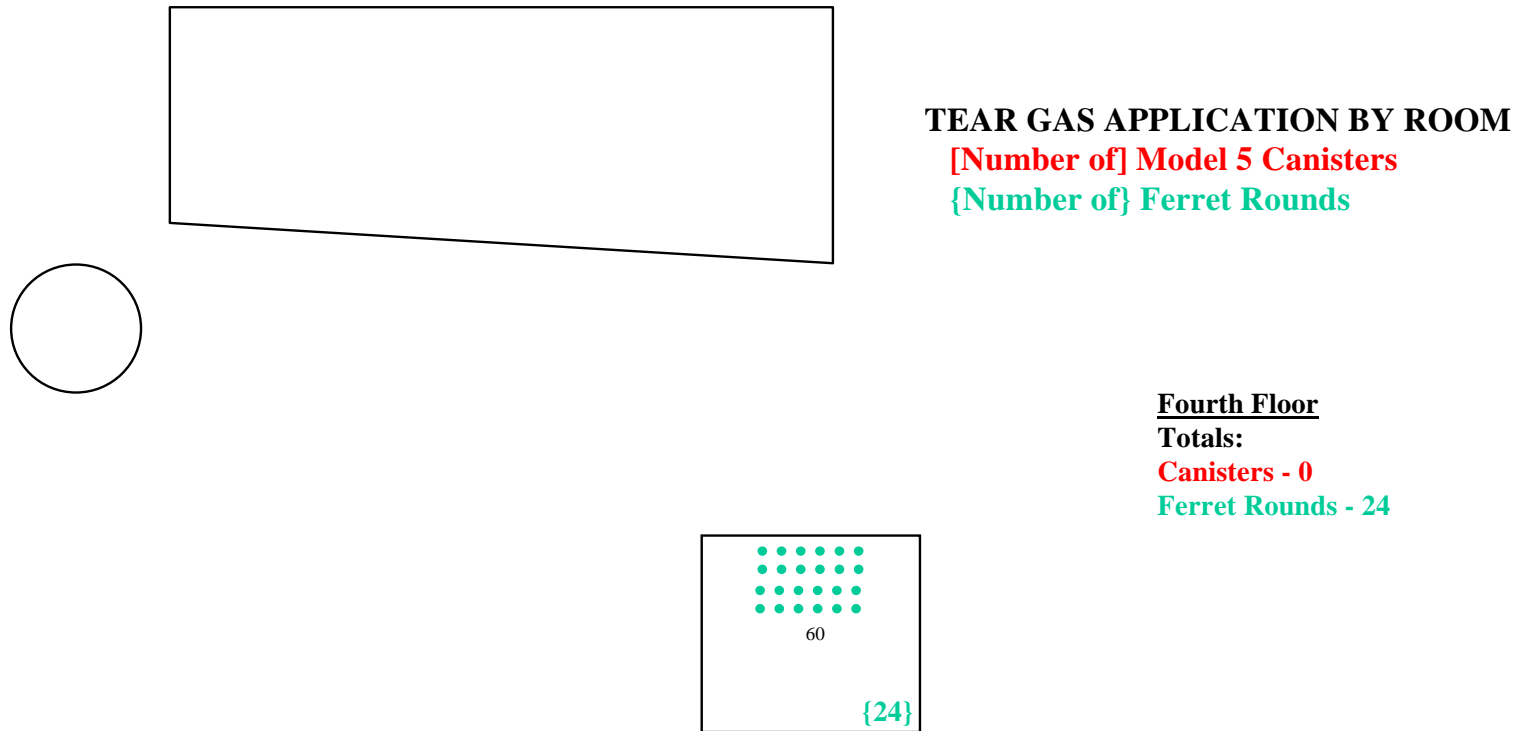


Figure 4.4. Placement of Model 5 Canisters and Ferrets on the Fourth Floor

5 ESTIMATION OF METHYLENE CHLORIDE AND CS CONCENTRATIONS INSIDE THE COMPLEX

In order to assess the flammability hazards caused by the use of tear gas in the Branch Davidian Complex, it was necessary to establish the local, time varying concentration of the tear gas components throughout the Complex. The Complex was composed of approximately 60 separate rooms, on four levels, with interconnecting hallways and stairways.

To estimate the concentrations throughout the Complex during the approximately 6 hour period before the fire started, the following information was required:

- ! Amount, location, and time of entry of the tear gas.
- ! Volume of the rooms (or other spaces) in which the tear gas was placed.
- ! Information required to estimate the movement of air (and tear gas) throughout the Complex due to the wind-driven ventilation.

The amount, location, and time of entry of the tear gas was specified in Section 4.

The Office of Special Counsel provided me with mensuration data developed by Vector Data Systems (U.K.) Ltd. which described the layout of the rooms, halls, and stairways in the Complex. Dimensions of the building and volumes of the rooms, halls, and stairways were provided. Figures 5.1 - 5.4 show the floor plans for the four levels of the Complex with the volumes of the individual rooms and other spaces designated.

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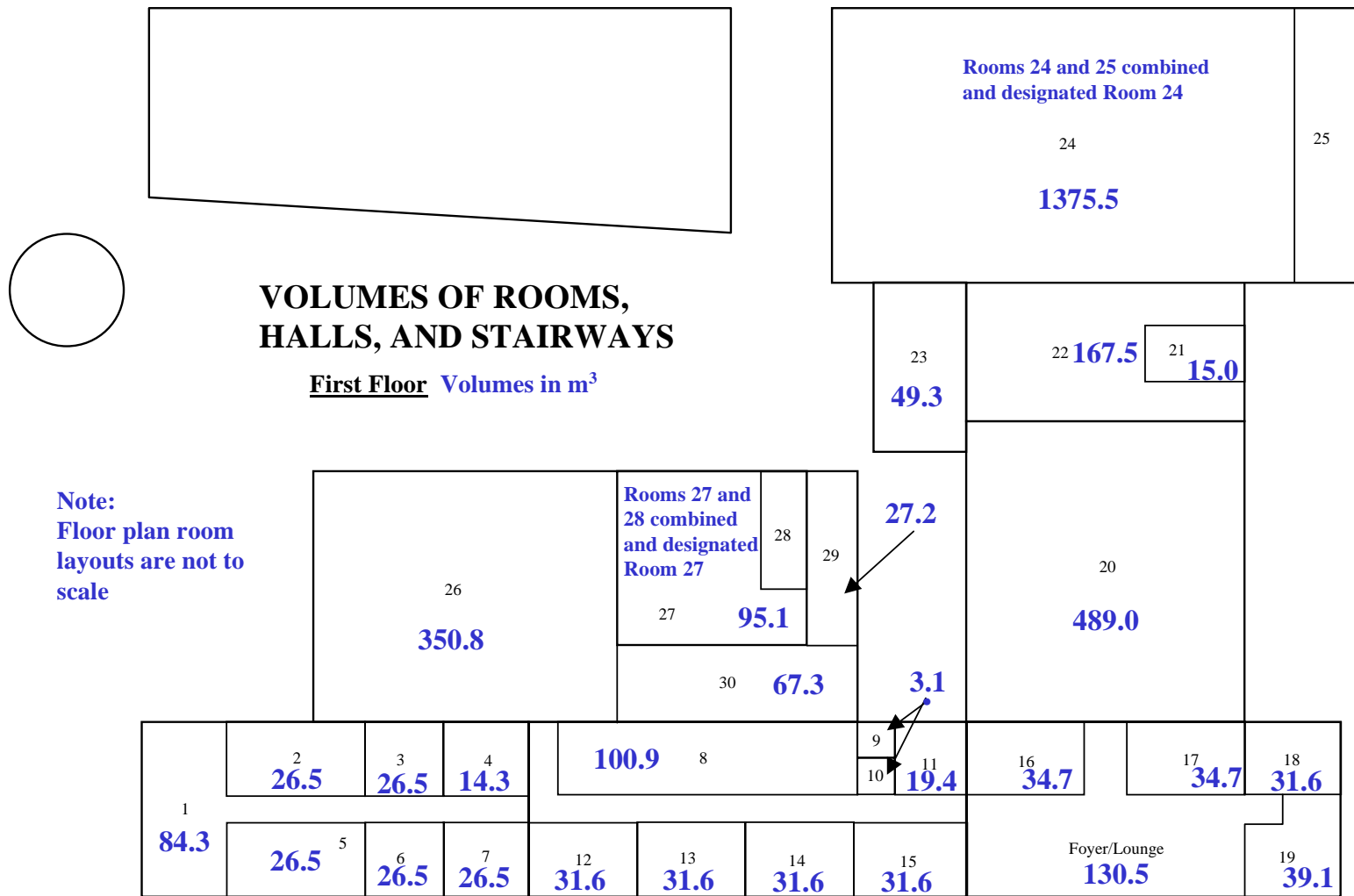


Figure 5.1. Volumes of Rooms, Halls, and Stairways on the First Floor

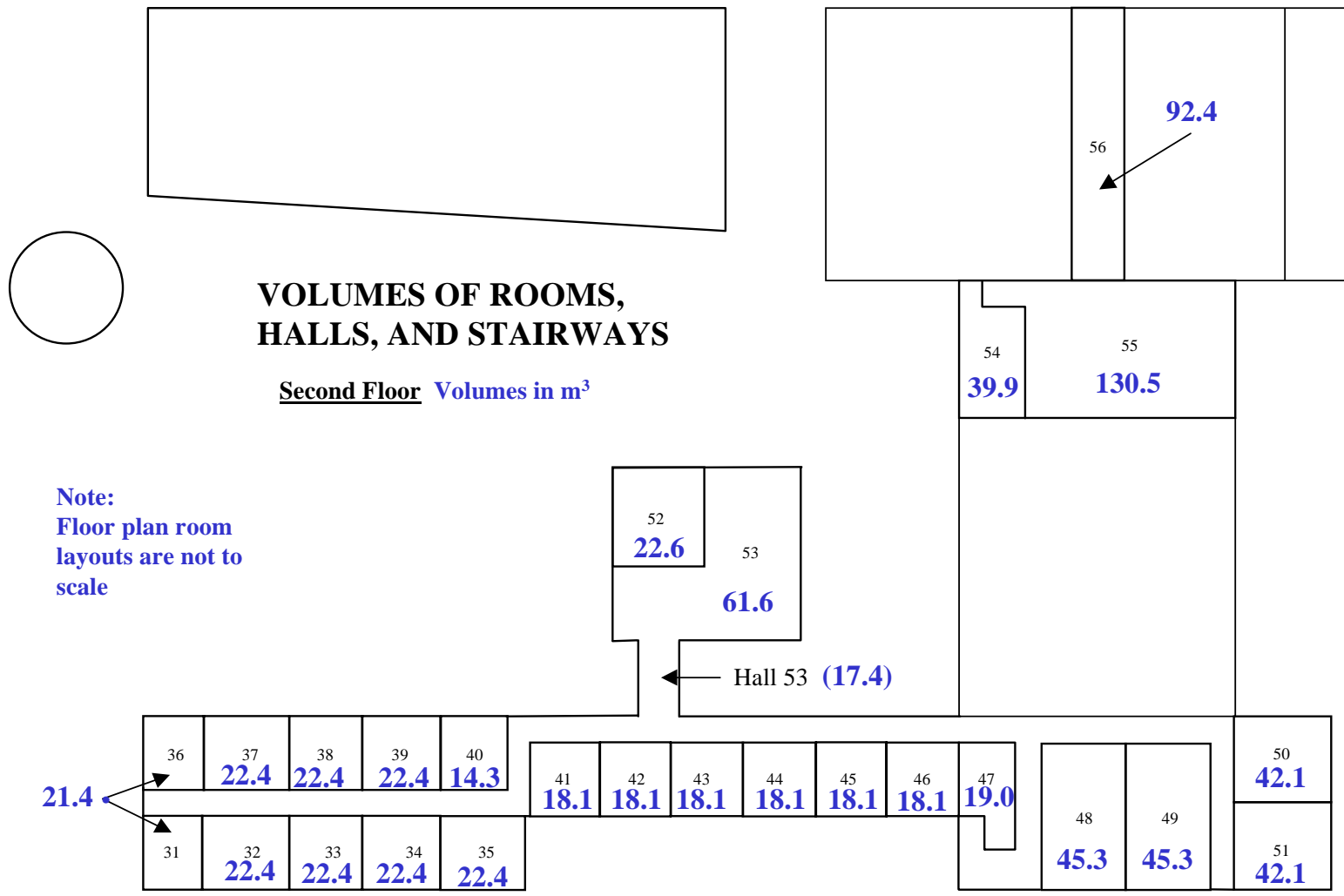


Figure 5.2. Volumes of Rooms, Halls, and Stairways on the Second Floor

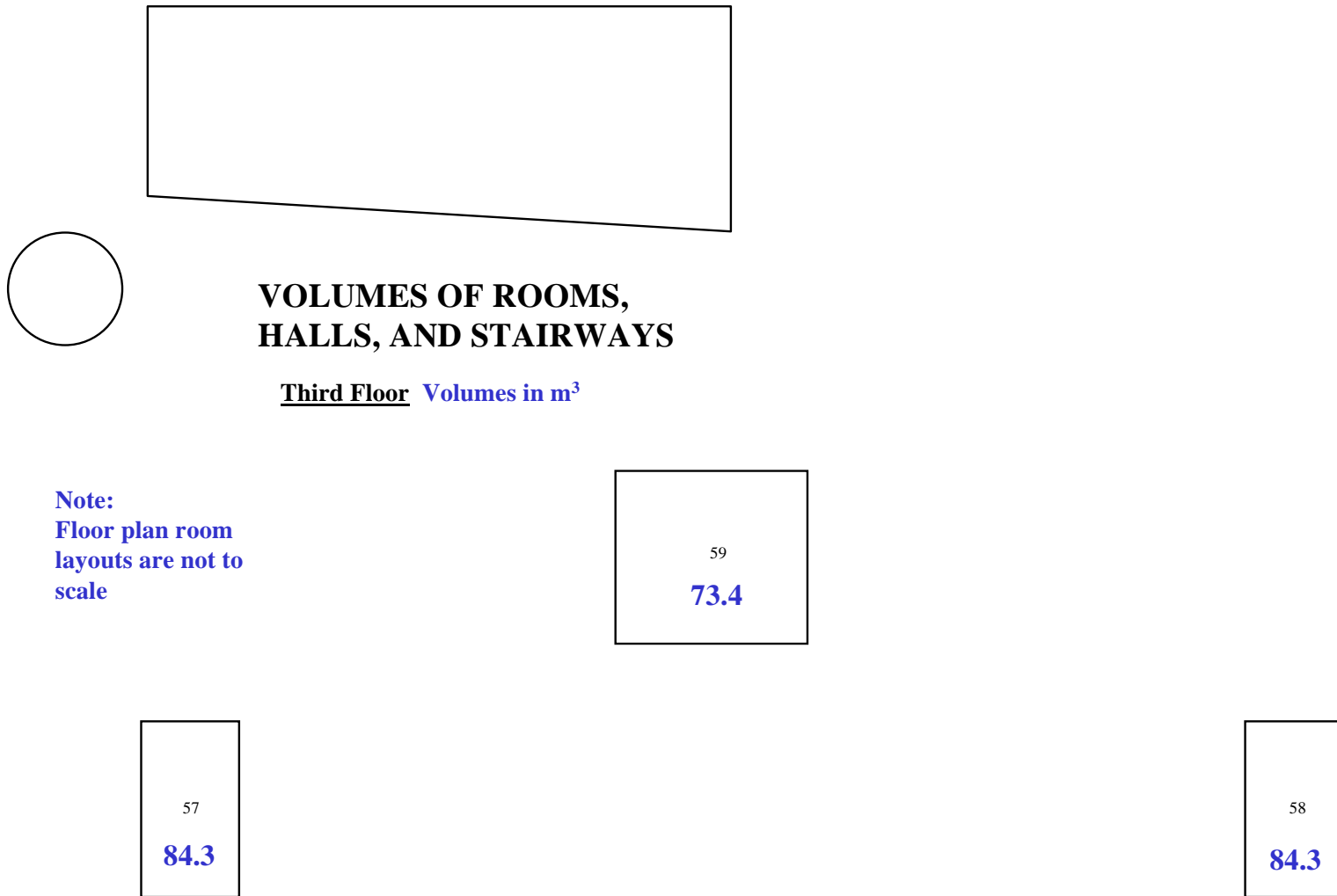
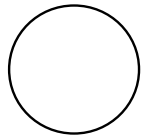
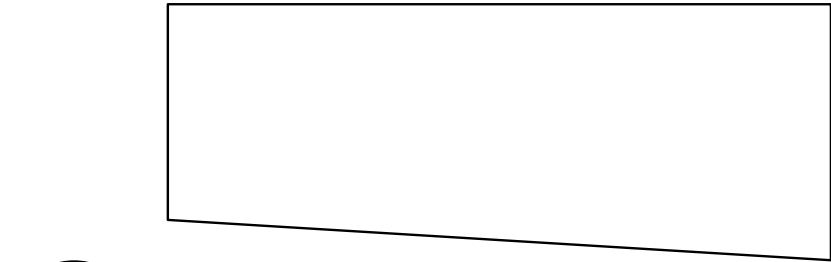


Figure 5.3. Volumes of Rooms, Halls, and Stairways on the Third Floor



VOLUMES OF ROOMS, HALLS, AND STAIRWAYS

Fourth Floor Volumes in m³

**Note:
Floor plan room
layouts are not to
scale**

60
84.3

Figure 5.4. Volumes of Rooms, Halls, and Stairways on the Fourth Floor

5.1 Description of the Complex

The Branch Davidian Complex was composed of approximately 60 separate rooms, on four levels, with interconnecting hallways and stairways. The plans showing the volumes of the rooms, hallways, and stairways for all four floors were shown in the previous section.

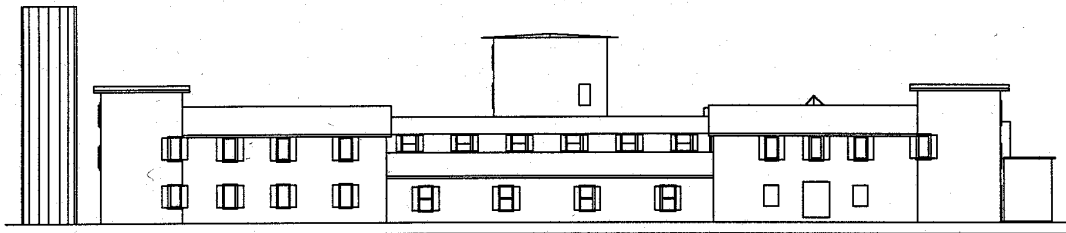
The primary purpose here is to describe additional features of the Complex which were necessary to estimate the effect of the strong wind on the ventilation of the Complex and the resulting concentrations of tear gas throughout.

Figure 5.5 shows an aerial view of the Complex in which the color codes assigned by the FBI in 1993 to the four sides of the Complex are shown. The “white” side is usually considered the front, the “black” side the back, and the “green” side is nearest the tornado shelter (on the left in Figure 5.5). The square “tower” feature, behind the front door of the Complex, and slightly toward the “red” side, reached the fourth floor level, and the concrete room popularly referred to as the “bunker” (Room 27, see Figure 4.1) was on the first floor level underneath this feature.

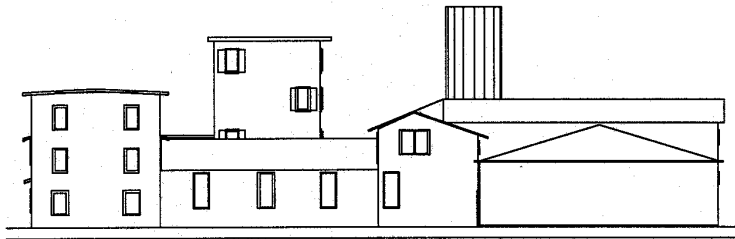


Figure 5.5. Aerial View of the Branch Davidian Complex

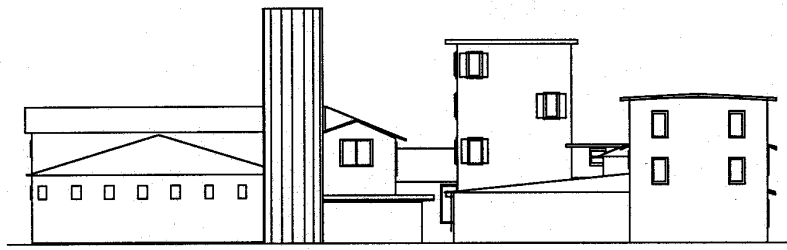
“White”, “Red”, “Green”, and “Black” Side elevations of the Complex are illustrated in Figure 5.6. The Office of Special Counsel provided me detailed dimensions of the complex, along with the positions and sizes of all windows and doorways in the complex, as well as a detailed specification of the schedule (time), location (position), and dimension of all openings created in the sides of the Complex by the combat engineering vehicles.



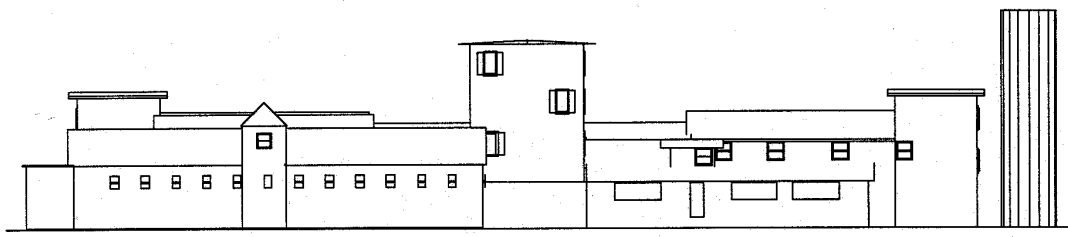
White Side Elevation



Red Side Elevation



Green Side Elevation



Black Side Elevation

Figure 5.6. Side Elevations of the Complex

5.2 Effect of Ventilation on Concentrations of Methylene Chloride and CS

5.2.1 Sources of Ventilation of the Complex

The term *ventilation* is used here to describe the flow of air through, and between, the compartments (rooms and other connecting spaces such as halls and stairways) of the Branch Davidian Complex. Airflow through the individual compartments of the building was caused by pressure differences between the compartments (air flows from regions of higher pressure to regions of lower pressure). The principal causes of such pressure differences are:

- ! wind;
- ! thermal buoyancy associated with temperature variations; and
- ! mechanical ventilation systems.

Given any of these potential causes for pressure differences, the distribution, size, and locations of openings connecting the individual compartments significantly affect the pressure distribution throughout the building.

There were no mechanical ventilation systems operating at the Complex on April 19, 1993. Furthermore, there were no heating or cooling systems operating which could have caused temperature variations sufficient to cause important thermal-buoyancy-driven airflows in the building complex. Consequently, the airflows throughout the building were essentially controlled by pressure distributions which resulted from the strong winds that impacted the building.

5.2.2 Description of Pressure (Wind) Induced Ventilation of the Complex

Airflows throughout the Complex were driven by pressure differences caused by the strong wind which impacted the building. The wind produced a velocity and pressure field (distribution) on the exterior surfaces of the building. The pressure distribution on a building's exterior surface are affected by:

- ! the roughness of the surrounding terrain (nonuniformity of ground surface, presence of vegetation, and presence of buildings or other obstacles);
- ! aspect ratio (height to width) of the individual exterior surfaces of the building; and
- ! the wind direction and velocity.

The wind pressure distribution on the exterior surfaces of the Branch Davidian Complex on April 19, 1993, was described, using standard engineering techniques, by the specification of *pressure coefficients* which indicate the "driving force" (due to the pressure) on the exterior surfaces and, as a result, for air flow through openings in the exterior walls of the Complex. The

wind pressure distribution around (the exterior of) the building is normally highest on the windward (upwind) side of the building, and it is highest at points where the direction of the wind is perpendicular to the (local) building face. The pressures on the exterior surface also vary in the vertical direction because the wind speed increases (from a near-zero value at the ground surface) with height. The wind pressures on the exterior of the building result in airflow through the exterior openings in the building and, in turn, drive the airflow patterns throughout the building complex. The complex pathways of air flow through the building are dependent on the size of all of the compartments in the building, the size and type of openings (doorways, windows, cracks) between the individual compartments, and the pattern of connection of all of the compartments.

5.2.3 Prediction of Ventilation of the Complex

Airflow models are used to simulate the rates of incoming and outgoing airflows for a building with known leakage under given weather and (wind) shielding conditions. Additional details about the flow paths and air-mass flows inside a building can be predicted using multizone airflow models (Feustal and Dieres, 1992). Multizone airflow network models simulate the complex flows in a building by accounting for the effects of internal flow resistances. Such models are based on the mass-balance equation, which (as applied in the present context) is simply a requirement that the flow into a given compartment is equal to the flow out of that compartment. The model must determine the (average) pressure which characterizes each of the zones (compartments). Given the specification of the flow network (connectivity), the sizes of the individual compartments, the characteristics of the connecting openings (which determine the resistances to flow through them), and the pressure distribution on the exterior of the building, a system of equations can be solved to calculate the pressures in each of the compartments and the resulting flow pattern that occurs throughout the building.

There has been extensive development of multizone airflow models due to the need to understand the air-mass flow in buildings for several reasons:

- ! The exchange of outside air with inside air is necessary for building ventilation, as well as to supply air necessary for combustion.
- ! Energy is consumed to heat or cool the incoming air to inside comfort temperature.
- ! The airflows throughout the building transport airborne particles, pollutant gases, biological organisms, and (in the case of fire) smoke, thus determining the concentrations to which the building occupants are exposed.

In this investigation, I constructed a multizone airflow computer model of the Branch Davidian Complex to estimate the concentrations of CS and methylene chloride which occurred throughout the Complex during the morning hours of April 19, 1993.

5.2.3.1 The COMIS Program

The COMIS program was developed beginning in the late eighties (Feustal et al., 1989) at the Lawrence Berkeley Laboratory. COMIS was chosen for the present work for several reasons:

- ! The model is non-proprietary and available to the public; the program used here was downloaded from the Internet.
- ! The model has been subjected to substantial testing for consistency and accuracy, and it has been subjected to fairly extensive verification and proof-testing.
- ! The model structure is modular, which extends its utility for such purposes as the present.
- ! The directions for use of the model are reasonably complete, and the specification of required input conditions is unambiguous.
- ! The numerical algorithm for solving the system of nonlinear equations is a proven method.

Although the COMIS program has been subjected to verification tests by comparison of the model's predictions with actual measurements of airflow in buildings as complex as the Branch Davidian Complex, I subjected it to several checks to verify its applicability for the present use. For example, I checked it by application to simple, single zone (compartment), applications where I was able to independently calculate the resulting concentration variation in the space due to air flow therein. Additional checks were made on the program's ability to accurately account for the changing amount of air contaminants (here CS and methylene chloride) as it was moved by the wind through the Complex. All such attempts verified the accuracy and consistency of the program results.

5.2.3.2 Data Required for the COMIS Program

I determined that the airflows in the Complex, and the concentrations of CS and methylene chloride which resulted, were the result (only) of the wind blowing on the Complex. As a result, the input data required for the COMIS calculation of the airflow throughout the Complex fell into two principal categories:

- ! Environmental Specifications;
 - " wind direction (with respect to the orientation of the building),
 - " wind velocity (speed) and variation thereof with height above the ground, which is determined by specification of the velocity at 10 meters elevation above the ground and the surface roughness (a parameter which characterizes the aerodynamic roughness of the site around the building),
 - " air temperature,
 - " humidity, and
 - " atmospheric (barometric) pressure.

! Building Specifications;

- " building exterior dimensions,
- " sizes, aspect ratios, and positions of all exterior doors, windows, and vents, and all openings made in the exterior and interior walls by the boom-mounted combat engineering vehicles,
- " dimensions of all compartments,
- " interconnectivity between compartments, and
- " sizes and types of all openings between compartments.

5.2.3.3 Predicted Room-Average Concentrations of Methylene Chloride and CS

Figures 5.7 - 5.16 show the COMIS-predicted room-average concentrations of methylene chloride and CS inside ten rooms of the Branch Davidian Complex for the period beginning at 6 a.m. and ending shortly after noon on April 19, 1993. These ten rooms were the rooms in the Complex with the highest concentrations of methylene chloride and CS. In order to illustrate the critical importance of the wind-driven ventilation of the Complex on the concentrations of tear gas within, the dashed lines show the maximum room-average concentrations reflecting the assumption of no ventilation. A CD-ROM containing the COMIS-predicted concentrations of methylene chloride and CS in all of the compartments of the Complex for this (most likely) scenario is attached to this report. For completeness, the CD-ROM also contains the COMIS-predicted concentrations of methylene chloride and CS for all of the alternate scenarios described in Section 4, which were considered earlier in my investigation.

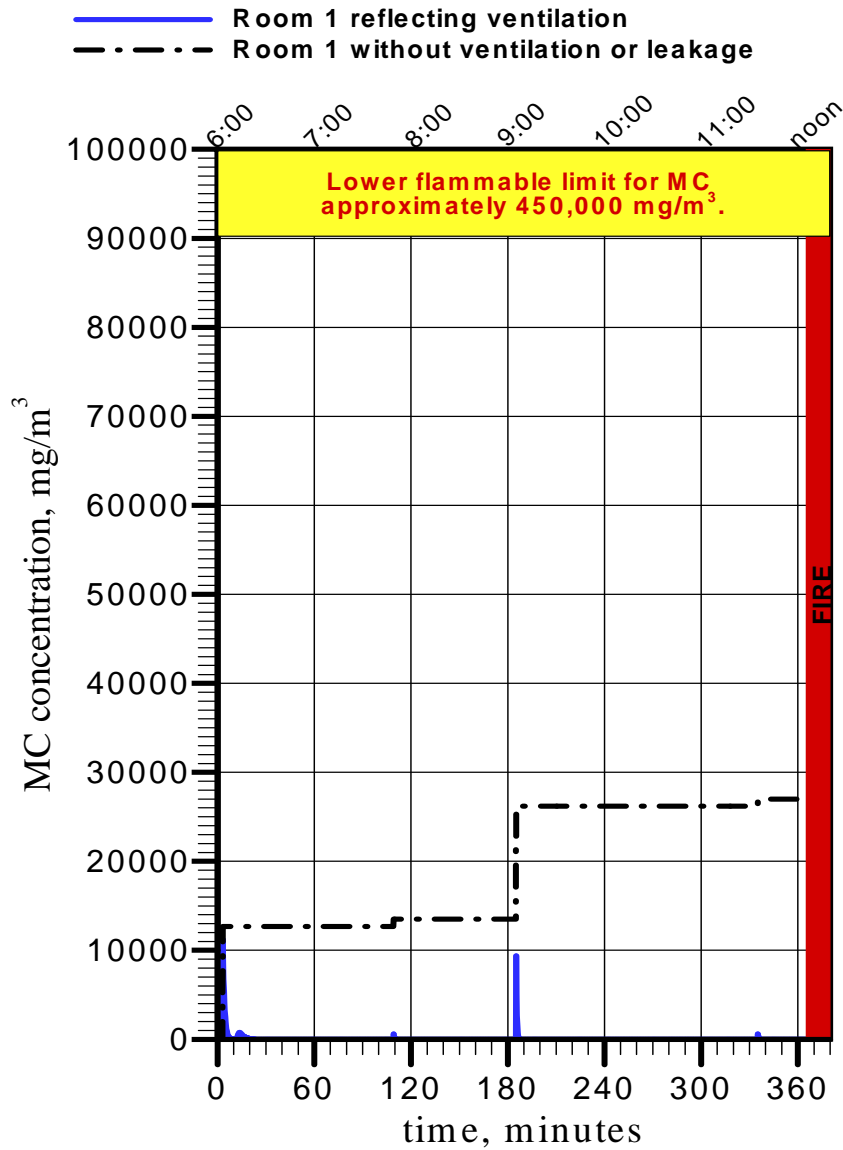
5.2.4. Analysis of Concentrations and Utilization for Toxicity Evaluations

Analysis of Figures 5.7 - 5.16, as anticipated, indicated that the effects of ventilation were to substantially reduce the concentrations of both methylene chloride and CS throughout the Complex. This reduction was due to mixing of the tear gas placed into the compartments with air flowing through the compartment, its resulting removal from that compartment to an adjacent compartment, and so on.

All of the COMIS predictions were provided to the Office of Special Counsel and its designated experts, for use in the assessment of the toxicological hazards to which the occupants of the Complex were exposed on April 19, 1993. Consideration of the potential for conditions to exist in which either the methylene chloride or CS could have caused or materially contributed to the fire which began shortly after noon on April 19, 1993, will be presented in the next section.

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METHYLENE CHLORIDE (MC)



CS

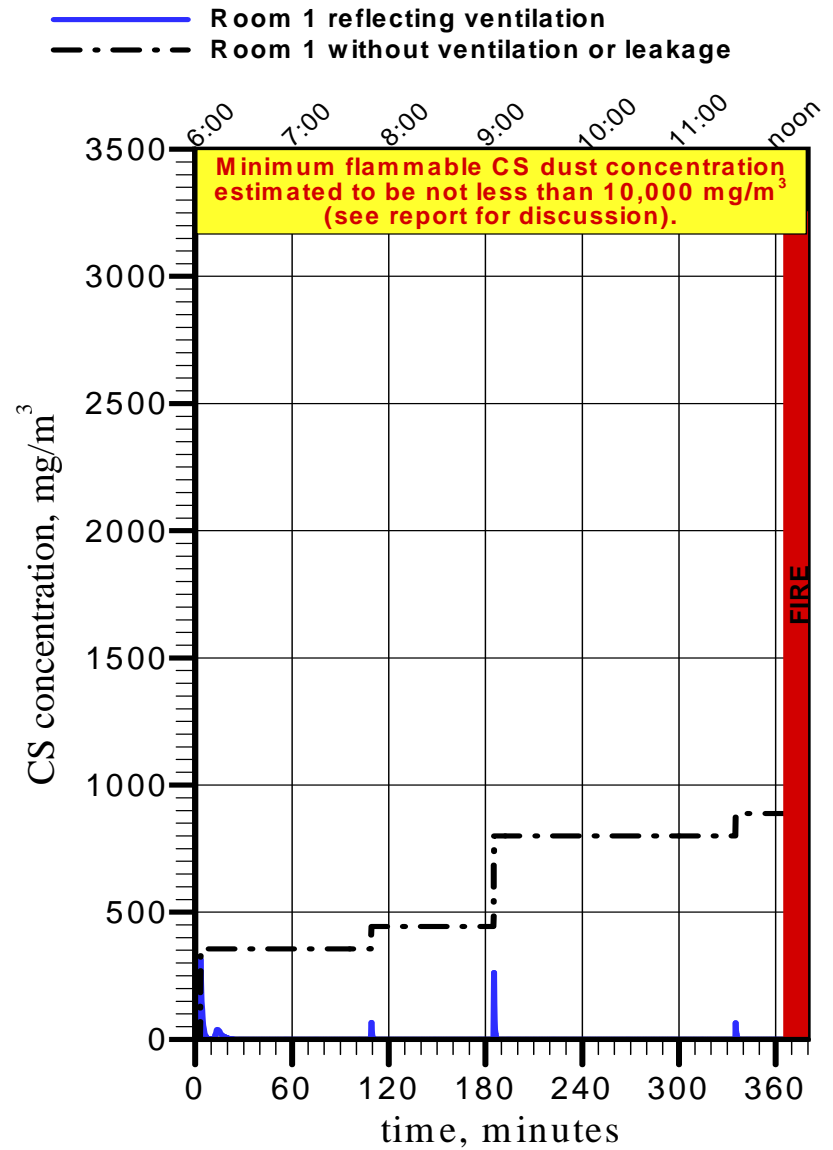
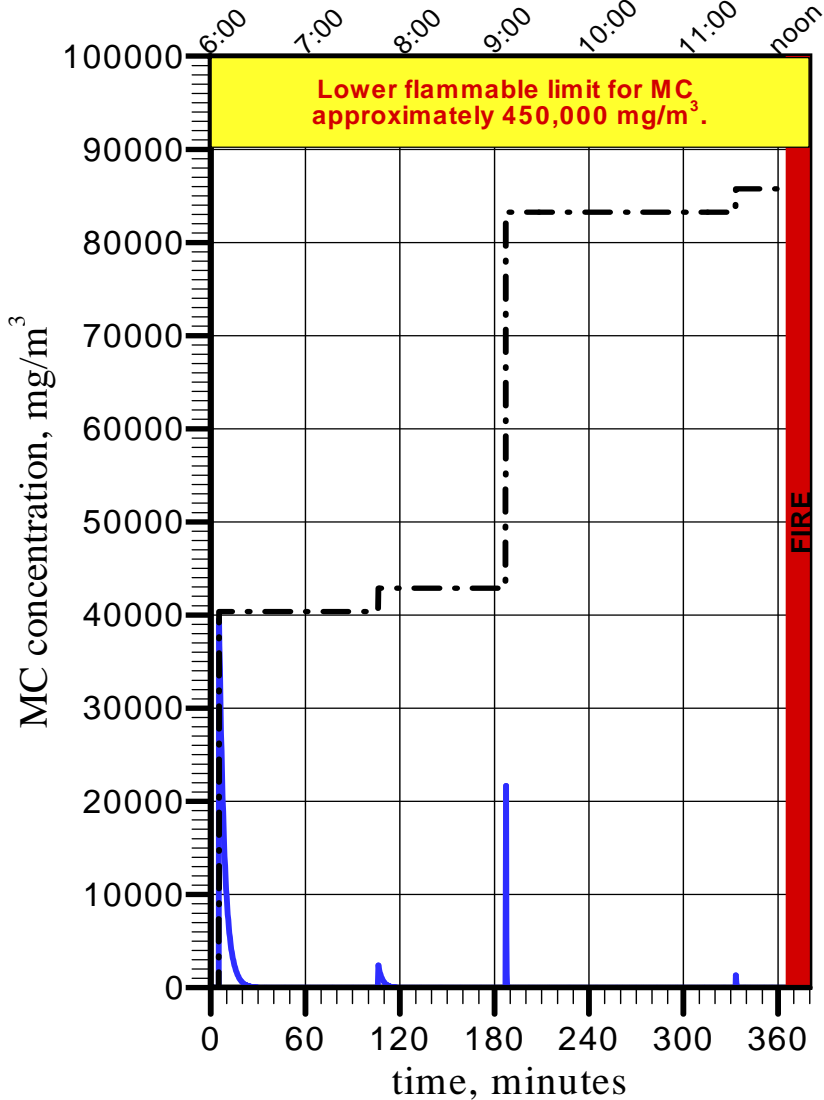


Figure 5.7. Methylene Chloride and CS Concentrations in Room 1

METHYLENE CHLORIDE (MC)

- Room 5 reflecting ventilation
- - - Room 5 without ventilation or leakage



CS

- Room 5 reflecting ventilation
- - - Room 5 without ventilation or leakage

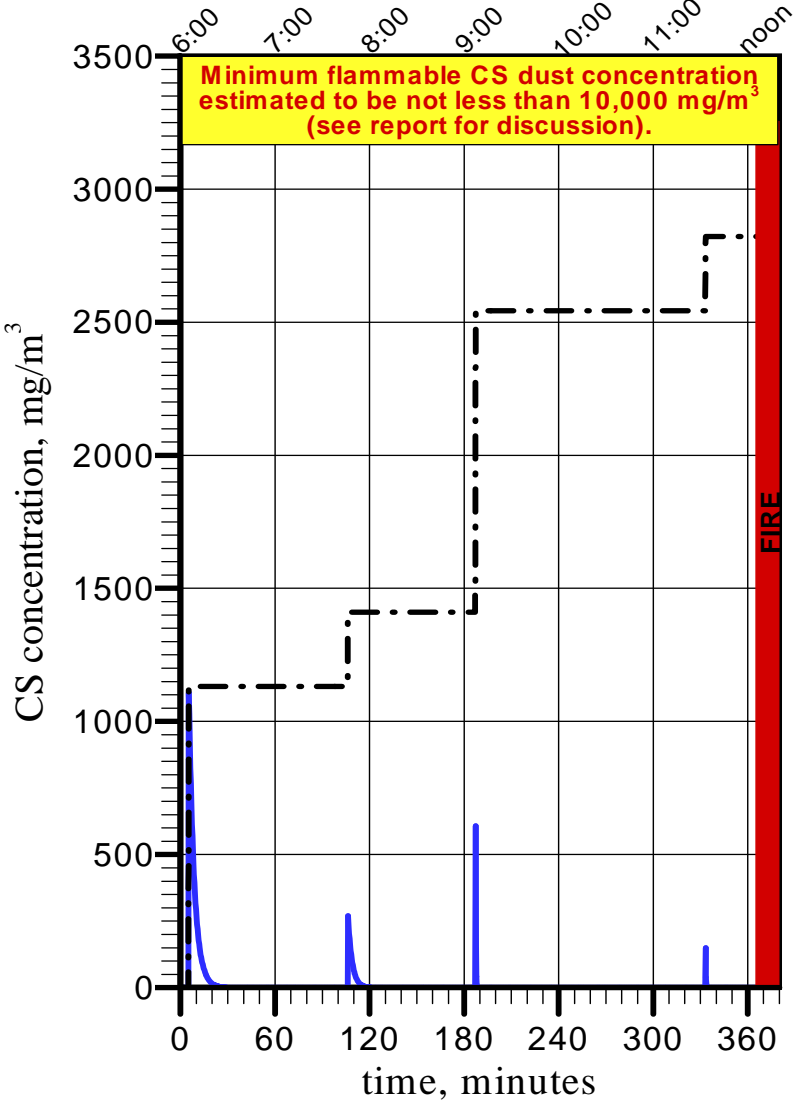
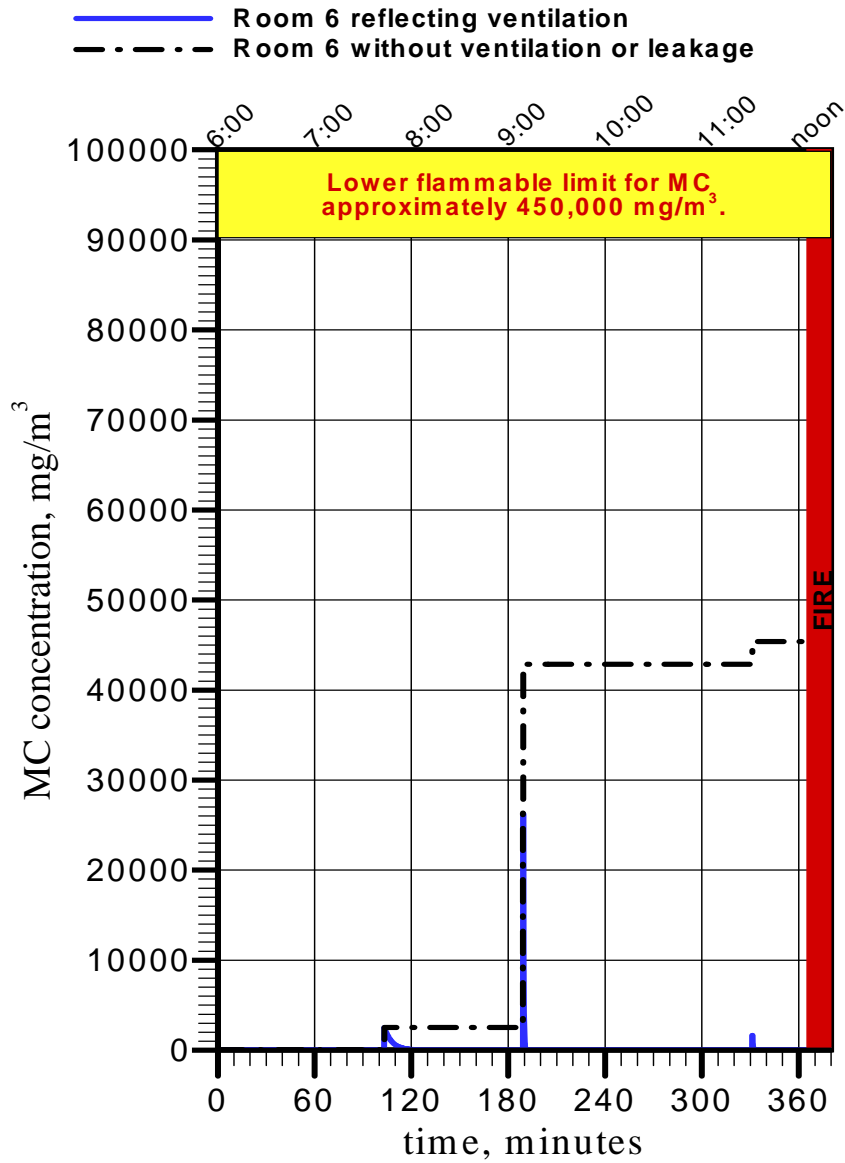


Figure 5.8. Methylene Chloride and CS Concentrations in Room 5

METHYLENE CHLORIDE (MC)



CS

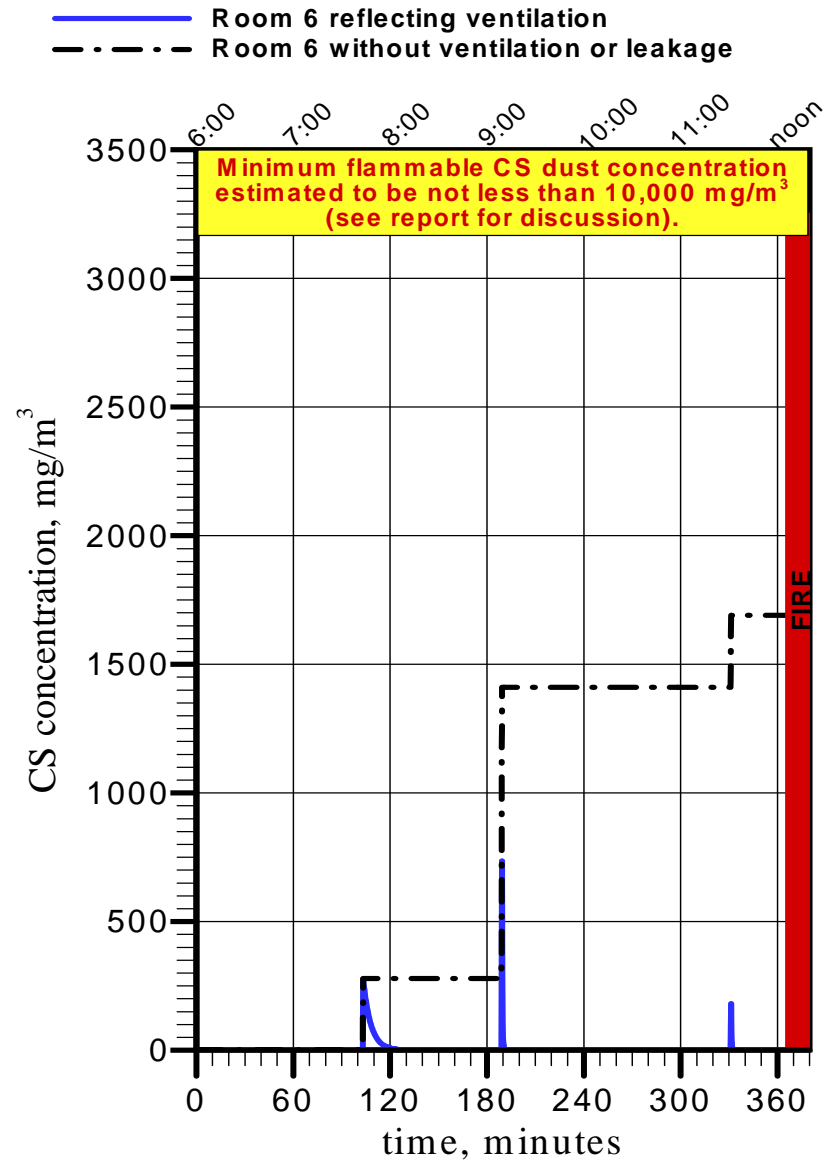
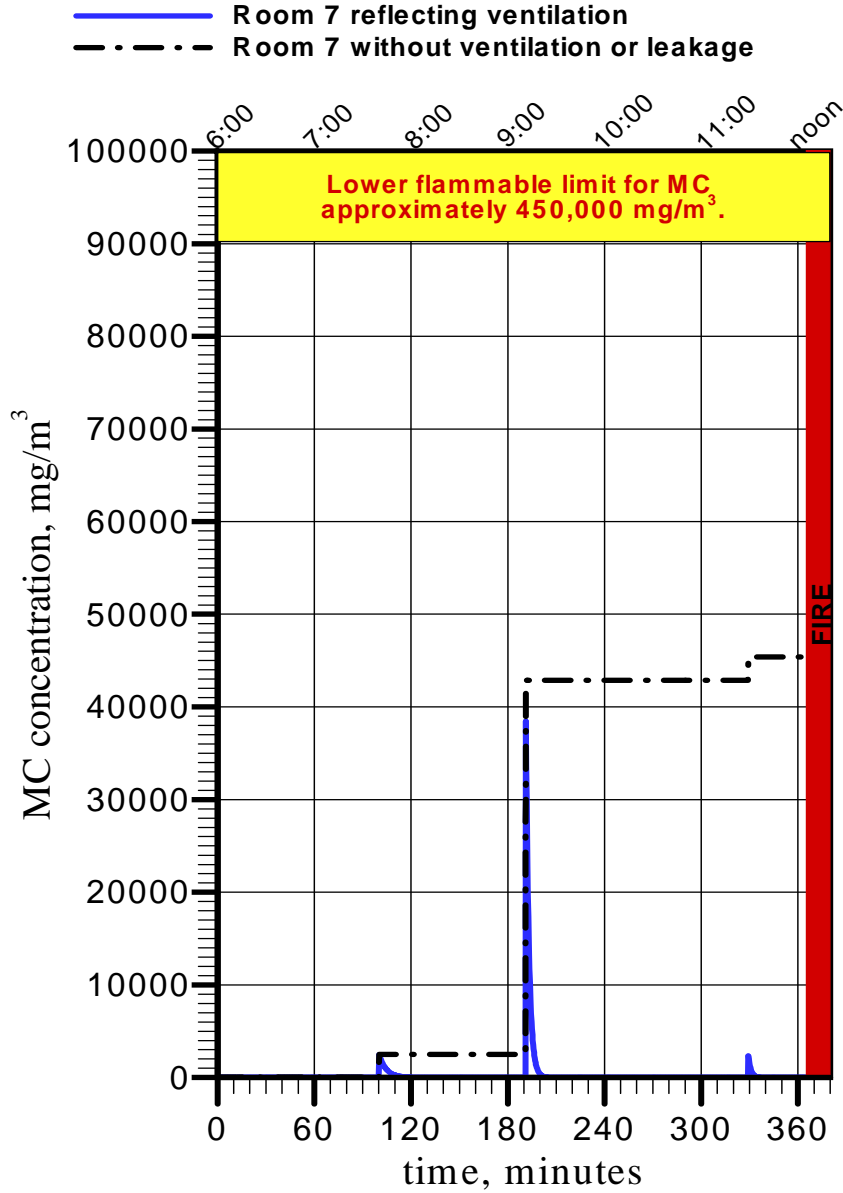


Figure 5.9. Methylene Chloride and CS Concentrations in Room 6

METHYLENE CHLORIDE (MC)



CS

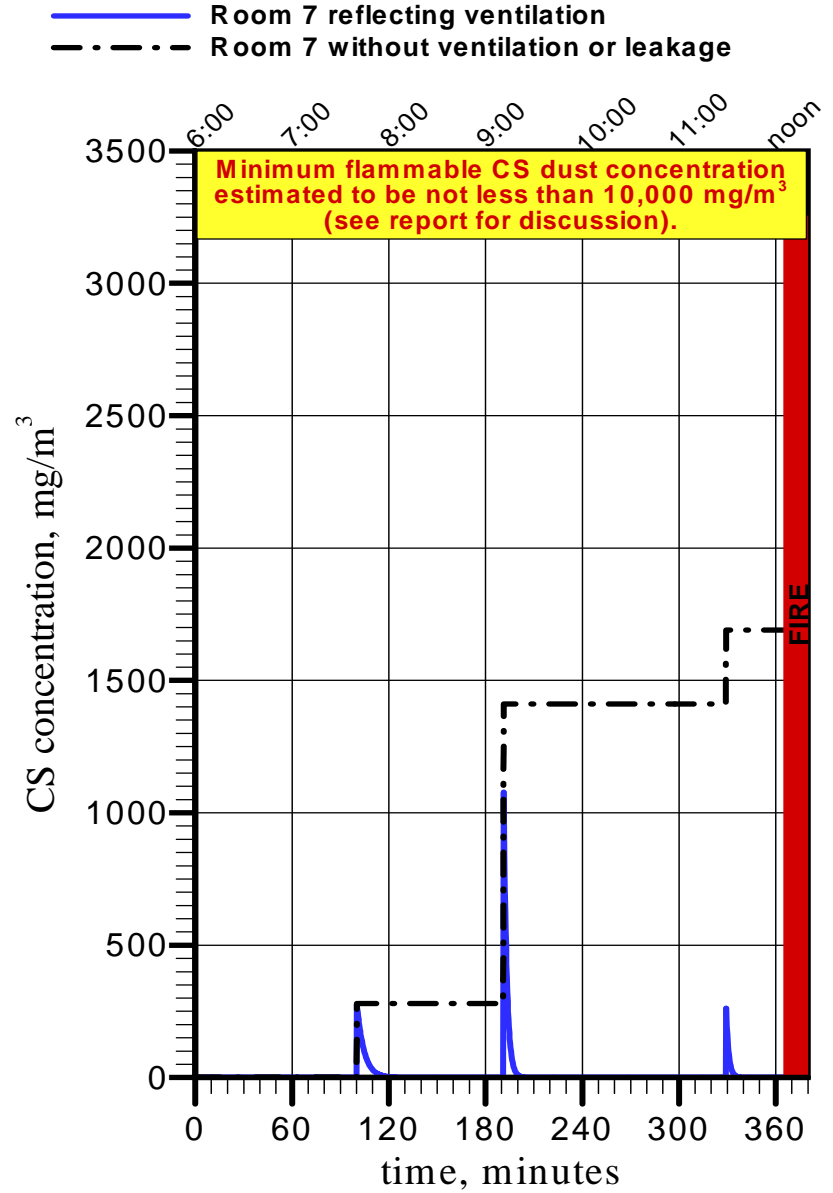
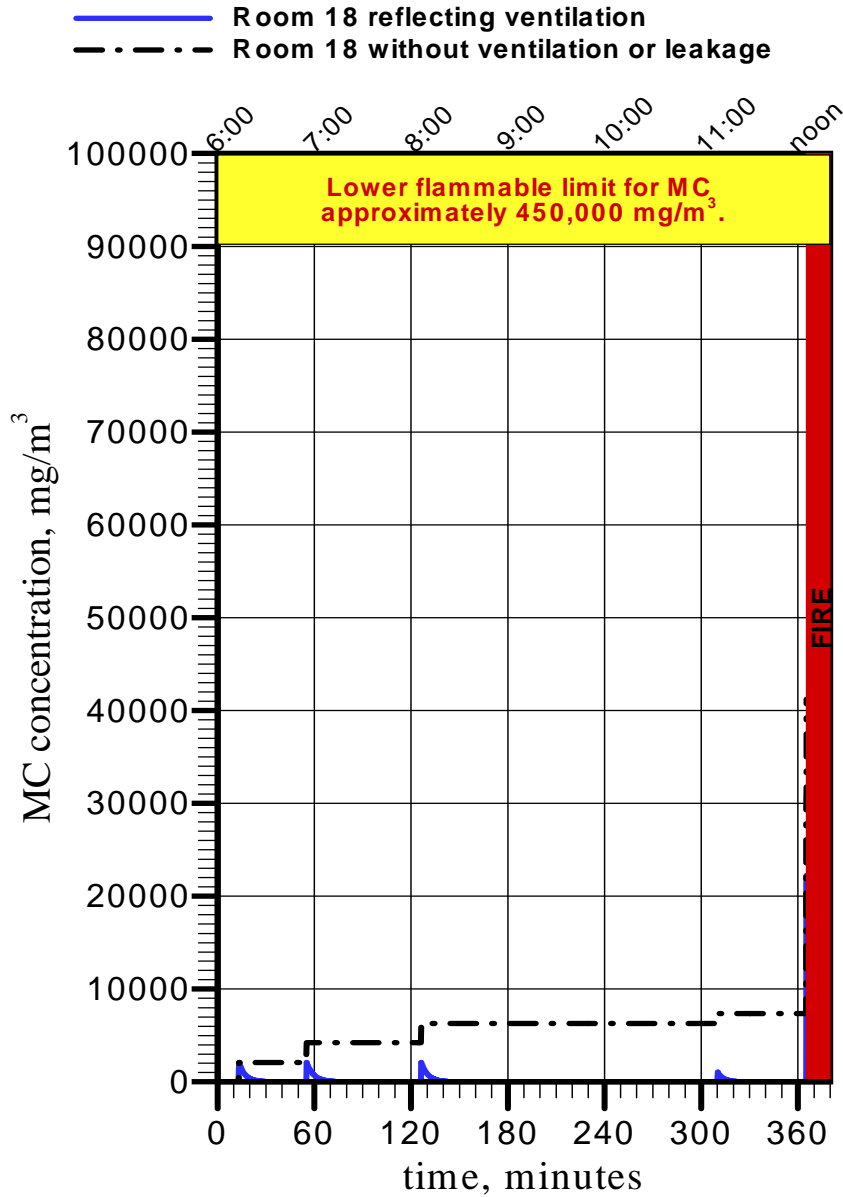


Figure 5.10. Methylene Chloride and CS Concentrations in Room 7

METHYLENE CHLORIDE (MC)



CS

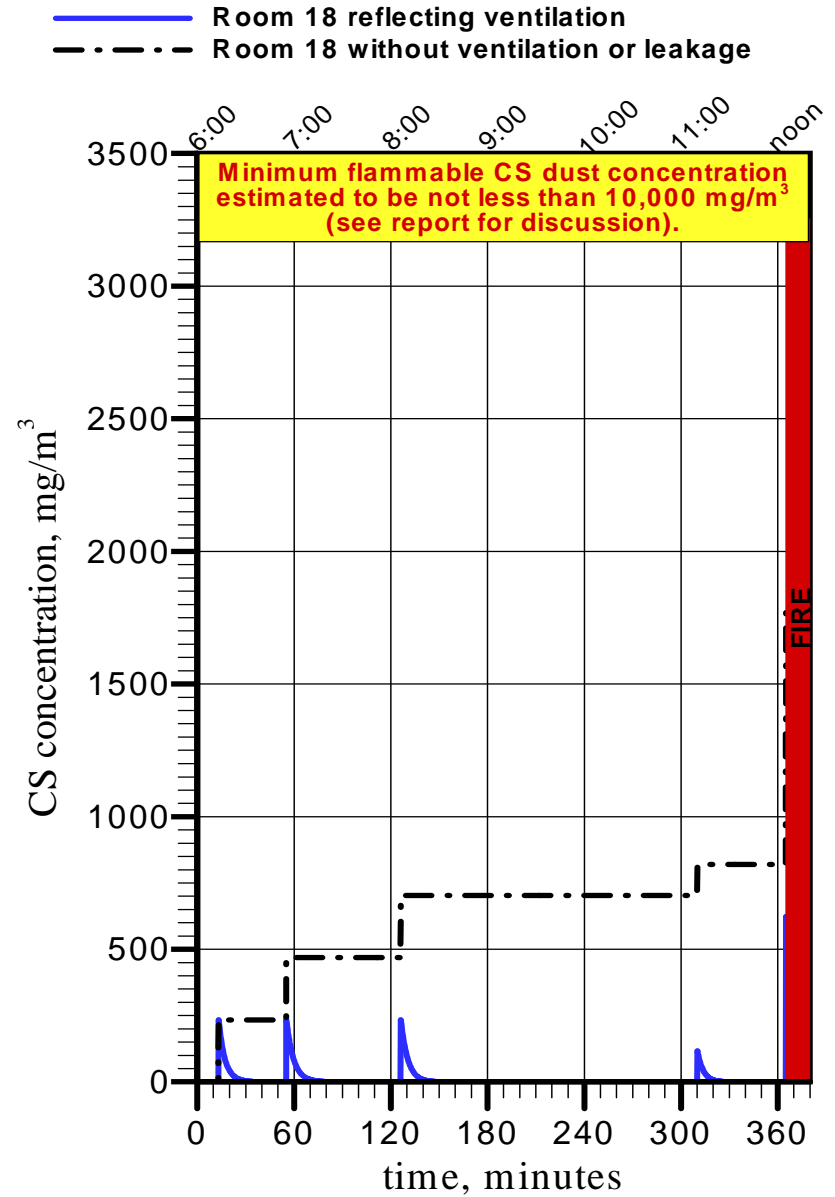
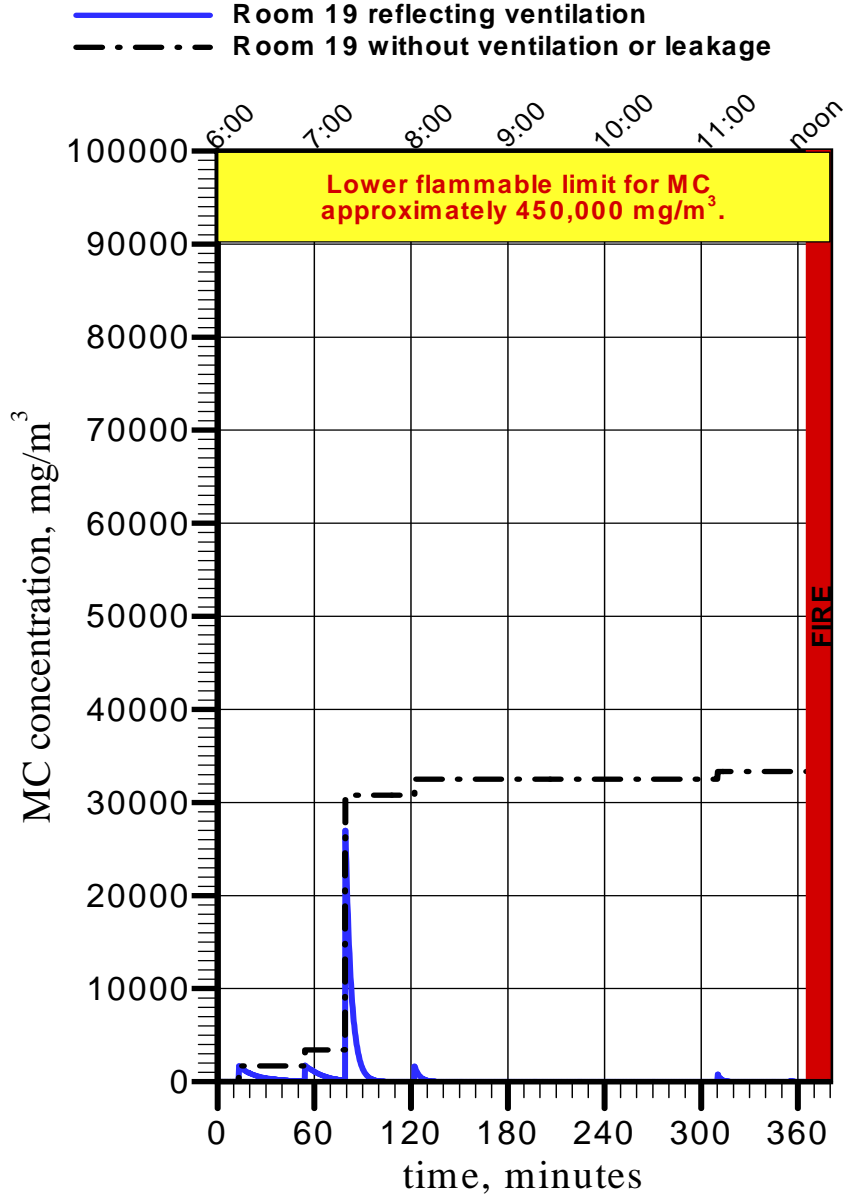


Figure 5.11. Methylene Chloride and CS Concentrations in Room 18

METHYLENE CHLORIDE (MC)



CS

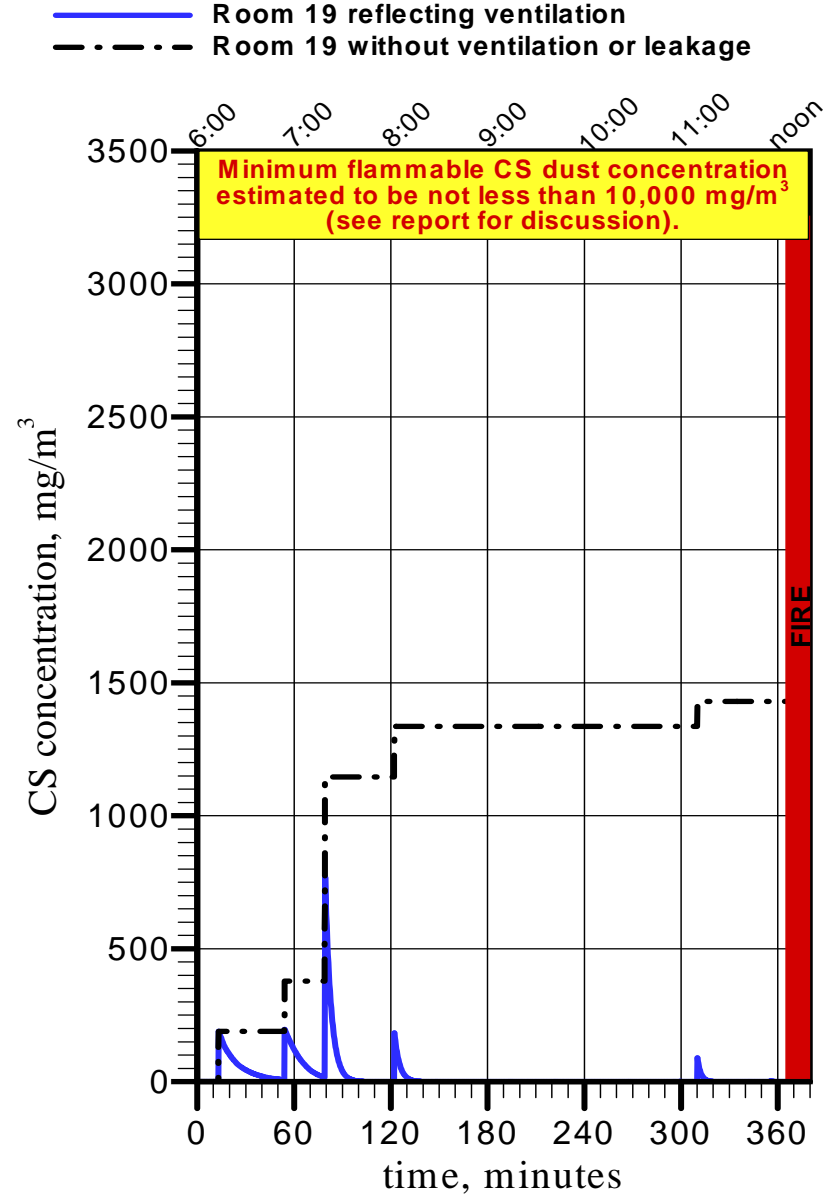
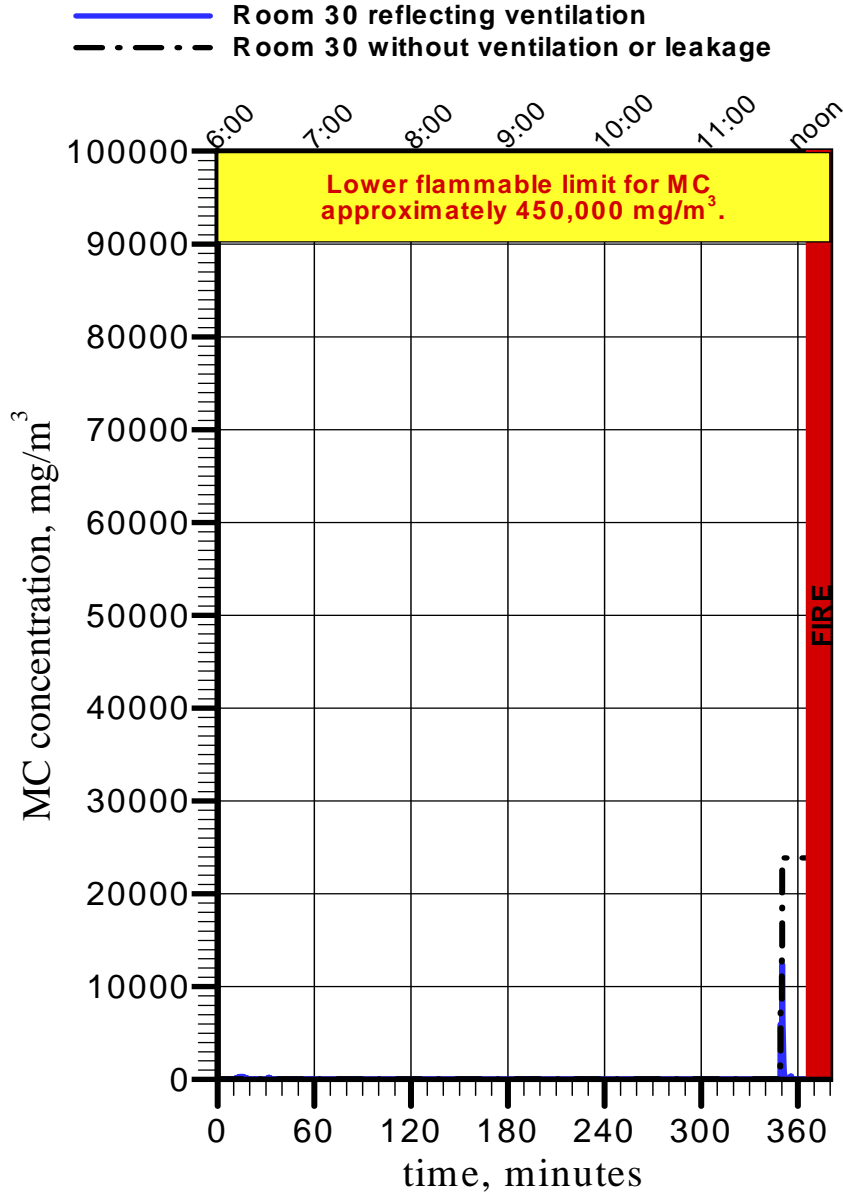


Figure 5.12. Methylene Chloride and CS Concentrations in Room 19

METHYLENE CHLORIDE (MC)



CS

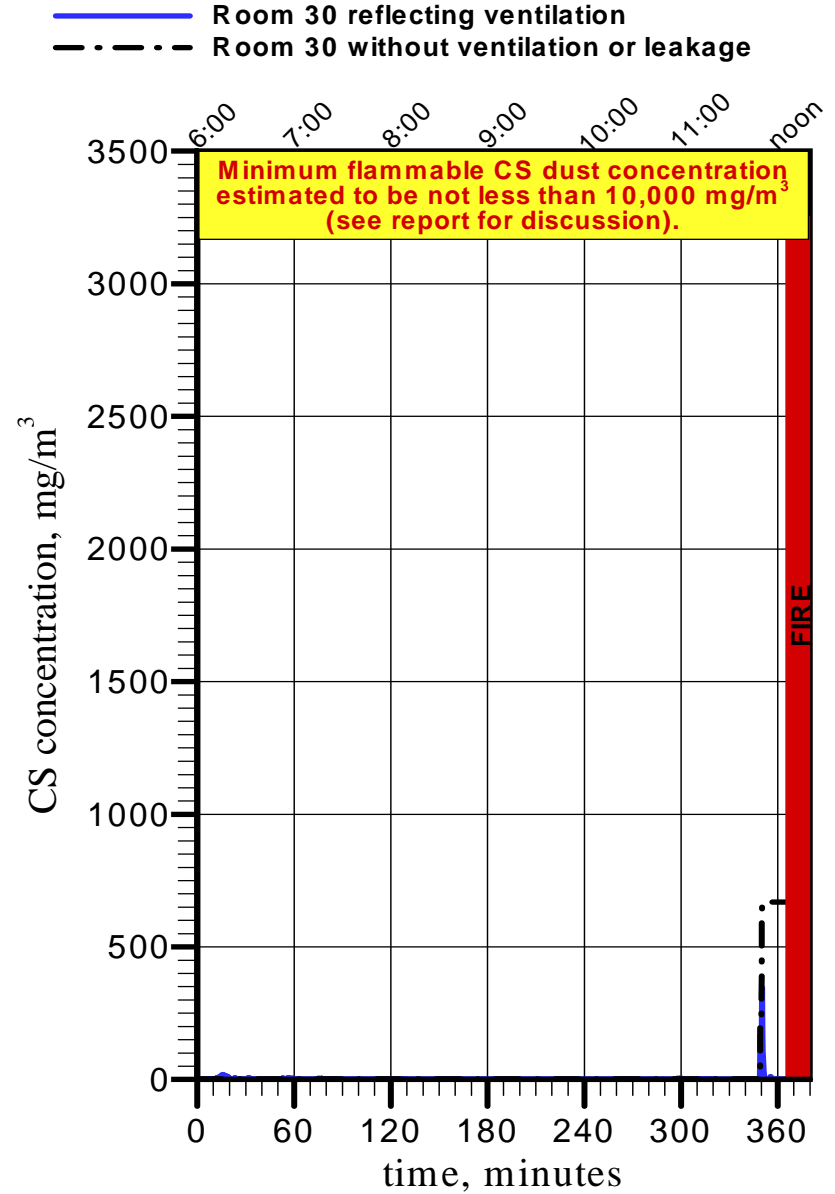
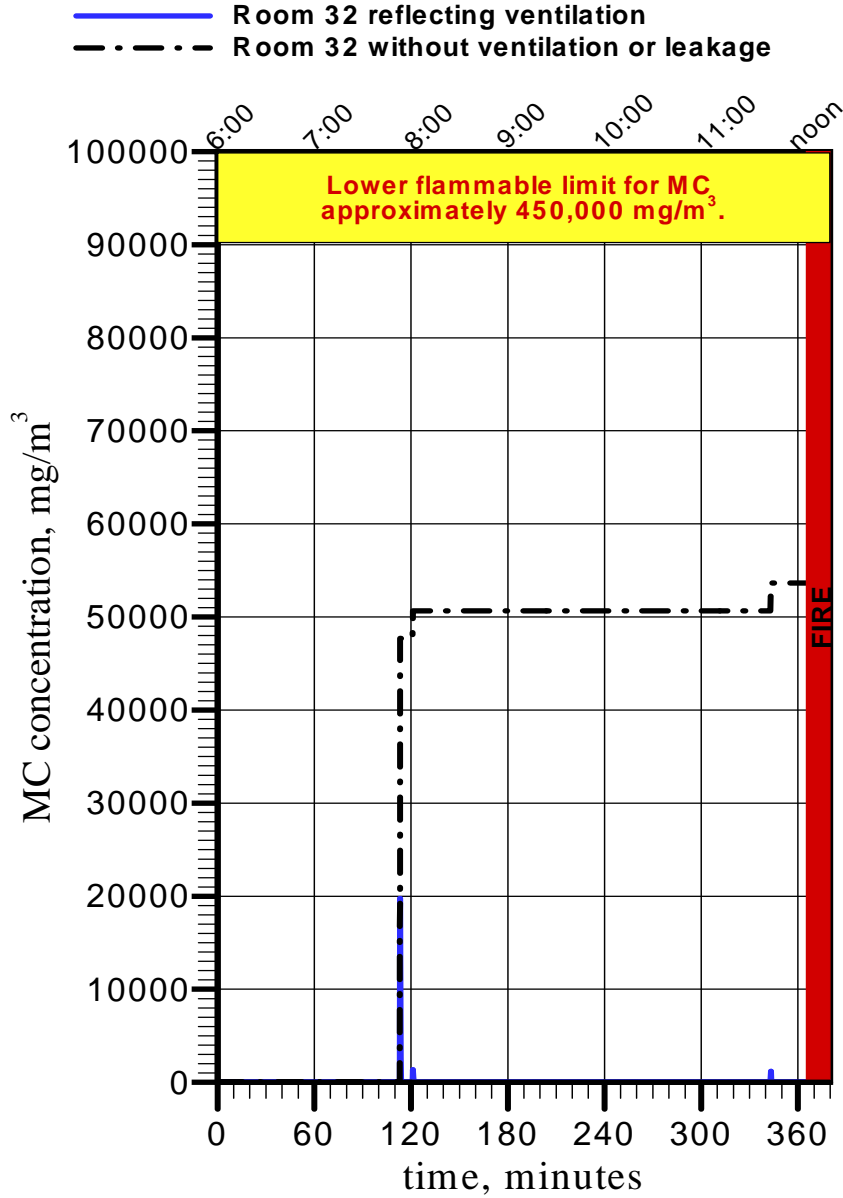


Figure 5.13. Methylene Chloride and CS Concentrations in Room 30

METHYLENE CHLORIDE (MC)



CS

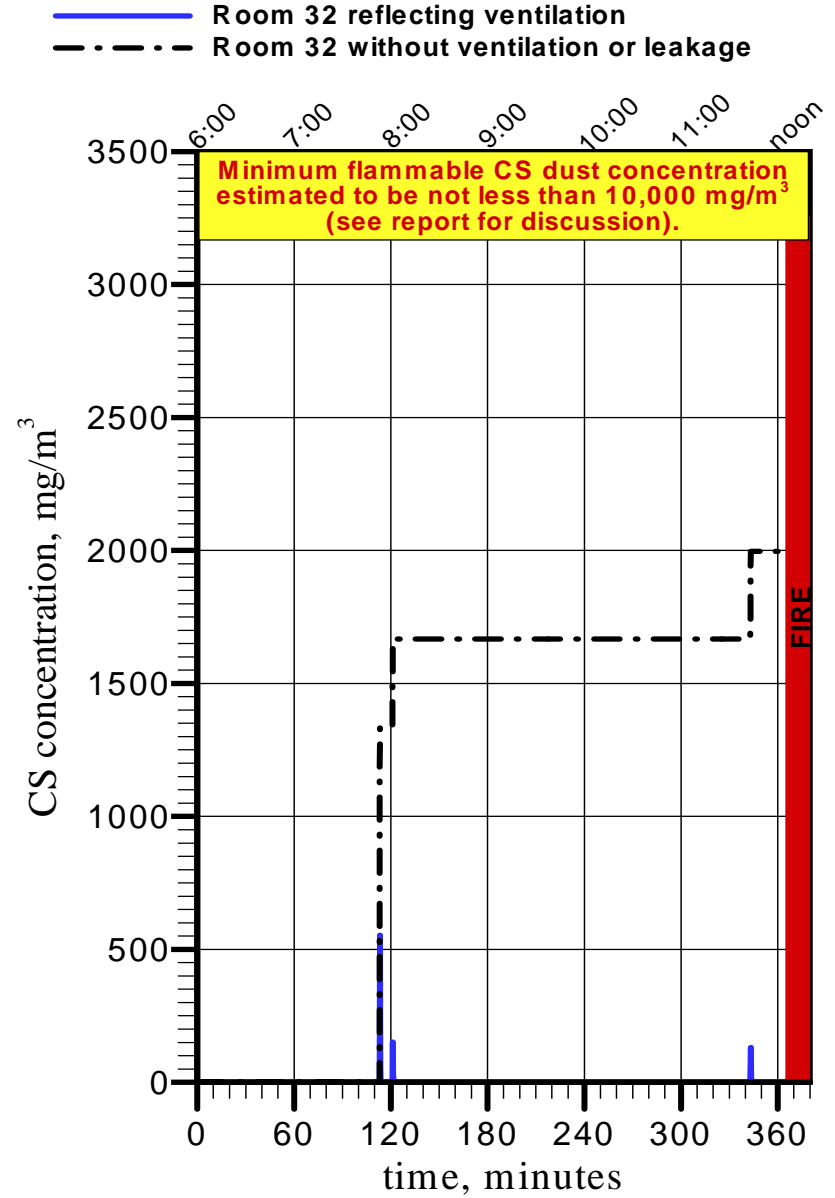
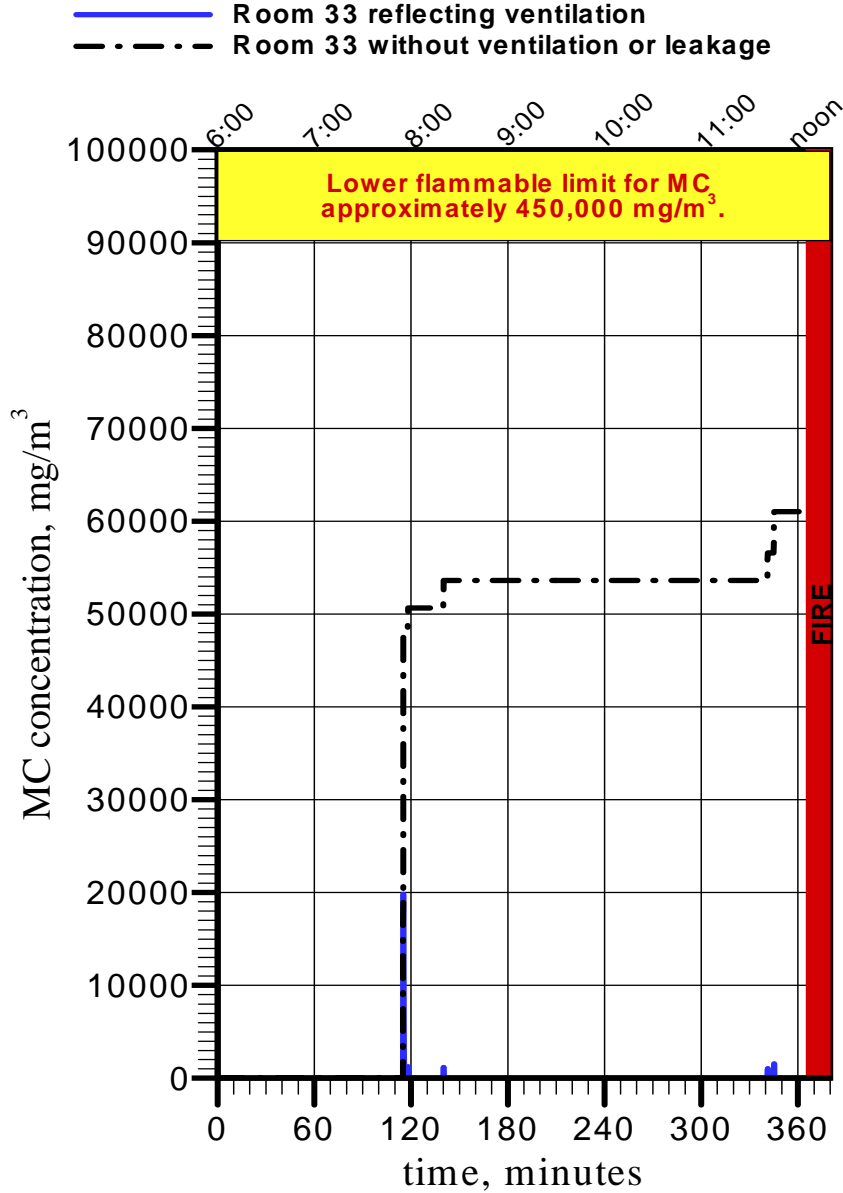


Figure 5.14. Methylene Chloride and CS Concentrations in Room 32

METHYLENE CHLORIDE (MC)



CS

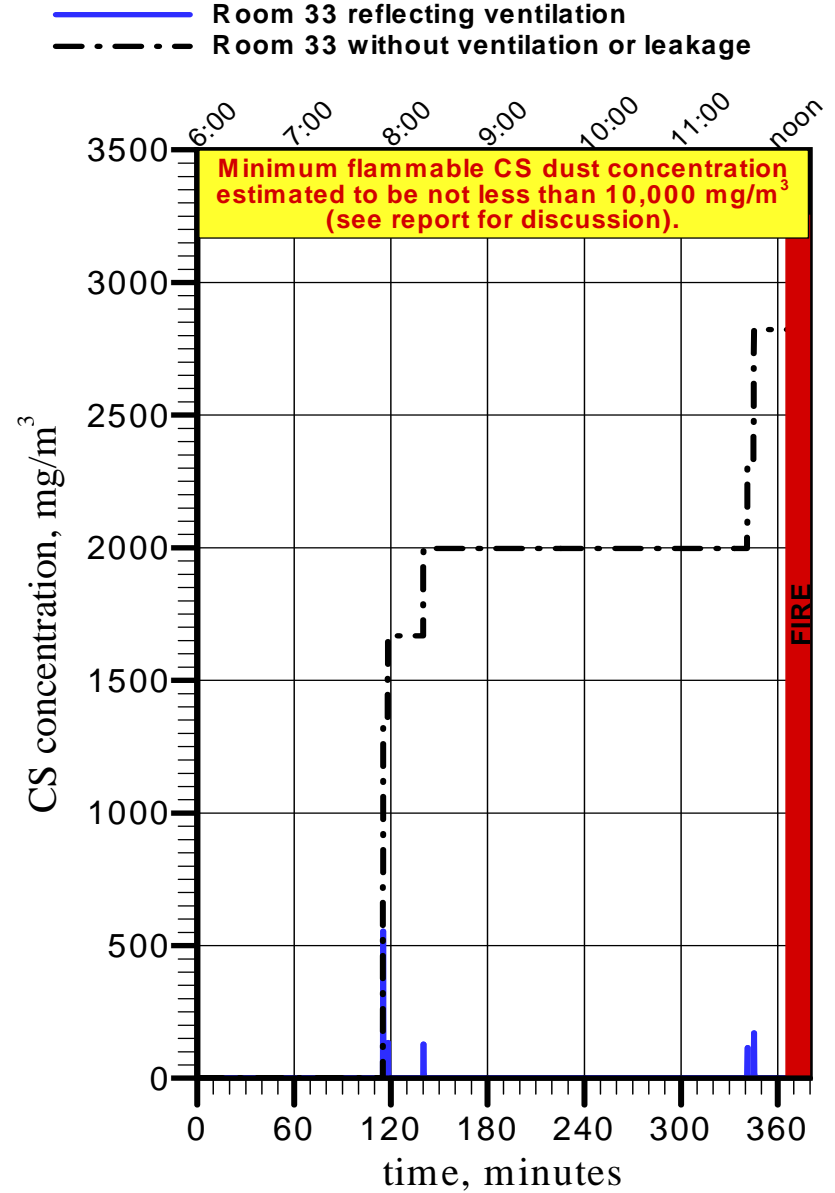
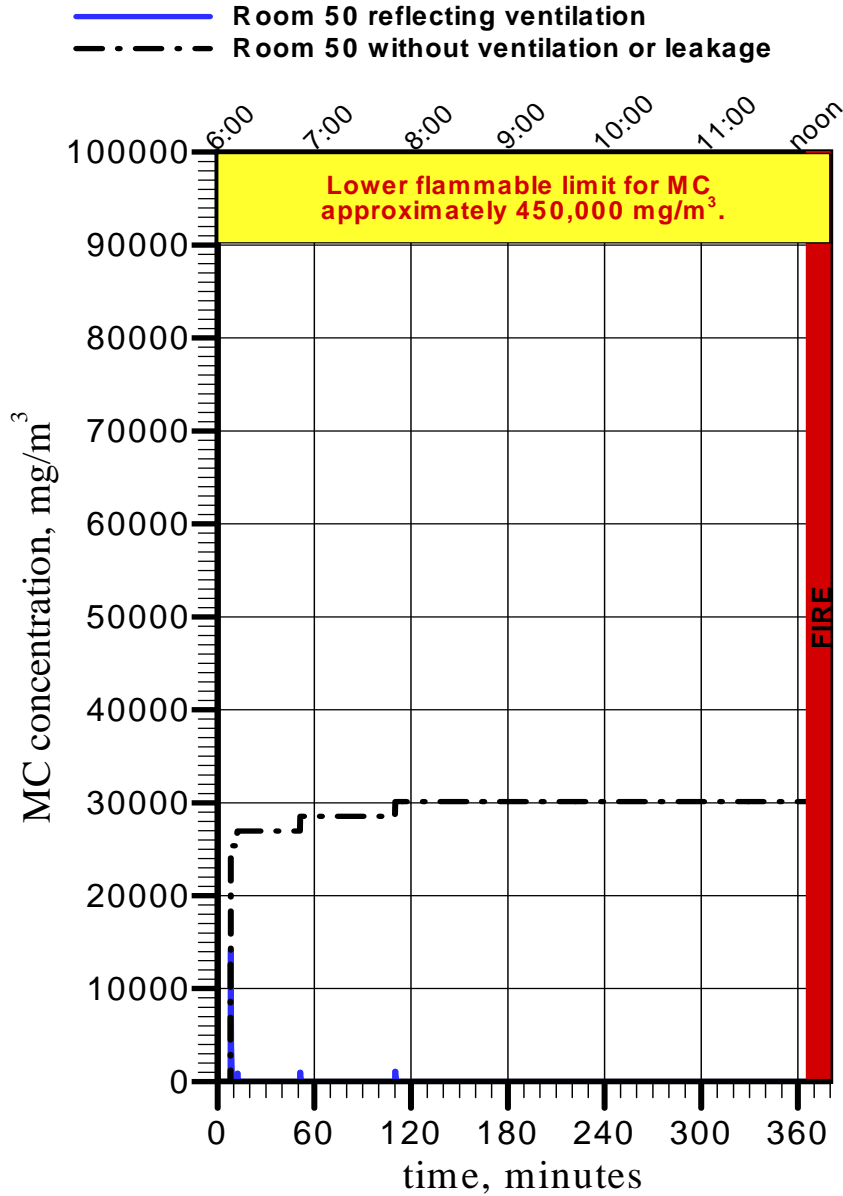


Figure 5.15. Methylene Chloride and CS Concentrations in Room 33

METHYLENE CHLORIDE (MC)



CS

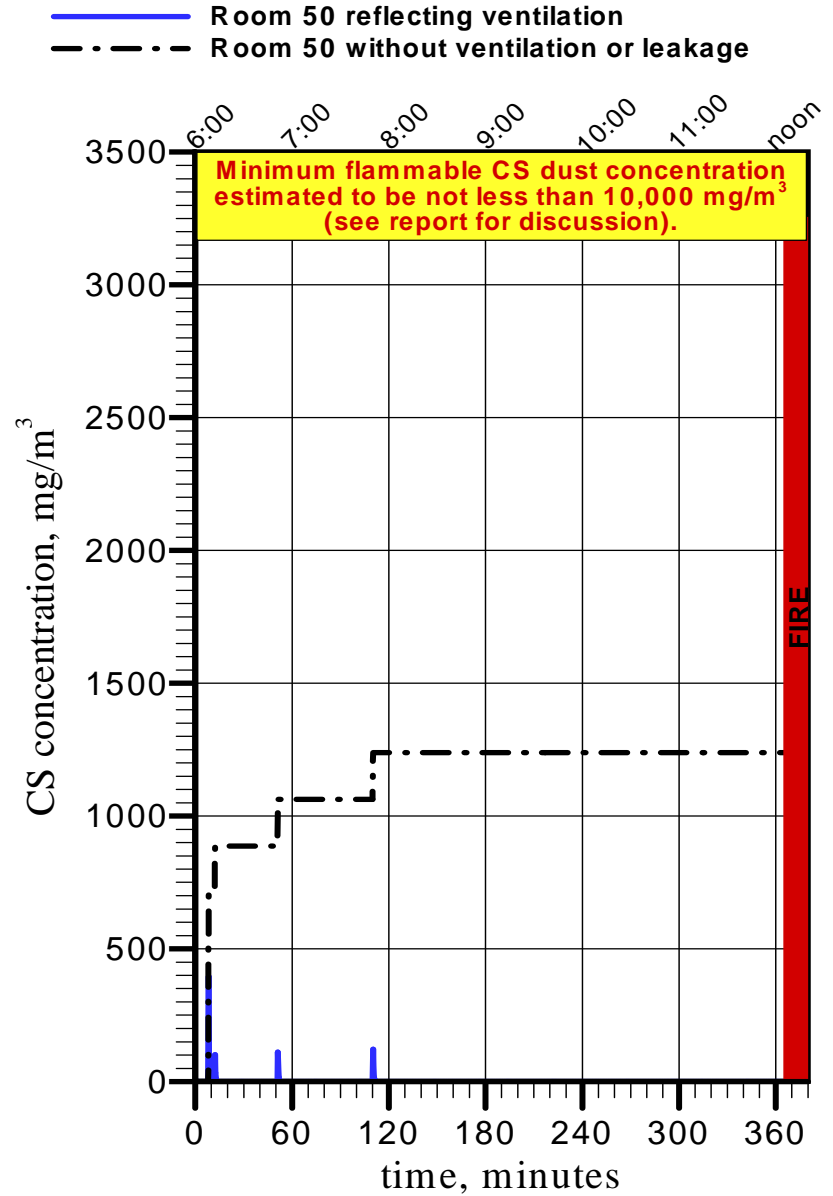


Figure 5.16. Methylene Chloride and CS Concentrations in Room 50

6 ASSESSMENT OF FLAMMABILITY HAZARDS

There have been numerous attempts to estimate the concentrations of CS and or methylene chloride inside the Branch Davidian Complex on April 19, 1993. These prior attempts uniformly assumed the insertion of a given amount of CS or methylene chloride (typically an assumed value for the contents of the tear gas device) into a space with a specified volume (typically, an assumed value, such as 10 m³, which might be characteristic of one of the smaller rooms in the Complex). Division of the amount of material by the volume of the room gives the estimated concentration (expressed here as milligrams per cubic meter (mg/m³)).

This method of concentration analysis assumes that the space into which the material is deposited is sealed and there are no means for its escape from that space. In reality, the compartments (rooms, stairways, and halls) of the Complex all had openings through which air flowed, thus diluting the tear gas. Section 5 of this report described the estimation of the ventilation, i.e. the flow of air throughout the Complex, and the resulting effect upon the concentration of the tear gas throughout the building. Direct comparison of the concentrations that actually occurred with those that reflect the assumption of no ventilation or leakage (as described above) indicated the critical importance of accounting for the ventilation of the building and the resulting airflows throughout the Complex (Figures 5.7 - 5.16).

For both methods of delivery of tear gas into the Branch Davidian Complex (Ferrets and Model 5 Protectojets) the CS was dissolved in methylene chloride in order to effect delivery of the tear gas in the form of an aerosol.

Each Ferret contained 33.25 grams of methylene chloride and 3.7 grams of CS. The Ferrets produced aerosol droplets by the high shear forces imposed on the liquid when the Ferret impacted a solid surface in the Complex. Since the characteristic of such impacts are highly variable, it is possible that in some cases the surfaces struck by the Ferret could have been wetted by the liquid, and in others that the Ferret did not break or deploy its contents. For purposes of this analysis, I assumed that every Ferret fired at the Complex hit and deployed in its intended target room.

The Model 5 Protectojet ejected a mixture of methylene chloride and (dissolved) CS using pressurized carbon dioxide as a propellant. A Model 5 Protectojet canister contained 1070 grams of methylene chloride, 30 grams of CS, and 700 grams of carbon dioxide. The Model 5 produced aerosol droplets by the high shearing forces exerted on the liquid as it was ejected under high pressure (the vapor pressure exerted by the liquid carbon dioxide) through the small orifice and outlet tube. It is also possible that if the jet (cloud) from the Model 5 directly impacted a solid surface in the Complex some of the liquid could be deposited on, and wet, the surface.

Consequently, methylene chloride could have been present at some time as liquid and/or vapor. Conversely, the CS was not present as a vapor because the temperatures achieved during placement in the Complex were not sufficiently high. For the concentrations of CS in methylene chloride in the Ferrets and the Model 5 Protectojets, it is justified to assume that the dissolved CS

did not affect the flammability properties of the methylene chloride in which it was dissolved. When the methylene chloride evaporated, the CS was suspended in the air, or deposited on surfaces in the Complex, in the form of very small solid particles (solid aerosol or dust).

It follows that assessment of the flammability hazard of the tear gas placed in the Complex requires consideration of the flammability properties of methylene chloride in the liquid and vapor forms and of the flammability properties of CS in solid (dust) form.

6.1 Methylene Chloride

Methylene chloride is a liquid at normal (ambient) temperatures. The liquid must be vaporized to form a gas, and it must be mixed with a sufficient amount of air before it can burn (react with the oxygen in the air). The lowest temperature of a liquid over which a flammable (capable of being ignited) vapor/air mixture exists is the liquid's *flashpoint*. The flashpoint is normally determined using a standard apparatus in which the liquid is heated in an enclosed container, or cup, and a small, non-luminous, pilot flame is introduced into the vapor space at frequent intervals through a port which is opened and closed automatically by a shutter. The flashpoint is taken as the lowest temperature of the liquid at which the vapor/air mixture ignites.

Classification of *flammable* liquids is usually based on the value of the liquid's flashpoint - the lower the flashpoint the greater the flammability. When methylene chloride is tested for flashpoint, with any of the several methods available, ignition of the vapor/air mixture over the "cup" does not consistently occur. Consequently, the flashpoint is reported as *None*. This does not mean that the methylene chloride will not burn. However, the negative test result does indicate that the liquid does not readily form ignitable vapor/air mixtures over its surface at moderate temperatures. That property is important to the assessment of the flammability of methylene chloride that may have existed as a liquid deposited on solid surfaces in the Complex. It can be concluded, therefore, that any methylene chloride that deposited, by "splashing" or any other method of deposition of the liquid on solid surfaces, would have to be heated in some manner well above the ambient temperatures in the Complex to be ignited.

The amount of liquid that might have been deposited on a surface by an impacting Ferret would not be expected to evaporate rapidly enough to form an ignitable vapor/air mixture over the surface. As will be shown below, the jet cloud ejected from the Model 5 Protectojet was cooled substantially (more than 40 C). Consequently, any liquid that might have been deposited on a surface by direct impact of the jet cloud from the Model 5 Protectojet would not be expected to evaporate rapidly enough to form a flammable vapor/air mixture over the surface.

For methylene chloride vapor to be flammable (capable of being ignited) it must be mixed with air in sufficient amounts to achieve the *lower flammable limit (LFL)* concentration. The LFL concentration of methylene chloride in air (at ambient temperatures) is variously reported to be between 12% and 14% (by gas volume). I have converted the lower value, 12%, to its equivalent value of approximately 450,000 mg/m³. Figures 5.7 - 5.16 clearly indicate that the room-average concentrations of methylene chloride that occurred were far below the concentration required to support combustion. In fact, the same figures show that even in the

absence of any ventilation the concentrations would never have exceeded about 20% of the lower flammable limit concentration which would support combustion.

6.1.1 Contribution of Methylene Chloride to Cause of Fire

Because the concentrations in air of methylene chloride could not have been sufficient (locally) to support combustion, and because the methylene chloride that might have deposited as a liquid on the surfaces in the Complex could not have achieved temperatures sufficient to allow its ignition, the methylene chloride could not have caused the fire.

6.1.2 Contribution of Methylene Chloride to Spread of Fire

Because the local concentrations of methylene chloride in air throughout the Complex were insufficient to support combustion, and because possible methylene chloride accumulations as liquid on surfaces in the Complex were not at sufficiently high temperature to allow ignition, the methylene chloride could not have materially contributed to the spread of the fire.

6.2 Orthochlorobenzylidenemalononitrile (CS)

With either method of tear gas introduction, after the methylene chloride evaporated, solid CS remained in the form of small particles, either suspended in the air or deposited on the surfaces in the Complex. At the (ambient) temperatures that prevailed in the Complex, there would have been no CS present in either liquid or vapor form. It follows that assessment of the fire hazard posed by the presence of CS in the Complex requires consideration of the flammability properties of the CS dust suspended in the air or deposited as layers of dust on the surfaces in the Complex.

The lower limit of flammability of CS dispersed as a solid material in air was not found in the literature. However, minimum values of flammable dust concentrations of the most flammable of dusts do not appear to be less than 10,000 - 20,000 mg/m³ (Hinds, 1999). Figures 5.7 - 5.16 clearly indicate that the room-average concentrations of CS that occurred were far below the concentration required to support combustion. In fact, the same figures show that even in the absence of any ventilation the concentrations would never have exceeded about 30% of the lower flammable limit concentration which would support combustion.

Any CS dust deposited in the Complex would have resulted in very shallow, thin layers, because of the small amounts of CS placed in the individual compartments. The largest (potential) concentration of CS placed in any one room in the Complex was in Room 5 (See Figure 4.1) where two Model 5 Canisters and 4 Ferrets were discharged, totaling approximately 75 grams CS. The floor surface area in Room 5 was approximately 10 square meters. Assuming half (which is unlikely) of the CS deposited uniformly on only one square meter of the floor (also, exceedingly unlikely), the average depth of the CS layer, assuming the bulk density of CS dust to be 0.25 g/cc, would be less than one-fifth of a millimeter (0.2 mm). At the (ambient) temperatures which prevailed in the Complex, such layers could not be ignited.

Summarizing, CS dust might have been suspended in the air in the Complex in two ways:

- ! The CS could have been entrained, due to its small particle size, in the turbulent flows of air caused by the high winds impacting (and ventilating) the building.
- ! CS which might have settled to the floor or other solid surfaces in the Complex could have been resuspended by movements of personnel, or by other mechanical actions.

It was shown in Section 5 that the room-average concentrations of suspended CS that might have possibly occurred throughout the Complex were not sufficient to support its combustion. Furthermore, the extremely small amounts of CS involved (in layers) were not sufficient (in quantity) to have been resuspended so as to cause local CS dust concentrations in the air sufficient to support its combustion.

6.2.1 Contribution of CS to Cause of Fire

Because the concentrations in air of CS solid (dust) could not have been sufficient (locally) to support combustion, the CS could not have ignited, and therefore could not have caused the fire.

6.2.2 Contribution of CS to Spread of Fire

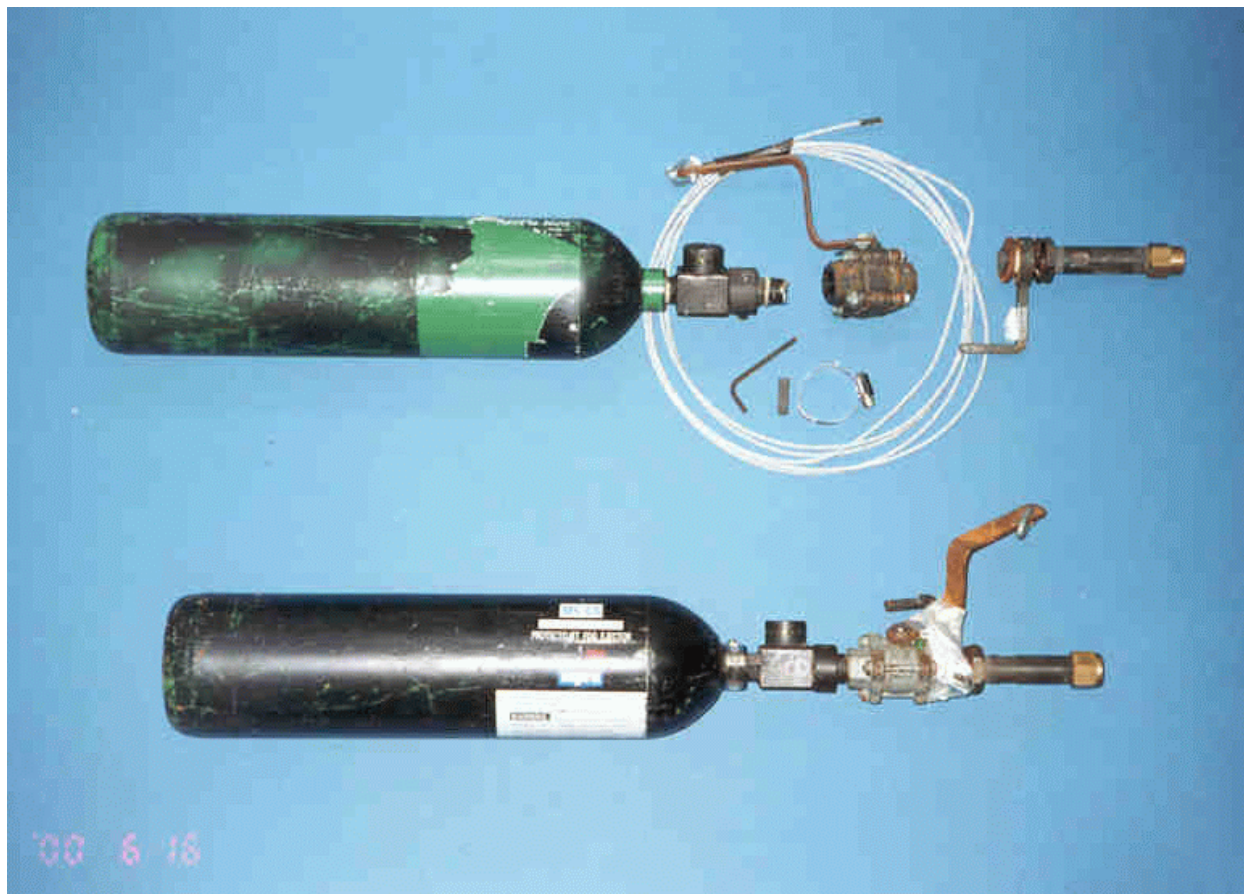
Because the local concentrations of CS in air throughout the Complex were insufficient to support combustion, and because possible CS dust accumulations on surfaces in the Complex were not sufficiently large, and were not sufficiently high temperature, to be ignited, the CS could not have materially contributed to the spread of the fire.

6.3 Analysis of Model 5 Protectojet Cloud Entering the Complex

The Model 5 Protectojet tear gas dispensers delivered (per charge) approximately 1070 grams of methylene chloride, 30 grams of CS (dissolved in the methylene chloride), and 700 grams carbon dioxide (used as the propellant) in a period of approximately 15 seconds. I had determined that the Ferret rounds ruptured upon impact with a solid surface, thereby releasing, effectively instantaneously, their contents with considerable forces which acted to throw the contents away from the device, thus ensuring effective mixing throughout the space where the Ferret ruptured. However, the tear gas was ejected from the Model 5 Protectojet through a small orifice and tube, forming a high velocity jet which produced the desired aerosol cloud, and I considered it necessary to determine whether the Model 5 Protectojets could have created a short term, local region of concentration of methylene chloride (in air) that could have been ignited had it contacted a sufficiently energetic ignition source (such as a lighted Coleman lantern). As a result, I informed the Office of Special Counsel that I wanted to explore this possibility, and they agreed. The Office of Special Counsel obtained for me, and I examined, the two Model 5 Protectojet tear gas dispensers used by the U.S. Government on April 19, 1993, at the Branch Davidian Complex. I investigated whether the methylene chloride in the jet could form

flammable mixtures (12% - 22% methylene chloride by volume) with air entrained into the jet.

The following photograph shows the two Model 5 Protectojets I examined. One of the Protectojets is shown in the condition in which I received it, and the other is shown partially disassembled. I disassembled the (second) Protectojet to determine the sizes of the orifice and discharge tube in order to develop an opinion on the (flammability) characteristics of the jet (cloud) that was ejected into the Complex.



I performed thermodynamic analyses which showed that the jet of methylene chloride, CS, and carbon dioxide exited the canister at temperatures about 40 C below the ambient temperature. At such temperatures, the methylene chloride vapor pressure is so low that maximum methylene chloride vapor concentrations would be less than one-half the lower flammable limit concentration (12%). This means that the methylene chloride (vapor) concentration in the jet could not have been flammable in the short period immediately following its exit from the Protectojet. Furthermore, thermodynamic analysis indicated that even though additional air mixed with the tear gas jet cloud, and additional methylene chloride evaporated from the (suspended) liquid droplets into the vapor phase (as the jet length increased), the maximum methylene chloride vapor concentrations would have always remained less than one-half the lower flammable limit concentration (due to the air addition). This means that the jet-

cloud which issued from the Protectojets never achieved methylene chloride vapor concentrations (in air) sufficient to be ignited. Consequently, I determined that the tear gas jet cloud that issued from the Model 5 Protectojet canisters could not have been ignited by contact with ignition sources which may have been present in the Complex.

6.4 Consideration of Other Expert Opinions

I have attempted in this investigation to explain any differences between my own findings, and those of other experts, on the questions about whether methylene chloride or CS were the cause of, or materially contributed to, the fire at the Branch Davidian Complex on April 19, 1993.

The Office of Special Counsel provided me reports, in voluminous detail, of numerous experts who have considered this matter. There appeared to me to be a consensus, among all experts whose opinions I reviewed, that answers to these questions required realistic quantification of the concentrations of the tear gas components in the Complex in order to determine whether sufficient concentrations were present that could have been ignited by sources of energy present in the Complex.

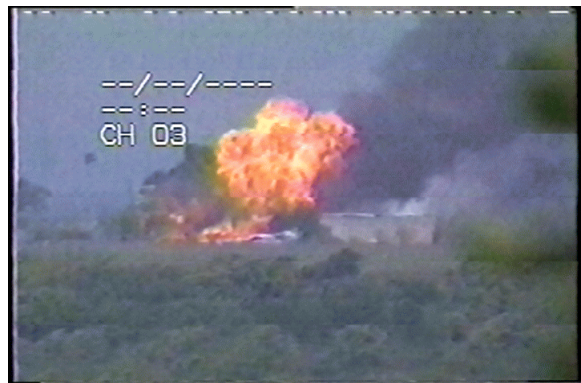
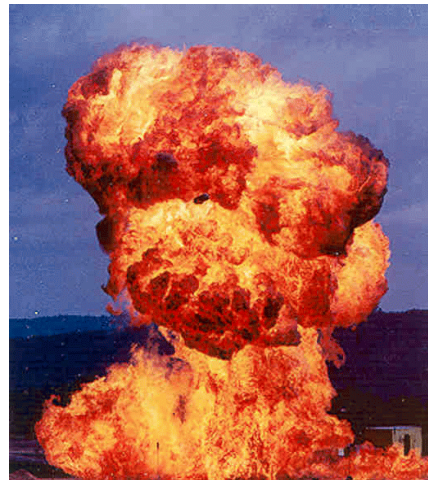
In my opinion, realistic and accurate estimation of the concentrations of CS and methylene chloride that occurred in the Complex on April 19, 1993, could not be accomplished without careful consideration of the effects of the ventilation of the Complex by the strong wind that was blowing during the entire morning. The Office of Special Counsel supported my efforts to identify, test, and implement a technique to estimate the effect of the wind-driven ventilation on the concentrations of tear gas in the Complex. In that respect, particularly, I believe I have enjoyed an advantage over those experts who have gone before me in this matter.

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7 THE BLEVE OBSERVED IN THE VICINITY OF THE BUNKER

At 12:26 p.m., a large fireball/explosion occurred during the fire which destroyed the Branch Davidian Complex. The fireball was recorded by several video cameras. The fireball occurred near the Complex's "bunker" which was situated below the central tower (See Figure 5.5). There have been suggestions that the event might have been associated with the detonation of high explosive material.

My review of several video recordings indicated immediately to me that the fireball was caused by a boiling liquid expanding vapor explosion (BLEVE). The first two pictures below (clockwise order) illustrate the characteristic features of BLEVES. The first is a picture of an (extensively studied, accidental) BLEVE of a railcar containing propane in Crescent City, Illinois, in 1970. The second is a picture of the (intentional, test) BLEVE of a small tank containing liquefied petroleum gas (LPG) taken in a research program at Queen's University in Ontario, Canada. These pictures indicate the characteristic shape and size of fireballs resulting from BLEVES of LPG containers ranging in size from a few gallons to approximately 10,000 gallons. The third and fourth pictures, respectively, are a video frame from television coverage and an aerial photograph of the Branch Davidian Complex fire on April 19, 1993.



BLEVES occur when compressed flammable gases, such as propane, are exposed to severe heating from fire which causes the tank to fail catastrophically. The tank contents are then released (essentially instantaneously) to the atmosphere. The pressurized contents partially vaporize and expand from the failed tank to form a liquid aerosol cloud which is then ignited by the fire that caused the tank failure. The characteristics of such an event are fundamentally different from the *detonation* of a high explosive material, the latter exhibiting burning (reaction) rates many times faster than the BLEVE, whose burning rates are classified as a *deflagration*.

The phenomenology of BLEVES has been studied extensively, and predictive methods have been developed and tested with which the fireball characteristics size and duration can be predicted given only the amount and identification of the pressurized gas contained in the tank.

I analyzed several video recordings of the fireball to estimate its maximum size and its duration (See Figure 7.1). The analysis indicated the maximum fireball size was approximately 20 meters and the duration was approximately 1.5 seconds. I used correlations available in the scientific literature (Center of Chemical Process Safety, 1994) to determine that the fireball size and duration were consistent with the release of approximately 35 - 40 kilograms of propane (See Figure 7.2).

Finally, the Office of Special Counsel provided photographs of, and dimensions of, a failed LPG tank (shown at right) which was found in the vicinity of the location where the fireball was observed. The failure of the tank near its top is characteristic of BLEVES of such containers because the highest temperatures of the metal are achieved in these areas (due to the absence of liquid on the inside wall surface), and because weak points in the structure typically occur at the welded seams and where penetrations (i.e. tank outlets) occur. I used the actual dimensions of the tank to calculate the volume of the tank (before rupture), and I determined that the maximum liquid contents of the tank (assumed to be propane) would have been about 62 kilograms. Consequently, the size and duration of the fireball that was observed are entirely consistent with the amounts of propane that could have been released from this tank.

Based on the foregoing analysis, I concluded that the fireball/explosion observed at 12:26 p.m. on April 19, 1993, at the Branch Davidian Complex was a BLEVE of the contents of the tank whose remains were found at the site.





Figure 7.1. Illustration of BLEVE Development from Two Camera Positions

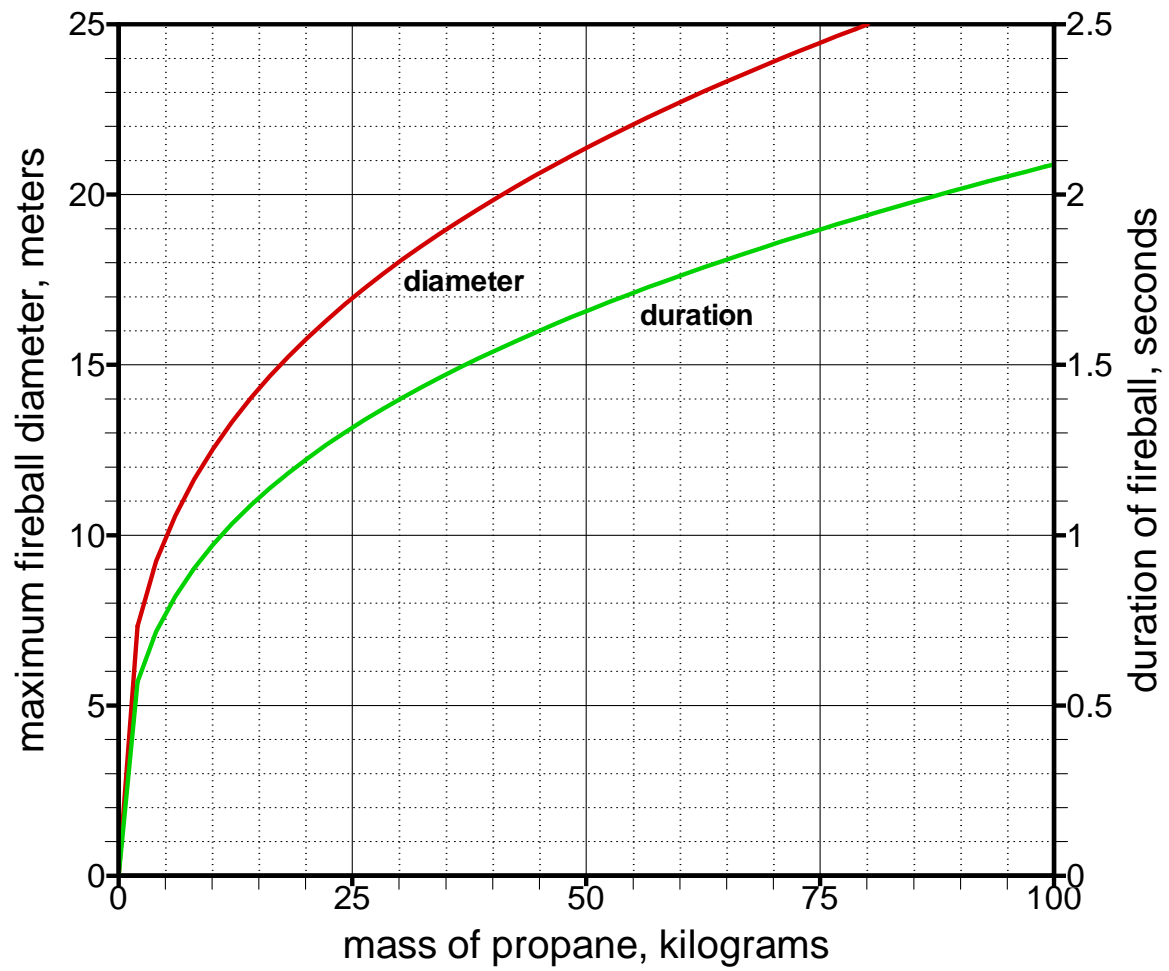


Figure 7.2. Prediction of Fireball Diameter and Duration

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8 CONCLUSIONS

8.1 Background

On September 9, 1999, the Attorney General of the United States appointed Senator John C. Danforth to investigate certain events that occurred at the Branch Davidian Complex near Waco, Texas on April 19, 1993. Senator Danforth established the Office of Special Counsel to carry out the investigation. In early December 1999, I was retained by the Office of Special Counsel to investigate the use of tear gas at the Branch Davidian Complex on April 19, 1993, and, subsequently, to investigate the explosion/fireball which was observed during the fire.

8.2 Tasks

I was tasked to determine:

- ! Whether the tear agents placed in the Complex caused the fire which destroyed the Complex,
- ! Whether the tear agents placed in the Complex importantly contributed to the fire spread, and
- ! The origin and cause of the explosion/fireball that was observed during the destruction of the Complex.

8.3 Analysis

I identified the pertinent flammability characteristics of the components of the tear gas used in the Complex, methylene chloride and CS. I analyzed the amounts, schedule, and location of placement of all of the tear gas that was placed in the Complex on April 19, 1993, and I calculated the physical states (solid, liquid, vapor) and the temperatures and concentrations of methylene chloride and CS which could have occurred throughout the Complex on that date. I analyzed video recordings of the explosion/fireball to determine its maximum size and duration in order to explain its origin and cause.

8.4 Cause of the Fire

I conclude that the tear gas, which contained methylene chloride and CS, as used in the Branch Davidian Complex, did not cause the fire.

8.5 Spread of the Fire

I conclude that the tear gas, which contained methylene chloride and CS, as used in the Branch Davidian Complex, did not materially contribute to the spread of the fire.

8.6 The Explosion/Fireball

I conclude that the explosion/fireball observed at 12:26 p.m. during the Branch Davidian Complex fire was a boiling liquid expanding vapor explosion (BLEVE) which resulted from the rupture, due to fire exposure, of a liquefied petroleum gas (LPG) tank. I also conclude that the fireball observed was consistent with that formed by the BLEVE of a quantity of propane that could have been contained in the ruptured tank found at the Complex.

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Appendix A

Brief Resume --- Dr. Jerry Havens

Dr. Havens is Distinguished Professor of Chemical Engineering at the University of Arkansas, where he teaches thermodynamics and mass, energy, and momentum transport phenomena. Dr. Havens is also Director of the University of Arkansas Chemical Hazards Research Center, which conducts major research programs to develop mathematical and wind-tunnel modeling methods for atmospheric dispersion of hazardous chemicals. He received his Bachelor of Science, Master of Science, and Doctor of Philosophy Degrees from the Universities of Arkansas (1961), Colorado (1962), and Oklahoma (1969), respectively. He has industrial experience with the Phillips Petroleum and Procter and Gamble Companies and served as an officer in the U.S. Army Chemical Corps. Dr. Havens' primary research interests are in nuclear, biological and chemical hazard assessment, with particular emphasis on atmospheric dispersion of hazardous gases and fire and explosion phenomena. He is internationally recognized as an expert in methodologies for predicting atmospheric dispersion of intentional or accidental releases of hazardous, denser-than-air gases, and the assessment of toxicity and fire hazards which result therefrom. At the University of Arkansas, Dr. Havens has conducted research to develop mathematical models for heavy gas dispersion for the U.S. Coast Guard (U.S. Department of Transportation) and the U.S. Environmental Protection Agency and is currently developing LNG vapor dispersion simulation methods for regulatory application for the Gas Research Institute. Dr. Havens has testified in government Marine Boards of Investigation into major marine shipping accidents involving hazardous materials and has published comprehensive reviews and assessments of techniques used to predict vapor dispersion from accidental spills of LNG as well as many other hazardous materials which produce flammability or toxicity hazards.

Dr. Havens joined the University of Arkansas in 1970. While on sabbatical leave in 1976-77, he served as full-time Technical Advisor to the Office of Merchant Marine Safety, U.S. Coast Guard, Washington, DC. He was technical advisor to the British Health and Safety Executive for the conduct of the Thorney Island Heavy Gas Trials in southern England in 1982. In October 1993 and again in 1994 he served on the Research Proposal Review Board of the Commission of European Communities Research and Development Directorate. In January 1994, Dr. Havens, serving as scientific advisor on gas dispersion, accompanied the International Medical Commission on Bhopal to Bhopal, India, to conduct epidemiological studies to determine health effects remaining there as a result of the catastrophic release of methyl isocyanate which occurred on December 3, 1984. He served in 1997-98 as a member of the SCOPE (Safety Controls Optimization by Performance Evaluation) panel for quantifying controls for reducing toxicity and flammable gas risks at the Hanford, Washington, radioactive waste tanks. Dr. Havens is currently a member of the Working Group on Destruction of Chemical Weapons of the Organization for the Prevention of Chemical Weapons (OPCW) Scientific Advisory Board. He also serves on the NOAA/National Ocean Service program review panel, on the International Editorial Board of the Institution of Chemical Engineering (Europe) journal, and the International Editorial Board of the Journal of Hazardous Materials. Dr. Havens is a registered professional engineer and holds memberships in the American Institute

of Chemical Engineers, Sigma Xi, and the American Chemical Society. He has served as consultant to numerous U.S. and international government agencies and industries and has published extensively in technical and scientific journals on the subjects of chemical hazards consequence and risk analysis.

Resume --- Dr. Jerry A. Havens

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AREAS OF EXPERTISE

Atmospheric dispersion of heavy gases; fire and explosion hazard assessment; nuclear, biological, chemical hazard assessment.

EDUCATION

BScE, University of Arkansas, 1961
MSChE, University of Colorado, 1962
PhDChE, University of Oklahoma, 1969

Dr. Havens is Distinguished Professor of Chemical Engineering at the University of Arkansas where he has been on the faculty since 1970; he is also Director of the U of A Chemical Hazards Research Center. He has industrial experience with the Phillips Petroleum and Procter and Gamble Companies and served as an officer in the U.S. Army Chemical Corps; he is a registered professional engineer.

Dr. Havens' primary research interests are in atmospheric dispersion of heavy gases and fire/explosion phenomena. He is internationally recognized as an expert in methodologies for predicting atmospheric dispersion of hazardous, denser-than-air gases. He served as full-time Technical Advisor to the Office of Merchant Marine Safety, U.S. Coast Guard, Washington, DC, and he was technical advisor to the (British) National Maritime Institute in the conduct of the Thorney Island Heavy Gas Trials in England in 1982. Dr. Havens has testified in Marine Boards of Investigation into major marine shipping accidents involving hazardous materials and has published comprehensive reviews and assessments of techniques used to predict vapor dispersion from accidental spills of LNG. He served in 1997-98 as a member of the SCOPE (Safety Controls Optimization by Performance Evaluation) panel for quantifying controls for reducing flammable gas risks at the Hanford, Washington, waste tanks; and he currently serves as a member of the Working Group on Destruction of Chemical Weapons of the Organization for the Prevention of Chemical Weapons Scientific Advisory Board.

He has served as consultant to numerous U.S. and international government agencies and industries, including

U.S. Army Ballistic Research Laboratory
U.S. Air Force Scientific Advisory Board
U.S. Coast Guard
U.S. Department of Energy
U.S. Environmental Protection Agency
U.S. Transportation Safety Board
National Academy of Sciences
National Manufacturers Association
Chemical Manufacturers Association
The Exxon Company
The Mobil Company

The Dow Chemical Company
The Olin Corporation
British Petroleum
British Gas
The Battelle Institute
British Health and Safety Executive
South Coast Air Quality Management District (California)

At the University of Arkansas Dr. Havens conducts a dense gas dispersion research program which has received approximately \$8 million in funding. He has conducted research to develop mathematical models for heavy gas dispersion for the U.S. Coast Guard and is currently evaluating three-dimensional hydrodynamic computer code models for LNG vapor dispersion for the Gas Research Institute (USA) and developing LNG vapor dispersion simulation methods for regulatory application for the Gas Research Institute.

The Arkansas State Board of Higher Education chose Dr. Havens to receive their first Award for Excellence in Research (1988).

In October 1993 and again in 1994 he was invited by the Commission of European Communities Research and Development Directorate to serve on their Research Proposal Review Board. The International Medical Commission on Bhopal invited Dr. Havens in January 1994 to be the only non-medical doctor on a 16-member team representing 14 countries; the Commission spent two weeks in Bhopal studying the Bhopal MIC release disaster. Dr. Havens also serves on the NOAA/National Ocean Service program review panel, on the International Editorial Board of the Institution of Chemical Engineering (Europe) journal, and the International Editorial Board of the Journal of Hazardous Materials.

Dr. Havens is a registered professional engineer and holds memberships in the American Institute of Chemical Engineers, Sigma Xi, and the American Chemical Society.

A selected list of relevant publications, presentations, and research reports pertaining to heavy gas dispersion and fire and explosion phenomena follows.

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Havens, J. A., "Improvements in Rational Dispersion Modeling for Consequence Assessment," Mary Kay O'Connor Process Safety Center Symposium, College Station, Texas, October 1999.

OTHER NATIONAL/INTERNATIONAL PRESENTATIONS AND PUBLICATIONS

Havens, J. A., "Risks in Marine Bulk Transport of Liquefied Natural Gas," National Academy of Sciences, Washington, DC, February 1978.

Havens, J. A., "Vapor Dispersion from Catastrophic LNG Spills onto Water," invited presentation, Illinois Institute of Technology, Chicago, Illinois, February 1978.

Havens, J. A., "Heavy Gas Dispersion Model Development," American Gas Association Gas Transmission Conference, Montreal, Canada, May 1978.

Havens, J. A., "Atmospheric Dispersion of Flammable Gas Following Catastrophic LNG Spills on Water," Fifth International Symposium on Transport of Dangerous Goods by Sea and Inland Waterway, Hamburg, Germany, April 1978.

Havens, J. A., "A Computational Evaluation of the SIGMET LNG Vapor Dispersion Model," Sixth International Symposium on Transport of Dangerous Goods by Sea and Inland Waterway, Tokyo, Japan, October 1980.

Havens, J. A., "Heavy Gas Dispersion Model Development," invited presentation, Kanazawa University, Kanazawa, Japan, October 1980.

Havens, J. A., "Comparison of Heavy Gas Dispersion Models," Twelfth International Technical Meeting on Air Pollution Modeling and its Applications, Menlo Park, California, August 1981.

Havens, J. A., "Heavy Gas Dispersion Model Development," invited presentation, von Karman Institute, Rhode Saint Genese, Belgium, March 1982.

Havens, J. A., "LNG Vapor Dispersion--A Review," invited presentation, Trondheim University, Trondheim, Norway, March 1982.

Havens, J. A., "Review of Predictive Models for LNG Vapor Dispersion," GRI/MIT LNG Safety Research Workshop, Massachusetts Institute of Technology, Cambridge, Massachusetts, March 1982.

Havens, J. A., "A Review of Mathematical Models for Heavy Gas Dispersion," invited presentation, Manchester University, Manchester, England, April 1982.

Havens, J. A., "Risks of Accidental Flammable Gas Releases," OYEZ International Symposium on Risk Assessment, London, England, June 1982.

Havens, J. A., "State of the Art in Heavy Gas Dispersion Modeling," invited lecture, Trans-Canada Pipeline Company, Toronto, Canada, May 1982.

Havens, J. A., "Experimental Heavy Gas Dispersion Research," invited presentation, Oklahoma State University, Stillwater, Oklahoma, March 1983.

Havens, J. A., "An Experimental Study of Gravity Spreading and Air Entrainment by Heavy Gas Instantaneously Released in a Calm Atmosphere," invited presentation, Delft University, Delft, Holland, September 1983.

Havens, J. A., "Heavy Gas Dispersion Research at the University of Arkansas," invited presentation, University of Tulsa, Tulsa, Oklahoma, March 1984.

Spicer, T. O. and J. A. Havens, "Modeling the Thorney Island Trials," Symposium on the Thorney Island Phase I Trials, Sheffield, England, April 1984.

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Havens, J. A., "Development of a Heavy Gas Dispersion Model for the U.S. Coast Guard Hazard Computer Systems," Third International Symposium on Heavy Gases and Risk Assessment, Bonn, Germany, November 1984.

Havens, J. A., "Heavy Gas Dispersion Modeling--Application to LNG/LPG Safety," sponsored by the Atmospheric

Environment Services of Canada, Toronto, Canada, January 1985.

Havens, J. A., "Atmospheric Dispersion of Heavy Gases: An Update," Third International Symposium on Risk Assessment in the Process Industries, University of Manchester, England, April 1985.

Havens, J. A., "Review of Atmospheric Dispersion Models for Hazardous Heavy Gases," Symposium on Catastrophic Gas Releases, National Manufacturers Association, Washington, DC, June 1985.

Havens, J. A., "Chemical Engineering Research in Heavy Gas Dispersion," Proceedings, 75th Anniversary Symposium of the Arkansas Chemical Industries, 1985.

Havens, J. A., "On the Rational Assessment of Chemical Hazards," Oxford Lecture Series, University of Arkansas, Fayetteville, Arkansas, February 1986.

Havens, J. A., "Heavy Gas Dispersion: An Overview," invited presentation, University of Oklahoma, Norman, Oklahoma, April 1986.

Havens, J. A., Keynote address on dense gas dispersion models, Determination of Atmospheric Dilution for Emergency Preparedness (Joint EPA-DOE Technical Workshop), Research Triangle Park, North Carolina, October 1986.

Havens, J. A., "Dense Gas Dispersion Modeling: An Overview," invited presentation, Institut fur Aerodynamik, Eidgenossische Technische Hochschule, Zurich, Switzerland, May 1988.

Havens, J. A., "Considerations for Dense Gas dispersion Modeling," lectures, American Institute of Chemical Engineers/Center for Chemical Process Safety short courses, Princeton, New Jersey, October 1988, and Houston, Texas, March 1989.

Havens, J. A., "Modeling Dense Gas Dispersion," invited presentation, Louisiana State University, Baton Rouge, Louisiana, March 1989.

Havens, J. A., "Dense Gas Dispersion Modeling," invited presentation, Indo-U.S. Workshop on Risk Assessment, New Delhi, India, December 1989.

Havens, J. A., "An Overview of Dense Gas Dispersion Modeling at the University of Arkansas," invited presentation, Rotary Club, Fayetteville, Arkansas, January 1990.

Havens, J. A., "An Overview of Dense Gas Dispersion Modeling," American Risk Management workshop, Clearwater Beach, Florida, April 1990.

Havens, J. A., AIChE/CCPS Continuing Education Short Course, "Atmospheric Dispersion Modeling," Chicago, Illinois, November 1990; Houston, Texas, April 1991; Pittsburgh, Pennsylvania, November 1991; New Orleans, Louisiana, April 1992.

Havens, J. A., "Field Experimental Research on Dense Gas Dispersion," International Workshop on Hazard Assessment on Disaster Mitigation in Petroleum and Chemical Process Industries, Madras, India, December 1990 (also in Journal of Hazardous Materials).

Havens, J. A., T. O. Spicer, S. Khajehnajafi, and T. Williams, "Developments in Liquefied Natural Gas Dispersion Modeling," International Conference and Workshop on Mitigating the Consequences of Accidental Releases of Hazardous Materials, New Orleans, Louisiana, May 1991.

Havens, J. A., "Methods for Dense Gas Dispersion Modeling," Fourth Symposium on Heavy Gases, Bonn, Germany, September 1991.

Havens, J. A. and H. L. Walker, "A New Push-Through Ultra-Low Speed Boundary Layer Wind Tunnel," 5th EURASAP International Workshop on Wind and Water Tunnel Modelling of Atmospheric Flow and Dispersion, Stevenage, England, October 1991.

Havens, J. A., "Dense Gas Dispersion Modeling and the DEGADIS Model," invited guest speaker, AIIE training seminars, Richland, Washington, January 1992 and New Orleans, Louisiana, April 1992.

Havens, J. A., "Dense Gas Dispersion Research at the University of Arkansas," invited presentation, AIChE local chapter meeting, El Dorado, Arkansas, April 1992.

Havens, J. A. and B. Bauer, "Modeling Dense Gas Releases at Gaz de France," poster session presentation at LNG-10, Kuala Lumpur, Malaysia, May 1992.

Havens, J. A., "DEGADIS and Dense Gas Dispersion Modeling: Future Emphases," invited guest speaker, US DOE/EPA Science Advisory Board Committee conference, Washington, DC, July 1992.

Havens, J. A., "Dense Gas dispersion Modeling Research at the University of Arkansas," invited guest speaker, CentraGas conference, Toronto, Ontario, Canada, October 1992.

Havens, J. A., "Dense Gas Dispersion Modeling with DEGADIS," invited guest speaker, NOAA/CAMEO meeting, Chicago, Illinois, January 1993.

Havens, J. A., "Dense Gas Dispersion Research in the U.S.," invited presentation, international conference Problem Clouds II, Amsterdam, The Netherlands, April 1993.

Havens, J. A., "The Role of Dispersion Models in Emergency Response and Community Notification," invited presentation, American Industrial Hygiene Conference and Exposition, New Orleans, Louisiana, May 1993.

Havens, J. A., "The Use of the DEGADIS Model for Use in Canadian Gas Industries," invited presentation, meeting of Canadian Gas Users' Group, Vancouver, British Columbia, Canada, May 1993.

Havens, J. A. and H. L. Walker, "A Research Program to Provide Wind-Tunnel Data Sets for the Validation of Mathematical Models for Dense Gas Dispersion in the Presence of Obstacles," 6th EURASAP International Workshop on Wind and Water Tunnel Modelling of Atmospheric Flow and Dispersion, Aso, Kumamoto, Japan, August 1993.

Havens, J. A., "Dense Gas Dispersion Research in the U.S.," 2nd Conference for European Research in Industrial Fires, Cadarache, France, May 1994.

Spicer, T. O. and J. A. Havens, "Application of Dispersion Models to Flammable Cloud Analyses," 6th Annual PetroSafe, Houston, Texas, February 1995.

Walker, H. L., T. Spicer, and J. Havens, live, on-site presentation of wind tunnel research facility, fX network "Breakfast Time," (nationally televised feature program), March 1995.

Havens, Jerry, Tom Spicer, Heather Walker, and Ted Williams, "Validation of Mathematical Models using Wind-Tunnel Data Sets for Dense Gas Dispersion in the Presence of Obstacles," 8th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Antwerp, Belgium, June 1995.

Havens, Jerry, Tom Spicer, Heather Walker, and Ted Williams, "LNG Vapor Dispersion Experiments for Complex Mathematical Model Evaluation," poster session presentation, LNG-11, Birmingham, England, July 1995.

Havens, Jerry, Tom Spicer, Heather Walker, and Ted Williams, "Regulatory Application of Wind Tunnel Models and Complex Mathematical Models for Simulating Atmospheric Dispersion of LNG Vapor," International Conference and Workshop on Modeling and Mitigating the Consequences of Accidental Releases of Hazardous Materials, New Orleans, Louisiana, September 1995.

Havens, J. A., "Atmospheric Dispersion of Ammonia Clouds," invited presentation, Ammonia Safety Summit, Ammonia Safety and Training Institute, Watsonville, California, October 8, 1998.

Havens, J. A., "Improvements in Rational Dispersion Modeling for Consequence Assessment," EUROMECH Colloquium 391, Prague, The Czech Republic, September 1999

MAJOR RESEARCH REPORTS

Havens, J. A., "U.S. Coast Guard Marine Board Investigation of Fire and Explosion on the Steamship SANSINENA in Los Angeles Harbor, testimony, U.S. Coast Guard Report 16732/71895, 1977.

Havens, J. A., "Predictability of LNG Vapor Dispersion from Catastrophic Spills onto Water," Report CG-M-09-77, Office of Merchant Marine Safety, U.S. Coast Guard Headquarters, Washington, DC, 1978.

Havens, J. A., "Report of Accidental LNG Spill at CAMEL LNG Facility, Arzew, Algeria," Cargo and Hazardous Materials Division, U.S. Coast Guard Headquarters, Washington, DC, 1978.

Havens, J. A., "Description and Assessment of the SIGMET LNG Vapor Dispersion Model," Report CG-M-79, Office of Merchant Marine Safety, U.S. Coast Guard Headquarters, Washington, DC, 1979.

Havens, J. A., "An Analysis of the Nonequilibrium Thermodynamics Model for Coupled Heat and Mass Transfer in Unsaturated Porous Media, University of Arkansas Experiment Station Report No. 67, 1980.

Havens, J. A., "Dispersion of Denser-than-Air Gases," Committee Report to the U.S. Air Force Scientific Advisory Board, November 1983.

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Spicer, T. O. and J. A. Havens, "Development of Vapor Dispersion Models for Nonneutrally Buoyant Gas Mixtures--Analysis of USAF/N₂O₄ Test Data," Final Report to U.S. Coast Guard, May 1986.

Havens, J. A., "Review of Hazard Assessment Procedures for Liquid Gun Propellants," Report to U.S. Army Ballistics Research Laboratory, Aberdeen Proving Ground, Maryland.

Havens, J. A. and T. O. Spicer, "Evaluation of 3-D Hydrodynamic Computer Models for Prediction of LNG Vapor Dispersion in the Atmosphere," Series of reports (including final report) to the Gas Research Institute, GRI Contract No. 5083-252-0788, 1983-88.

Spicer, T. O. and J. A. Havens, "Development of Vapor Dispersion Models for Nonneutrally Buoyant Gas Mixtures--Analysis of USAF/NH₃ Test Data," Final Report to U.S. Coast Guard, March 1988.

Havens, J. A. and T. O. Spicer, "Modification and Extension of LNG Vapor Dispersion Simulation Methods for Regulatory Application," series of reports to Gas Research Institute, GRI Contract No. 5086-252-1287, 1988-present.

Havens, J. A. and T. O. Spicer, "LNG Vapor Dispersion Prediction with the DEGADIS Dense Gas Dispersion Model," Gas Research Institute Report No. 89-0242, 1990.

Havens, J. A. and T. O. Spicer, "Feasibility Assessment of a Conjunctive Modeling Approach for LNG Vapor Dispersion Prediction," Gas Research Institute Report, 1991.

Havens, Jerry, Tom Spicer, and Heather Walker, "Regulatory Application of Wind Tunnel Models and Complex Mathematical Models for Simulating Atmospheric Dispersion of LNG Vapor," Gas Research Institute Report No. 92-0257, August 1994.

Havens, Jerry and Tom Spicer, "LNG Vapor Dispersion Case Analyses for the ENAGAS Company," Topical Report for Gas Research Institute, November 1994.

Havens, Jerry, Heather Walker, and Tom Spicer, "Characterization of the LGFSTF Wind Tunnel in Preparation for

the DOE/EPA Hazardous Chemical Evaporation Rate Experiments," U.S. DPE/EPA Chemical Hazards of Atmospheric Releases Research (CHARR) Program Report, March 1995.

Havens, Jerry, Tom Spicer, and Heather Walker, "Evaluation of Mitigation Methods for Accidental LNG Releases: Volume 1/5--Wind Tunnel Experiments and Mathematical Model Simulations to Study Dispersion of a Vapor Cloud Formed following LNG Spillage into a Diked Area Surrounding a Storage Tank," Topical Report for Gas Research Institute, November 1996.

Havens, Jerry, Tom Spicer, and Heather Walker, "Evaluation of Mitigation Methods for Accidental LNG Releases: Volume 2/5--Wind Tunnel Experiments and Mathematical Model Simulations to Study Heat Transfer from a Flat Surface to a Cold Nitrogen Cloud in a Simulated Atmospheric Boundary Layer," Topical Report for Gas Research Institute, November 1996.

Havens, Jerry, Tom Spicer, and Heather Walker, "Evaluation of Mitigation Methods for Accidental LNG Releases: Volume 3/5--Wind Tunnel Experiments for Mitsubishi Heavy Industries, Ltd.," Topical Report for Gas Research Institute, November 1996.

Havens, Jerry, Tom Spicer, and Heather Walker, "Evaluation of Mitigation Methods for Accidental LNG Releases: Volume 4/5--Wind Tunnel Experiments for Osaka Gas Company," Topical Report for Gas Research Institute, November 1996.

Spicer, Tom, Jerry Havens, and Heather Walker, "Evaluation of Mitigation Methods for Accidental LNG Releases: Volume 5/5--Using FEM3A for LNG Accident Consequence Analysis," Topical Report for Gas Research Institute, April 1997.

Brief Resume --- Dr. Tom Spicer

Dr. Spicer is Professor of Chemical Engineering at the University of Arkansas where he teaches courses on chemical process safety, heat transport, and modeling and computational methods. Dr. Spicer also collaborates in the Chemical Hazards Research Center (CHRC) at the University of Arkansas; the CHRC conducts major research programs to develop and verify mathematical and wind tunnel models of the atmospheric dispersion of hazardous chemicals. He received his Bachelor of Science in Chemical Engineering, Master of Science in Chemical Engineering, and Doctor of Philosophy in Engineering from the University of Arkansas in 1981, 1983, and 1985, respectively. He has industrial experience with Arkansas Eastman Company. Dr. Spicer's primary research interests are in the assessment of hazards from airborne contaminants and from fire and explosion phenomena. He is internationally recognized as an expert in modeling atmospheric releases of airborne contaminants, particularly those which are denser than air. Since joining the faculty of the University of Arkansas in 1985, Dr. Spicer has conducted research and developed mathematical models of denser-than-air contaminant dispersion for the U.S. Coast Guard, U.S. Air Force, U.S. Department of Transportation, and the U.S. Environmental Protection Agency. Present research is directed to developing atmospheric dispersion models for regulatory application to the liquefied natural gas (LNG) industry for the Gas Research Institute. Dr. Spicer is a registered professional engineer and holds memberships in the American Institute of Chemical Engineers and Sigma Xi. He has served as a consultant to numerous governmental agencies and industries, and his work has been published in technical and scientific journals on the subjects of chemical hazard consequences and risk analysis.

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EDUCATION

PhD, Engineering, University of Arkansas, 1985
MS, Chemical Engineering, University of Arkansas, 1983
BS, Chemical Engineering, University of Arkansas, 1981

PROFESSIONAL EXPERIENCE

Professor, Department of Chemical Engineering, University of Arkansas,
1996 - present
Associate Professor, Department of Chemical Engineering, University of Arkansas,
1988 to 1996
Assistant Professor, Department of Chemical Engineering, University of Arkansas,
1984 to 1988
Graduate Teaching Assistant, Department of Chemical Engineering, University of
Arkansas, 1981
Cooperative Education Student, Arkansas Eastman, Batesville, Arkansas, 1978-79

PROFESSIONAL AFFILIATIONS

Air and Waste Management Association
American Institute of Chemical Engineers
American Society of Engineering Education
Omega Chi Epsilon
Registered Professional Engineer - Arkansas
Sigma Xi
Tau Beta Pi

HONORS

Outstanding Co-op Student, University of Arkansas, 1980
Outstanding Senior Undergraduate in Chemical Engineering, American Institute of
Chemists Award, University of Arkansas, 1981
Beeler Fellowship, University of Arkansas, 1982-84

SERVICE

Fayetteville Habitat for Humanity, Site Selection and Building Committees; Board of Directors
Cooperative Emergency Outreach, Board of Directors
Chemical Engineering Computing Facility and Use Committee (Chairman)
Chemical Engineering Graduate Studies Committee
College of Engineering Computer Advisory Committee
College of Engineering Academic Ethics Board
ASEE Midwest Section Bylaws Committee
ASEE Midwest Section Meeting Paper Committee

PROFESSIONAL ACTIVITIES

Refereed Journal Articles

1. Spicer, T.O., and J.A. Havens, "Modeling the Phase I Thorney Island Experiments," *Journal of Hazardous Materials*, June 1985.
2. Havens, J.A., P.J. Schreurs, and T.O. Spicer, "Analysis and Simulation of Thorney Island Trial 34," *Journal of Hazardous Materials*, November 1987.
3. Spicer, T.O., and J.A. Havens, "Field Test Validation of the DEGADIS Model," *Journal of Hazardous Materials*, November 1987.
4. Havens, J., and T.O. Spicer, "Software Review - TECJET: An Atmospheric Dispersion Model," *Risk Analysis*, Vol. 10, No. 3, 1990.
5. Hanna, S., P. Chatwin, E. Chikhliwala, R. Londergan, T. Spicer, and J. Weil, "Results from the Model Evaluation Panel," *Plant/Operations Progress*, Vol. 11, No.1, January 1992.
6. Havens, J., H. Walker, and T.O. Spicer, "Wind-Tunnel Data Sets for Complex Dispersion Model Evaluation," *Journal of Loss Prevention in the Process Industries*, Vol.7, No.2, 1994.
7. Baik, J.H., H. Walker, T.O. Spicer, and J. Havens, "Measurement of Low Velocities in CO₂/Air Mixtures Using Hot-Wire/Film Anemometry," *Process Safety and Environmental Protection: Transactions of the Institution of Chemical Engineers Part B*, Vol. 74, May 1996.
8. Spicer, T.O., J.H. Baik, and J. Havens, "Molecular Diffusion Effects on Entrainment in Wind Tunnel Studies of Dense Gas Dispersion," *Process Safety and Environmental Protection: Transactions of the Institution of Chemical Engineers Part B*, Vol. 74, August 1996.
9. Spicer, T.O., and J. Havens, "Application of Dispersion Models to Flammable Cloud Analyses," *Journal of Hazardous Materials*, Vol. 49, 1996.

Symposium Proceedings

1. Havens, J.A., and T.O. Spicer, "Further Analysis of Catastrophic LNG Spill Vapor Dispersion," *Heavy Gas and Risk Assessment--II*, S. Hartwig (ed.), 1983.
2. Havens, J.A., and T.O. Spicer, "Gravity Spreading and Air Entrainment by Heavy Gases Instantaneously Released in a Calm Atmosphere," I.U.T.A.M. Symposium on Atmospheric Dispersion of Heavy Gases and Small Particles, Den Haag, The Netherlands, 1983.
3. Spicer, T.O., and J.A. Havens, "Development of a Heavier-than-Air Gas Dispersion Model for the U.S. Coast Guard Hazard Assessment Computer System," *Heavy Gas and Risk Assessment--III*, S. Hartwig (ed.), 1985.
4. Spicer, T.O., and J.A. Havens, "Application of a Heavy Gas Dispersion Model to the Prediction of Dispersion of Nitrogen Tetroxide," JANNAF Safety and Environmental Protection Subcommittee Meeting, Monterey, CA, 1985.
5. Spicer, T.O., J.A. Havens, P.A. Tebeau, and L.E. Key, "DEGADIS--A Heavier-than-Air Gas Atmospheric Dispersion Model Developed for the U.S. Coast Guard," Air Pollution Control Association Annual Meeting, Minneapolis, MN, 1986.
6. Spicer, T.O., and J.A. Havens, "Gravity Flow and Entrainment by Dense Gases Released Instantaneously into Calm Air," Third International Symposium on Stratified Flows, Pasadena, CA, 1987.
7. Spicer, T.O., J.A. Havens, and L.E. Key, "Evaluation of the DEGADIS Dispersion Model Using Data from Field Releases of Pressurized Ammonia," Air Pollution Control Association Annual Meeting, New York, NY, 1987.
8. Havens, J.A., T.O. Spicer, and P.J. Schreurs, "Evaluation of 3- Dimensional Numerical Atmospheric Dispersion Models," International Conference on Vapor Cloud Modeling, Boston, MA, 1987.
9. Havens, J.A., T.O. Spicer, and D.E. Layland, "A Dispersion Model for Elevated Heavy Gas Jet Releases," International Conference on Vapor Cloud Modeling, Boston, MA, 1987.
10. Spicer, T.O., J.A. Havens, and L.E. Key, "Extension of DEGADIS for Modeling Aerosol Releases," International Conference on Vapor Cloud Modeling, Boston, MA, 1987.
11. Spicer, T.O., J.A. Havens, and L.E. Key, "Uncertainties in the Application of Atmospheric Dispersion Models in the Presence of Jet Releases, Aerosol Releases, or Heterogeneous Surface Roughness," JANNAF Safety and Environmental Protection Subcommittee Meeting, Monterey, CA, 1988.
12. Spicer, T.O., and J. Havens, "Modeling HF and NH₃ Spill Test Data Using DEGADIS," 1988 Summer National Meeting of the American Institute of Chemical Engineers, Denver, CO, 1988.
13. Spicer, T.O., J. Havens, and D. Guinnup, "A Dispersion Model for Gas Pipeline Accidental Releases," 1989 Spring National Meeting, American Institute of Chemical Engineers, April 1989.
14. Havens, J.A., T.O. Spicer, and D. Guinnup, "Extension of the DEGADIS Atmospheric Dispersion Model for Elevated Jet Releases," 6th International Symposium - Loss Prevention and Safety Promotion in the Process Industries, Oslo, Norway, June 1989.

15. Spicer, T.O., and J. Havens, "Modeling Aerosol Dispersion for Accident Consequence Analyses," 1990 American Institute of Chemical Engineers Spring National Meeting, Orlando, FL, 1990.
16. Havens, J., T.O. Spicer, S. Khajehnajafi, and T. Williams, "Developments in Liquefied Natural Gas Dispersion Modeling," International Conference and Workshop on Modeling and Mitigating the Consequences of Accidental Releases of Hazardous Materials, AIChE, New Orleans, LA, May 1991.
17. Touma, J.S., D. Guinnup, and T.O. Spicer, "Development of a Guidance Document for the Application of Refined Dispersion Models for Air Toxics Releases," 85th Annual Meeting of the Air and Waste Management Association, Kansas City, MO, June 1992.
18. Miller, Billy D., and T.O. Spicer, "Spreading And Vaporization of LNG Spills on Land," American Gas Association Distribution Transmission Conference and Exhibit, Orlando, FL, May 1993.
19. Ohba, R., H. Mishima, and T.O. Spicer, "The Calculation of LNG Vapor Dispersion," Japan Society for Aeronautical and Space Sciences (West Branch), Nagasaki, Japan, November 1993.
20. Spicer, T.O., and J. Havens, "Application of Dispersion Models to Flammable Cloud Analyses," 6th Annual Petro-Safe, Houston, February 1995.
21. Havens, J., T.O. Spicer, H. Walker, and T. Williams, "Validation of Mathematical Models for Dense Gas Dispersion in the Presence of Obstacles using Wind-Tunnel Data Sets," 8th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Antwerp, Belgium, June 1995.
22. Havens, J., T.O. Spicer, H. Walker, and T. Williams, "Regulatory Application of Wind Tunnel Models and Complex Mathematical Models for Simulating Atmospheric Dispersion of LNG Vapor," International Conference and Workshop on Modeling and Mitigating the Consequences of Accidental Releases of Hazardous Materials, New Orleans, September 1995.
23. Havens, J., T.O. Spicer, H. Walker, and S. Wiersma, "The Effects of Structures on Large LNG Spills," 1998 Process Plant Safety Symposium, October, 1998.
24. Havens, J.A., and T.O. Spicer, "Improvements in Rational Dispersion Modeling for Consequence Assessment," EUROMECH Colloquium 391, Prague, The Czech Republic, September 1999.
25. Spicer, T.O., and J.A. Havens, "Description and Analysis of Atmospheric Dispersion Tests Conducted by EPA at the DOE Hazmat Spills Center," International Conference and Workshop on Modeling and Mitigating the Consequences of Accidental Releases of Hazardous Materials, San Francisco, September 1999.
26. Havens, J.A., and T.O. Spicer, "Improvements in Rational Dispersion Modeling for Consequence Assessment," Mary Kay O'Connor Process Safety Center Symposium, College Station, Texas, October 1999.

Research Reports

1. Havens, J.A., and T.O. Spicer, "Analysis of Nitrogen Tetroxide Releases into the Atmosphere--Consideration of Dense Gas Effects," U.S. Coast Guard, Washington, DC, 1983.

2. Havens, J.A., and T.O. Spicer, "Development of an Atmospheric Dispersion Model for Heavier-than-Air Gas Mixtures," U.S. Coast Guard Report No. CG-D-23-85, Washington, DC, 1985.
3. Spicer, T.O., "Mathematical Modeling and Experimental Investigation of Heavier-than-Air Gas Dispersion in the Atmosphere," Doctoral Dissertation, University of Arkansas, Fayetteville, AR, 1985.
4. Spicer, T.O., and J.A. Havens, "Development of Vapor Dispersion Models for Nonneutrally Buoyant Gas Mixtures--Analysis of USAF/N₂O₄ Test Data," USAF Engineering and Services Laboratory, May 1986.
5. Spicer, T.O., "Using Different Time Averaging Periods in DEGADIS," Exxon Education Foundation, July 1987.
6. Havens, J.A., T.O. Spicer, and P.J. Schreurs, "Evaluation of 3-D Hydrodynamic Computer Models for Prediction of LNG Vapor Dispersion in the Atmosphere," Gas Research Institute Report 5083-252-0788, August 1987.
7. Spicer, T.O., and J.A. Havens, "Development of Vapor Dispersion Models for Nonneutrally Buoyant Gas Mixtures--Analysis of USCG/NH₃ Test Data," USAF Engineering and Services Laboratory, October 1988.
8. Havens, J.A., and T.O. Spicer, "A Dispersion Model for Elevated Dense Gas Jet Chemical Releases," Environmental Protection Agency, 1988.
9. Havens, J.A., and T.O. Spicer, "Review of Phosgene Release Mitigation Methodology and Development of a Mathematical Model for Reactive Spray - Curtain Design," Chemical Manufacturer's Assoc., 1988.
10. Spicer, T.O., and J.A. Havens, "Users Guide for the DEGADIS 2.1 Dense Gas Dispersion Model," Environmental Protection Agency, Report EPA-450/4-89-019, 1989.
11. Spicer, T.O., "Implementation of DEGADIS V2.1 on a Personal Computer," American Petroleum Institute, 1990.
12. Havens, J., and T.O. Spicer, "LNG Vapor Dispersion Prediction with the DEGADIS Dense Gas Dispersion Model," Gas Research Institute Report 89/0242, 1990.
13. Havens, J.A., and T. Spicer, "Feasibility Assessment of a Conjunctive Modeling Approach for LNG Vapor Dispersion Prediction," Gas Research Institute Report, 1991.
14. Havens, J.A., and T.O. Spicer, "Evaluation of Wind Tunnel Simulation and Complex Mathematical Simulation of LNG Vapor Dispersion," Gas Research Institute Topical Report, 1992.
15. Havens, J.A., and T.O. Spicer, "Prediction of LNG Vapor Dispersion with the FEM3A Model for Comparison with Mercure Model Predictions," Gas Research Institute Topical Report, 1992.
16. Havens, J., and T.O. Spicer, "A Comparison/Evaluation of DEGADIS and NOAA-DEGADIS," Report to Environmental Protection Agency, 1992.
17. Spicer, T.O., "Application of DEGADIS to Example Chemical Release Scenarios," Report to Environmental Protection Agency, 1992.
18. Spicer, T.O., "Screening Methods for Consequence Analyses: Release Rate and Dispersion Estimates for Denser-than-Air Gases and Aerosols," Report to Environmental Protection Agency, 1993.
19. Havens, J., T.O. Spicer, and H. Walker, "Regulatory Application of Wind Tunnel

- Models and Complex Mathematical Models for Simulating Atmospheric Dispersion of LNG Vapor,” Gas Research Institute Topical Report, 1994.
20. Havens, J., and T.O. Spicer, “LNG Vapor Dispersion Case Analyses for the ENAGAS Company,” Gas Research Institute Topical Report, 1994.
 21. Havens, J.A., and T.O. Spicer, “Mathematical Modeling of Water Spray Curtain Mitigation of Accidental Hydrogen Fluoride Releases,” Allied Signal Report, 1995.
 22. Havens, J., H. Walker, and T. Spicer, “Characterization of the LGFSTF Wind Tunnel in Preparation for the DOE/EPA Hazardous Chemical Evaporation Rate Experiments,” U.S. DOE/EPA Chemical Hazards of Atmospheric Releases Research (CHARR) Program Report, March 1995.
 23. Havens, J., T.O. Spicer, and H. Walker, “Evaluation of Mitigation Methods for Accidental LNG Releases: Volume 1/5--Wind Tunnel Experiments and Mathematical Model Simulations to Study Dispersion of a Vapor Cloud Formed following LNG Spillage into a Diked Area Surrounding a Storage Tank,” Topical Report for Gas Research Institute, November 1996.
 24. Havens, J., T.O. Spicer, and H. Walker, “Evaluation of Mitigation Methods for Accidental LNG Releases: Volume 2/5--Wind Tunnel Experiments and Mathematical Model Simulations to Study Heat Transfer from a Flat Surface to a Cold Nitrogen Cloud in a Simulated Atmospheric Boundary Layer,” Topical Report for Gas Research Institute, November 1996.
 25. Havens, J., T.O. Spicer, and H. Walker, “Evaluation of Mitigation Methods for Accidental LNG Releases: Volume 3/5--Wind Tunnel Experiments for Mitsubishi Heavy Industries, Ltd.,” Topical Report for Gas Research Institute, November 1996.
 26. Havens, J., T.O. Spicer, and H. Walker, “Evaluation of Mitigation Methods for Accidental LNG Releases: Volume 4/5--Wind Tunnel Experiments for Osaka Gas Company,” Topical Report for Gas Research Institute, November 1996.
 27. Spicer, T.O., J. Havens, and H. Walker, “Evaluation of Mitigation Methods for Accidental LNG Releases: Volume 5/5--Using FEM3A for LNG Accident Consequence Analysis,” Topical Report for Gas Research Institute, February 1997.

Invited Lectures and Presentations

1. Mathematical Modeling and Experimental Investigation of Heavier-than-Air Gas Dispersion in the Atmosphere, Oklahoma State University, Stillwater, OK, April 1985.
2. Dispersion Modeling Workshop, Dow Chemical Company, Freeport, TX, March 1987.
3. Fundamentals of Denser-than-Air Gas Dispersion, EPA Modeling Workshop for Toxic Air Contaminants, Kansas City, Mo, June 1988; San Francisco, CA, October 1988.
4. Model Evaluation Workshop, International Conference and Workshop on Modeling and Mitigating the Consequences of Accidental Releases of Hazardous Materials, New Orleans, May 1991.
5. Application of the DEGADIS Dispersion Model to Accidental Releases of Hazardous Chemicals, Los Angeles City Fire Department, Los Angeles, CA, August 1993.
6. Boiling and Spreading of LNG Pools, Supplemental Gas Committee American Gas Association Roundtable, New Orleans, March 1994.
7. Application of the DEGADIS Dispersion Model to Accidental Releases of Anhydrous

- Ammonia, Joint Gas Research Institute and Fertilizer Institute Workshop, New Orleans, September 1994.
8. Validation of FEM3A for Dense Gas Dispersion in the Presence of Obstacles Using Wind-Tunnel Data Sets, Japanese National Committee of LNG Safety Study Meeting, Nagasaki, Japan, June 1995.
 9. Validation of FEM3A for Dense Gas Dispersion in the Presence of Obstacles Using Wind-Tunnel Data Sets, Mitsubishi Heavy Industries, Ltd., Heat Transfer Laboratory Staff Seminar, Nagasaki, Japan, June 1995.

Presentations

1. Application of a Heavy Gas Dispersion Model to the Prediction of Dispersion of Nitrogen Tetroxide, JANNAF Safety and Environmental Protection Subcommittee Meeting, Monterey, CA, November 1985.
2. DEGADIS--A Heavier-than-Air Gas Atmospheric Dispersion Model Developed for the U.S. Coast Guard, Air Pollution Control Association Annual Meeting, Minneapolis, MN, June 1986.
3. Field Test Validation of the DEGADIS Model, Second Symposium on Heavy Gas Dispersion Trials at Thorney Island, Sheffield, England, September 1986.
4. Gravity Flow and Entrainment by Dense Gases Released Instantaneously into Calm Air, Third International Symposium on Stratified Flows, California Institute of Technology, Pasadena, CA, February 1987.
5. Evaluation of the DEGADIS Dispersion Model Using Data from Field Releases of Pressurized Ammonia, Air Pollution Control Association Annual Meeting, New York, NY, June 1987.
6. Extension of DEGADIS for Modeling Aerosol Releases, International Conference on Vapor Cloud Modeling, Boston, MA, November 1987.
7. Uncertainties in the Application of Atmospheric Dispersion Models in the Presence of Jet Releases, Aerosol Releases, or Heterogeneous Surface Roughness, JANNAF Safety and Environmental Protection Subcommittee Meeting, Monterey, CA, 1988.
8. Modeling HF and NH₃ Spill Test Data Using DEGADIS, 1988 Summer National Meeting of the American Institute of Chemical Engineers, Denver, CO, 1988.
9. A Dispersion Model for Gas Pipeline Accidental Releases, 1989 Spring National Meeting, American Institute of Chemical Engineers, Houston, TX, April 1989.
10. Modeling Aerosol Dispersion for Accident Consequences Analyses, 1990 Spring National Meeting of the American Institute of Chemical Engineers, Orlando, FL, 1990.
11. DEGADIS Dense Gas Dispersion Model, Gas Research Institute Project Advisors Meeting, Fayetteville, AR, 1990.
12. Development of a Guidance Document for the Application of Refined Dispersion Models for Air Toxics Releases, 85th Annual Meeting of the Air and Waste Management Association, Kansas City, MO, June 1992.
13. Spreading and Vaporization of LNG Spills on Land, American Gas Association Distribution Transmission Conference and Exhibit, Orlando, FL, May 1993.

14. Application of Dispersion Models to Flammable Cloud Analyses, 6th Annual Petro-Safe, Houston, TX, February 1995.
15. Description and Analysis of Atmospheric Dispersion Tests Conducted by EPA at the DOE Hazmat Spills Center, International Conference and Workshop on Modeling and Mitigating the Consequences of Accidental Releases of Hazardous Materials, San Francisco, September 1999.

Poster Presentations

1. Spicer, T.O. and J.A. Havens, "Gravity Flow and Entrainment by Dense Gases Released Instantaneously into Calm Air," Third International Symposium on Stratified Flows, Pasadena, CA, 1987.
2. Havens, J., T. O. Spicer, H. Walker, and T. Williams, "LNG Vapor Dispersion Experiments for Complex Mathematical Model Evaluation," LNG-11; 8th International Conference and Exhibition on LNG, 3-6 July 1995, Birmingham, U.K.

COMIS Source Data

Alternate Case 1

Alternate Case 2

Alternate Case 3

Alternate Case 4

Most Likely Case