Fire performance of engineered floor/ceiling systems and impact on occupant safe escape in residential basement fire scenarios

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Fire Performance of Engineered Floor/Ceiling Systems and Impact on Occupant Safe Escape in Residential Basement Fire Scenarios

October 27th, 2011

Joseph Su

NRC Fire Research Program

National Research Council Canada | Conseil national de recherches Canada

Canada

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Fire Performance of Houses – Outline

- Background
- Objectives
- Experimental Program
- Key Findings

Background

- Advent of new materials and innovative products/systems used in construction of houses
- Need to better understand performance and impact on the life safety of occupants under fire conditions

Objectives

To better understand

- the factors that affect the life safety of occupants
- the impact of residential construction products and systems on life safety of occupants

in single-family houses in the event of a fire

Experimental Program

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- Multi-phase studies – Fire Performance of Houses
- Phase 1 – basement fires and unprotected floor assemblies over basement
  - To study impact on the ability of occupants on upper storeys to escape from the perspective of tenability and structural integrity of tests assembly as egress routes
  - To determine the sequence of fire events
- Phase 1b – basement fires and protected floor assemblies over basement
  - To study impact of protection measures on the life safety of occupants

Test Facility

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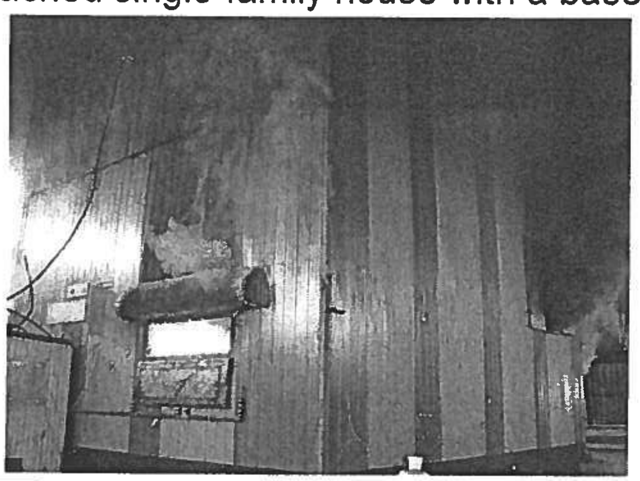
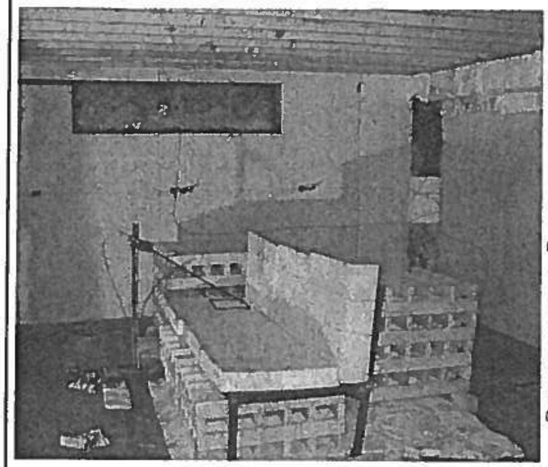
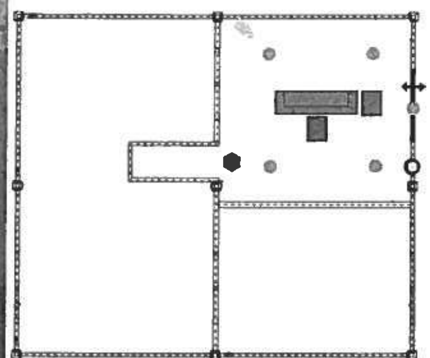
- A full-scale test house simulating a two-storey detached single-family house with a basement



Basement

- Relatively severe, fast-growing fire to challenge the floor above

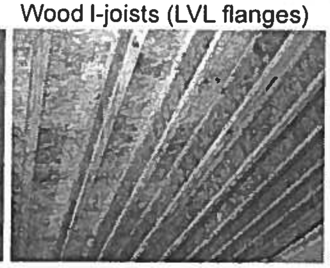




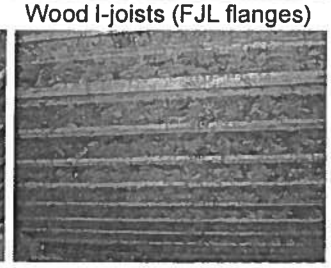
Phase 1 – Basement Fires and Unprotected Basement Ceiling (Unprotected Assemblies)

Solid wood joists

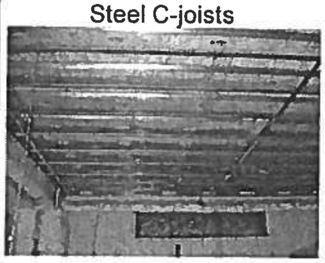
Wood I-joists (LVL flanges)



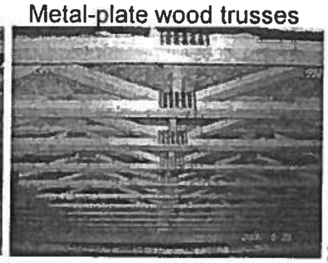
Wood I-joists (FJL flanges)



Steel C-joists



Metal-plate wood trusses



Metal-web wood trusses

First Storey

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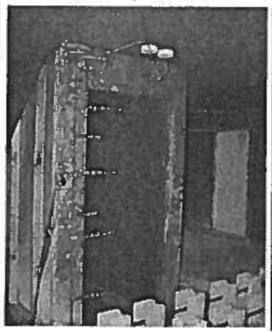
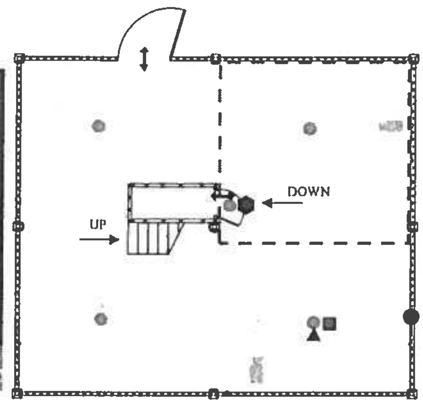
- State of doorway to basement:
  - Open
  - Closed





First Storey
Loading on Test Floor Assembly

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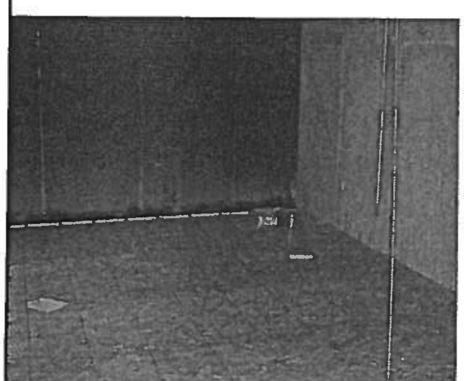
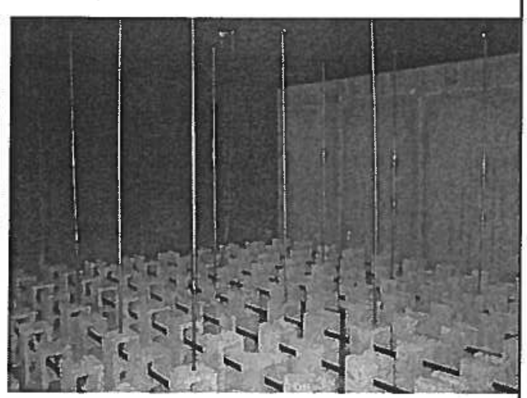
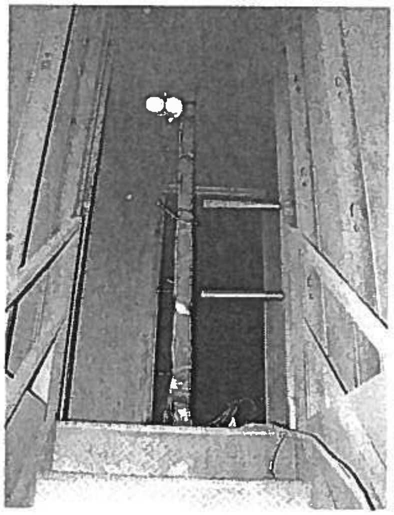
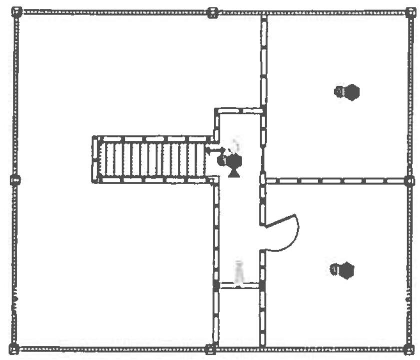
- OSB Subfloor
- 0.95 kPa imposed load (20 psf, i.e. ½ NBC design load)
- Self-weight of test floor assembly



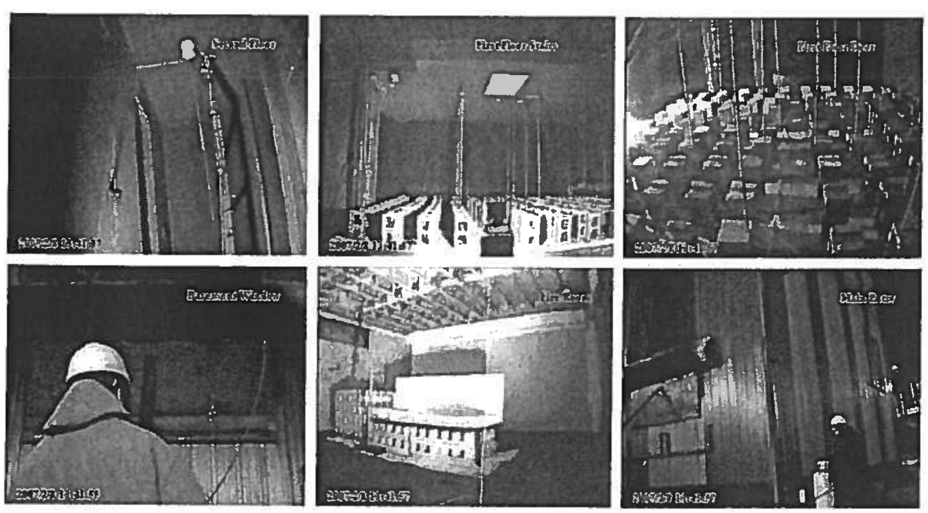


Second Storey



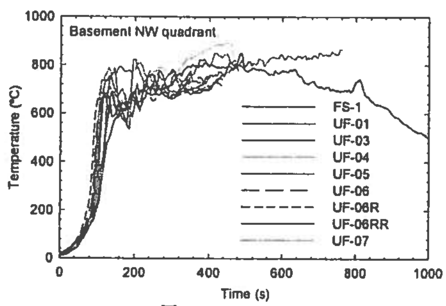


Video of A Fire Test

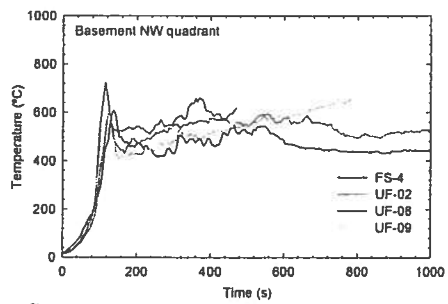


Fire Scenarios

open basement doorway



closed basement doorway



Temperatures in basement fire room at 2.4 m height

- Relatively severe, fast-growing fire in the basement
- Very reproducible fire exposure
- Challenge to the structural integrity of unprotected floor systems

Measurements and Analysis

- Smoke alarm responses
- Estimation of time to untenable conditions
- Structural response of floor assemblies

Smoke Alarm Responses

Smoke alarm location	Basement fire room		1st storey		2nd storey corridor		2nd storey bedroom (open)		2nd storey bedroom (closed)	
type	I	P 2	I 3	P 4	I 5	P 6	I 9	P 10	I 7	P 8
Tests with open basement doorway										
Test UF-01	-	40	75	85	125	135	140	150	200	205
Test UF-03	-	48	58	73	123	133	143	143	218	228
Test UF-04	-	30	65	85	115	130	160	225	230	250
Test UF-05	-	45	40	55	130	145	155	165	245	275
Test UF-06	-	45	75	85	115	125	130	200	230	255
Test UF-06R	-	38	58	78	113	123	138	163	198	223
Test UF-06RR	-	43	73	78	128	138	143	153	223	248
Test UF-07	-	50	40	55	110	130	130	145	190	210
Tests with closed basement doorway										
Test UF-02	-	42	72	97	172	182	212	n.a.	427	541
Test UF-08	-	50	85	95	205	205	220	210	515	515
Test UF-09	-	44	79	89	179	179	209	204	479	459

Tenability Analysis

- Untenable conditions
  - Smoke obscuration (optical density measurements)
  - Toxic, asphyxiant gases ($CO/CO_2/O_2$ measurements)
  - Heat (temperature measurements)

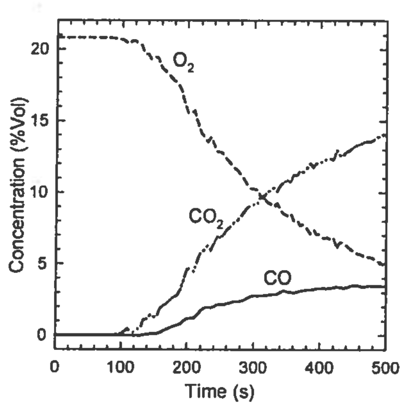
Tenability Analysis – Estimation of Time to Untenable Conditions

- ISO 13571 and SFPE Handbook
- Tenability limit values used
  - smoke obscuration: optical density (OD) = 2 m^{-1}
  - asphyxiant gas exposure (CO, CO_2, vitiated O_2)
  - heat exposure

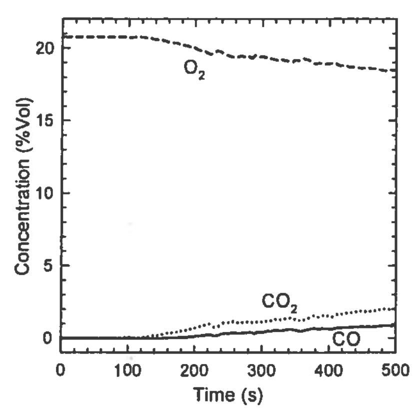
    fractional effective dose (FED)
    - FED = 1 for a healthy adult of average susceptibility
    - FED = 0.3 for a more susceptible person
- Example

Tenability Analysis – gas measurements

open basement doorway



closed basement doorway



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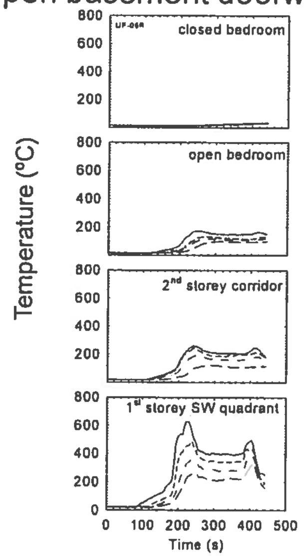
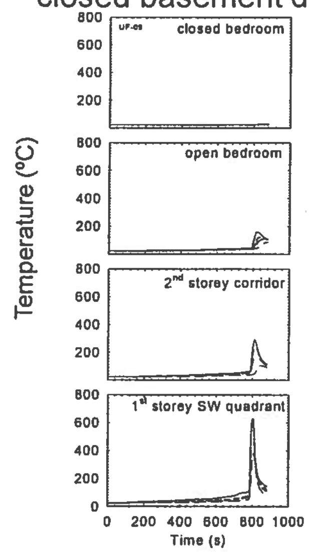
Tenability Analysis – temperature measurements

open basement doorway



closed basement doorway



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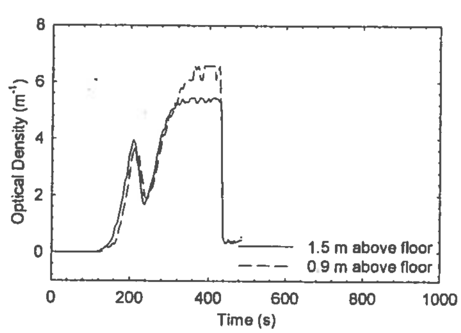
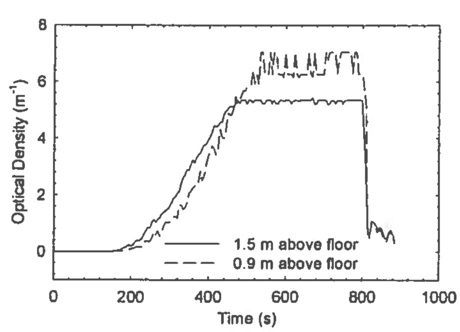
Tenability Analysis – optical density measurements

open basement doorway



closed basement doorway



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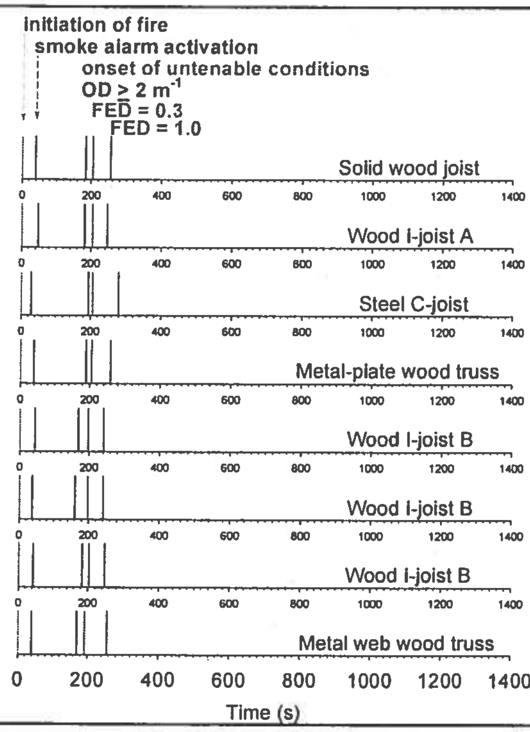
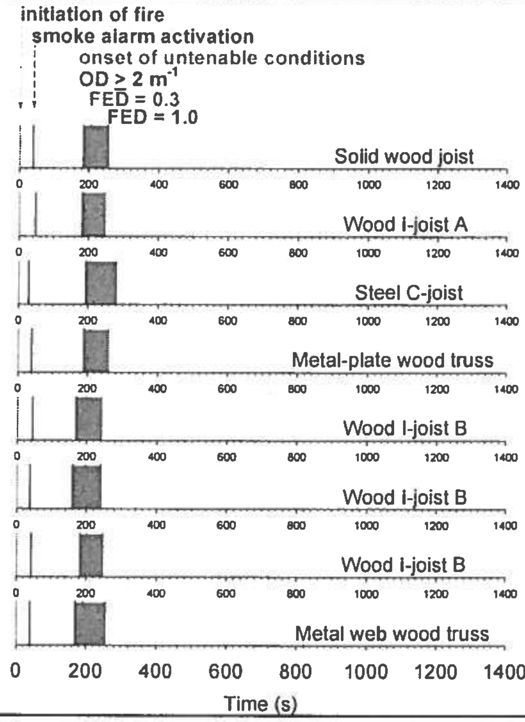
Tenability Analysis – estimation of time to untenable conditions

- Depending on many factors
  - Fire characteristics and house geometry
  - Endpoints for tenability analysis (incapacitation used)
  - Occupant characteristics, activities, susceptibility, thresholds/tenability limits
  - Each occupant likely to have a different time
- Tenability limit/threshold values used
  - Smoke obscuration: optical density (OD) = 2 m^{-1}
  - CO/CO_2 or heat exposure: fractional effective dose approach
    - FED = 1 for a healthy adult of average susceptibility
    - FED = 0.3 for a more susceptible person

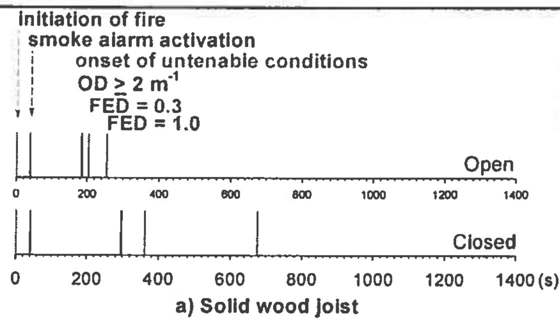
open basement doorway



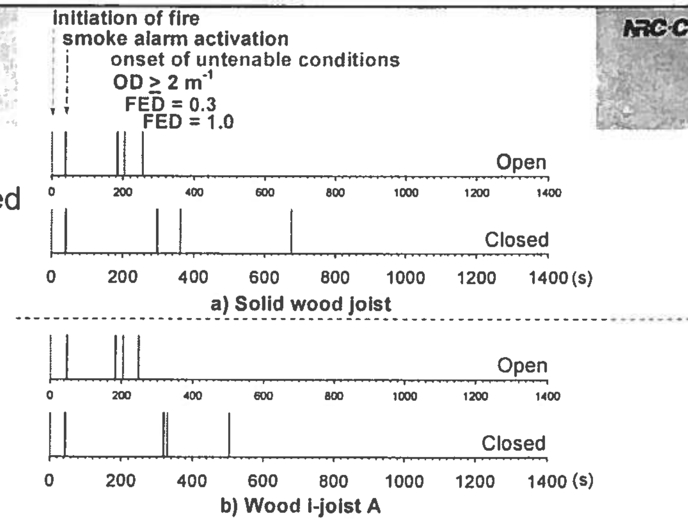
open basement doorway



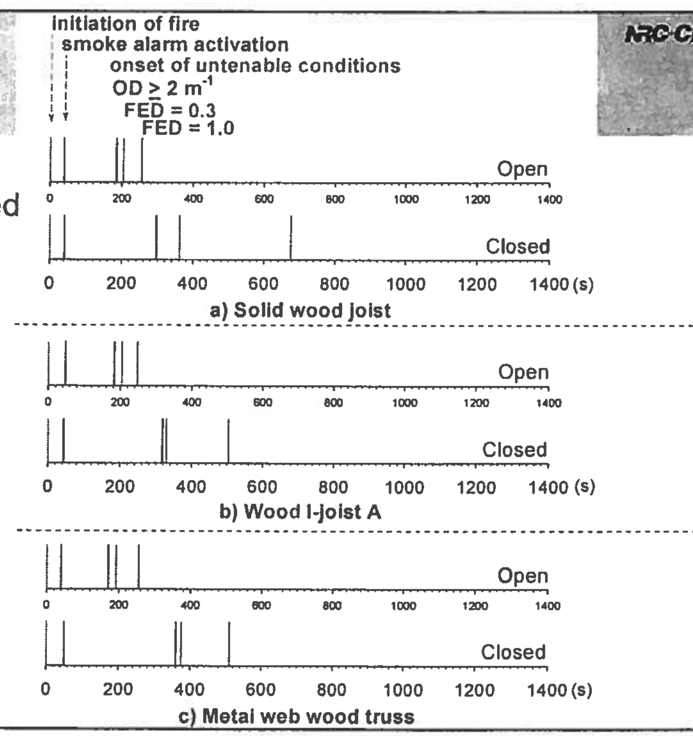
Comparison: open vs closed basement doorway



Comparison: open vs closed basement doorway



Comparison: open vs closed basement doorway



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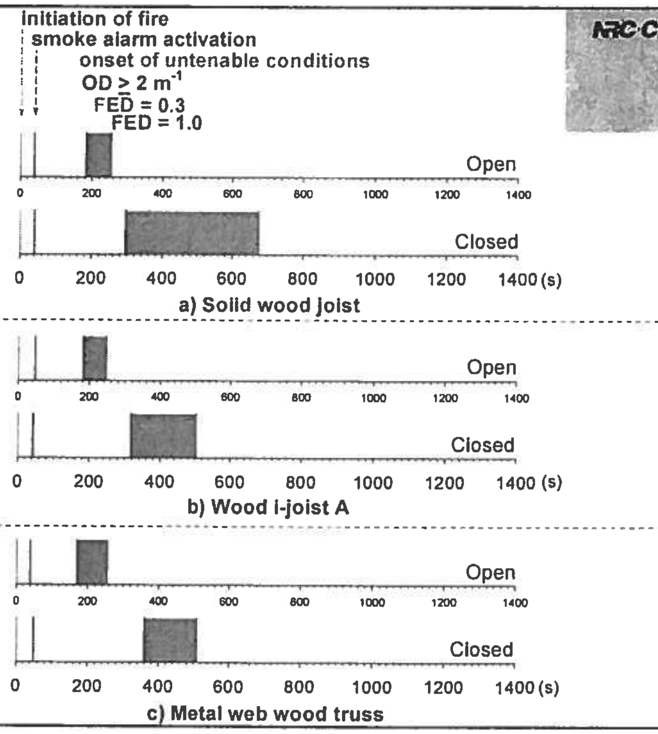
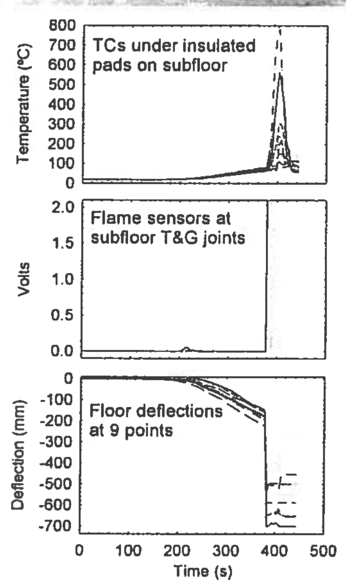


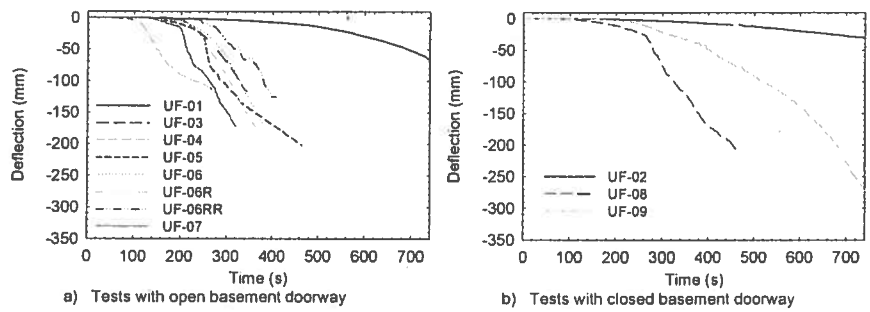
Structural Response of Test Assemblies

- Measurements on test assembly to determine time to floor failure
  - Temperatures
  - Flame penetration
  - Deflections
  - Visual observations



Structural Response of the Test Assemblies

- Deflection prior to floor failure

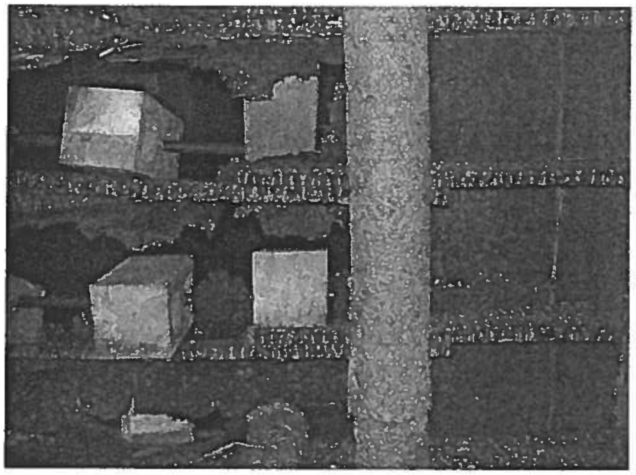


Primary Mode of Floor Failure

- Solid wood joist assemblies
  - subfloor failure (burn through)
  - most of the joists charred but still in place
- Engineered floor assemblies
  - joist or truss failure
  - collapse into the basement

Primary Mode of Floor Failure

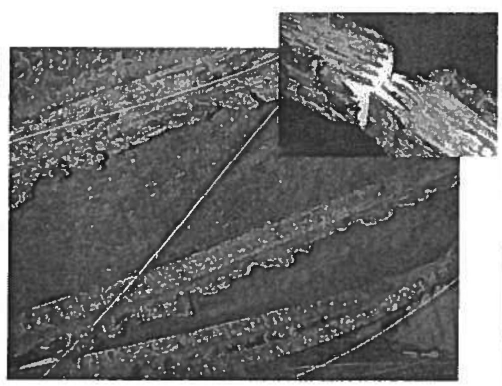
Solid wood joist assemblies: subfloor failure (burn through)



Primary Mode of Floor Failure

Wood I joists A and B: web materials burned through

Wood I-joist B: breakdown at finger joints of lumber flanges



Primary Mode of Floor Failure

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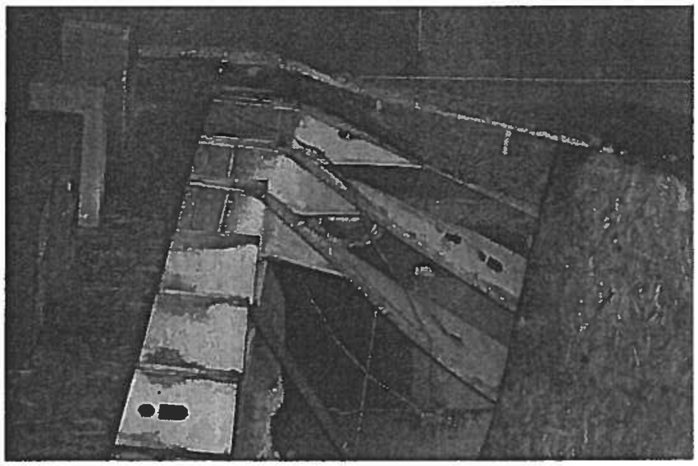
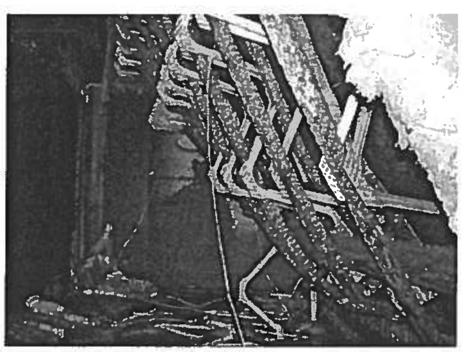
Steel C-joists: lost strength and deformed

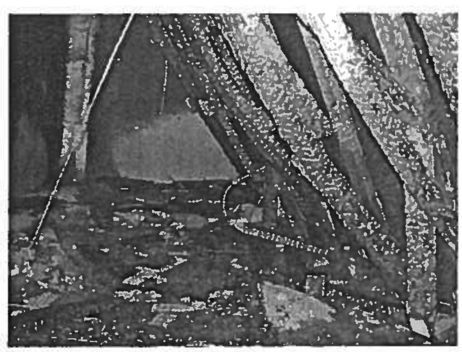


Primary Mode of Floor Failure

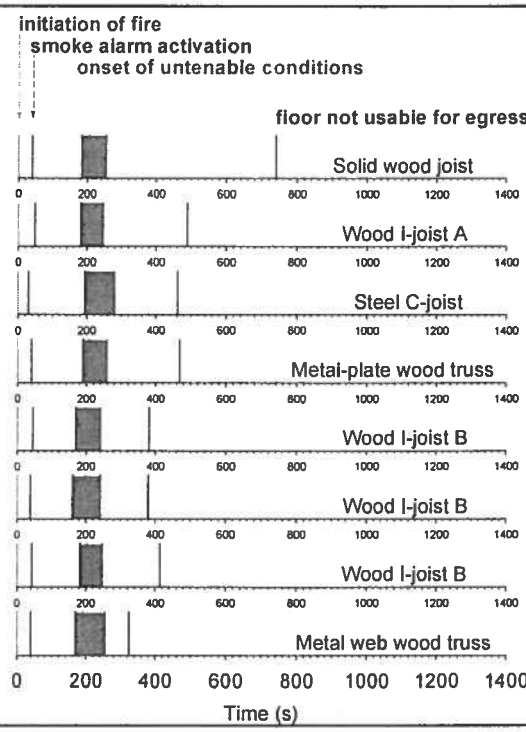
NRC·CNRC

Metal-web & metal-plate wood trusses: metal-wood connections

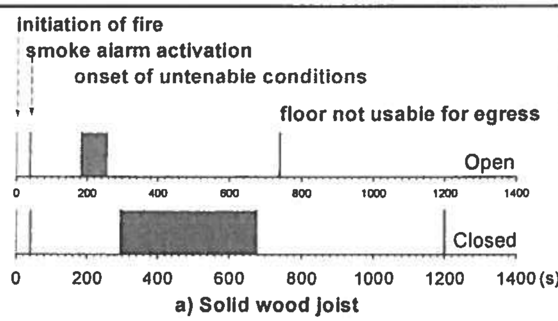




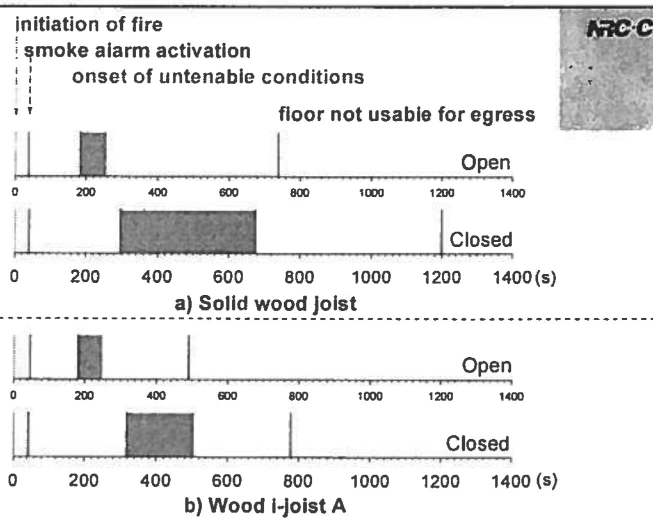
open basement doorway



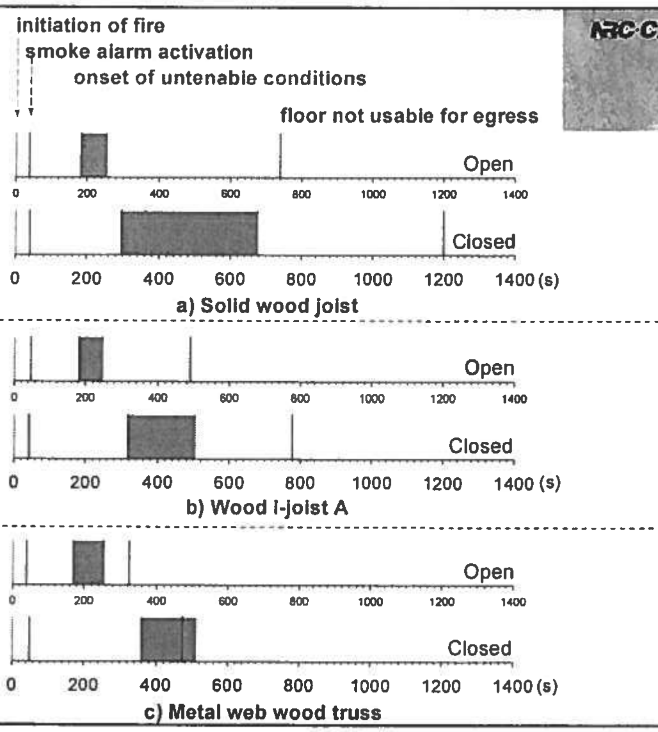
Comparison: open vs closed basement doorway



Comparison: open vs closed basement doorway



Comparison: open vs closed basement doorway



Key Findings – Phase 1

- **Tests with an open stairwell to the basement**
  - Fire events followed a chronological sequence:
    - initiation of the fire
    - activation of smoke alarms
    - loss of tenable conditions in open areas on upper storeys
    - finally structural failure of the test floor assembly
  - Untenable conditions for occupants in open areas on upper storeys were reached at approximately the same time regardless of the type of the test floor assemblies
  - The untenable conditions were reached before failure of the test floor assemblies occurred

Key Findings – Phase 1 (continued)

- **Limited tests with a closed door to the basement**

  3 assemblies: solid wood joist, wood I-joist, metal-web wood truss
  - Reduced the rate of fire growth in the basement
  - Slowed the transport of combustion products from the basement to the upper storeys
  - Delayed the time to reach tenability limits for occupants on upper storeys
  - Delayed the times for the test floor assemblies to reach structural failure
  - Metal-web wood truss assembly failed before tenability limits were reached in open areas on upper storeys

Key Findings – Phase 1 (continued)

- **All tests**
  - The time to reach failure for the engineered assemblies was shorter than for the solid wood joist assemblies
  - Untenable conditions were not reached, for the duration of the tests, in the second-storey bedroom where the door to the bedroom was kept closed
  - Results support the code requirement for working interconnected smoke alarms on each level of a house to alert occupants as early as possible in the event of a fire
  - Results reinforce the importance of continued public education on home fire safety, fire emergency preparedness and immediate evacuation upon a fire alert

Phase 1 Final Reports

Fire Performance of Houses

Phase 1

Study of Unprotected Floor Assemblies in Basement Fire Scenarios

- Summary http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr252/rr252.pdf
- Part 1 http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr246/rr246.pdf
- Part 2 http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr247/rr247.pdf
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- Part 6 http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr251/rr251.pdf

Phase 1b - Protected Floor/Ceiling Assemblies and Impact on Occupant Safety

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- Engineered floor systems protected by gypsum board, sprinkler or suspended ceiling
- Impact of the protection measures on life safety of occupants from the perspective of
  - tenability for occupants on upper storeys
  - structural integrity of test assemblies as egress routes

Test Assemblies and Protection on Ceiling

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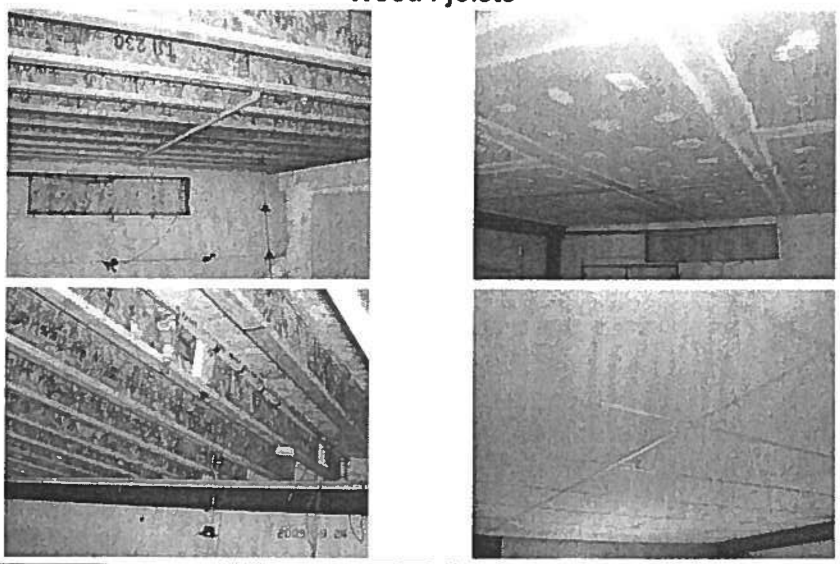
Test Assembly	Gypsum board ceiling only	Suspended ceiling only	Sprinklered only
Wood I-joist	√	√	√
Metal web wood truss	√		√
Steel C-joist	√		
Solid wood joist	√		

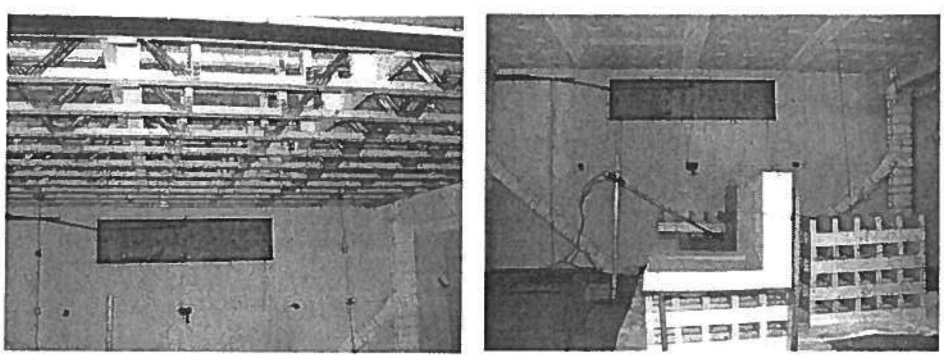
Basement Ceiling Protection

Wood I-joists



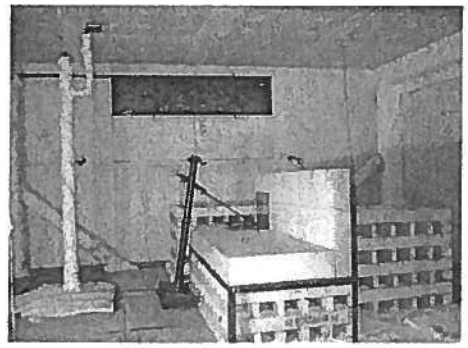
Basement Ceiling Protection

Metal-web wood trusses



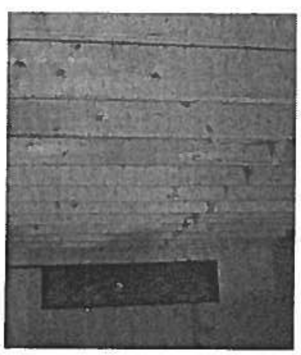
Basement Ceiling Protection

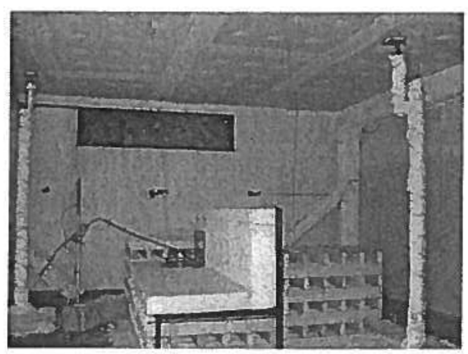
Steel C-joists



Basement Ceiling Protection

Solid wood joists





Test Facility – First Storey

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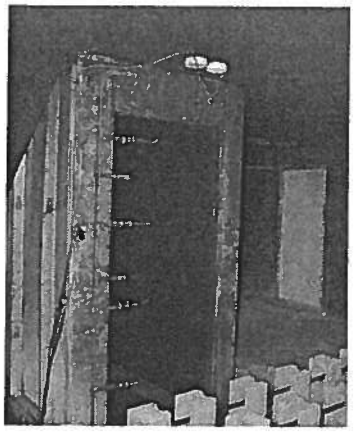
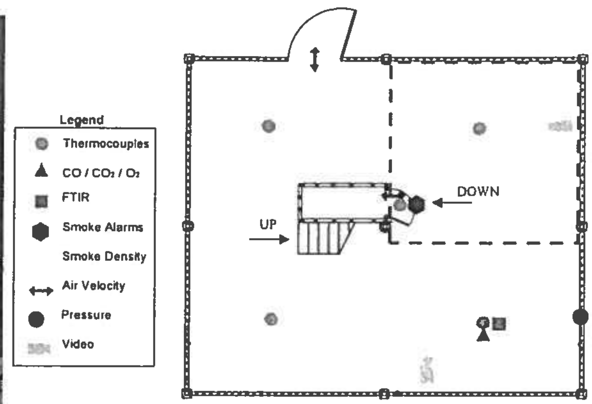
- Open doorway to basement:





Typical Results for Gypsum Board Protection

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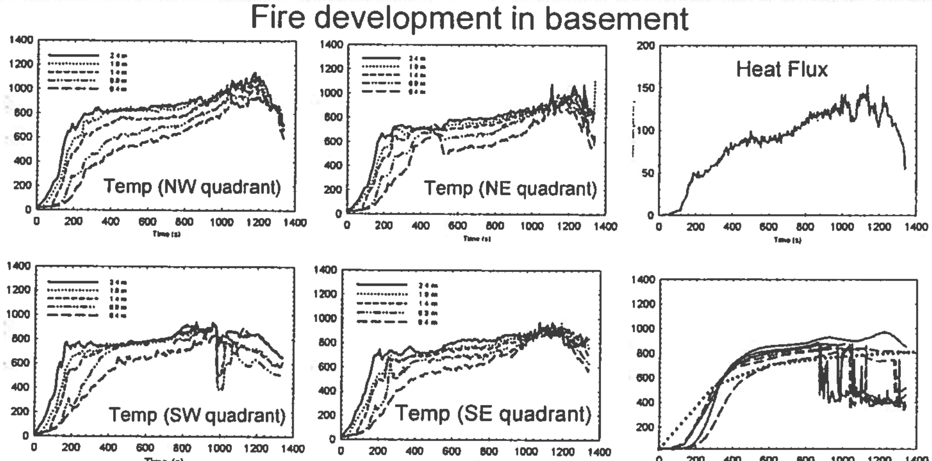
Fire development in basement



- Temperatures 800-1000°C
- Heat flux up to 150 kW/m^2

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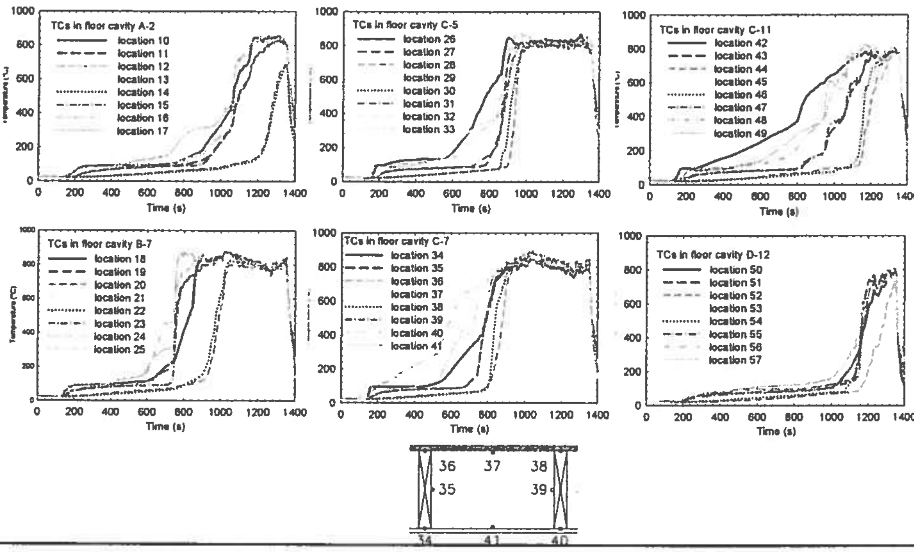
Typical Results for Gypsum Board Protection

Temperature measurements in test floor cavities



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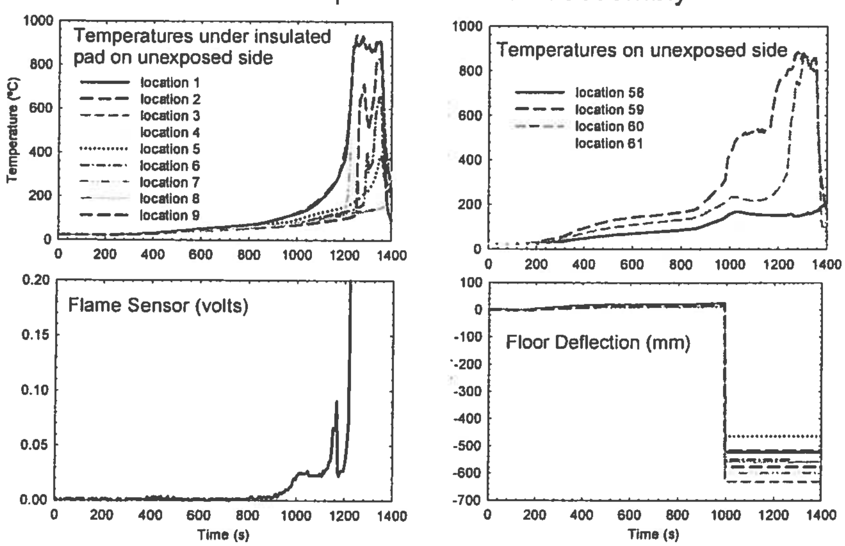
Typical Results for Gypsum Board Protection

Structural response of the test assembly



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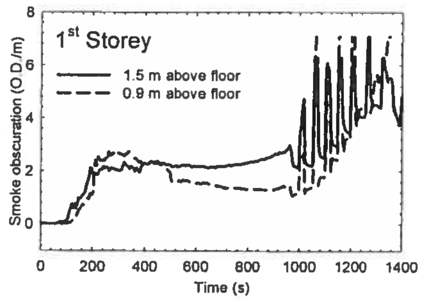
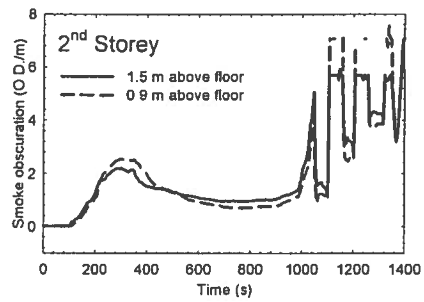
Visual Obscuration by Smoke

Optical density (m^{-1}) measurements on upper storeys





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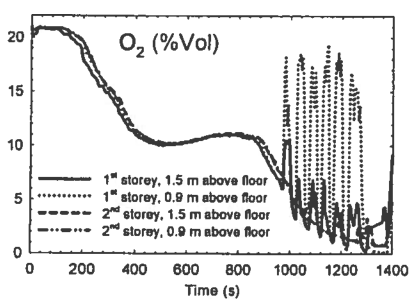
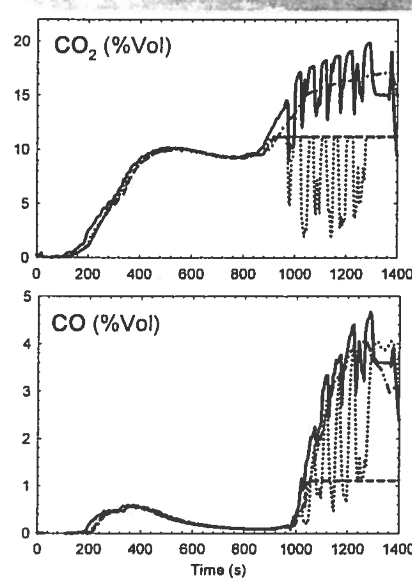
Exposure to O_2 vitiation, CO_2 and CO

Gas measurements on upper storeys





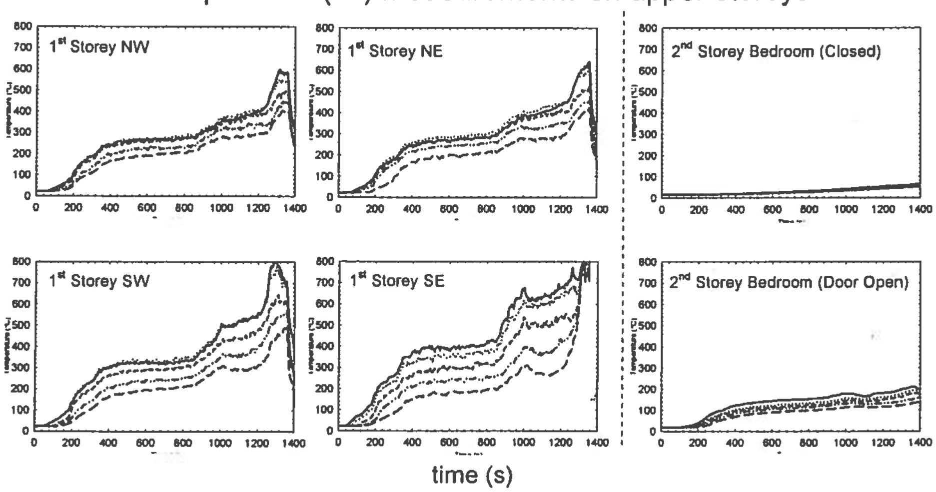
Exposure to O_2 vitiation, CO_2 and CO

Time (s) to specified FED

Fractional Effective Dose	FED = 0.3	FED = 1.0
CO alone – 1st storey	337	922
CO with CO_2 hyperventilation – 1st storey	272 ± 20	352 ± 30
Low O_2 hypoxia – 1st storey	557	947
CO alone – 2nd storey corridor	357	967
CO with CO_2 hyperventilation – 2nd storey corridor	297 ± 20	377 ± 30
Low O_2 hypoxia – 2nd storey corridor	592	977
High CO_2 hypercapnia – 1st storey	412	527
High CO_2 hypercapnia – 2nd storey corridor	432	552

Exposure to heat

Temperature (°C) measurements on upper storeys

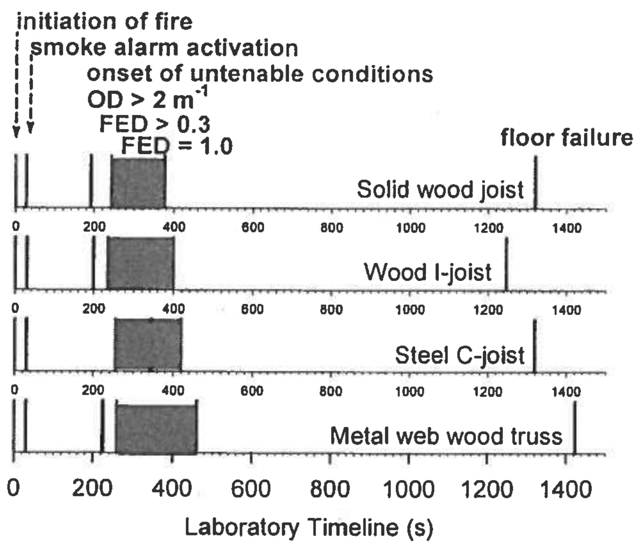


Exposure to Convected Heat

Time (s) to specified FED

	FED = 0.3	FED = 1.0
1st storey SE quadrant	242	292
1st storey SW quadrant	242 ± 10	287 ± 15
1st storey NE quadrant	257	312
1st storey NW quadrant	257	317
2nd storey corridor	317 ± 15	407 ± 25
2nd storey open bedroom	472	697
2nd storey closed bedroom	(FED<0.06)	(FED<0.06)

Results – Assemblies Protected by Gypsum Board Ceiling



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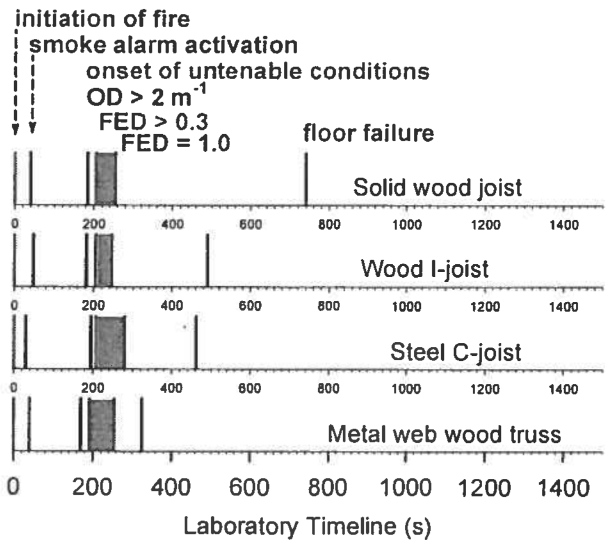
Previous Phase-1 Results – Assemblies without Protection



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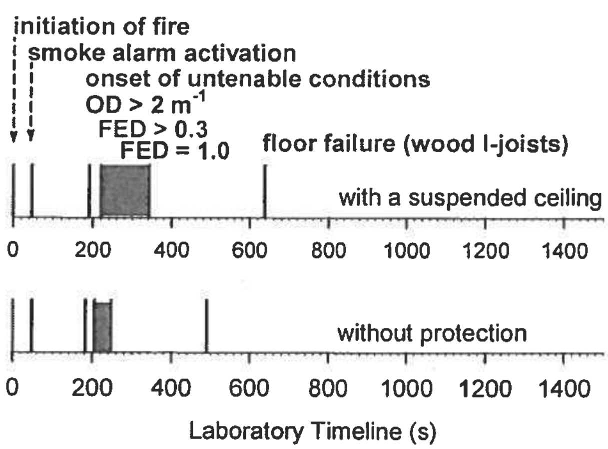
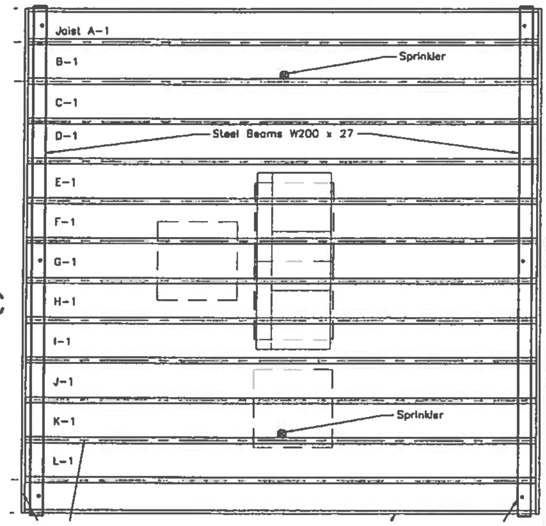
Results – Assemblies Protected by Mineral Fiber Panels (Suspended Ceiling)



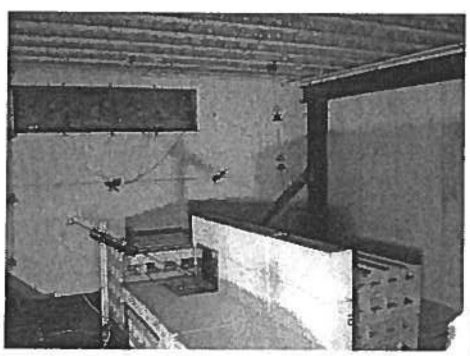
Assemblies Protected by Residential Sprinkler

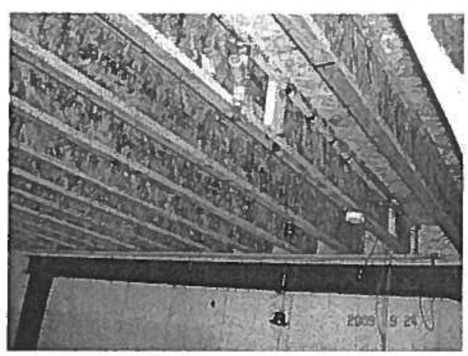
Sprinkler Design A

- Use with wood I-joists
- Two pendent sprinklers:
  3.66 m (12 ft) apart along the centerline
- K factor 4.9
- Temperature rating 68°C
- Designed for operation:
  1 bar (15 psi)
  72 Lpm (19 USgpm)/head



Sprinkler Design A





- 1" CPVC plastic piping
- Flow tests (static water supply pressure: 50 psi)
  - 2 sprinklers open: 144 Lpm (38 USgpm), 15 psi at farthest head
  - 1 sprinkler open: 98 Lpm (25.9 USgpm), 27.9 psi (at farthest head)

Fire Development – Temperatures/heat flux in basement fire room

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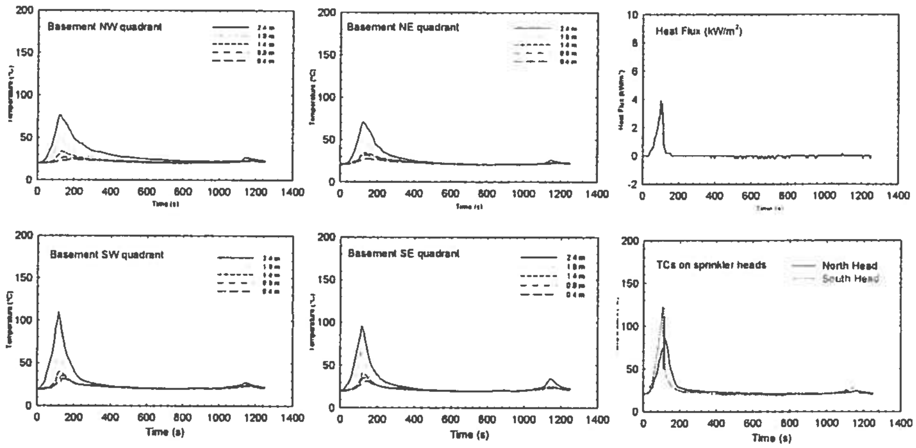

- single sprinkler activation at 106 s (south head only)

Exposure to O_2 vitiation, CO_2 and CO

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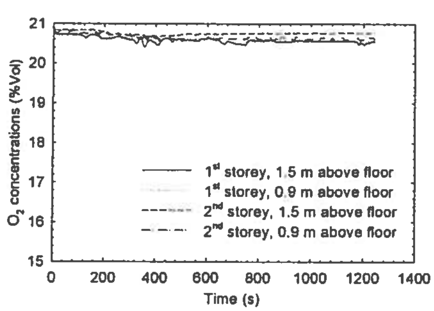
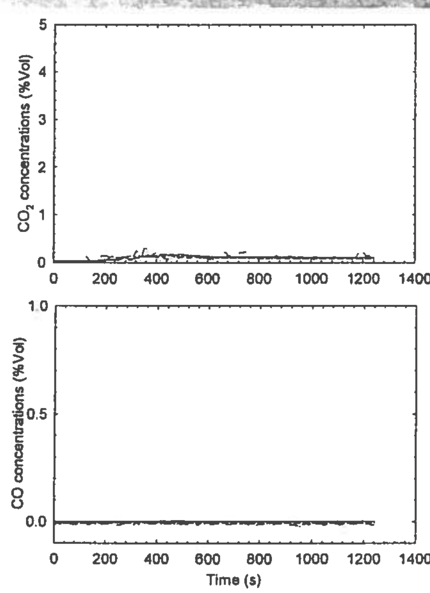
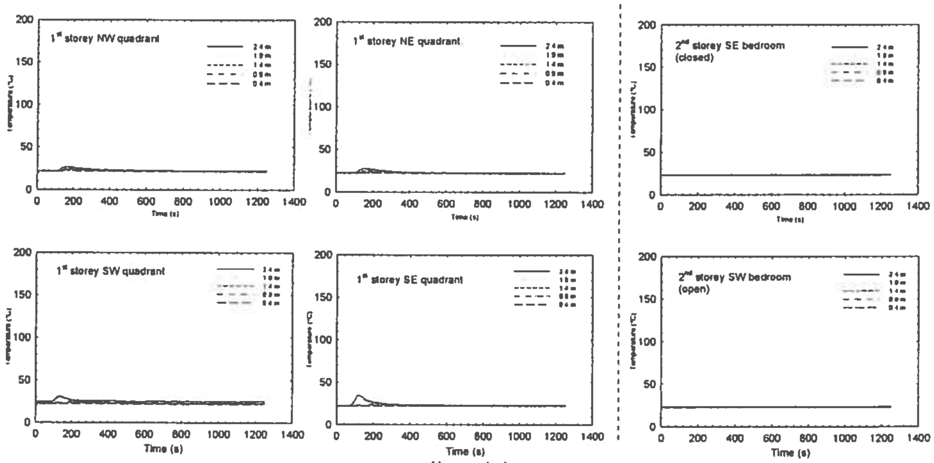
Gas measurements on upper storeys





Exposure to Heat

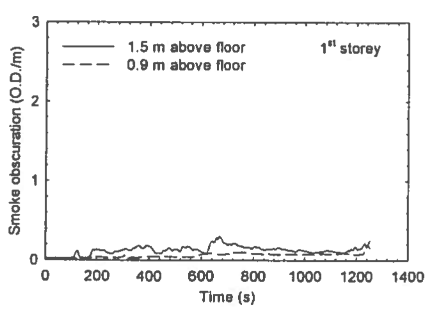
Temperature (°C) measurements on upper storeys

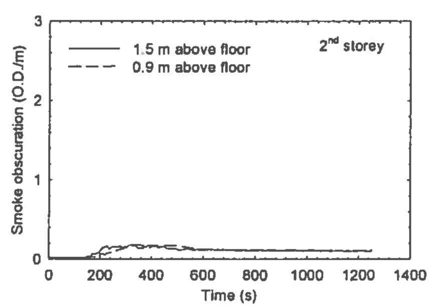


time (s)

Visual Obscuration by Smoke

Optical density (m^{-1}) measurements on upper storeys





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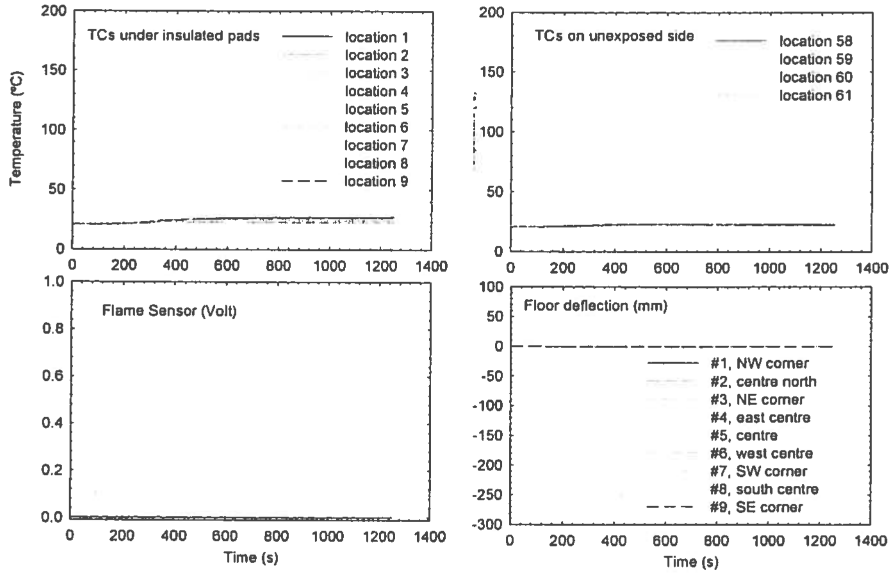
Structural Response of the Test Assembly

Temperature/flame/deflection measurements in the test assembly



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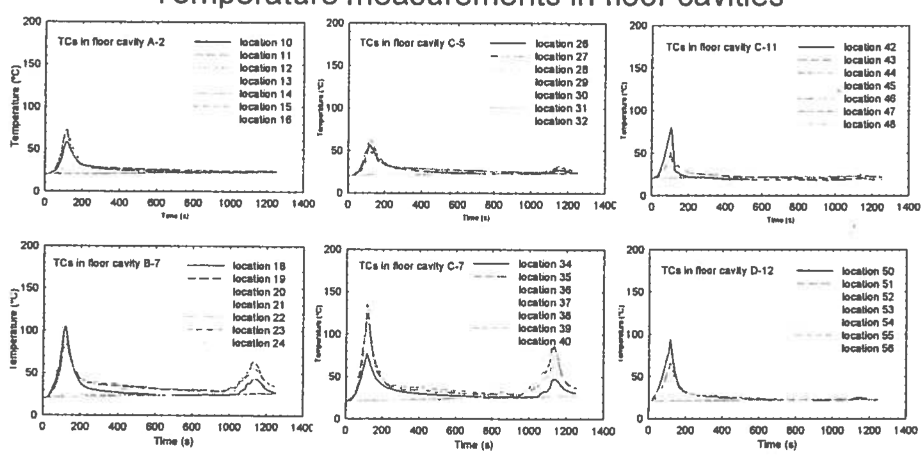
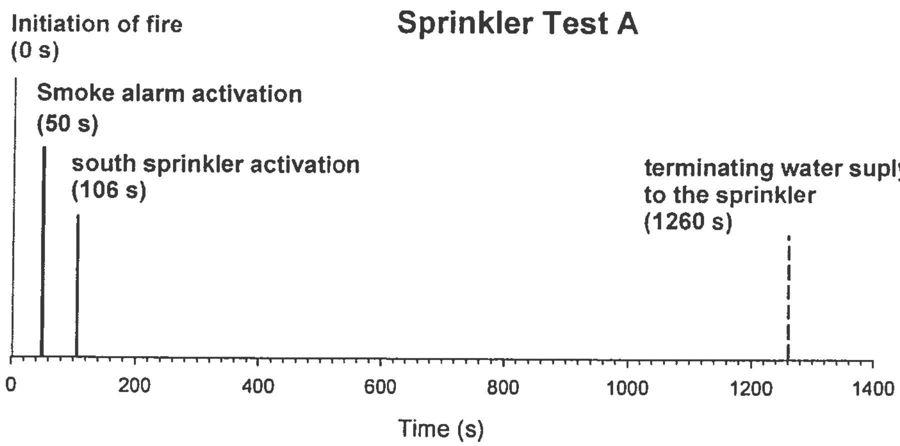
Temperature measurements in floor cavities

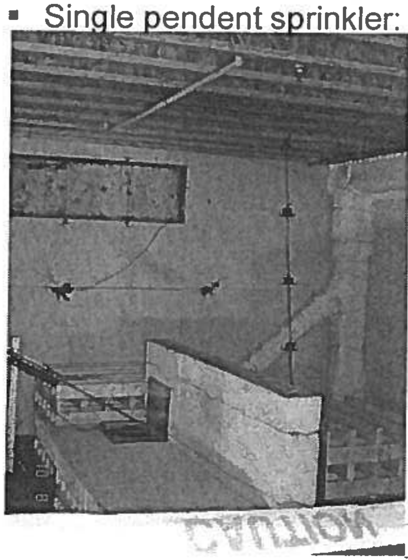


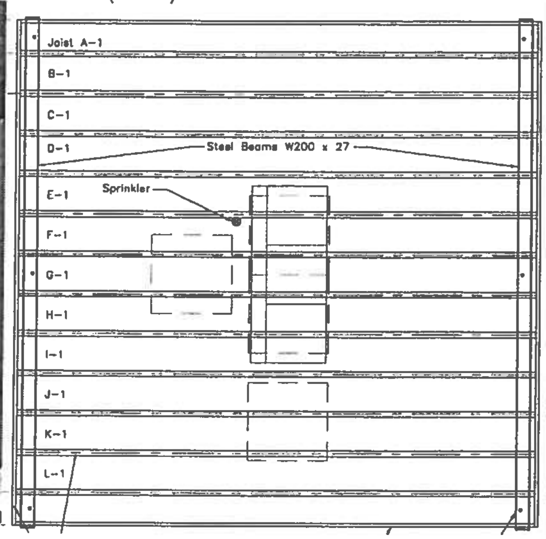
Sequence of Events in Sprinkler Test A



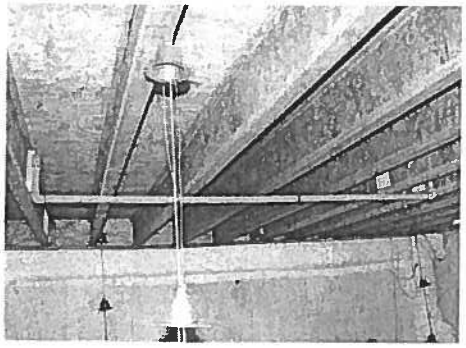
Sprinkler Design B

- Single pendent sprinkler: 3.05 m (10 ft) from south and east walls



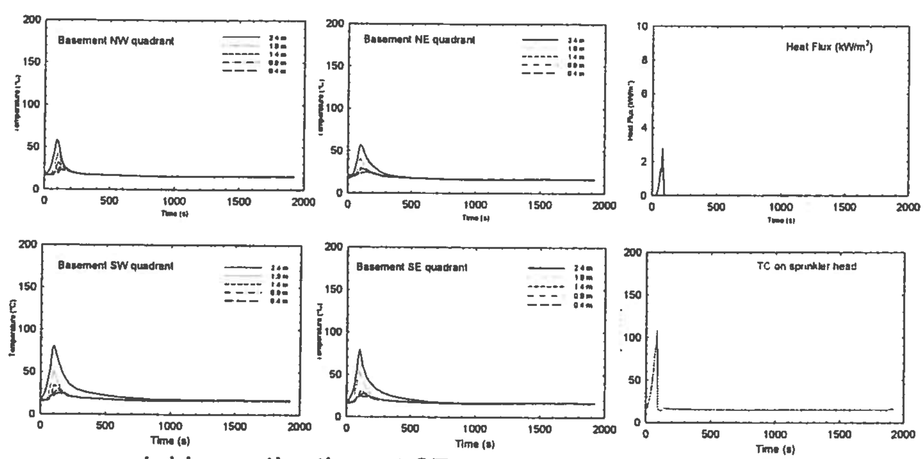


Sprinkler Design B



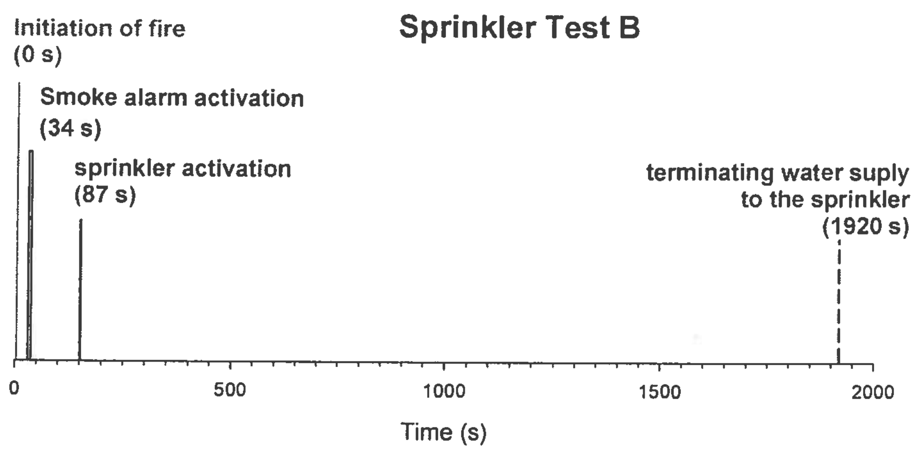
- 1" CPVC plastic piping
- Flow test (static water supply pressure: 50 psi)
  - 83.2 Lpm (22 USgpm), 20.2 psi at the head

Fire Development – Temperatures/heat flux in basement fire room



- sprinkler activation at 87 s

Sequence of Events in Sprinkler Test B



Smoke Alarm Responses in All Tests

Location	Basement fire room	1st storey		2nd storey corridor		2nd storey open bedroom		2nd storey Closed bedroom	
Type of Smoke Alarm	P	I	P	I	P	I	P	I	P
Test PF-01	27	37	57	102	112	117	127	242	282
Test PF-02	30	45	55	110	125	145	140	235	265
Test PF-03	45	95	105	175	175	210	na	na	na
Test PF-03B	34	79	94	196	176	na	na	na	na
Test PF-04	30	40	55	115	125	140	na	235	255
Test PF-05	47	67	87	127	137	147	na	267	282
Test PF-06	55	85	95	185	195	360	410	na	na
Test PF-06C	30	75	90	140	145	150	160	220	250

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Key Findings – Phase 1b

- Gypsum board protected floor assemblies
  - Similar or slightly improved tenability conditions
  - Significantly improved structural performance
  - Three engineered assemblies matching the solid wood joist assembly in term of time for structural fire endurance
- Suspended ceiling
  - Marginal benefit as a protection measure
- Residential sprinkler systems
  - Tenable conditions in the test house
  - Effective protection for structural integrity of the test assembly as egress routes

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Phase 1b Reports

RR-307: *Performance of protected ceiling/floor assemblies and impact on tenability with a basement fire scenario*

http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr307.pdf

RR-308: *Experiments of sprinkler protected ceiling/floor assemblies in a basement fire scenario*

http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr308.pdf

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Acknowledgments

Project Partners:

- *Canadian Automatic Sprinkler Association*
- *Canada Mortgage and Housing Corporation*
- *Canadian Wood Council*
- *Cement Association of Canada*
- *City of Calgary*
- *City of Edmonton*
- *FPInnovations*
- *Gypsum Association*
- *North American Insulation Manufacturers Association*
- *Ontario Ministry of Community Safety and Correctional Services/Office of the Fire Marshal*
- *Ontario Ministry of Municipal Affairs and Housing*
- *Wood I-Joist Manufacturers Association*

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Thank you!

Questions?

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