NIST Special Publication 1128

Summary of Workshop for Urban and Wildland-Urban Interface (WUI) Fires: A Workshop to Explore Future Japan/USA Research Collaborations

Samuel L. Manzello
Sayaka Suzuki
Keisuke Himoto

National Institute of Standards and Technology • U.S. Department of Commerce

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Summary of Workshop for Urban and Wildland-Urban Interface (WUI) Fires: A Workshop to Explore Future Japan/USA Research Collaborations

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Engineering Laboratory

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Kyoto University

August 2011

U.S. Department of Commerce
Rebecca M. Blank, Acting Secretary

National Institute of Standards and Technology
Patrick D. Gallagher, Under Secretary of Commerce for Standards and Technology and Director

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CODEN: NSPUE2

Table of Contents

1. Introduction

1. 1 Objective of this Workshop

An international workshop was held within the Fire Research Division at NIST's Engineering Laboratory on June 27th, 2011. The workshop was entitled "Urban and Wildland-Urban Interface (WUI) Fires: A Workshop to Explore Future Japan/USA Research Collaborations." The workshop was organized by Dr. Samuel L. Manzello (NIST/USA) and Dr. Keisuke Himoto (Kyoto University/Japan).

WUI fires have caused significant destruction in the USA. In 2003, WUI fires in the vicinity of San Diego, California (USA) displaced nearly 100,000 people and destroyed over 3000 homes, leading to over $2B in insured losses. Most recently, WUI fires that occurred in Southern California in 2007 and 2008 displaced tens of thousands of people and destroyed several thousand structures. Because of the current historic role in wildland fire fighting (not WUI fires), little effort has been spent on improving understanding of WUI fire behavior. There is a lack of quantitative information on the processes of structure ignition in WUI fires. Post-fire damage studies suggest that firebrands are a major cause of structural ignition in WUI fires.

Japan has been plagued by large urban fires for many years. Japan is a country subjected to many earthquakes due to its geographical location. After these earthquakes occur, many fires are produced. Exterior claddings and ceramic roofing tiles are displaced as a result of the earthquakes exposing bare wood members that are easily ignited due to external heating. As in WUI fires, firebrands are produced as structures burn and with the presence of high winds these firebrands are dispersed throughout the atmosphere and produce spot fires which result in severe urban fires. Exposure to wind-blown fire plumes downwind of the burning area also presents difficulty in firefighting and evacuation operations. Mitigation of urban fire spread is also of special importance to Japan from a historical perspective. Kyoto is one of the few remaining cities in Japan with traditional wooden structures that are vulnerable to ignition and preservation of such structures is of great importance from a cultural heritage point of view. As part of this workshop, presentations were delivered from leading researchers in Japan and the USA in the areas of urban and WUI fire spread.

The goal of this workshop was to open a dialogue for new research collaborations between both countries in an effort to develop scientifically based building codes/standards that will be of use to both countries to reduce the devastation caused by urban and WUI fire spread.

1.2 Program of Workshop

8:55 am - 9:05 am

Dr. William Grosshandler (Deputy Director of Engineering Laboratory, NIST)

Welcome To NIST

9:05 am – 9:15 am

Dr. Samuel L. Manzello (NIST)

Workshop Objectives

Japanese Perspective (Dr. K. Himoto, Kyoto University, Moderator)

9:15 am - 9:35 am

Dr. Masahiko Shinohara (National Research Institute of Fire and Disaster)

Formation of Fire Whirls Downwind of Fires

9:35 am – 9:55 am

Professor Takeyoshi Tanaka (Kyoto University)

Fires in March 11 Tsunami Earthquakes

9:55 am – 10:15 am

Professor Ai Sekizawa (Tokyo University of Science)

Effectiveness and its Limit of Fire-fighting Force in Controlling Post-Earthquake Fires

BREAK

10:30 am – 10:50 am

Dr. Keisuke Himoto (Kyoto University)

Physics-based Modeling of Post-earthquake Fire Spread

10:50 am – 11:10 am

Professor Yoshifumi Ohmiya (Tokyo University of Science)

Fire Spread Caused by Flame Ejected from an Opening

11:10 am – 11:30 am

Dr. Tomoaki Nishino (Kobe University)

Evacuation Simulation in the Conflagrations Induced by Kanto Earthquake 1923 and Kyoto Earthquake 20XX

USA Perspective (Dr. Samuel L. Manzello, NIST, Moderator)

1:00 pm – 1:20 pm

Mr. Ethan Foote (Northern California Fire Prevention Officers/CALCHIEFS)

The Wildland-Urban Interface Fire Problem

1:20 pm – 1:40 pm

Mr. Alexander Maranghides (NIST)

The Wildland-Urban Interface: A Coupled Problem

1:40 pm – 2:00 pm

Professor Carlos Fernandez-Pello (University of California-Berkeley)

Ignition of Cellulose Fuel Beds by Hot Metal Particles

BREAK

2:15pm – 2:35 pm

Professor Rachel Davidson (University of Delaware)

An Urban Fire Simulation (UFS) Model

2:35 pm – 2:55 pm

Dr. Samuel L. Manzello (NIST)

Quantifying Structure Vulnerabilities to Ignition from Wind Driven Firebrand Showers

2:55 pm – 3:15 pm

Dr. Sayaka Suzuki (NIST)

Ignition Regimes Maps for Materials Exposed to Firebrand Showers Using NIST Dragon's LAIR Facility

3:15 pm - 3:35 pm

Professor Albert Simeoni (Worcester Polytechnic Institute)

Wildland Fuel Burning Dynamics

3:45 pm – 4:30 pm

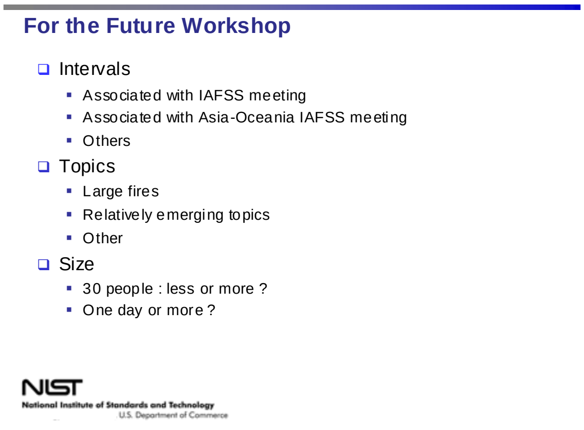
OPEN DISCUSSION (ALL) ON AREAS OF FUTURE COLLABORATION

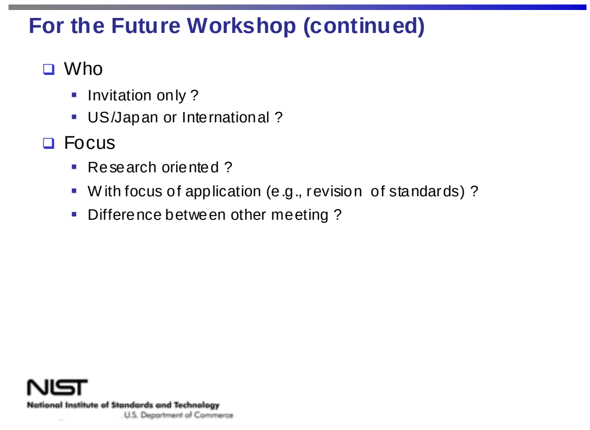
All presentations are in Appendix 2

2. Discussions

2.1 Inputs related to the Future Workshop

NIST presentation about discussions for Future Workshop is summarized below





Open Discussion on areas of Future Collaboration

- Regarding workshop size (internationally or US/Japan only, the number of people, the number of topics), the following suggestions were obtained:
  - The size of the workshop should be limited to less than 50 participants to afford the opportunity for intimate discussions.
  - The workshop duration should be expanded to two days to allow break-out sessions.
  - US/Japan theme was ideal since both countries are very interested in large outdoor fires; the damage from such fires to infrastructure is of great interest to both countries.
  - Consider inviting other researchers from countries worried about similar issues.
  - Suggested by some participants to video/web conference so that more people can attend due to travel restrictions; others felt this was a bad idea and can be remedied by asking one representative to present work from their respective organization.
  - Workshop needs 2 or 3 key speakers and a few topics; variety is needed but too many topics will lose focus.
  - Further engage representatives from standards and codes organizations, such as International Organization for Standardization (ISO), National Fire Protection Association (NFPA), and International Code Council (ICC).
  - It is necessary to engage the disaster related research community as a whole and include research focused on costs associated with mitigation strategies (economic analyses).Consider support from existing fire research community to host future workshops.

- Workshop should not be every year; perhaps every 2 or 3 years since one year is too short to make a substantial progress on research.

2.2 Summary

An international workshop was held within the Fire Research Division at NIST's Engineering Laboratory on June 27th, 2011. The workshop was entitled "Urban and Wildland-Urban Interface (WUI) Fires: A Workshop to Explore Future Japan/USA Research Collaborations." Thirteen presentations were delivered in the areas of urban fire spread in Japan and WUI fire spread in the USA. Six presentations were delivered from the Japanese perspective; from evacuation/firefighter-response models, to fire whirl research, to post-tsunami fires following historical earthquakes in Japan. Seven presentations were delivered from the USA perspective; from the overall view of WUI fire problem, to detailed ignition studies on fuel beds, to vulnerabilities of structures to firebrand showers. The goal of this workshop was to open a dialogue for new research collaborations between both countries in an effort to develop scientifically based building codes/standards that will be applicable to both countries to reduce the devastation caused by urban and WUI fire spread. The workshop was considered a success and was intended to be a first step in bringing together a diverse group of researchers and code officials. The valuable input received for future efforts will be considered by Drs. Manzello and Himoto when considering the next workshop.

The purpose of this NIST special publication is to document presentations and discussions. Participants from the workshop will prepare papers for publication in a special issue of *Fire Safety Journal*, a leading international archival publication in fire safety science. Dr. Manzello and Dr. Himoto (Kyoto University/Japan) will serve as Co-Guest Editors of the special issue. The publication in a special issue of *Fire Safety Journal* is currently in process.

3. Acknowledgements

The excellent presentations from all the presenters are really appreciated. The valuable input of all participants is warmly appreciated. The U.S. Department of Homeland Security Science and Technology Directorate sponsored the production of this material under Interagency Agreement IAA HSHQDZ-10-X-00288 with the National Institute of Standards and Technology (NIST).

Appendix 1

Attendance List

Name	**Organization**	
Dan Bailey	International Code Council	USA
Nelson Bryner	NIST	USA
Steve Cauffman	NIST	USA
Bert Coursey	Department of Homeland Security (DHS)	USA
Rachel Davidson	University of Delaware	USA
David D. Evans	Cabezon Group, Inc.	USA
A. Carlos Fernandez-Pello	University of California at Berkeley	USA
Ethan Foote	Northern California Fire Prevention Officers/California Fire Chiefs Association	USA
Daisuke Goto	Tokyo University of Science (TUS)	Japan
Ichiro Hagiwara	Building Research Institute	Japan
Anthony Hamins	NIST	USA
Keisuke Himoto	Kyoto University	Japan
Junya Iwasaki	Hokkaido University	Japan
Rik Johnsson	NIST	USA
Takashi Kashiwagi	NIST (Retired)	USA
Eric Letvin	NIST	USA
Sizheng Li	University of Delaware	USA
Samuel L. Manzello	NIST	USA
Alex Maranghides	NIST	USA
Ken Matsuyama	TUS	Japan
Steve McCabe	NIST	USA
Masayuki Mizuno	TUS	Japan
Yuji Nakamura	Hokkaido University	Japan
Tomoaki Nishino	Kobe University	Japan
Yoshifumi Omiya	TUS	Japan
William Pitts	NIST	USA
Stephen Quarles	Institute for Business and Home Safety	USA
James G. Quintiere	University of Maryland	USA
Ron Rehm	NIST (Retired)	USA
L. Ray Scott	Home Safety Foundation	USA
Ai Sekizawa	TUS	Japan
Masahiko Shinohara	National Research Institute of Fire and Disaster	Japan
Albert Simeoni	Worcester Polytechnic Institute	USA

Paul Stregevsky	DHS	USA
Kuma Sumathipala	American Wood Council	USA
Sayaka Suzuki	NIST	USA
Takeyoshi Tanaka	Kyoto University	Japan
Jiann Yang	NIST	USA

Appendix 2

Presentations delivered in this workshop

Urban and Wildland-Urban Interface Fires: A Workshop to Explore Future Japan/USA Research Collaborations

Dr. Samuel L. Manzello
Engineering Laboratory (EL)
National Institute of Standards and Technology (NIST)
Gaithersburg, MD 20899-8662 USA

Dr. Keisuke Himoto
Kyoto University
Kyoto, JAPAN

Japan/USA Workshop
June 27th, 2011

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Wildland-Urban Interface (WUI) Fires

WUI – structures and wildland vegetation coexist

Of the 10 largest fire loss incidents (> $1B) in U.S. history, 5 were WUI fires - all within the last 17 years

Cedar Fire about to engulf the Scripps Ranch residential community

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Wildland-Urban Interface (WUI) Fires

2003
Southern California Fire

2007 Southern California Fire

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U.S. Department of Commerce

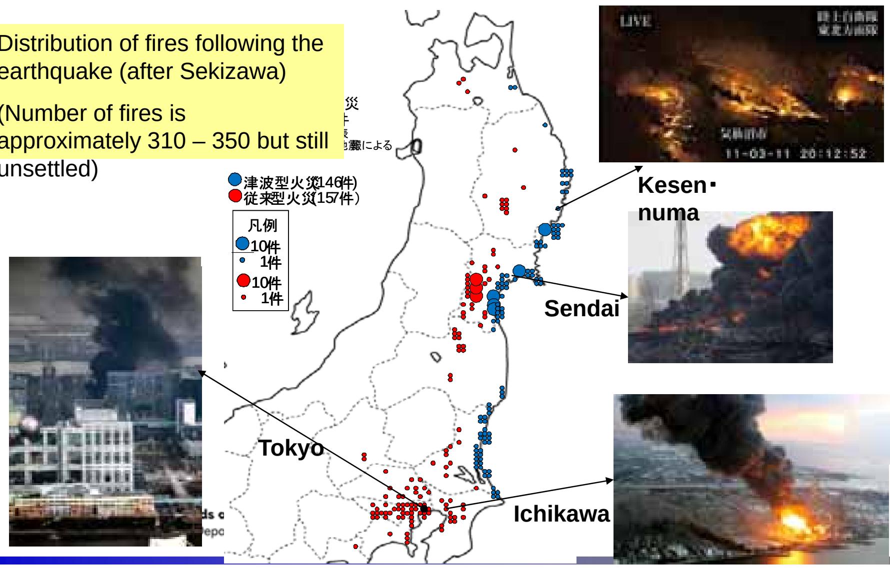
1995 Kobe Earthquake January 17, 1995

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Various Types of Fires Occurred Following the Earthquake

Distribution of fires following the earthquake (after Sekizawa)

(Number of fires is approximately 310 – 350 but still unsettled)



Japanese Perspective

- Formation of Fire Whirls Downwind of Fires
  - Dr. Masahiko Shinohara (National Research Institute of Fire and Disaster)
- Fires in March 11 Tsunami Earthquake
  - Professor Takeyoshi Tanaka, Kyoto University
- Effectiveness and its Limit of Fire-fighting Force in Controlling Post-Earthquake Fires
  - Professor Ai Sekizawa, Tokyo University of Science
- Physics-Based Modeling of Post-Earthquake Fire Spread
  - Dr. Keisuke Himoto, Kyoto University
- Fire Spread Caused by Flame Ejected from An Opening
  - Professor Yoshifumi Ohmiya, Tokyo University of Science
- Evacuation Simulation in the Conflagrations Induced by Kanto Earthquake 1923 and Kyoto Earthquake 20XX
  - Dr. Tomoaki Niishino, Kobe University

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USA Perspective

- The Wildland-Urban Interface (WUI) Fire Problem
  - Mr. Ethan Foote (Northern California Fire Prevention Officers/CALCHIEFS)
- The Wildland-Urban Interface: A Coupled Problem
  - Mr. Alexander Maranghides, NIST
- Ignition of Cellulose Fuel beds by Hot Metal Particles
  - Professor A. Carlos Fernandez-Pello, University of California
- An Urban Fire Simulation (UFS) Model
  - Professor Rachel Davidson, University of Delaware
- Quantify Structure Vulnerabilities to Ignition from Wind Driven Firebrand Showers
  - Dr. Samuel L. Manzello, NIST
- Ignition Regime Maps for Materials Exposed to Firebrand Showers Using NIST Dragon's LAIR Facility
  - Dr. Sayaka Suzuki, NIST
- Wildland fuel burning dynamics
  - Professor Albert Simeoni, Worcester Polytechnic Institute

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Objective:

Fire Spread in urban and WUI fires of great interest to Japan and USA

Explore areas of mutual collaborative interest on these topics

Can common areas be found to provide scientific basis for building codes/standards in both countries?

Other ideas welcome

Provide input on future workshop ideas at end of the day

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Workshop Documentation

NIST will issue a Special Publication
All presentations will be included

Manuscripts will be published in a special issue of
Fire Safety Journal
Guest Editors:
Drs. Manzello and Himoto

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U.S. Department of Commerce

Formation of fire whirls downwind of fires

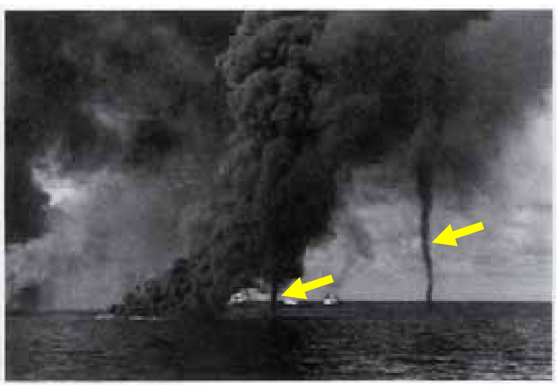
Masahiko SHINOHARA
National Research Institute of Fire and Disaster, Japan

Formation of fire whirls downwind of fires

Contents

Background

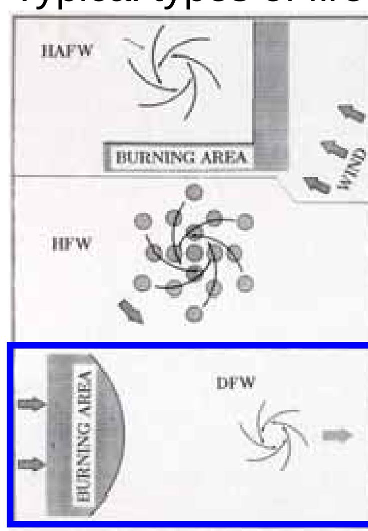
(*Yomiuri shinbun* October .27 2003) (AP)



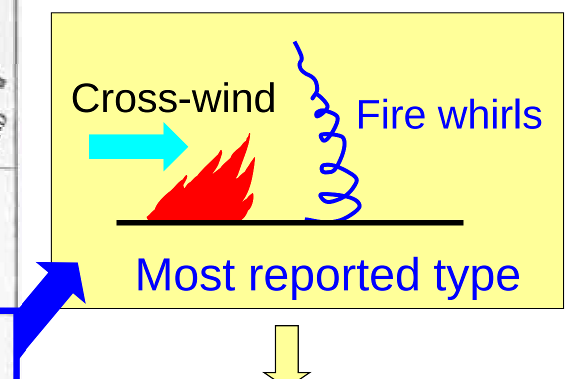
(Wood, V. T., Monthly Weather Review, Vol.120, 1992. Photo by Steve Campbell,1990)

Background

Typical types of fire whirls in fire incidents



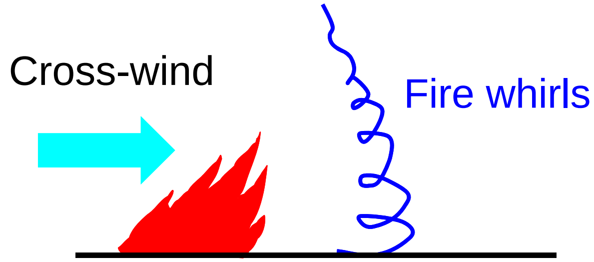
(Soma,S. and Saito,K. *Comb. Flame.* Vol.86. 1991)



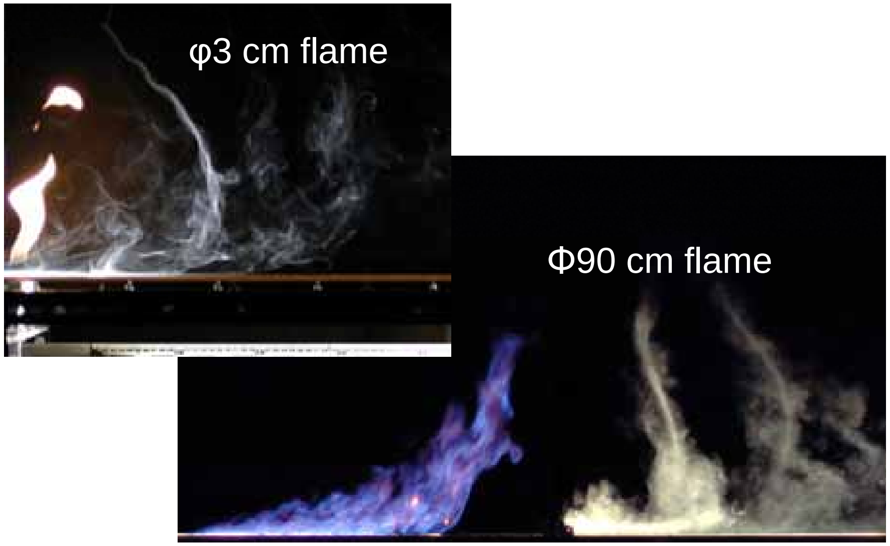
We do not know
why fire whirls occur
in this condition.

Purpose

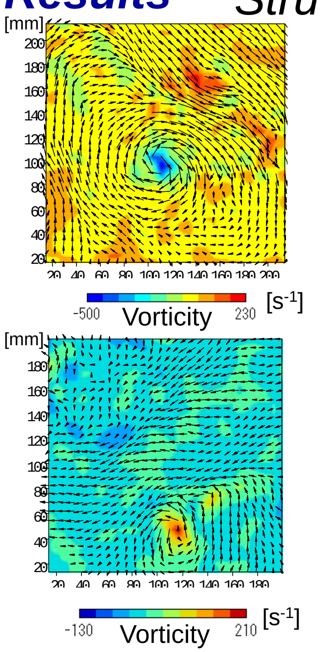
To understand formation mechanisms of fire whirls downwind of fire areas

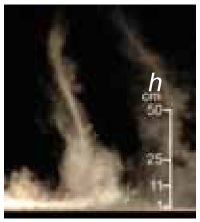


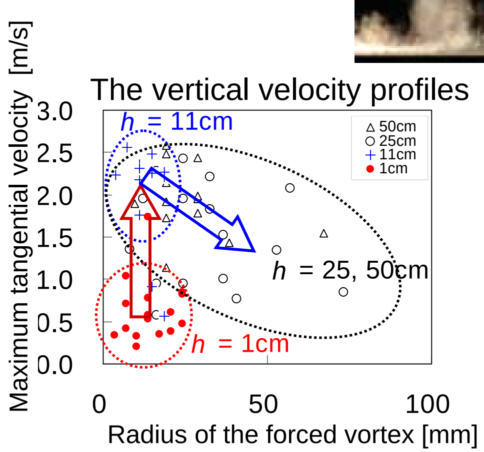
Experiments



Results *Structure of fire whirls*

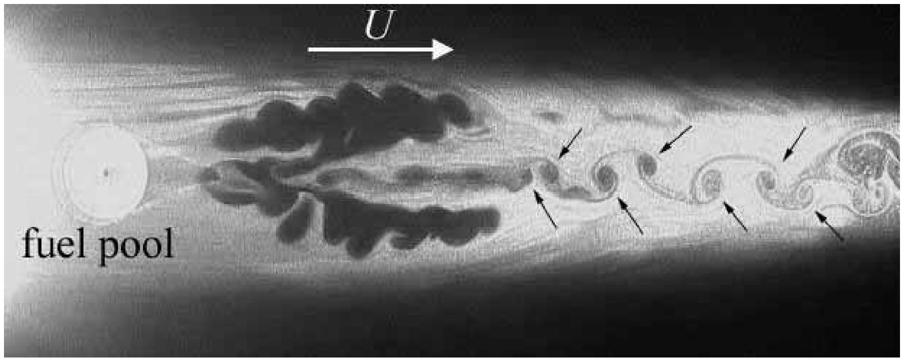






(Shinohara, M., Matsushima, S., 2007)

Results *Structure of fire whirls*



Cross-sectional view U = 0.49m/s h_{sw} =40 mm D = 80 mm Fuel: Methanol

(Shinohara, M. and Kudo, K., 2004)

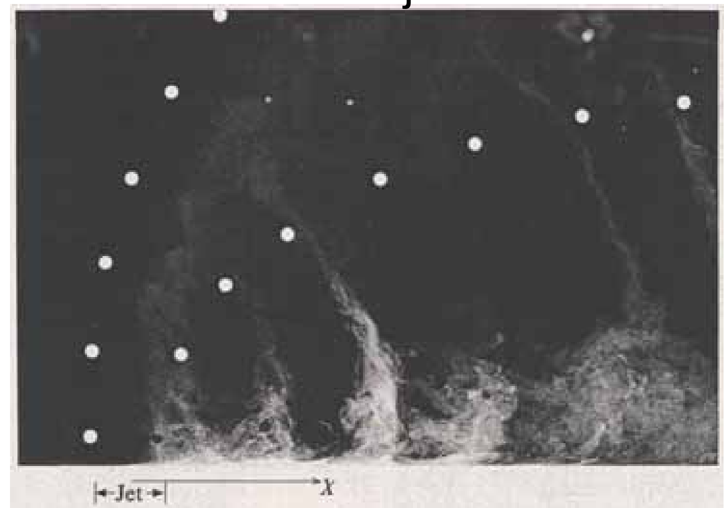
STRUCTURE: Pairs of alternating counter-rotating periodical vortices

≒ Kármán vortex, jet wake

Origin of fire whirls

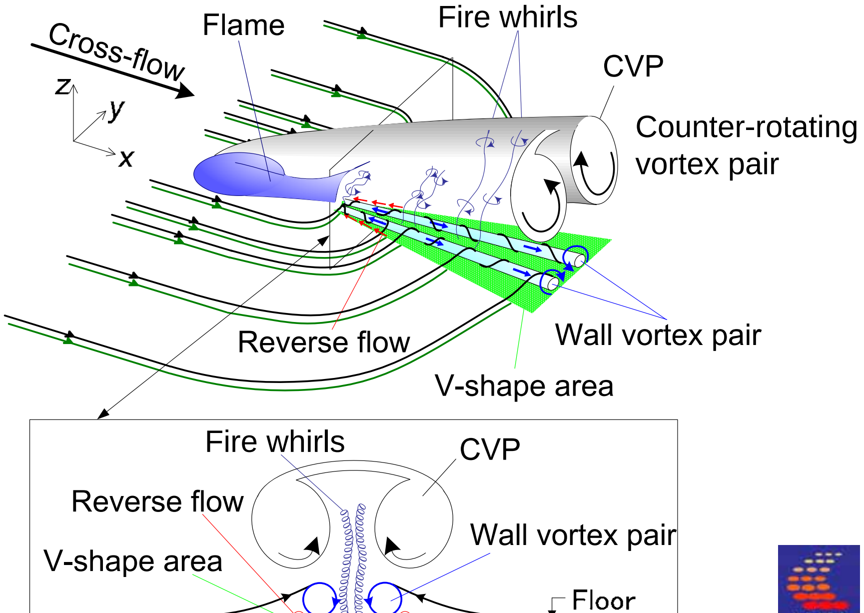
ORIGIN: Velocity boundary layer on the floor, downwind of a flame
≠ Kármán vortex
= Jet wake

Side view of "jet wake"

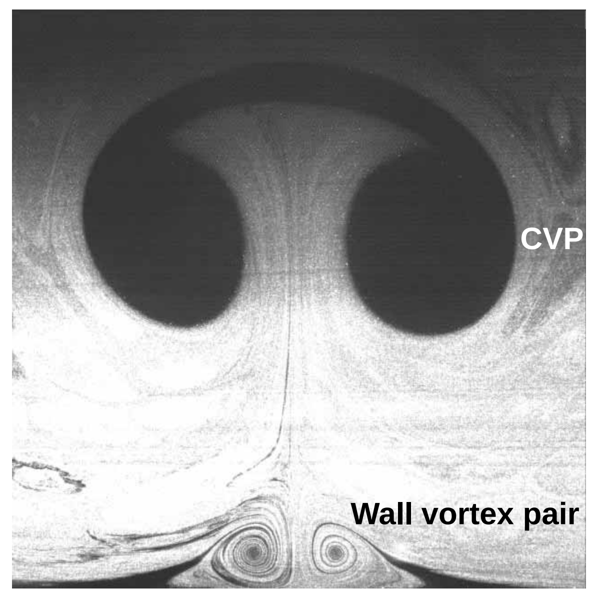


(Fric, T. F. and Roshko, J. Fluid Mech. 279, 1994)

Airflow structure downwind of a flame

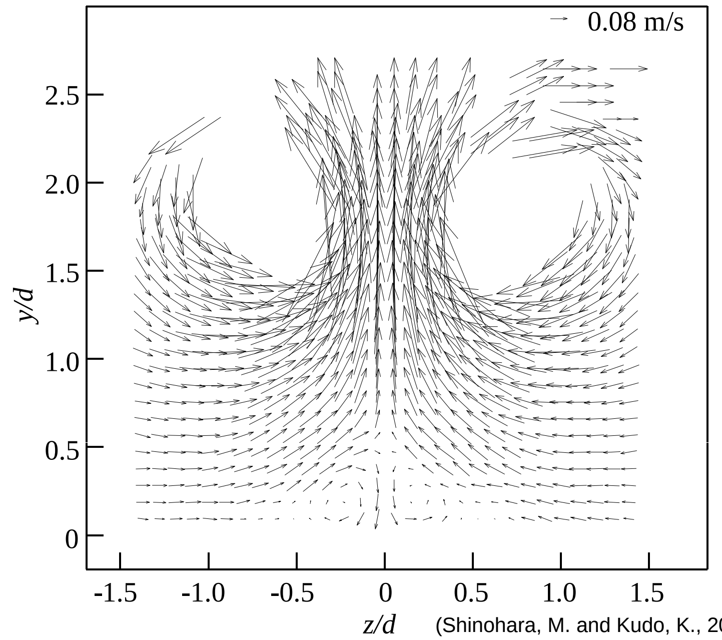


View from the end of the flow



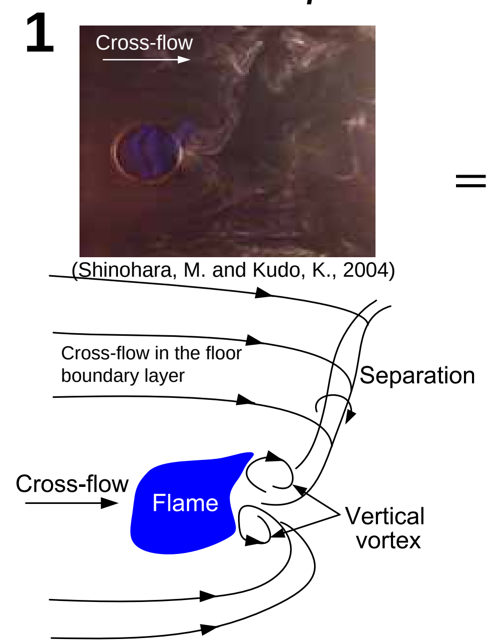
Fuel pool :D=3cm, x=18cm ,U=0.55m/s
(Shinohara, M. and Kudo, K., 2004)

Projected velocity vectors in yz plane

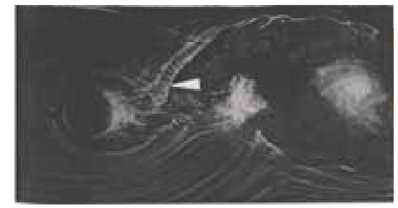


(Shinohara, M. and Kudo, K., 2004)

Formation process for vertical vortices

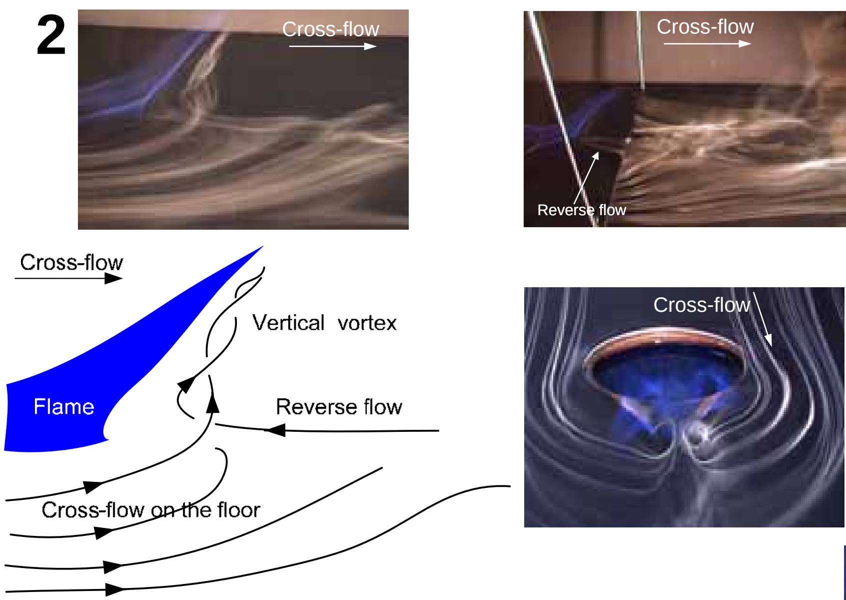


= Jet wake



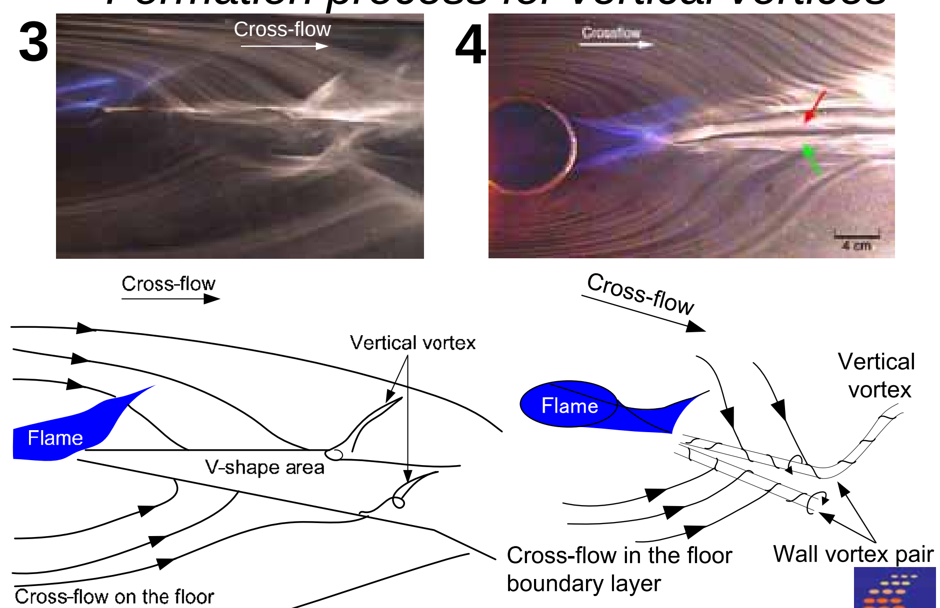
(Fric, T. F. and Roshko, J. Fluid Mech., 1994)

Formation process for vertical vortices



(Shinohara, M. and Kudo, K., 2004)

Formation process for vertical vortices



(Shinohara, M. and Kudo, K., 2004)

Formation process for vertical vortices

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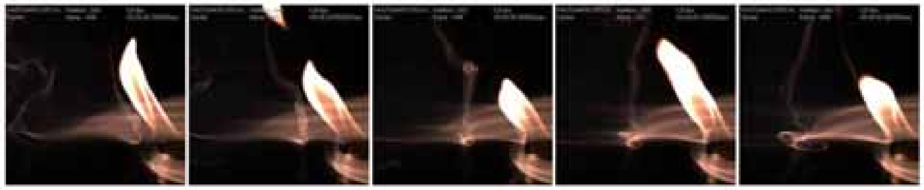

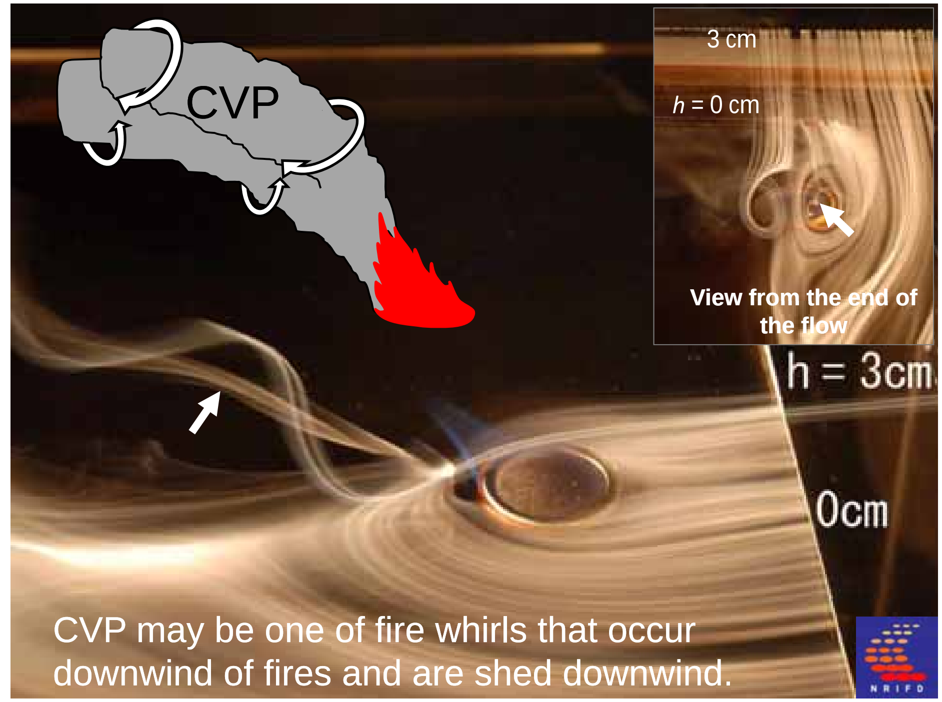

Formation process for vertical vortices

2

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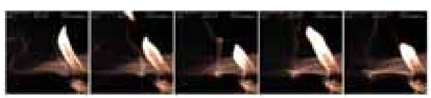
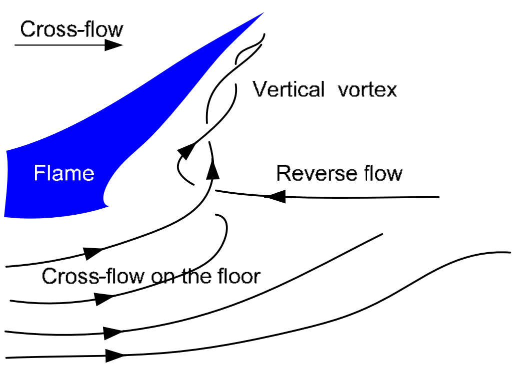
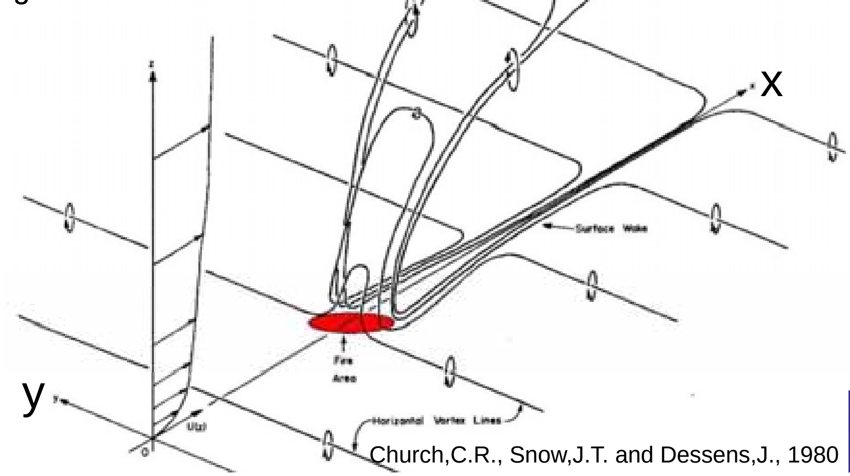




Formation mechanism of a CVP within plumes

Church's hypothesis:

Tilting and subsequent stretching of the **horizontal spanwise vorticity** in the lower surface velocity boundary layer on the ground



Church,C.R., Snow,J.T. and Dessens,J., 1980

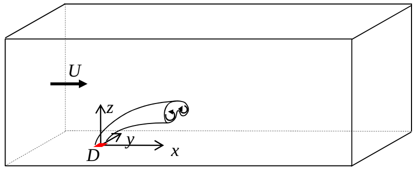
Numerical simulations

Incompressible flows | **Boussinesq approximation**

$$\nabla \cdot \boldsymbol{V} = 0$$

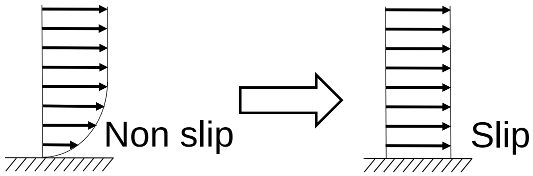
$$\frac{D\boldsymbol{V}}{Dt} = -\nabla P + \frac{1}{Re}\nabla^2 \boldsymbol{V} + \frac{Gr}{Re^2}T\boldsymbol{k}$$

$$\frac{D\boldsymbol{T}}{Dt} = \frac{1}{Re\,Pr}\nabla^2 \boldsymbol{T}$$



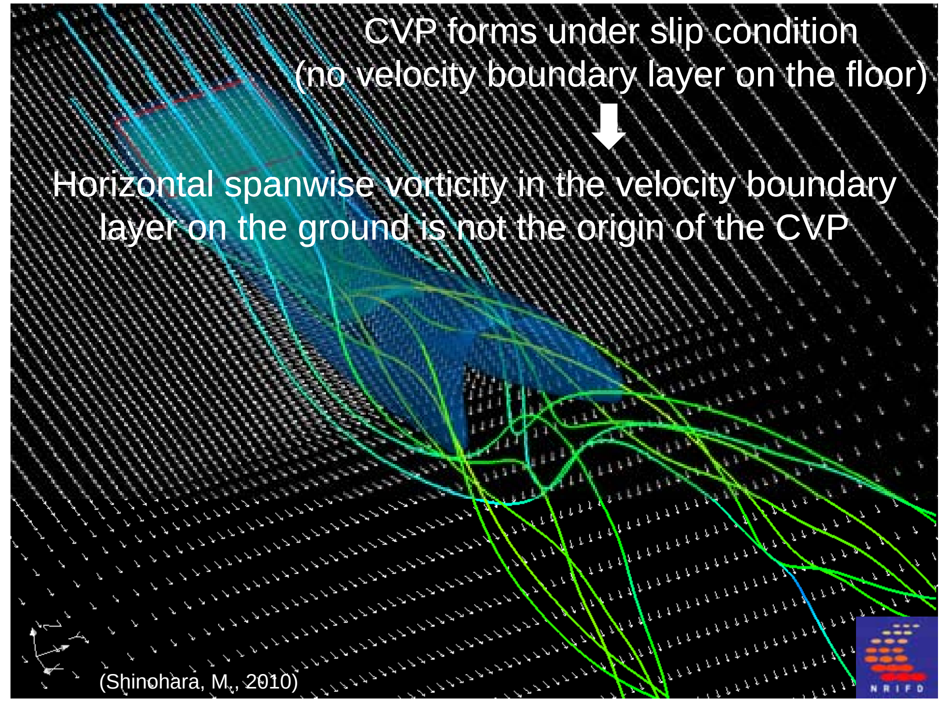
$Pr = 0.717$
$Re = 114$
$Gr = 10^5$

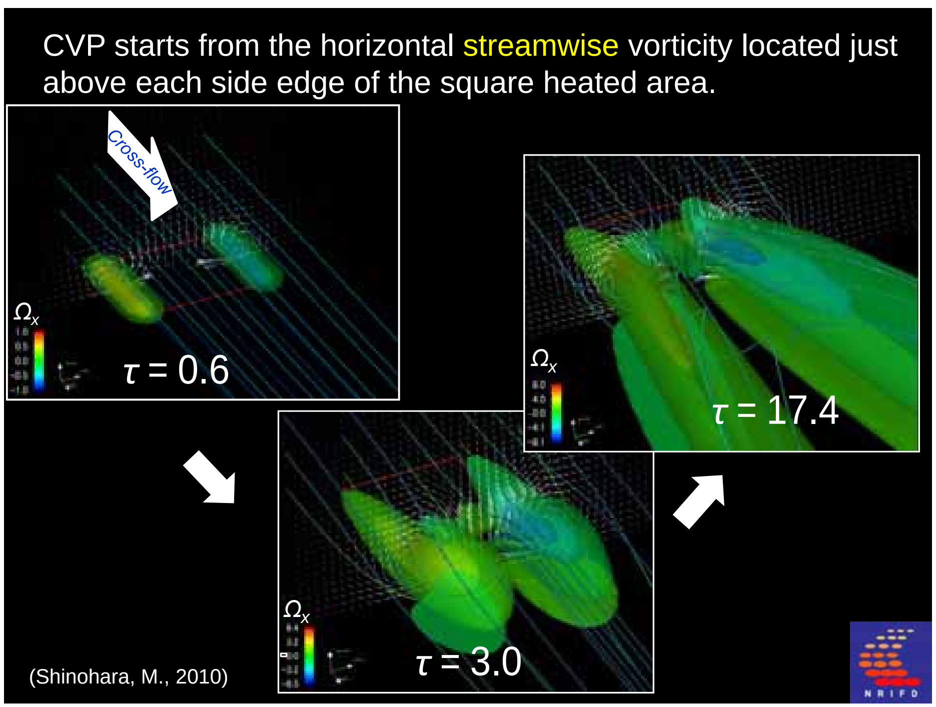
Boundary conditions

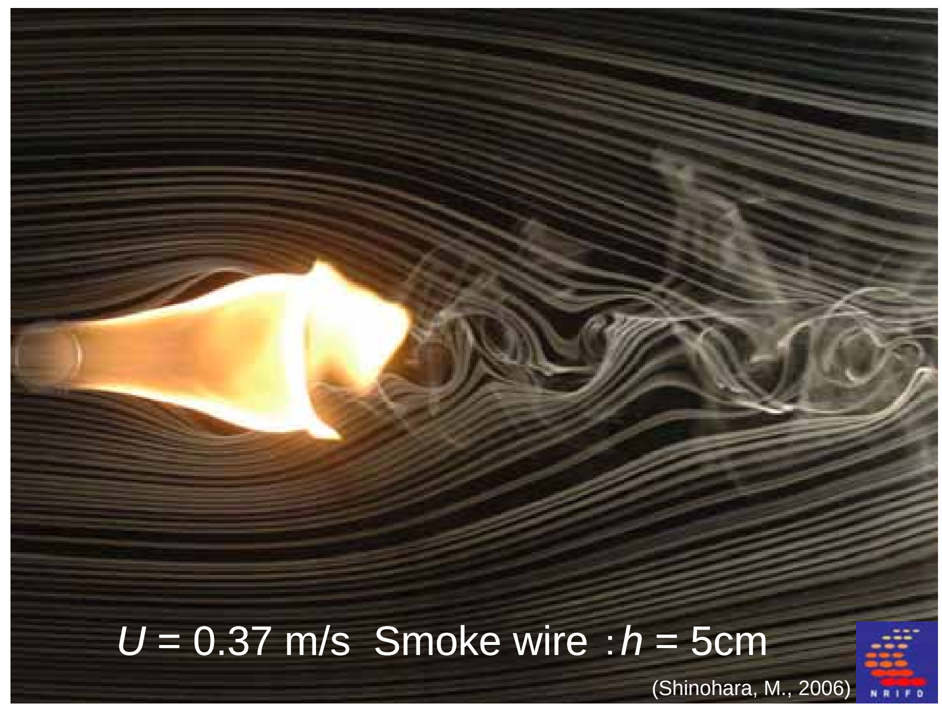


Non slip: $U = V = W = 0$, $\frac{\partial T}{\partial Z} = 0$

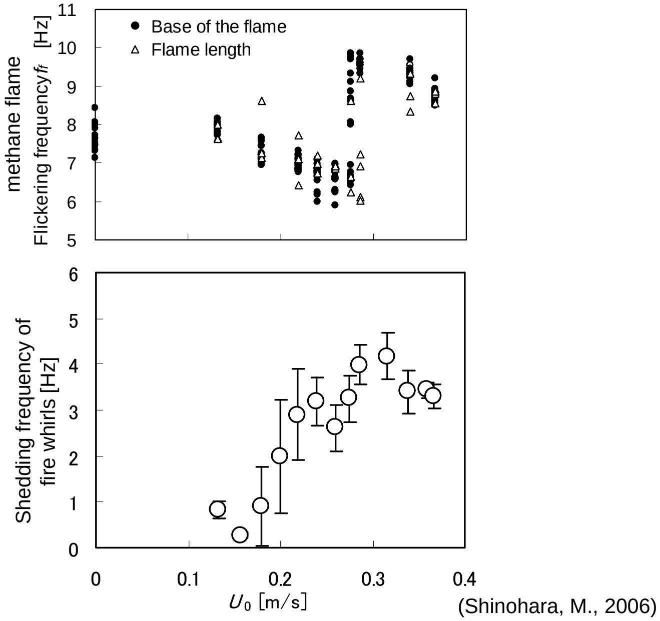
Slip: $\frac{\partial U}{\partial Z} = \frac{\partial V}{\partial Z} = 0$ $W = 0$, $\frac{\partial T}{\partial Z} = 0$







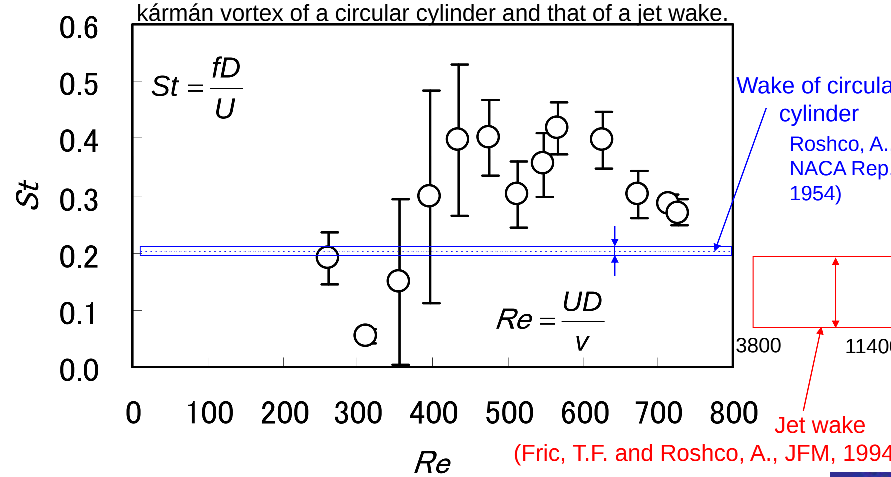
Fire whirls Shedding frequency



(Shinohara, M., 2006)

Variation of Strouhal number of fire whirls with Reynolds number

The range of *St* of fire whirls is much wider than that of a kármán vortex of a circular cylinder and that of a jet wake.

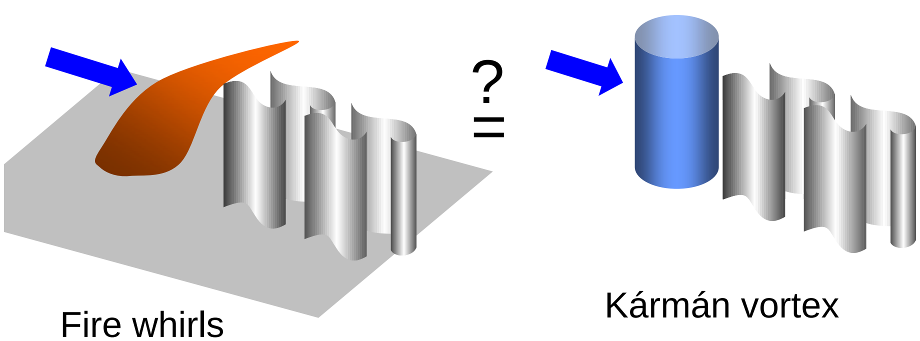


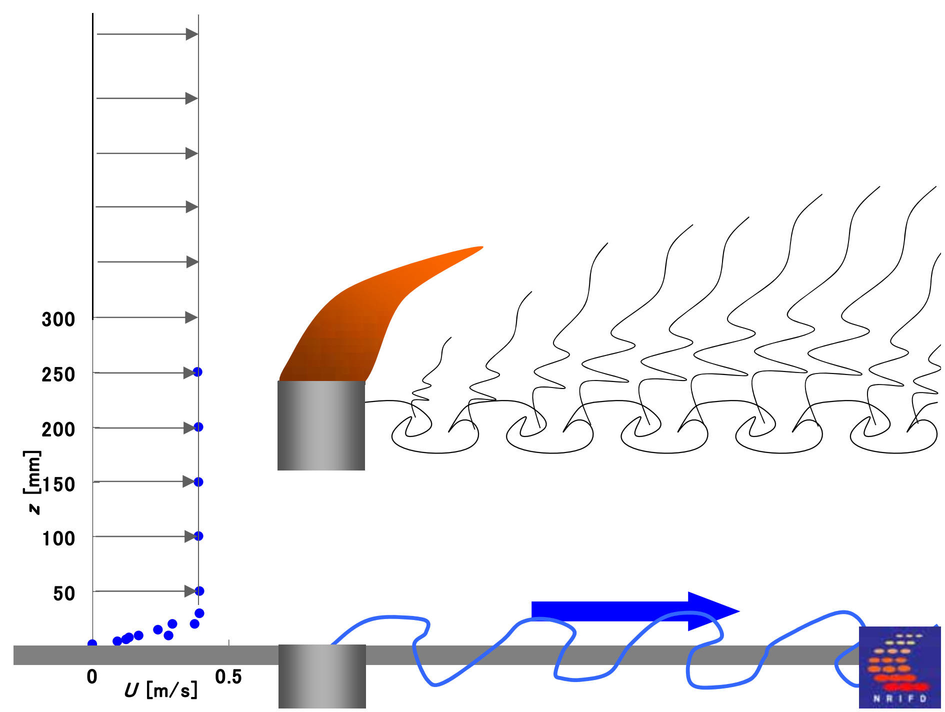
This may be caused by simultaneous occurrence of some formation process.

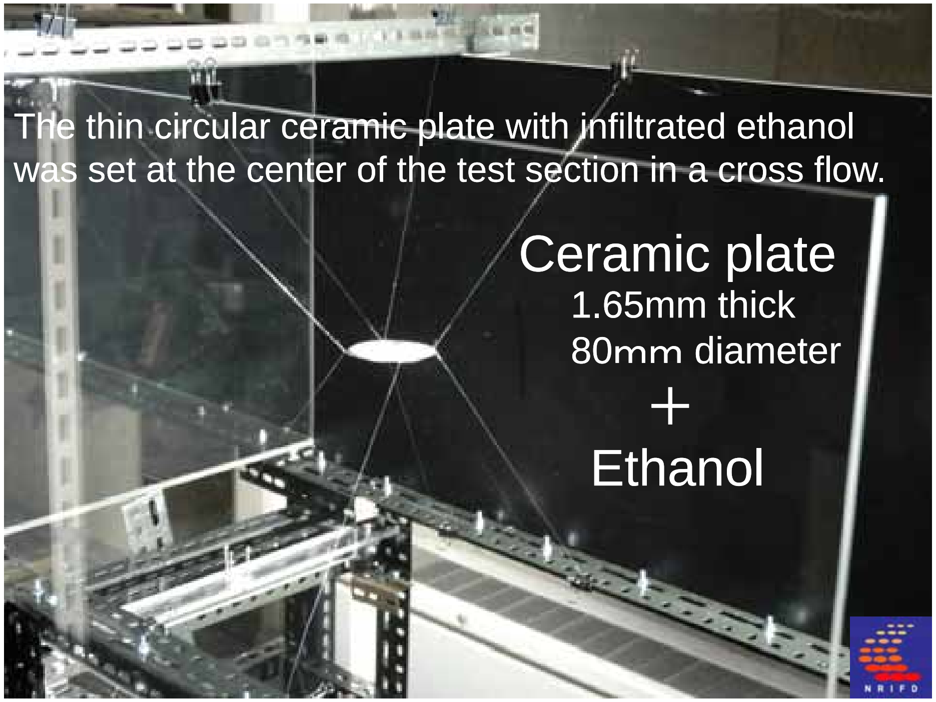
(Shinohara, M., 2006)

Effects of the ground on formation of fire whirls

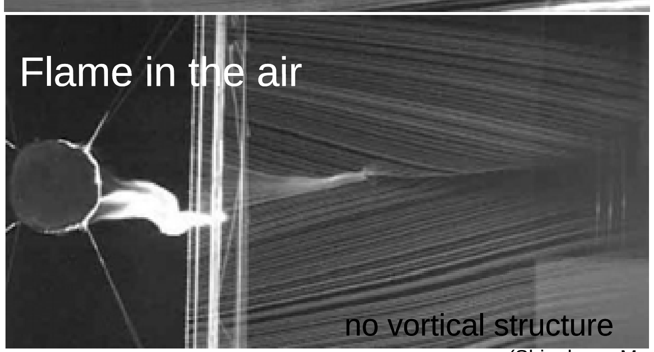
Formation mechanism



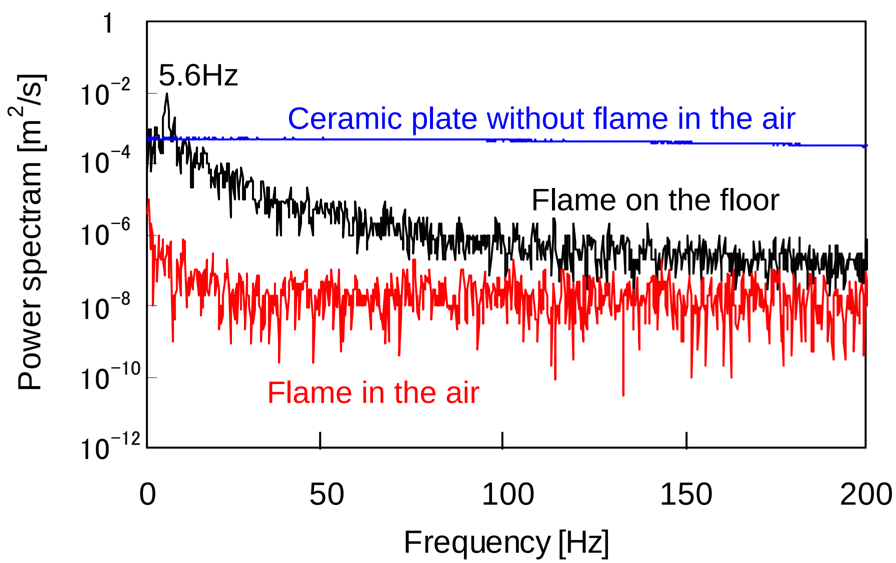




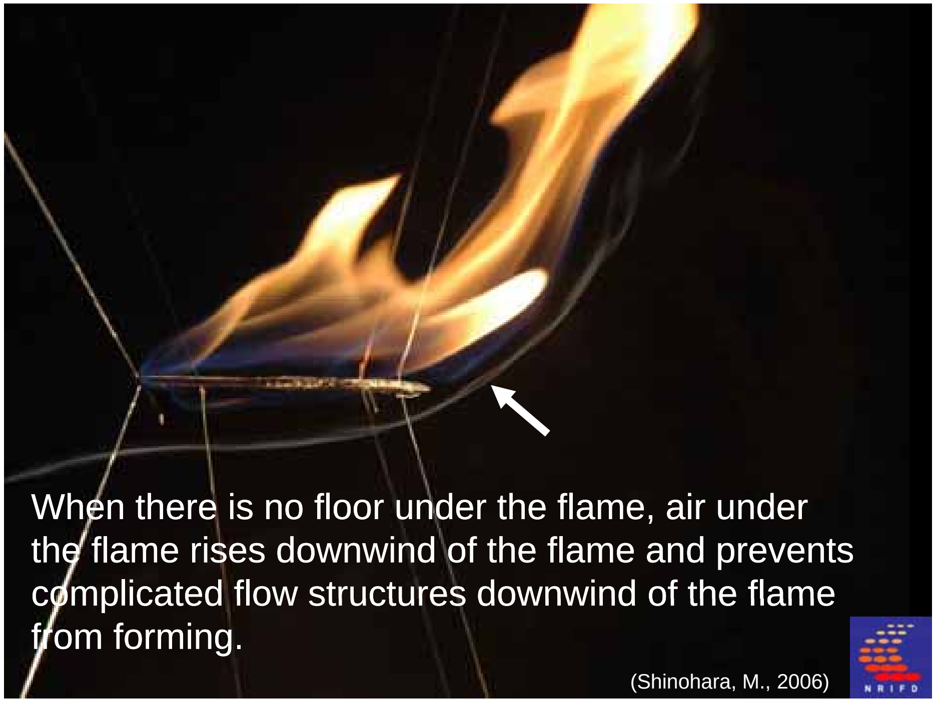
(Shinohara, M., 2006)



(Shinohara, M., 2006)



(Shinohara, M., 2006)



When there is no floor under the flame, air under the flame rises downwind of the flame and prevents complicated flow structures downwind of the flame from forming.

(Shinohara, M., 2006)

Conclusion

1. Fire whirls that occur downwind of a flame in a cross flow start from the velocity boundary layer on the floor.

2. 5 types of the beginning of vertical vortex was found:
   1) the separation of the flow in the velocity boundary layer on the floor.
   2) the combination of the reverse flow and cross-wind
   3) starting from the rim of the V-shaped area
   4) wall vortex pair
   5) CVP of the plume of a flame

3. When there was no floor under the flame, there were no vortical structures such as fire whirls downwind of a flame and air under the flame rose downwind of the flame.
   This result suggests that the complicated flow structure in the velocity boundary layer on the floor have an important role for fire whirls to form.

Conclusion

4. The flame flickering frequency in a cross-flow did not coincide with the fire whirl shedding frequency.

5. The range of the Strouhal number of fire whirls downwind of a flame is much wider than that of either the Kármán vortex wake in a flow past a circular cylinder or a jet wake. This may be caused by simultaneous occurrence of some formation process.

6. CVP originates not from horizontal spanwise vorticity in the velocity boundary layer on the floor around the heated area, but from horizontal streamwise vorticity just above each side of the heated area.

References

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・Shinohara, M., Matsushima, S., Proc. of 2007 ASME IMECE2007-41711, 2007.
・Shinohara, M., Proc. of the International Heat Transfer Conference, IHTC14-23283, 2010.

Acknowledgement

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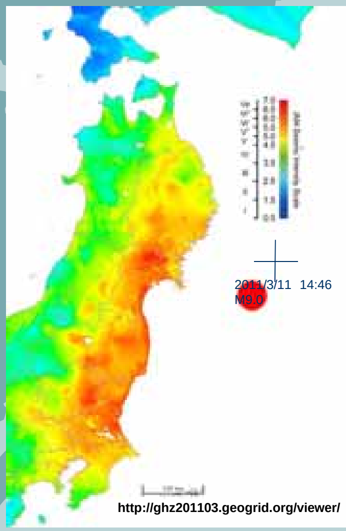
We thank Prof. Kazuhiko Kudo from Hokkaido University and colleagues at NRIFD for their helpful advice and discussions.

Fires in March 11 Tsunami Earthquake

Tanaka Takeyoshi
DPRI, Kyoto University



1. Earthquake

① Date and Time: March 11, 2011
② Epicenter: Off Sanriku(38. 1° N、142. 9°E)
Depth 24km
④ Magnitude (moment): 9. 0

2. Damages

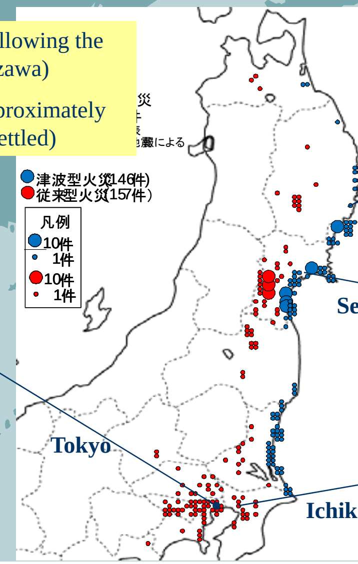
①Human Damage (6/11)
- Deaths: 15,405
- Missing: 8,095
- Casualties: 5,365

②Houses and Buildings (6/9)
- Totally destroyed: 112,528
- Severely damaged: 75,463
- Partially damaged: 344,551

Various Types of Fires Occurred Following the Earthquake

Distribution of fires following the earthquake (after Sekizawa)

(Number of fires is approximately 310 – 350 but still unsettled)

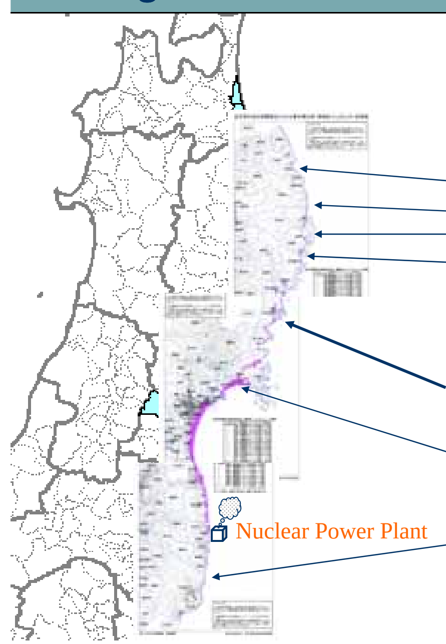


Fire Occurrence Rate in Inland Area

Majority of building damages was caused by tsunami. The prefectures in the table were relatively unaffected by the tsunami
- ●Building damages by shaking were relatively light for the level of seismic intensities
- ●Fire occurrence rates were small considering the level of seismic intensities
- ●Fire occurrence rates relative to the numbers of damaged buildings were very high
- ●It is necessary to reconsider the estimation method of fire occurrence rate in earthquakes

Prefecture	Damage of buildings		Number of fires	Damage buildings/Fires	
	Totally destroyed	Severely damaged		Totally destroyed	Totally destroyed ＋Severe damage
Ibaraki	1632	9161	37	44	292
Chiba	728	2733	14	52	247
Saitama	7	41	13	0.54	3.7
Tokyo	9	113	34	0.26	3.6
Kanagawa	0	11	6	0	1.8
Kobe	67000		176	380	

Large Scale Fires Following The Tsunami



All the large scale conflagrations occurred along the submerged coastal area, which is totaled to be 400 km^2.

Iwate prefecture
- Noda-mura
- Taro-cho (Miyako-shi)
- Yamada-cho
- Oh・tsuchi-cho

Miyagi prefecture
- Shishi・ori area (Kesen・numa-shi)
- Uchinowaki area (Kesen・numa-shi)
- Oh・ura area (Kesen・numa-shi)
- Oh・shima area (Kesen・numa-shi)
- Kadowaki area (Ishi・no・maki-shi)

Fukushima prefecture
- Kunohama (Iwaki-shi)

（Not yet investigated due to the proximity to Fukushima nuclear power plant)

Cause of Large Conflagration in the Area Attacked by Tsunami

The cause of the large conflagrations is complex, involving many factors such as follows:

- Debris transported and diffused by Tsunami
- Oil spilled from broken oil containers
- Ignition of electric devices soaked with salt water
- Difficulty in fire suppression

Debris Conveyed by Tsunami

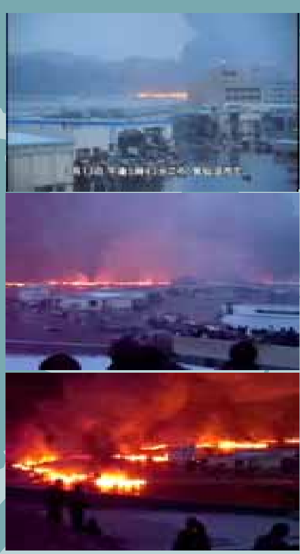
Burned area in Oh・tsuchi-cho (after Yamada lab., Univ. of Tokyo)

- Tsunami leaves various debris, e.g. destroyed houses, cars, household goods.
- The debris cover ground surface indifferent of building sites, streets, open spaces.

Burned debris in Oh・tsuchi-cho

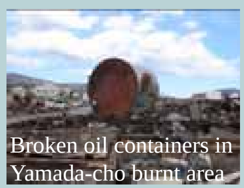
Debris in Kadowaki area (Ishinomaki-shi)

Breakage of Oil Containers and Spillage of Oil

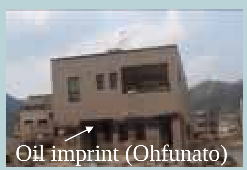


Spread of burning oil in Kesen・numa bay

- In Kesen・numa, 22 oil containers were destroyed by Tsunami and oils were drifted in the bay and submerged areas
- Similar problems happened in other cities, which caused conflagrations in some of the cities
- Oil imprints are seen on building walls and debris even where there was no fire



Broken oil containers in Yamada-cho burnt area



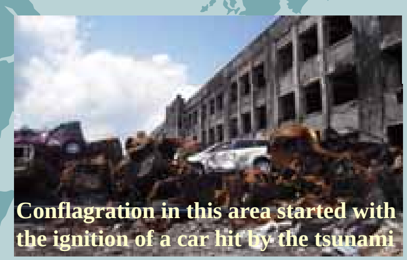
Oil imprint (Ohfunato)

Broken oil containers in Kesen・numa

Ignition by Short Circuit Suspected

- Ignitions by short circuit of electric devices soaked with sea water are suspected
- Houses and cars burning by unknown causes are often seen in drifting debris
- Ignition of cars were witnessed at several scenes

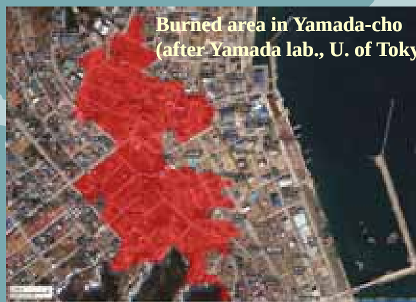
At Hitachi harbor, 1300 cars for export were burned by the fire spread from an ignited car



Conflagration in this area started with the ignition of a car hit by the tsunami

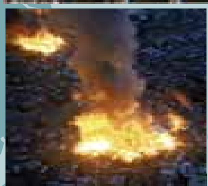
A number of burned cars are seen almost every place of fire

Difficulty in Fire Suppression



Fire suppression was made difficult by:

- Hindrance of fire fighters' access by debris and water covering streets
- Damage of fire fighting resources, e.g. hydrants, fire engines
- Threat of tsunami



http://www.yomiuri.co.jp/feature/graph/201012wind/garticle.htm?ge=863&gr=3497&id=105147

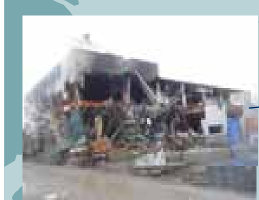
The conflagration in Yamada-cho was only 2 small fires that would have been quickly extinguished if it were normal time, but fire fighting means had been lost despite of plenty of water existed.

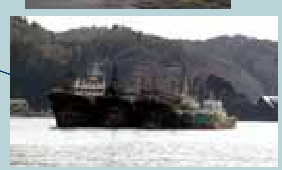
Fire Hazard to Tsunami Refuges

- As a tsunami prone area, each city had designated schools etc. as tsunami refuges for residents
- But the fire hazards had not been considered
- Residents had to abandon refugees because of fires following the tsunami

Damages to Industries by Fire

- As off-Sanriku ocean is among the world richest fishery water, fishery related industries are the main industry of this region
- Many industry facilities and reinforced buildings that survived tsunami were destroyed by fire
- In Kesen・numa, a number of ships were destroyed by fire caused by oil fire drifting the bay

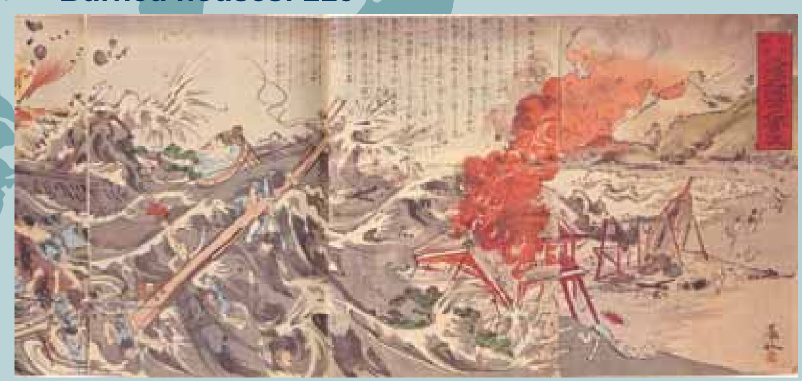




Are Fires in Tsunami Unusual?

Meiji Sanriku Earthquake Tsunami (1896)

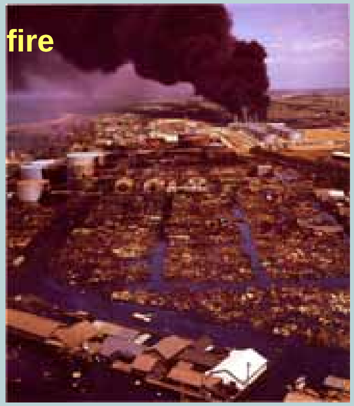
- Seismic Intensity: 2～3
- Tsunami height: 15～20m (North Sanriku)
- Deaths: 22,000
- Burned houses: 216



Are Fires in Tsunami Unusual?

Niigata Earthquake (1964)

- The earthquake was followed by a tsunami
- An oil container exploded and spilled oil drifted to residential area with tsunami
- 286 houses were burned by the fire



Are Fires in Tsunami Unusual?

S-W off Hokkaido Earthquake (1993)

- Deaths: 240
- Burned houses: 189
- Tsunami at Aonae area, Okushiri island was followed by fire

Aonae area on fire

Aonae area devastated after tsunami and fire

Isn't that we have overlooked the usual nature of tsunami fires?

- A tsunami in the past demonstrated one aspect of its fire each
- The last tsunami revealed many aspects of fires all together

On behalf of Japanese people who suffered from the tsunami, I would like to thank you all for the sincere sympathies you have extended to us. Thank you so much indeed!

何人も一島嶼(とうしょ)にてはあらず、	No man is an island
其(そ)は本土そのもの;	entire of itself;
人は皆、陸(くが)の一塊(ひとくれ)、	every man is a piece of the continent,
本土の一片(ひとひら)	a part of the main.
一塊の土を海の洗い去れば、	If a clod be washed away by the sea,
其は祖国の失せるなり	our country is the less
ジョン ダン:「誰がために鐘は鳴る」より	from 'For whom bell toll', John Donne (slightly changed)

Workshop on Wildland and Urban Interface Fire
June 27, 2011 at NIST

Effectiveness and its Limit of Fire-fighting Force in Controlling Post-earthquake Fires

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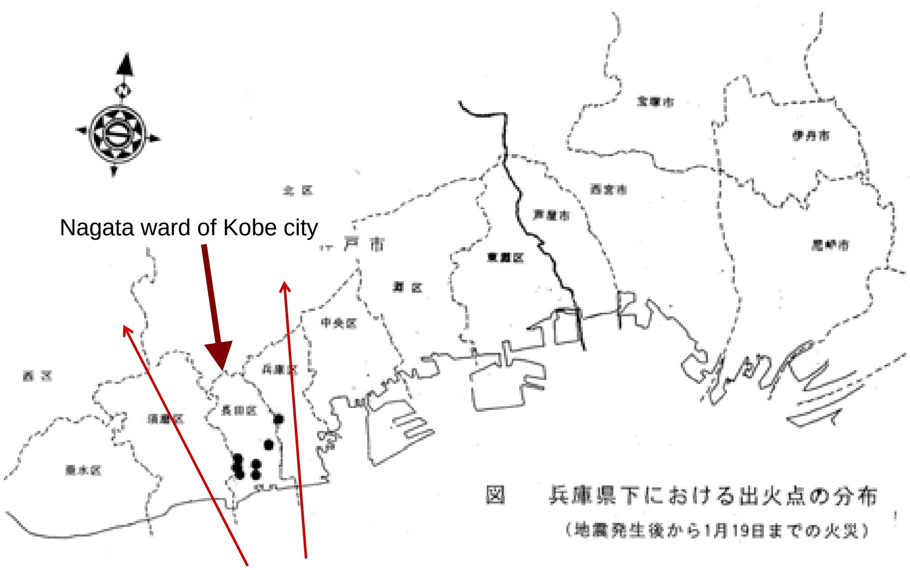
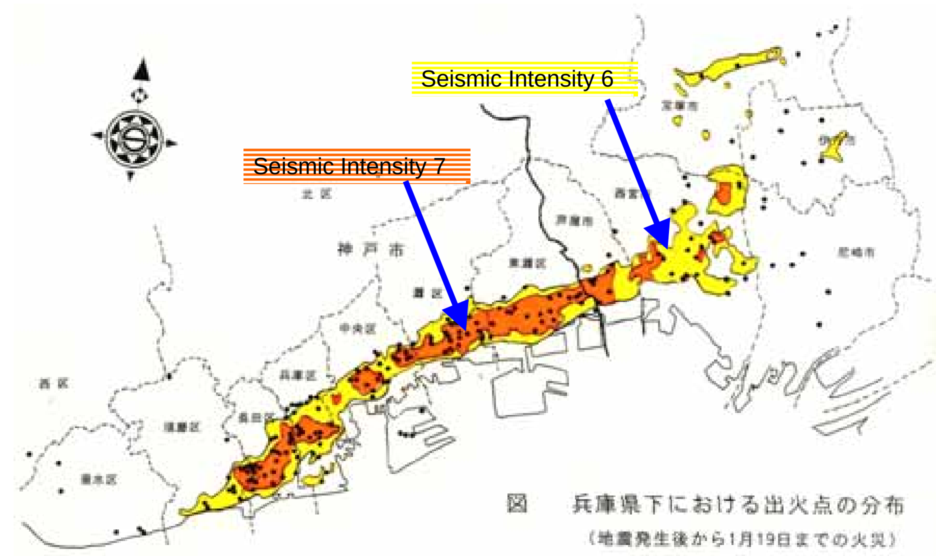
1995 Kobe Earthquake January 17, 1995



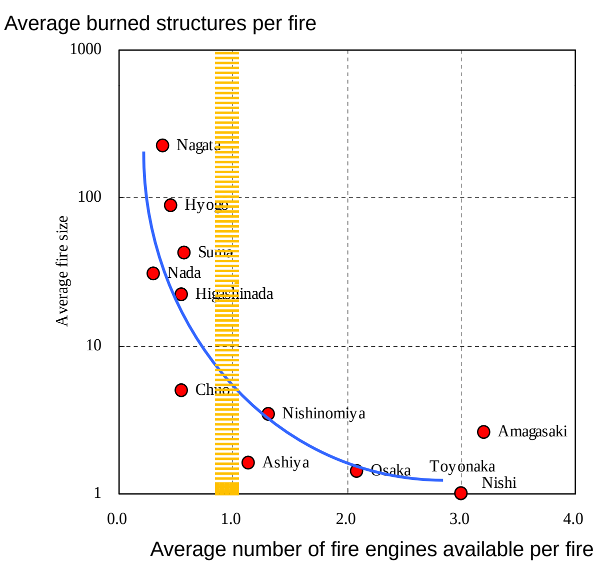
Regional distribution of very large post-earthquake fires that exceeded 10,000 m^2 in the 1995 Kobe earthquake.

1995 Kobe Earthquake January 17, 1995

Regional distribution of all post-earthquake fires including small fires in the 1995 Kobe earthquake.



Regional distribution of all post-earthquake fires and the areas by level of seismic intensity in the 1995 Kobe earthquake.



Relation between the average fire size and the number of fire engines dispatched per fire at the Hanshin-Awaji Earthquake by region.

Real-time Simulation System for supporting fire-fighting operation against post-earthquake fires

Two purposes of developing this system for supporting fire-fighting operation

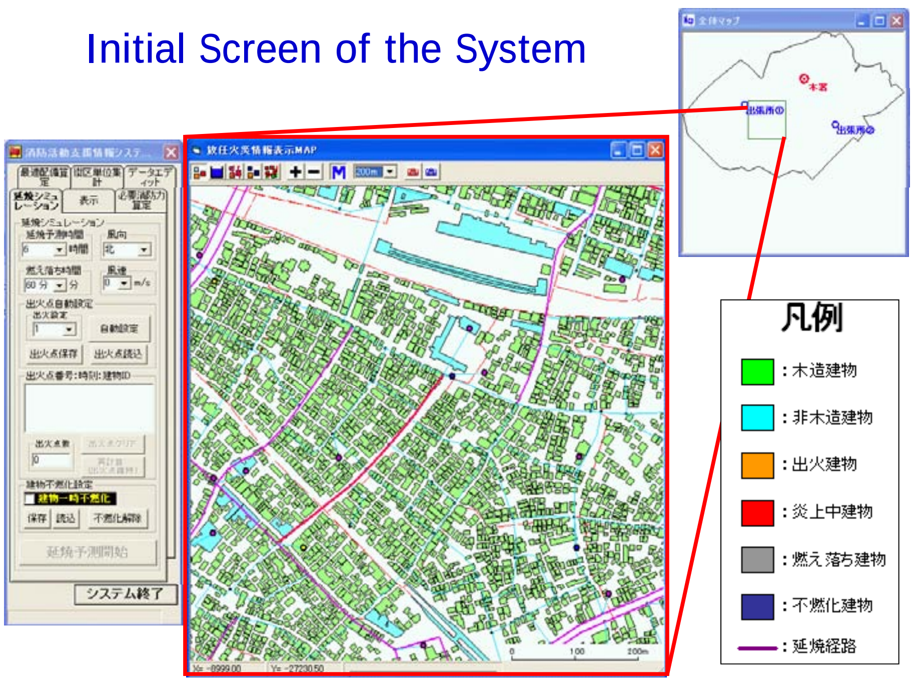
- To maximize the performance of fire brigades' operation for fire-fighting against simultaneous multiple fires with limited existing resources by the quick prediction of fire spread and the optimum deployment of fire engines.
- To demonstrate the certain threshold or the limit of capacity of fire brigades in controlling multiple post-earthquake fires even with its optimum operation based on the case studies using this system.

System for supporting fire-fighting operation against post-earthquake fires

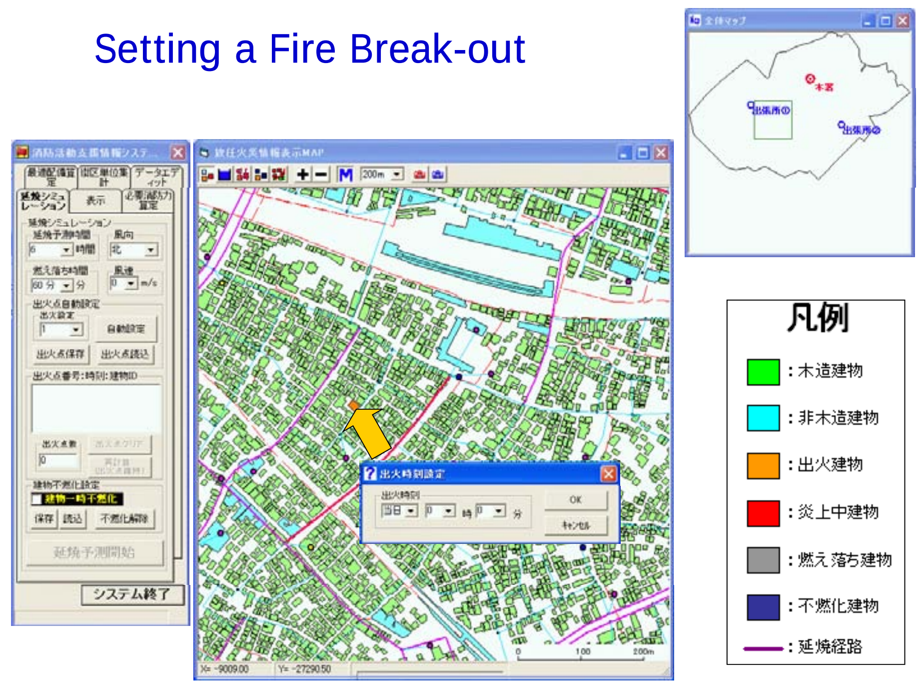
has the following three functions;

- Real-time simulation system for predicting fire spread.
- Prompt estimate of required resources such as # of fire engines and water supply to control fires.
- Prediction of the optimum deployment of fire engines against simultaneous multiple post-earthquake fires together with the resulting performance of that operation at some certain lapse time.

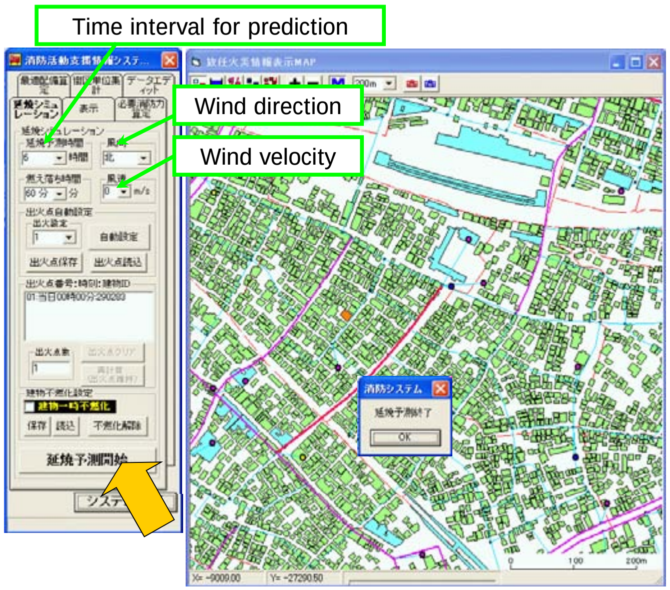
Initial Screen of the System

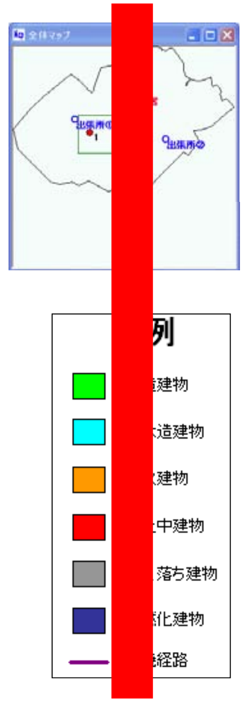


Setting a Fire Break-out

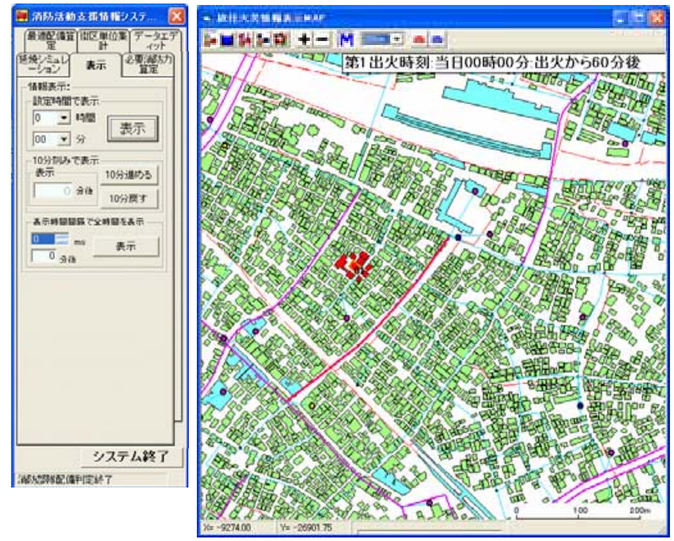


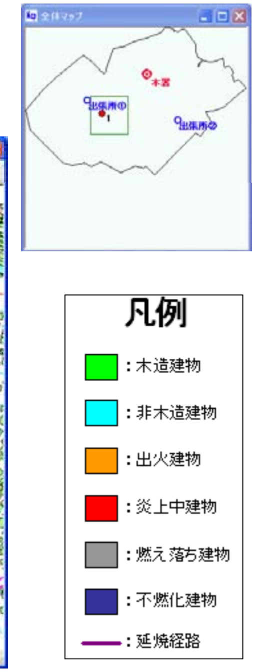
Prediction of Fire Spread



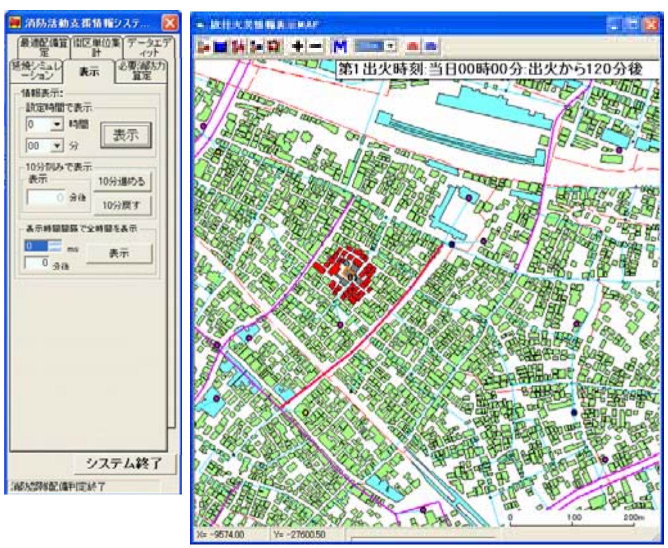


Estimated Fire Spread at 60 min. after Break-out

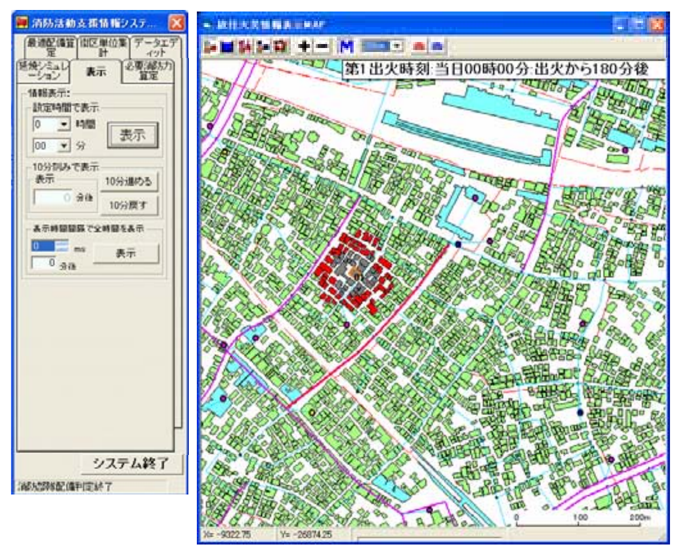


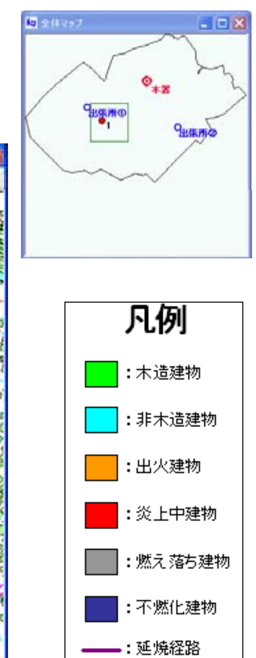


Estimated Fire Spread at 120 min. after Break-out

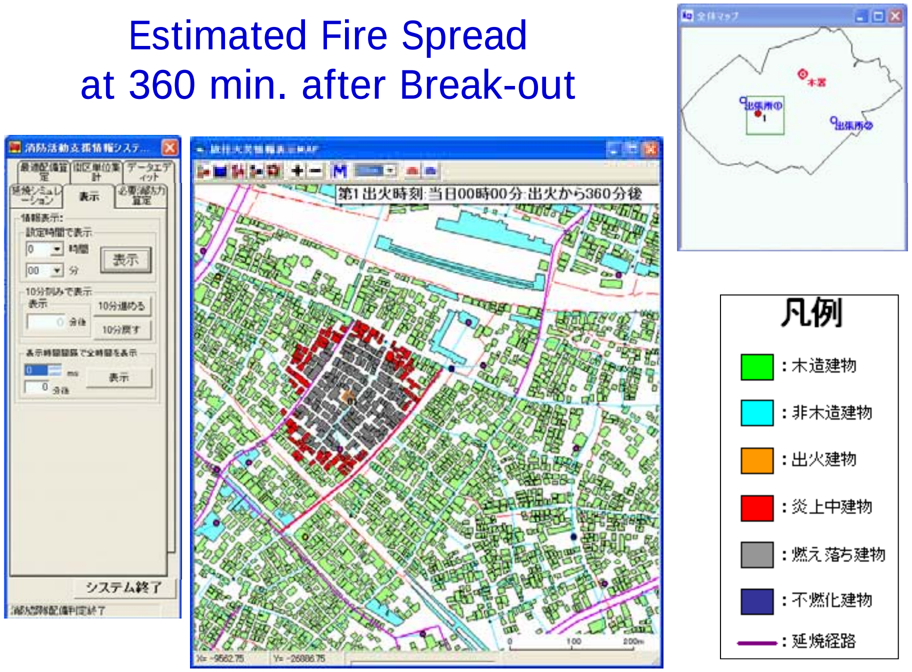


Estimated Fire Spread at 180 min. after Break-out

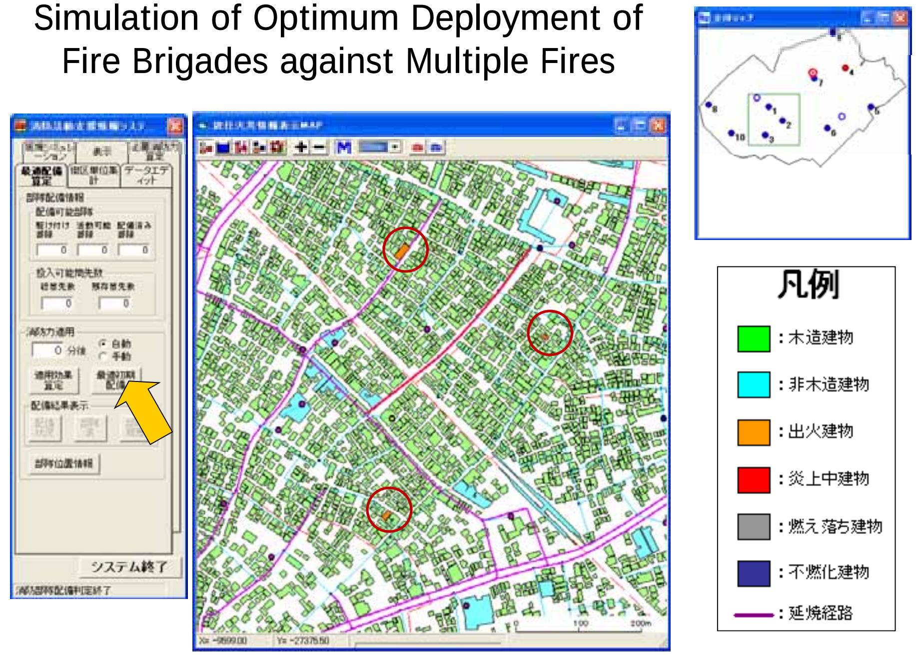




Estimated Fire Spread at 360 min. after Break-out

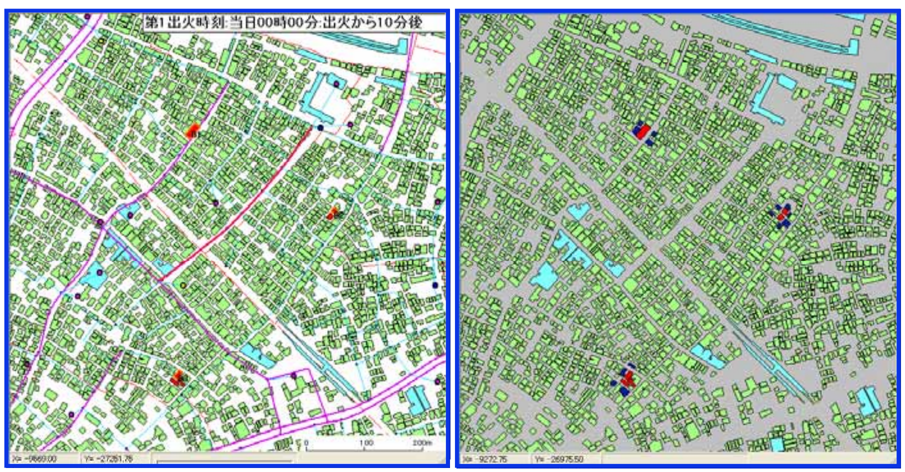


Simulation of Optimum Deployment of Fire Brigades against Multiple Fires



10 min. after Optimum Deployment of Fire Brigades

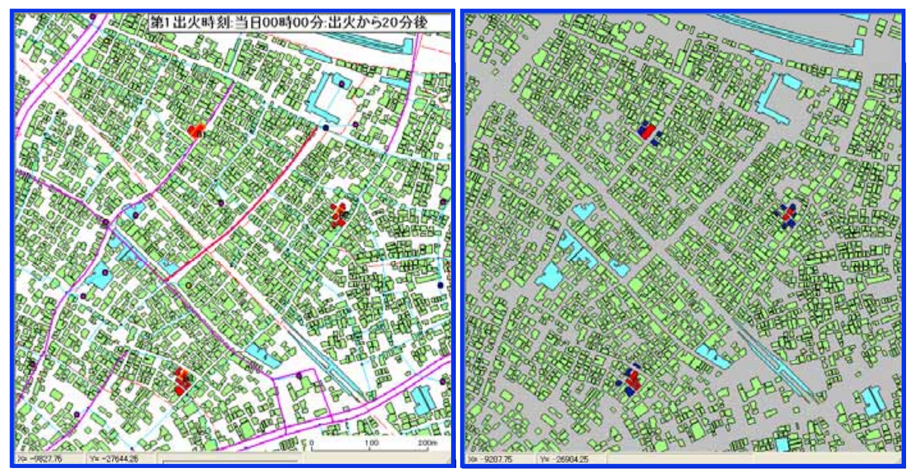
Without attendance | With optimum deployment



放任火災 | 最適運用

20 min. after Optimum Deployment of Fire Brigades

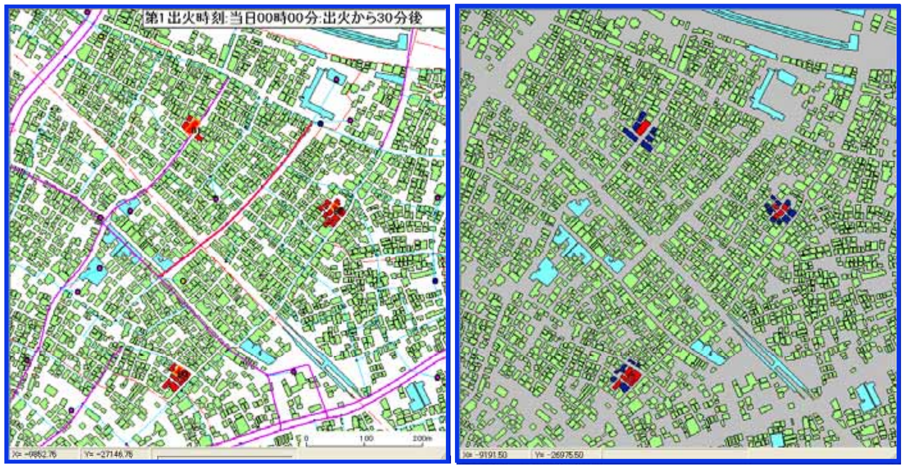
Without attendance | With optimum deployment



放任火災 | 最適運用

30 min. after Optimum Deployment of Fire Brigades

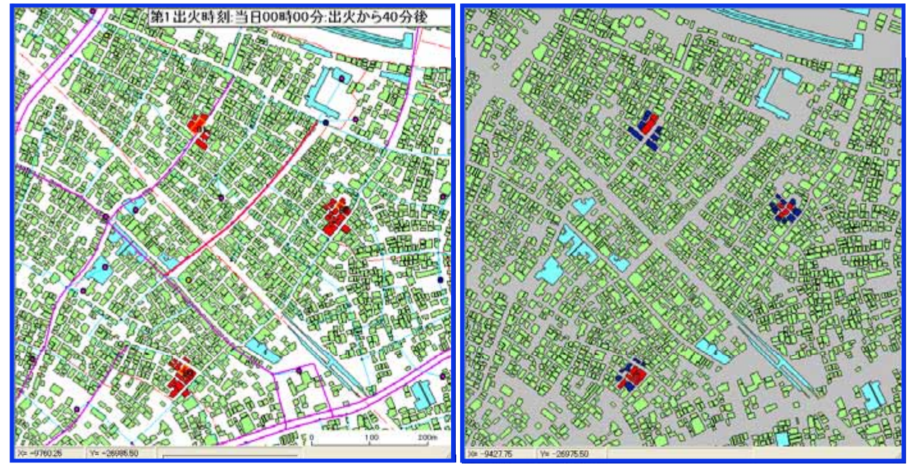
Without attendance　　With optimum deployment



放任火災　　最適運用

40 min. after Optimum Deployment of Fire Brigades

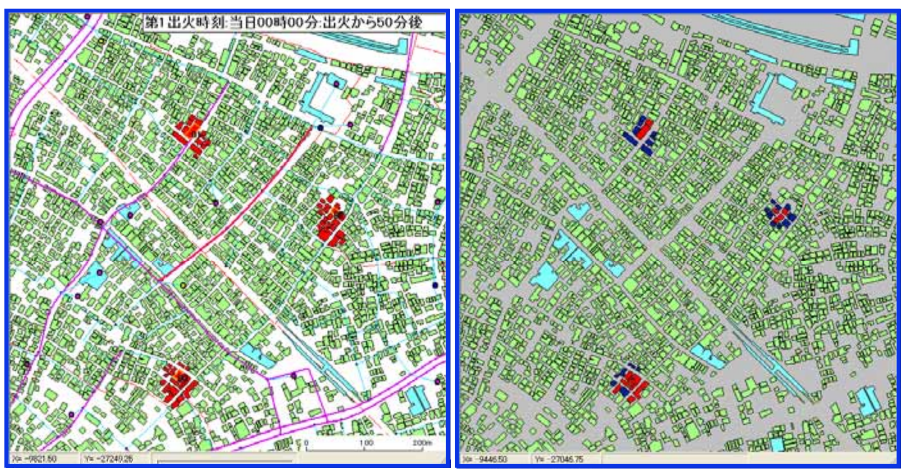
Without attendance　　With optimum deployment



放任火災　　最適運用

50 min. after Optimum Deployment of Fire Brigades

Without attendance　　With optimum deployment



放任火災　　最適運用

List of Allocation of Fire Engine Companies for Optimum Deployment

火災ごとの部隊配備状況

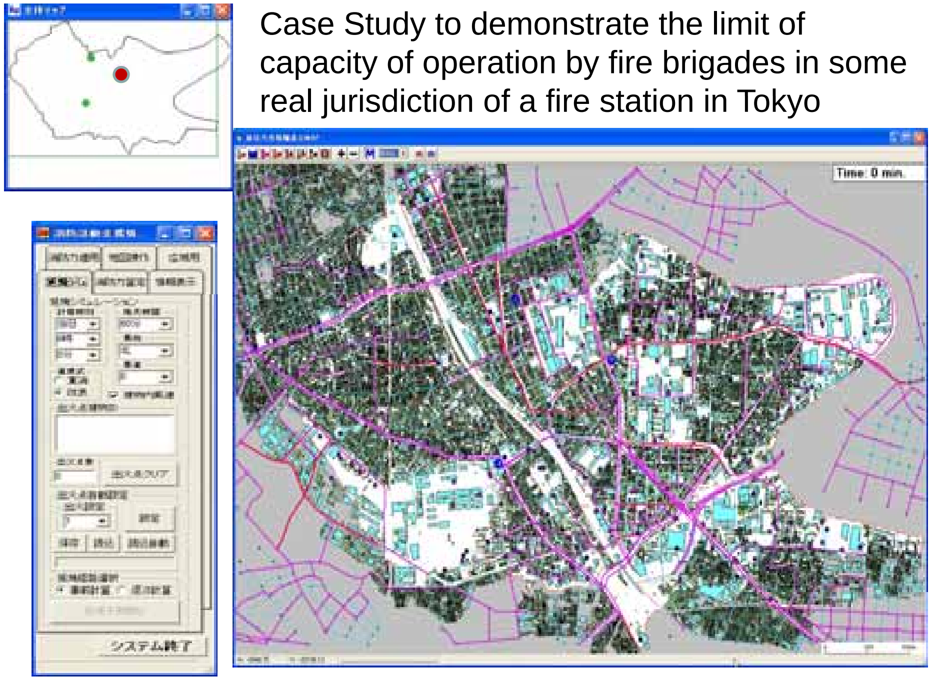
編集(E)

No.	署所	部隊ID	火災ID:01	火災ID:02	火災ID:03	火災ID:04	火災ID:05	火災ID:06
1	1:本署	1						
2	1:本署	2						
3	1:本署	3			○:25:8.7			
4	2:出張所①	1					○:36:30.0	
5	2:出張所①	2	○:12:30.0					
6	3:出張所②	1					○:12:30.0	
7	3:出張所②	2						△:0:30.0
8	集計	配備結果	▲劣勢:10/20	●放任:8/8	○鎮火:1/11	●放任:7/7	△優勢:8/36	○鎮火:1/13
9								
10								
11								
12								
13								
14								
15								

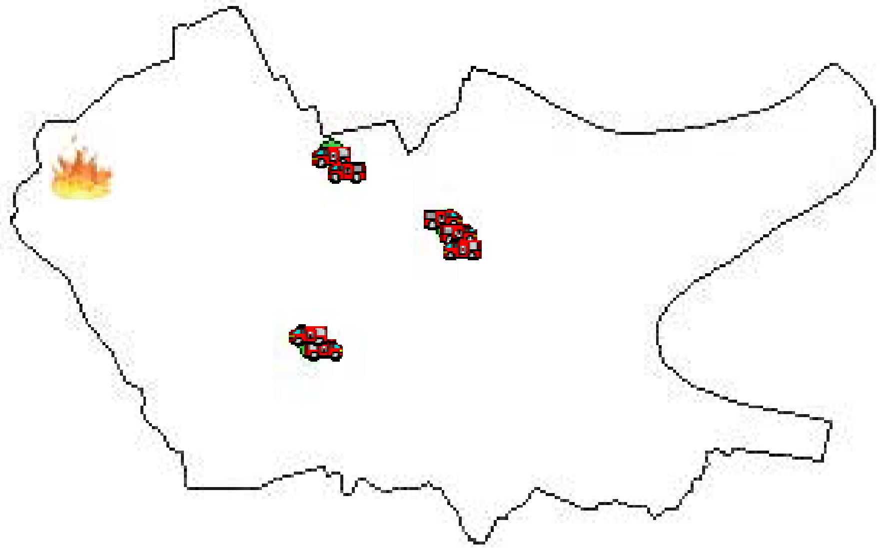
Predicted Output of Performance

- ● : No attendance
- ○ : Control Successfully
- △ : Ascendant (>50% reduction of fire size)
- ▲ : Deteriorated (<50% reduction of fire size)

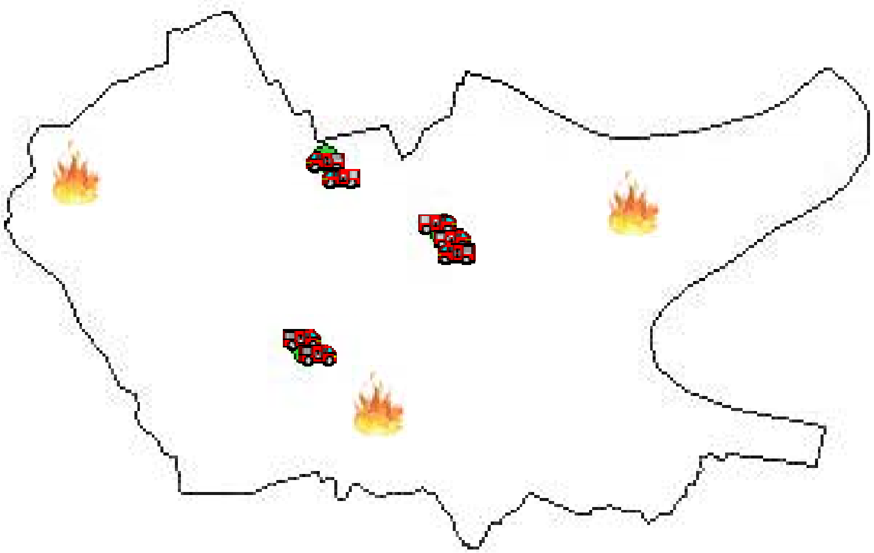
Case Study to demonstrate the limit of capacity of operation by fire brigades in some real jurisdiction of a fire station in Tokyo



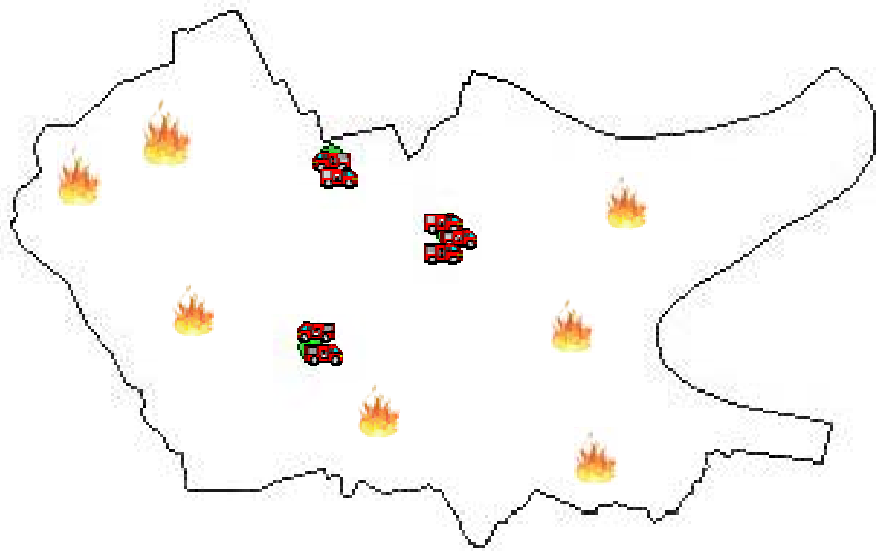
Optimum deployment of fire brigades against one fire



Optimum deployment of fire brigades against three fires



Optimum deployment of fire brigades against seven fires



Concluding Remarks

- The effective fire-fighting operation by fire brigades is one of key issues in mitigating fire damage caused by post-earthquake fires.
- Therefore, for the purpose of controlling the fire spread after a disastrous earthquake, emergency response for fire-fighting against simultaneous multiple fires by fire brigades should be done effectively with limited existing resources.
- However, there is naturally some certain limit of fire fighting operation against multiple fires even with the optimum deployment of fire engines.

Concluding Remarks *(continued)*

- If the number of fires per fire engine exceeds 1.0 for example, the drastic increase of fire damage may occur due to unattended and/or uncontrollable fires by fire brigades.
- In order to maximize the performance of fire brigades for controlling fires, the increase of water cisterns without dependence on fire hydrant is essential as a prerequisite condition. Also, required are the road network available for smooth movement of fire engines along with the system for quicker collection of disaster information.
- Public awareness on the limitations of fire-fighting force and promoting safety urban planning and community-based disaster mitigation should be much more emphasized.

Thank you for your attention

Questions?

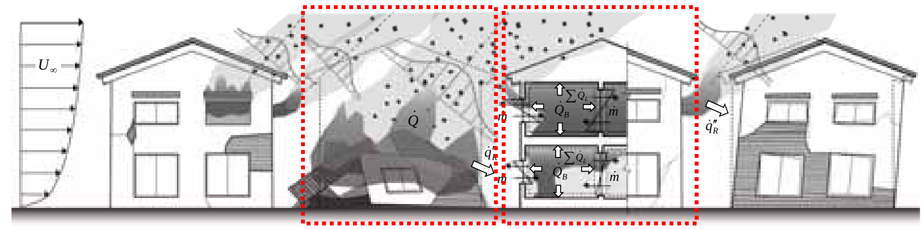
A Post-earthquake Fire Spread Model and its Application to the Fire Safety Evaluation of Architectural Monuments in Kyoto

Keisuke Himoto (Kyoto University)

Post-earthquake Fire Spread Model

- Urban Fire = Group of Building Fires
  - Fire behavior of individual building:
    - One-layer zone model for uncollapsed buildings
    - Flame model for collapsed buildings
  - Building-to-building fire spread

Two Modes of Building Fire:

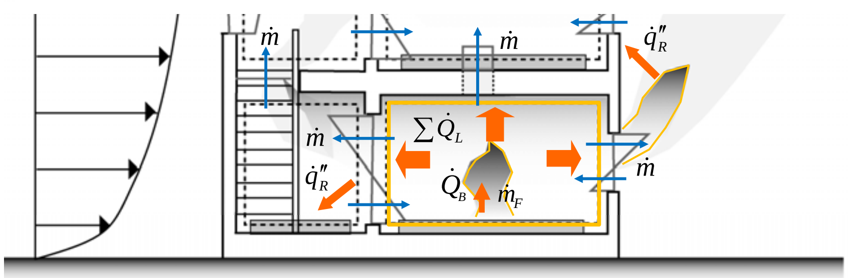


II. Crib Fire (Flame Model)

I. Compartment Fire (One-Layer Zone Model)

Fire Behavior of Individual Building (Zone Model)

- Mass $\frac{d}{dt}(\rho_i V_i) = \sum_j (\dot{m}_{ji} - \dot{m}_{ij}) + \dot{m}_{F,i}$
- Energy $\frac{d}{dt}(c_p \rho_i T_i V_i) = \dot{Q}_{B,i} - \sum_j \dot{Q}_{L,ij} + \sum_j (c_p \dot{m}_{ji} T_j - c_p \dot{m}_{ij} T_i) - \dot{m}_{F,i} L_P$
- Species $\frac{d}{dt}(\rho_i V_i Y_{X,i}) = \sum_j (\dot{m}_{ji} Y_{X,j} - \dot{m}_{ij} Y_{X,i}) + \dot{\Gamma}_{X,i}$
- State $P = \rho_i R T_i$



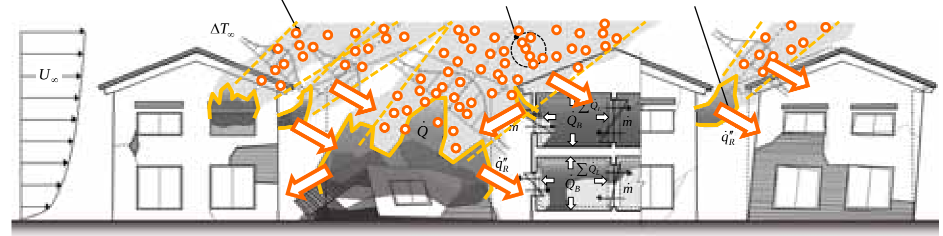
Building-to-building Fire Spread

- Causes of Fire Spread
  - Radiation from Compartment Gas & External Flame
  - Convection from Wind Blown Fire Plume
  - Spotting of Burning Firebrands

Temperature rise due to wind-blown fire plume

Spotting of firebrands

Thermal radiation from fire involved building



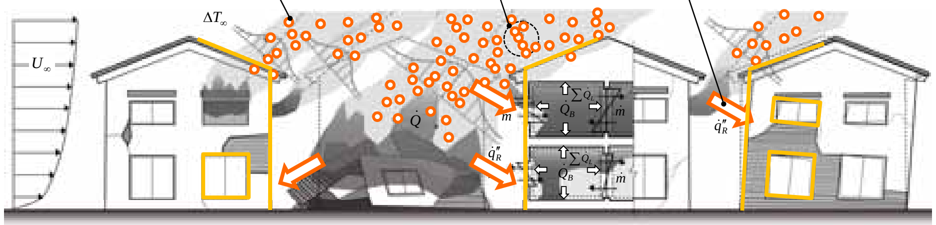
Building-to-building Fire Spread

- Criteria for Ignition
  - Incident Heat Flux through Opening
  - Surface Temperature of Exterior Wooden Wall
  - Spotting of Burning Firebrands

Temperature rise due to wind-blown fire plume

Spotting of firebrands

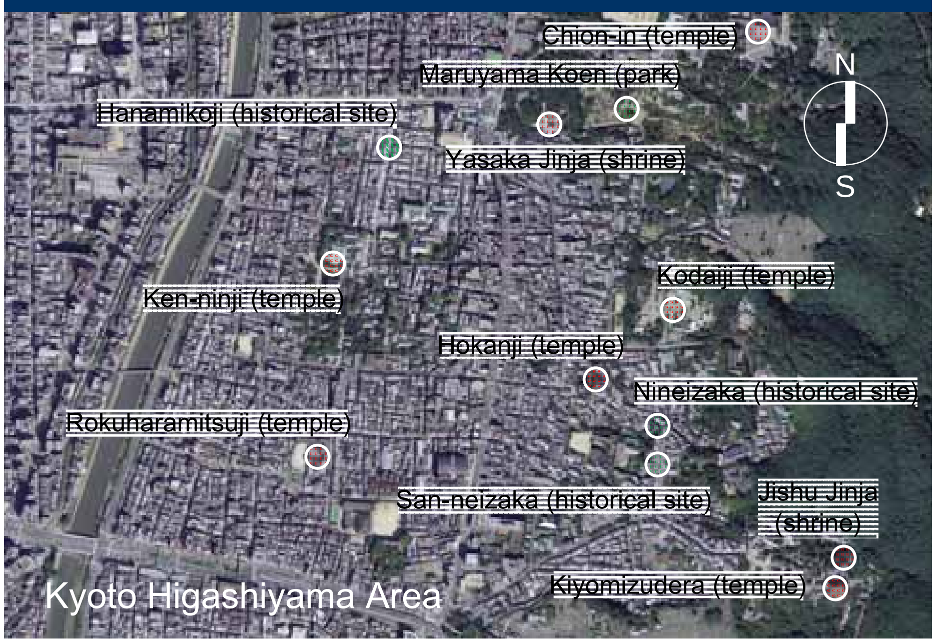
Thermal radiation from fire involved building



Architectural Monuments in Kyoto City

- Agglomeration of architectural monuments
  - Designated important cultural property : 201 / 2,259
  - National treasure : 40 / 215
- Monuments characterizes city of Kyoto
- Monuments are mostly wooden constructions

Location of Architectural Monuments in Kyoto City

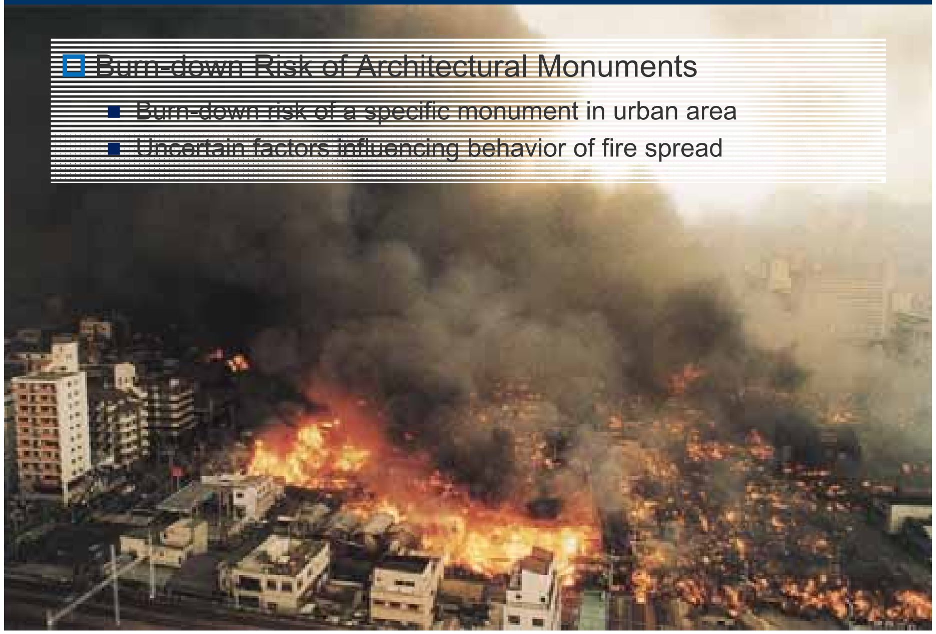


Burn-down Risk of Architectural Monuments

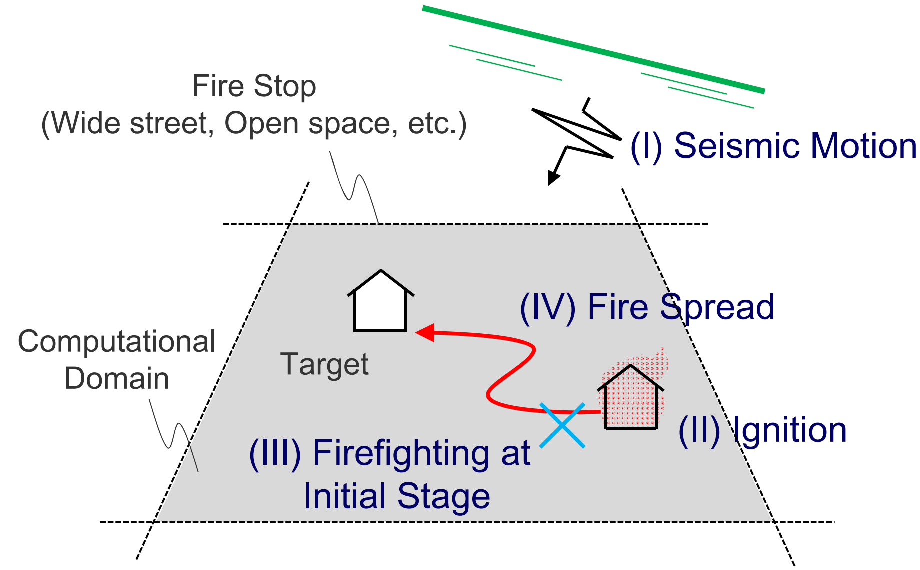
- Fire started within its own site
- Fire spread started from its neighborhood area

Objective of This Study

- Burn-down Risk of Architectural Monuments
  - Burn-down risk of a specific monument in urban area
  - Uncertain factors influencing behavior of fire spread

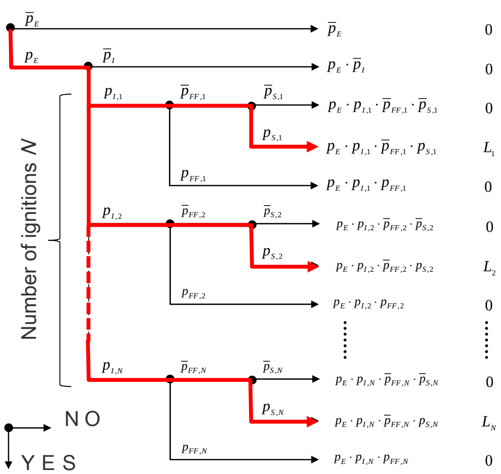


Burn-down Scenario of an Architectural Monument



Burn-down Risk due to Fire Spread

Causes of Damage				Probability	Loss
(I) Seismic Motion	(II) Ignition	(III) Fire-fighting	(IV) Fire spread		



Burn-down Risk:

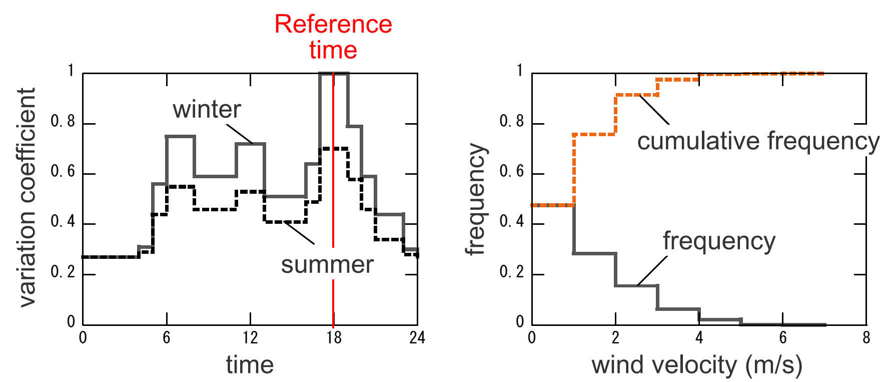
$$R_k = p_{E,k} \cdot \sum_{i=1}^{N} \left[p_{I,i} \cdot \bar{p}_{FF,i} \cdot p_{S,i} \right]$$

Type of Earthquake

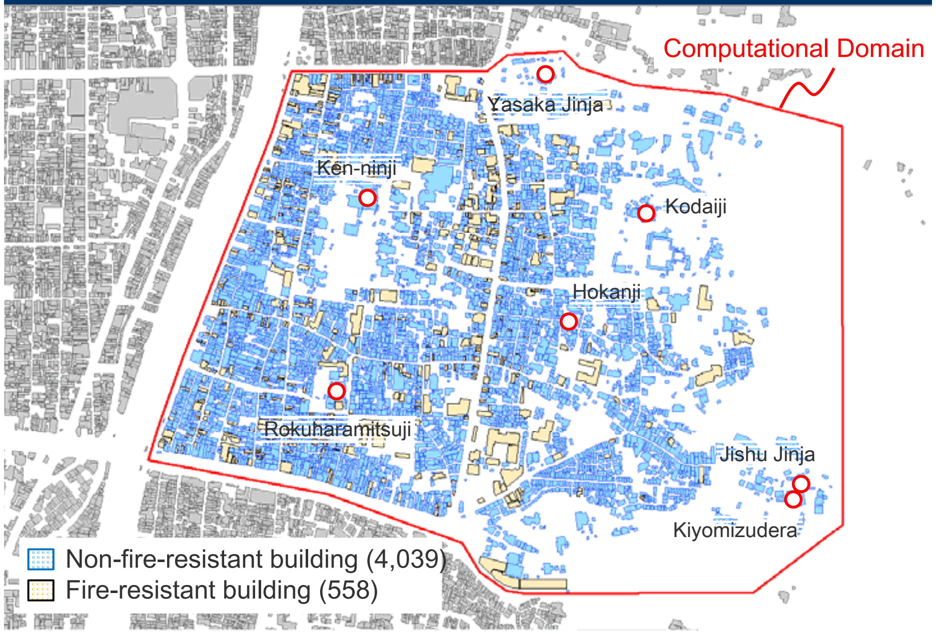
Number of Ignitions

Monte Carlo Simulation

- Uncertain Factors
  - (II) Ignition condition (date and time, number, location)
  - (III) Firefighting condition (extinguishment at initial stage)
  - (IV-a) Damage condition of buildings (5 levels)
  - (IV-b) Weather condition (wind velocity, direction)



Monuments in the Computational Domain



Scenario Earthquakes

a. Hanaore Fault
b. Momoyama-Shishigatani Fault
c. Ujigawa Fault
d. Kashihara-Mizuo Fault
e. Komyoji-Kanegahara Fault
f. Arima-Takatsuki Fault
g. Biwako-Seigan Fault
h. Nankai-Tohnankai Earthquake

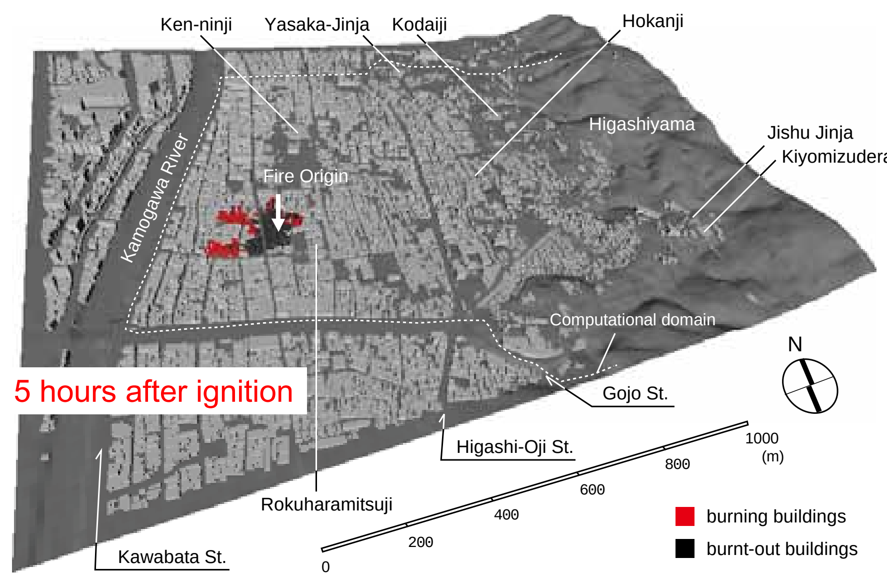
* Local government of Kyoto (2003)

Outline of the Scenario Earthquakes

Scenario earthquakes			Uncertain factors							
ID	Name	M	(II) Reference Ignition Probability $p_{ign,0}$ (×10-3)	(III) Probability of extinguishment at initial stage P_{ext}	(IV-a) Damage level of buildings: (0) No damage	(1) Minor	(2) Moderate	(3) Major	(4) Collapse	(IV-b) Weather condition
A	Hanaore Fault	7.5	0.169	0.2	0.348	0.127	0.114	0.292	0.119	AMeDAS Weather Data
B	Momoyama-Shishigatani Fault	6.6	0.085		0.517	0.093	0.131	0.207	0.051	
C	Ujigawa Fault	6.5	0.042		0.979	0.008	0.004	0.008	0	
D	Kashihara-Mizuo Fault	6.6	0.042		0.996	0.004	0	0	0	
E	Komyoji-Kanegahara Fault	6.3	0.042		1	0	0	0	0	
F	Arima-Takatsuki Fault	7.2	0.042		0.970	0.021	0.004	0.004	0	
G	Biwako-Seigan Fault	7.7	0.085		0.920	0.064	0.008	0.008	0	
H	Nankai-Tohnankai Earthquake	8.5	0.042		0.996	0.004	0	0	0	

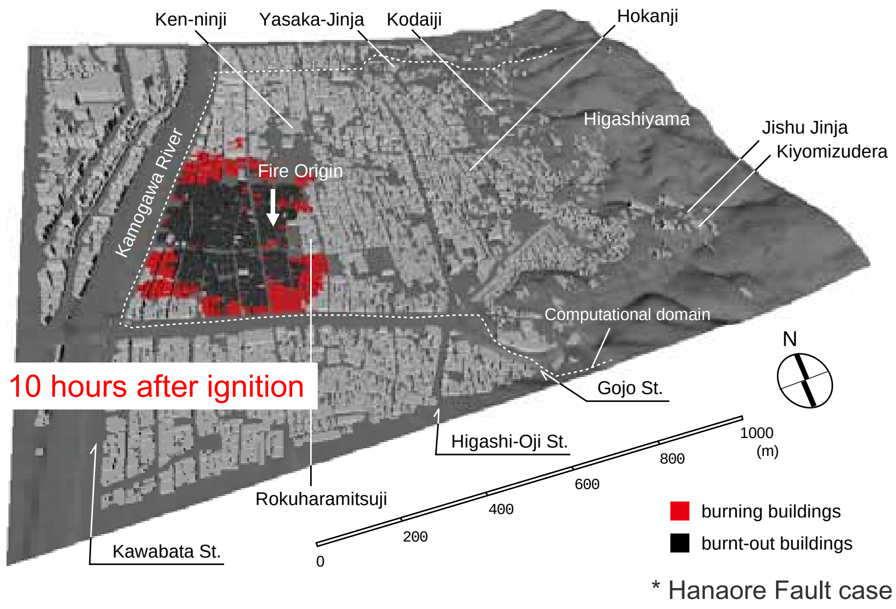
0.2 ~ | 0.1 ~ 0.2 | 0.05 ~ 0.1

An Example of the Fire Spread Simulation



* Hanaore Fault case

An Example of the Fire Spread Simulation



* Hanaore Fault case

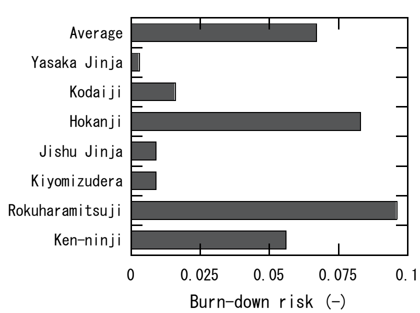
Burn-down Risk of Architectural Monuments

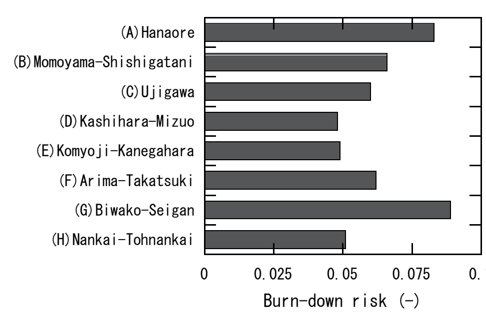
Scenario earthquakes		Burn-down risk due to post-earthquake fire spread R_k							
ID	Name	average	Yasaka Jinja	Kohdaiji	Hokanji	Jishu Jinja	Kiyomizudera	Rokuharamitsuji	Ken-ninji
A	Hanaore Fault	0.067	0.003	0.016	0.083	0.009	0.009	0.096	0.056
B	Momoyama-Shishigatani Fault	0.057	0.005	0.015	0.066	0.007	0.006	0.075	0.055
C	Ujigawa Fault	0.050	0.004	0.012	0.060	0.011	0.011	0.059	0.055
D	Kashihara-Mizuo Fault	0.039	0.006	0.010	0.048	0.007	0.007	0.045	0.041
E	Komyoji-Kanegahara Fault	0.041	0.002	0.016	0.049	0.009	0.009	0.048	0.043
F	Arima-Takatsuki Fault	0.053	0.006	0.016	0.062	0.008	0.008	0.065	0.054
G	Biwako-Seigan Fault	0.078	0.007	0.024	0.089	0.018	0.018	0.093	0.083
H	Nankai-Tohnankai Earthquake	0.041	0.004	0.010	0.051	0.009	0.009	0.048	0.045

0.05 ~   0.05 ~ 0.02   0.01 ~ 0.02

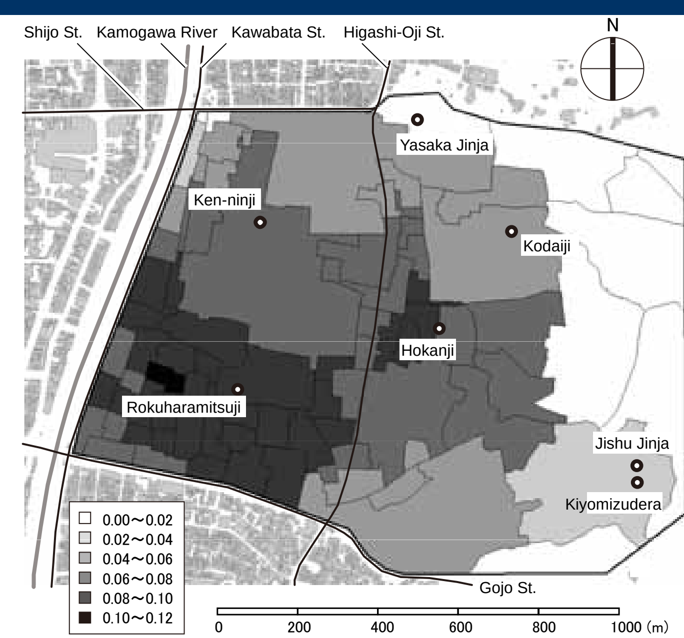
Burn-down Risk of Architectural Monuments

- Results of the Estimation
  - Burn-down risk of "Hokanji", "Rokuharamitsuji", and "Ken-ninji" are close to the average of all buildings in their neighborhood.
  - Burn-down risk was estimated high if "(II) ignition probability" was "high", and "(IV-a) damage level of buildings" was "low".



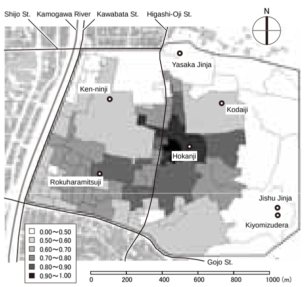


Average Burn-down Risk

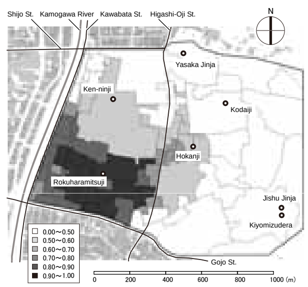


Integrated Approach Involving Neighborhood

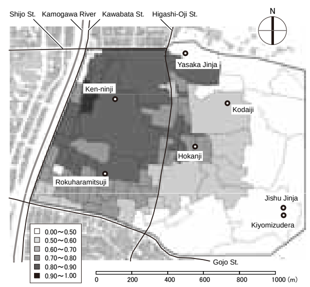
- Probability of Concurrent Burning (80%) as Reference
  - Hokanji : 7 towns
  - Rokuharamitsuji : 17 towns
  - Ken-ninji : 2 towns



Hokanji



Rokuharamitsuji



Ken-ninji

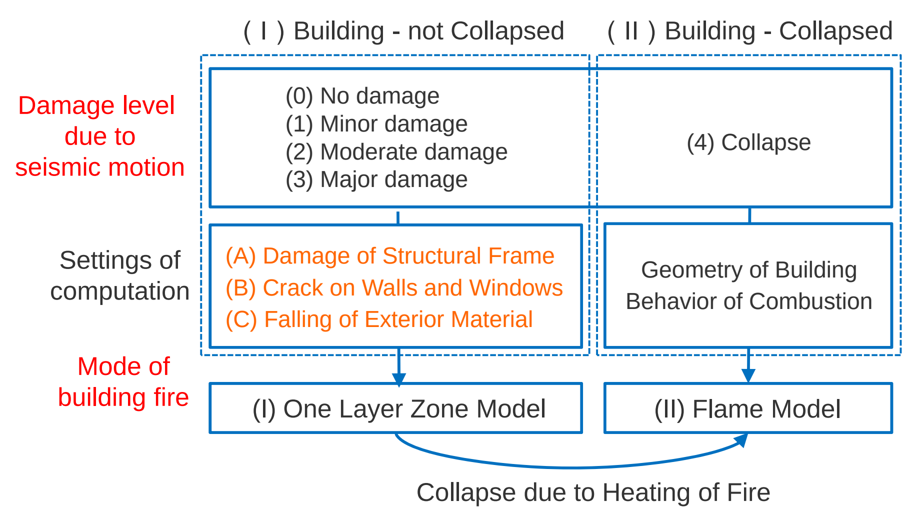
Conclusions

- Burn-down Risk of Architectural Monuments in Kyoto
  - Scenario-based event-tree analysis using a physics-based urban fire spread model
  - 7 architectural Monuments under 8 scenario earthquakes
- Fire Safety of Architectural Monuments
  - Fire safety of architectural monuments is not independent from the state of their neighborhood
  - Integrated approach involving neighborhood is required in order to maintain fire safety of architectural monuments

Level of Structural Damage due to Seismic Motion

Level of Structural Damage	Definition
(0) no damage	i. No apparent damage observed from outdoor ii. Minor damage on roofing tiles iii. Crack on a portion of partition walls or finishing materials
(1) minor	i. Damage on most of bricks and a portion of roofing tiles ii. Falling of finishing materials iii. Minor crack on some walls and groundwork
(2) moderate	i. Crack on most of partitioning walls or finishing materials ii. Major damage on roofing tiles iii. Major crack on groundwork
(3) major	i. Damage on most of exterior and partition walls ii. Extensive falling of exterior and interior finishing materials iii. Failure of braces, columns, and beams iv. Damage on flooring materials
(4) collapse	i. Extensive damage through roof, wall, floor, and frame ii. Significant deformation of buildings

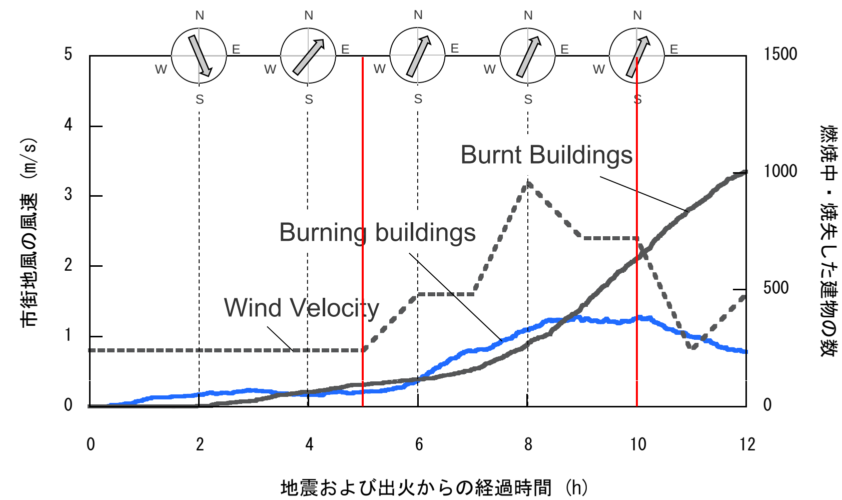
"Level of Damage" and "Modes of Building Fire"



Target Architectural Monuments

Name of Site	Name of Structure
Yasaka Jinja	Ishi-Dorii, Honden, Massha Ebisusha Shaden, Rohmon
Kodaiji	Kaizando, Kangetsudo, Santei & Shiguretei, Tamaya, Omotemon
Hokanji	Goju-no-toh
Jishu Jinja	Haiden, Honden, Sohmon
Kiyomizudera	Hondo, Niohmon, Umadome, Nishimon, Sanju-no-toh, Shoroh, Kyodoh, Tamuradoh, Asakuradoh, Chinjudoh, Honboh Kita Sohmon, Todoroki Mon, Shakadoh, Shakadoh, Amidadoh, Okunoin, Koyasutoh
Rokuharamitsuji	Hondoh
Ken-ninji	Hohjoh, Chokushimon

Wind Velocity and Number of Burnt Buildings



Fire Spread Caused by Flame Ejected from an Opening

Effect of a Facing Wall on Façade Flames
&
A Model for Compartment Fire Behavior Incorporating Fire Growth and Vitiation

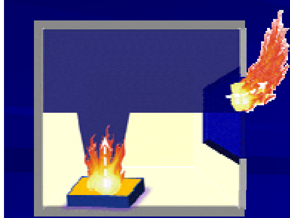
Yoshifumi Ohmiya

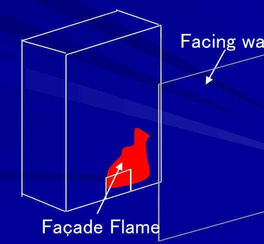
Tokyo University of Science

Outline

1) *Effect of a Facing Wall on Façade Flames*

2) *A Model for Compartment Fire Behavior Incorporating Fire Growth and Vitiation*





Effect of a Facing Wall on Façade Flames

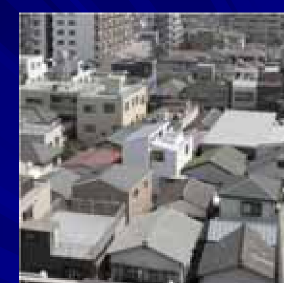
INTRODUCTION

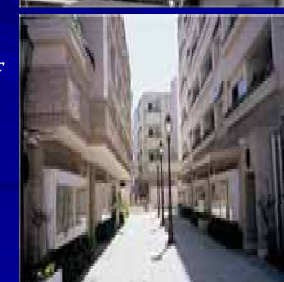
DESCRIPTION OF EXPERIMENT
- *Experimental apparatus*
- *Measurements*
- *Experimental procedure*
- *Experimental conditions*

EXPERIMENTAL RESULTS
- *Temperature distribution of ejected flame*
- *Flame height*
- *Heat fluxes from the external flames*

Introduction

- *In Japan, there are many high-density residential district where pitch between buildings is very narrow.*
- *When a fire occurs in a building, the fire damage may extend to adjacent buildings by flames ejected from openings of the building because of the proximity of buildings.*



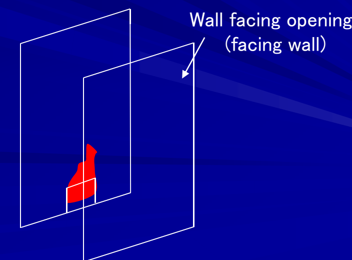


Introduction

- *The flame ejected from an opening may show different behaviors from one in no adjacent building condition.*
- *When a comprehensive fire performance design is carried out,*
  - *it is essential to verify prevention of fire spread to upper floors from the floor of fire origin.*

Introduction

- *The effect on the ejected flames owing to the presence of a wall facing to the opening (facing wall) was investigated*
  - *heat fluxes to the façade wall and the facing wall from flames ejected from the opening*
  - *temperature distribution in ejected flames*
  - *flame height*



Experimental apparatus

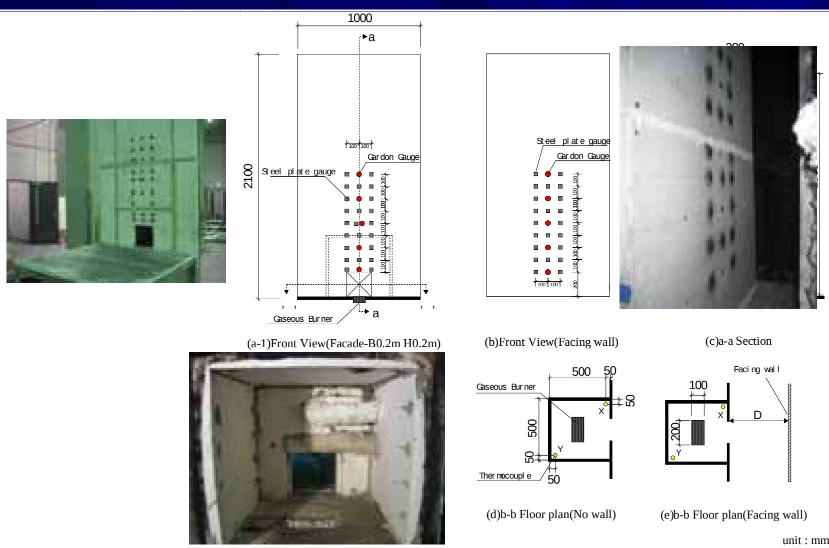
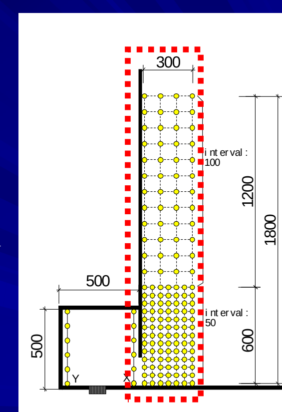


Fig. Experimental setup

Measurements

Temperature distribution of flames ejected from the opening

- *A measurement net (0.3 m width x 1.8 m height) located in the center of the opening*
- *The interval distance between the each thermocouple was every 0.05 m up to 0.6 m from the lower edge of opening and every 0.1 m from 0.6 m up to 1.8 m*



Measurements

Incident heat flux

- *Gardon type heat flux gauges (Medtherm LTD.) and steel plate gauges*
- *The steel plate gauge with thermocouples spot-welded to the back of the steel plate*

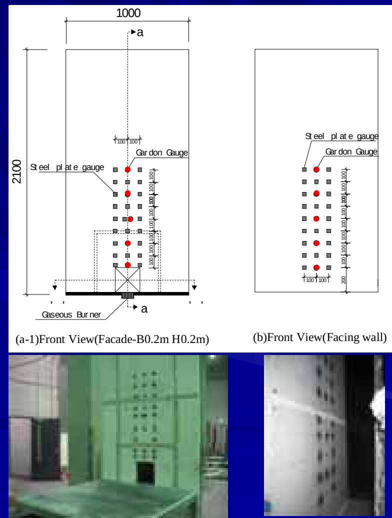
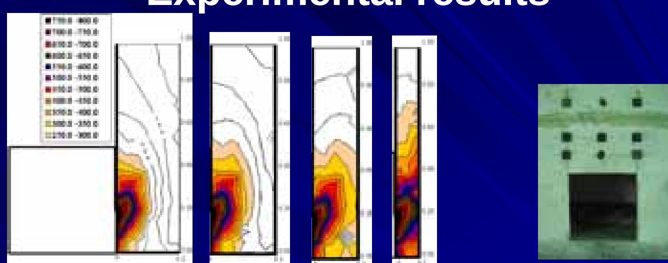


Table Experimental conditions

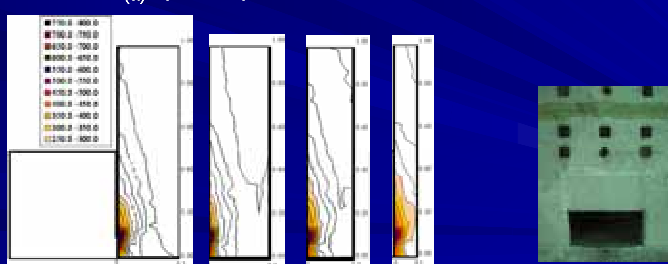
Case No.	Opening Geometry		Ventilation Factor	Heat Release Rate	Distance between two walls
	Breath (m)	Height (m)	$AH^{1/2}$ ($m^{5/2}$)	$1800\ AH^{1/2}$ (kW)	D (m)
1	0.2	0.2	1.8×10^{-2}	32.2	-
2					0.3
3					0.2
4					0.1
5	0.2	0.1	6.3×10^{-3}	11.4	-
6					0.3
7					0.2
8					0.1
9	0.1	0.2	8.9×10^{-3}	16.1	-
10					0.3
11					0.2
12					0.1

Experimental results



1) Without facing wall 2) D=0.3 m 3) D=0.2 m 4) D=0.1 m

(a) B0.2 m × H0.2 m



1) Without facing wall 2) D=0.3 m 3) D=0.2 m 4) D=0.1 m

(b) B0.2 m × H0.1 m

Fig. Temperature distribution of ejected flame with opening size

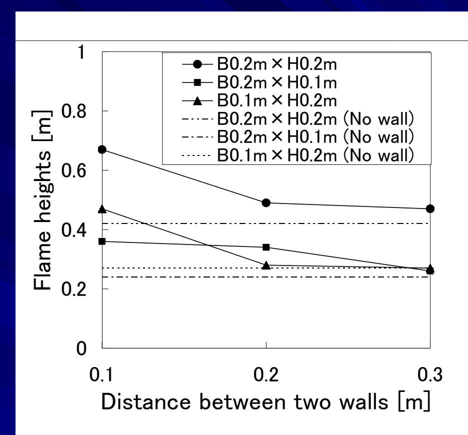


Fig. Flame height measured from neutral plane as a function of distance between façade wall and facing wall

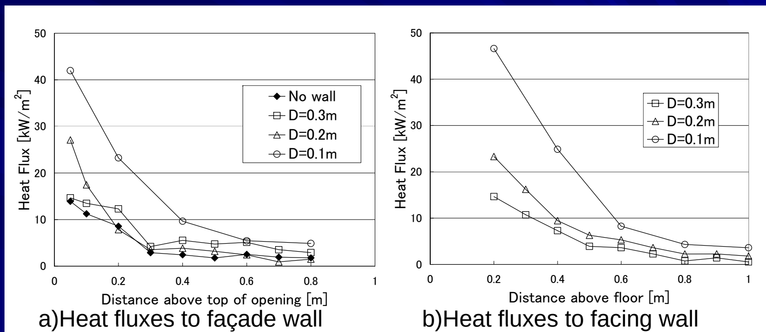


Fig. Heat flux rate to each wall (B0.2 m x H0.2 m)

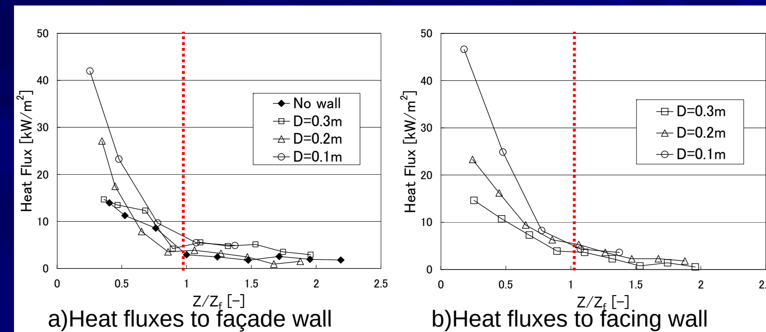


Fig. Heat flux rate to each wall (B0.2 m x H0.2 m)

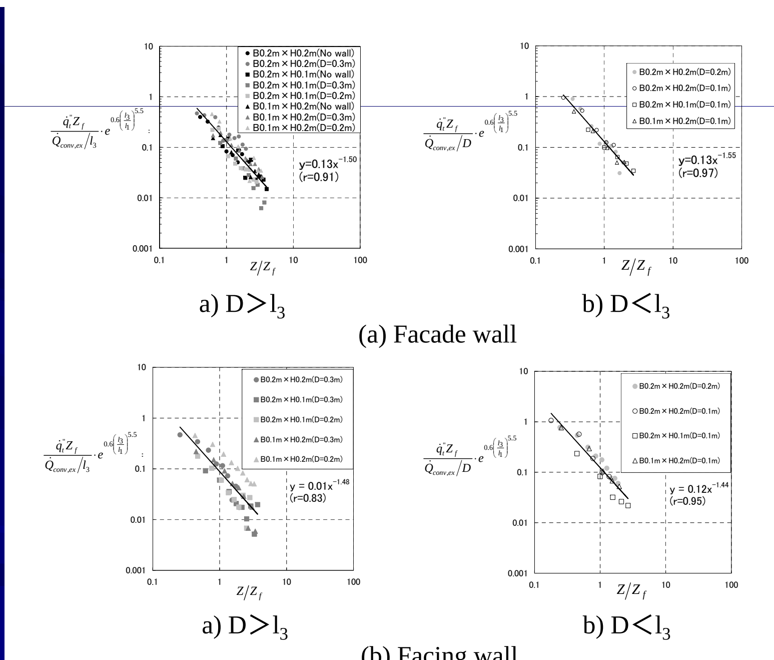


Fig. Non-dimensional height and Non-dimensional heat flux to each wall

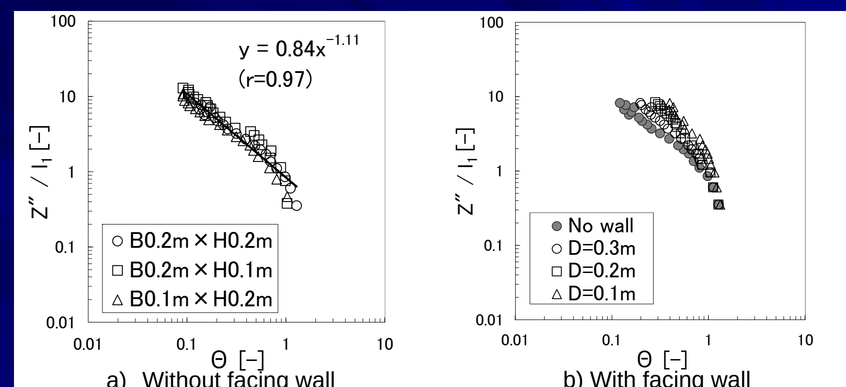


Fig. Non-dimensional temperature distribution on the centerline of flame

A Model for Compartment Fire Behavior Incorporating Fire Growth and Vitiation

INTRODUCTION

FORMULATION

Integration zone model

Fuel burning behavior

EXPERIMENT FOR VERIFICATION OF MODEL

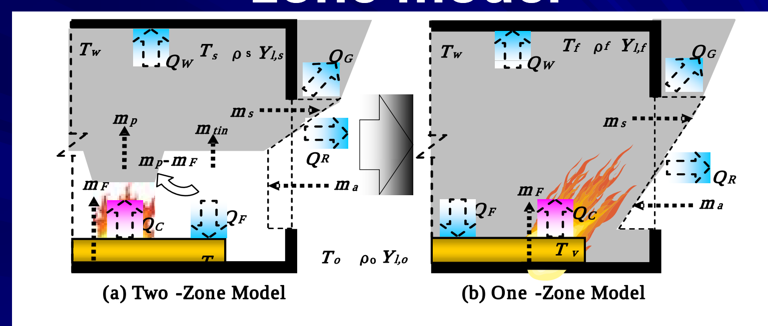
Introduction

- *To predict fire behavior in a building, researchers have actively developed numerical analysis models based on the concept of zone.*
- *The predictions (smoke yield, maximum temperature in compartment, fire duration etc.) are necessary for the fire safety design of a building.*

Introduction

- *Two formulations about a predictive model for compartment fire behavior as follows.*
  - *(i) Fuel burning behavior based on the changes in the concentration of chemical species and the rate of heat transfer*
  - *(ii) Integration zone model composed of a one-zone model and a two-zone model*
- *The validity of this model is verified by the experiments performed with a scale model.*

Formulation of integration zone model



fuel burning behavior.

Fig. Schematic of integration zone model and balance of physical quantities

Formulation of fuel burning behavior

i. *Mass loss rate of fuel*
ii. *Rate of thermal feedback from surroundings*
iii. *Rate of heat transfer from flame*
iv. *Heat release rate within a compartment*
v. *Consumption and production rates of chemical species*
vi. *Heat release rate outside a compartment*

The six items associated with the fuel burning behavior are formulated for application to a two-zone model and a one-zone model.

formulated these equations about HRR to describe the fuel-controlled and ventilation-controlled fires.

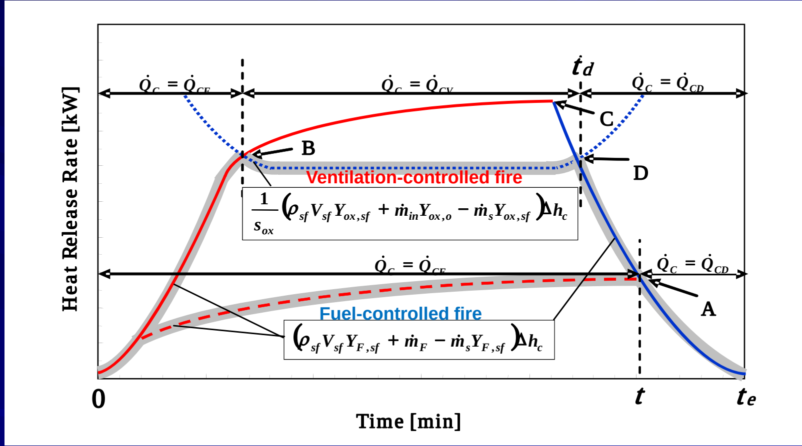


Fig. Transition of heat release rate within a compartment

Experimental apparatus

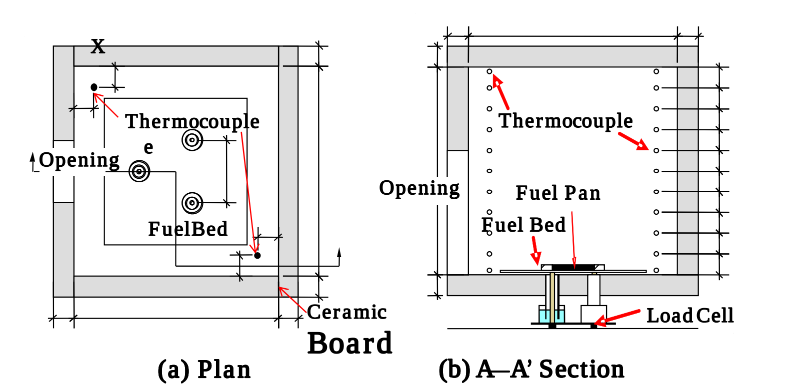
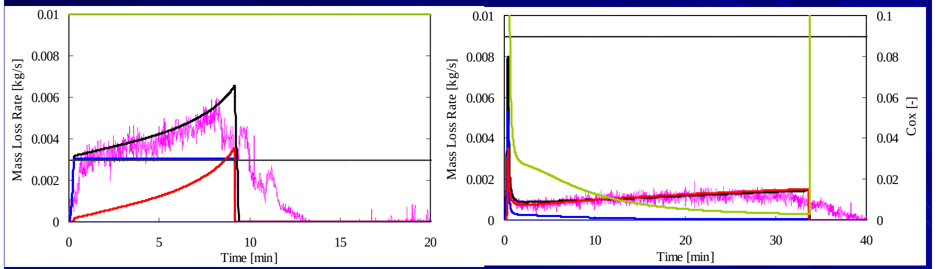


Fig. Schematic of the compartment and measurement layout(mm)

Experimental conditions

< Opening Conditions >	Unit	Values					
Opening area / Floor area	–	1/50	2/50	5/50	10/50	15/50	20/50
Width	m	0.1	0.14	0.225	0.32	0.39	0.45
Height	m	0.2	0.28	0.45	0.64	0.78	0.9
$AH^{1/2}$	$m^{5/2}$	0.0089	0.0207	0.068	0.1638	0.2686	0.3842
< Fuel Conditions >	Unit	Values					
Type	–	A1		A2		A4	
Size	m×m	0.32×0.32		0.45×0.45		0.64×0.64	
Surface area	m^2	0.1		0.2		0.41	
Weight	kg	2.38					

Comparison of results of calculations and experiments



(a) fuel-controlled (b) ventilation-controlled

Fig. Results of burning model concerning mass loss rate

Combustion governing factor and Mass loss rate

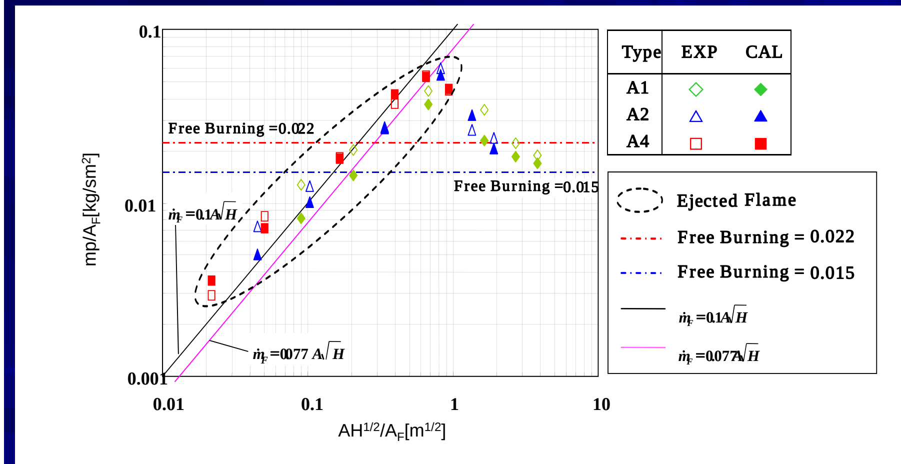


Fig. Mass loss rate per unit area versus combustion governing factor

Conclusions

Effect of a Facing Wall on Façade Flames

- *The effects of a facing wall on flames ejected from compartment were investigated*
  - *flame height, inside and outside temperatures and heat fluxes.*

A Model for Compartment Fire Behavior Incorporating Fire Growth and Vitiation

- *A simplified prediction model for the compartment fire behavior was developed, which introduced the following new concepts: (i) the prediction of the fuel mass loss rate focused on the stoichiometric relation between oxygen and fuel in zone and the thermal feedback from surroundings, (ii) the integration of a two-zone model for a growth stage and a one-zone model for a fully developed stage.*

Thank you very much for your attention.

Evacuation Simulation in the Conflagrations Induced by Kanto Earthquake 1923

Tomoaki NISHINO

Ph.D., Assistant Professor
Kobe University, Japan
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Contents

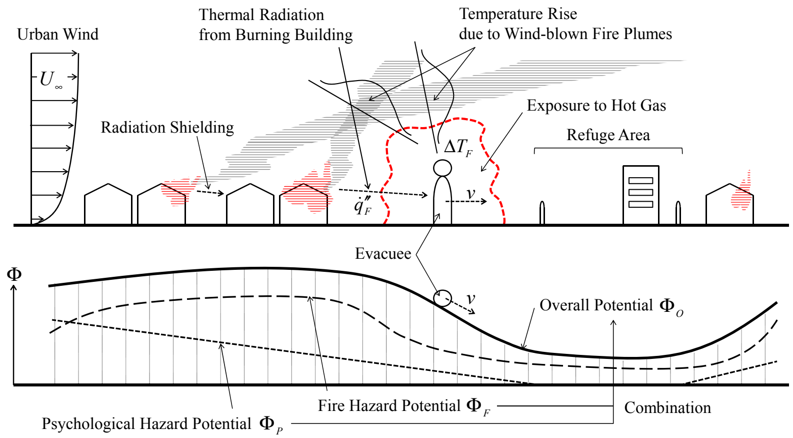
- Modeling of City Evacuation in Conflagration
- Model Validation
  - Kanto Earthquake Conflagration (1923)

Kanto Earthquake Conflagration (1923)

Kobe Earthquake Conflagration (1995)

Model Concept

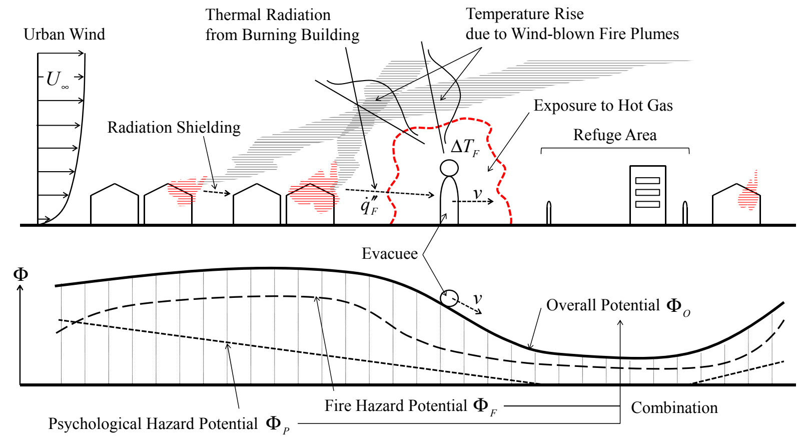
- Potential-based Agent Model
  - An Evacuee Travels from High Hazard level Point to Low Point
  - Hazard Levels are Evaluated by Fire Plumes and Refuge Areas



Model Concept

- Overall Potential Φ_O

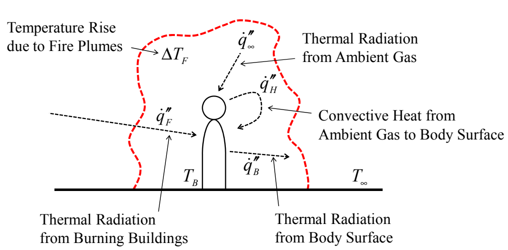
$$\Phi_O = \Phi_F + \Phi_P = \chi_F\left(\dot{q}'' + h\Delta T\right) + \chi_P \sum_{i \in R} l_i$$

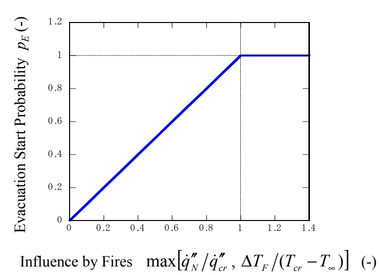


Model Concept

- Start of Evacuation
  - Probabilistic Modeling
  - Evacuation Start Probability is modeled by Influences from Fires

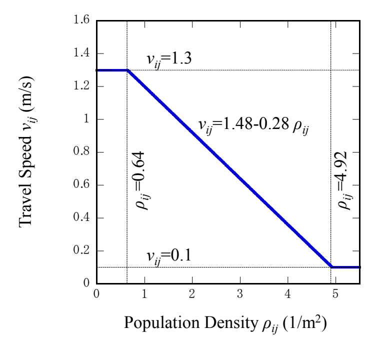
$$p_E = \max\left(\frac{\dot{q}''_N}{\dot{q}''_{cr}}, \frac{\Delta T}{T_{cr} - T_\infty}\right)$$





Model Concept

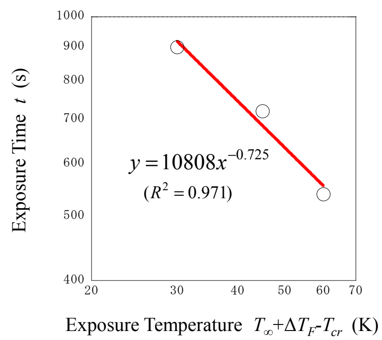
- Travel Speed v
  - Flow of Evacuees at Each Road is Assumed to be Uniform
  - Travel Speed of an Evacuee is Calculated by Density-Speed Equation



$$v_{ij} = \begin{cases} 1.3 & (\rho_{ij} < 0.64) \\ 1.48 - 0.28\rho_{ij} & (0.64 \le \rho_{ij} < 4.92) \\ 0.1 & (4.92 \le \rho_{ij}) \end{cases}$$

Model Concept

- Failure of Evacuation
  - Cause of Death is Focused on Burn of Respiratory Organs by Inhaling Hot Gas
  - Cumulative Exposure Temperature is used for Failure Judgment



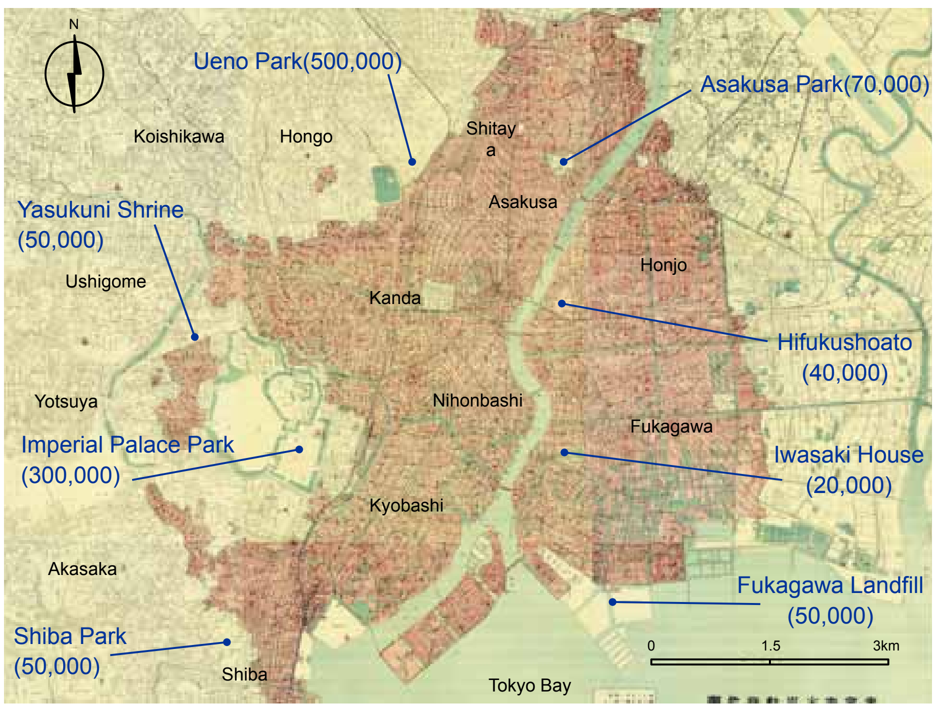
$$\int_t (T_\infty + \Delta T - T_{cr})^{0.725} dt > 10808.0$$

$$(R^2 = 0.971)$$

Model Validation

- Kanto Earthquake Conflagration (1923)

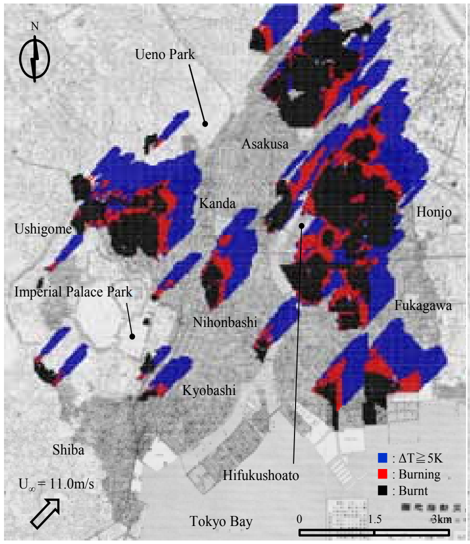
Date of Conflagration	1923. 9.1 11:58 ~ 1923. 9.3 10:00
Number of Evacuees	1,356,740
Number of Fatalities	68,660 (Fire : 65,902)
Number of Burnt Buildings	219,084 (34.7km^2)



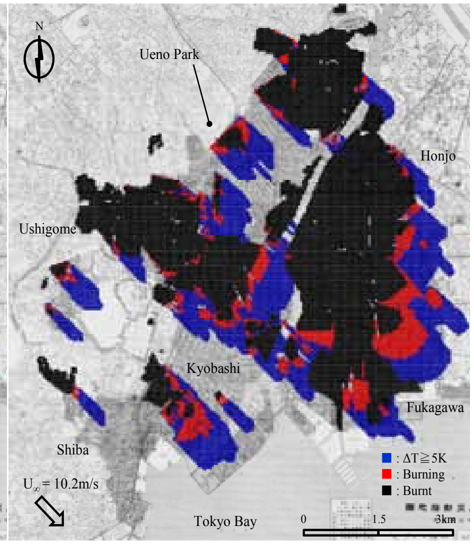
Reconstruction of the Fires

- Scanning the Field Survey Data

Examples of Reconstructed Fires

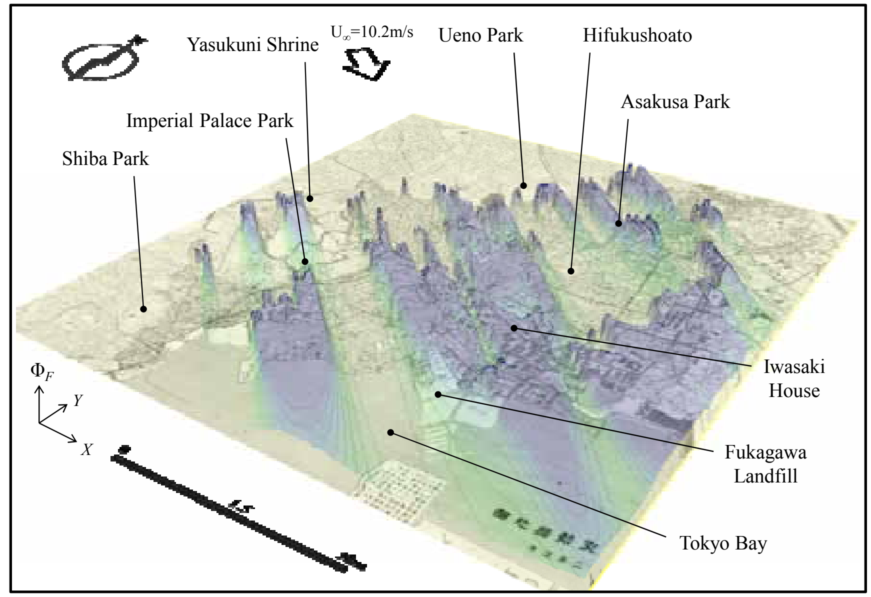


4hrs after the earthquake

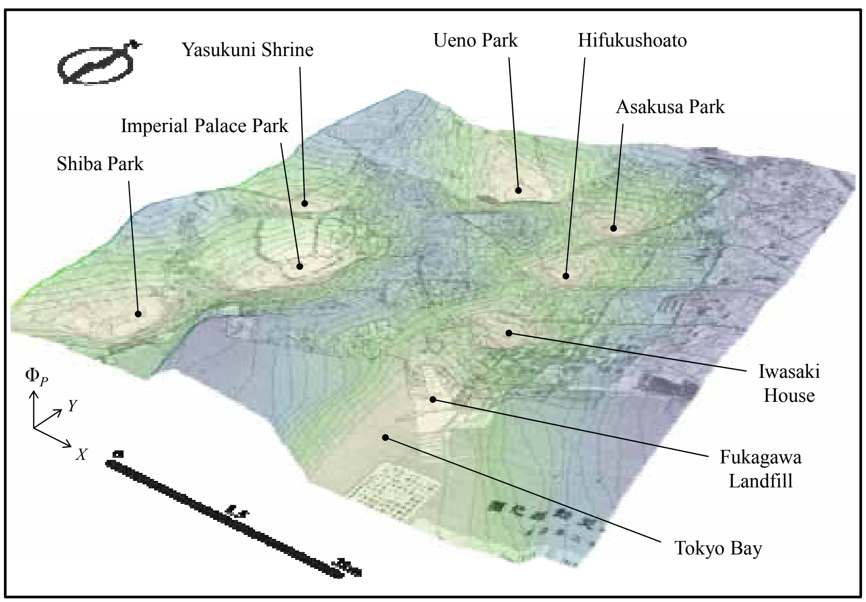


8hrs after the earthquake

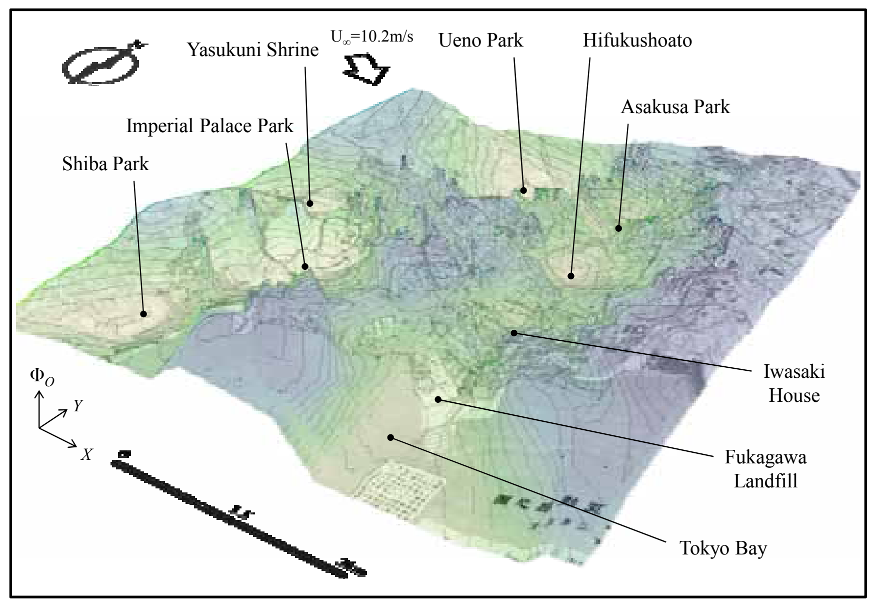
Distribution of Fire Hazard Potential (8hrs)

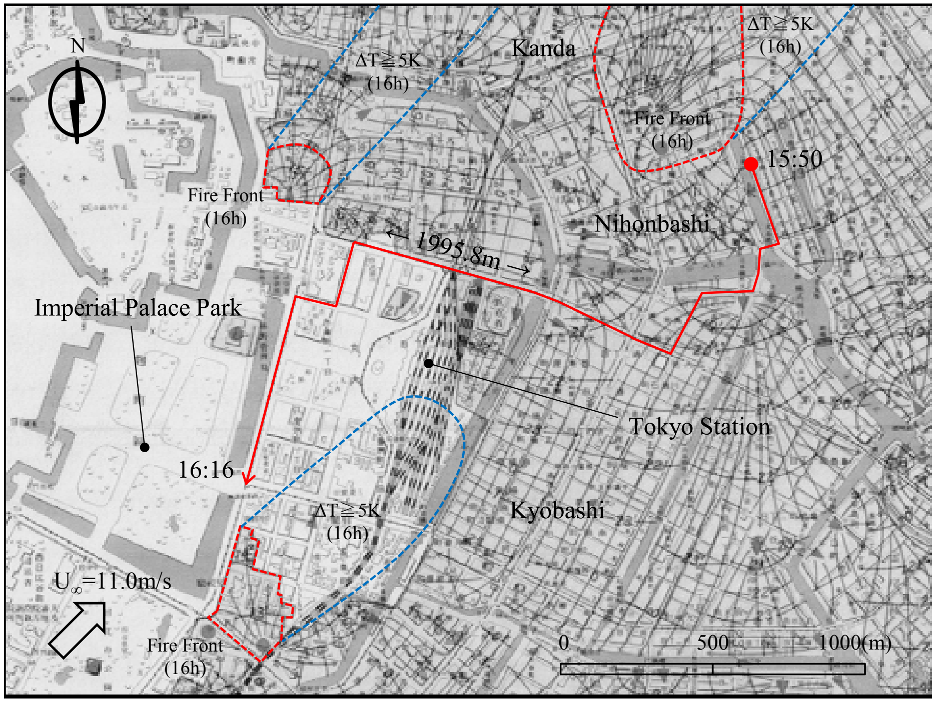


Distribution of Psychological Hazard Potential



Distribution of Overall Potential (8hrs)

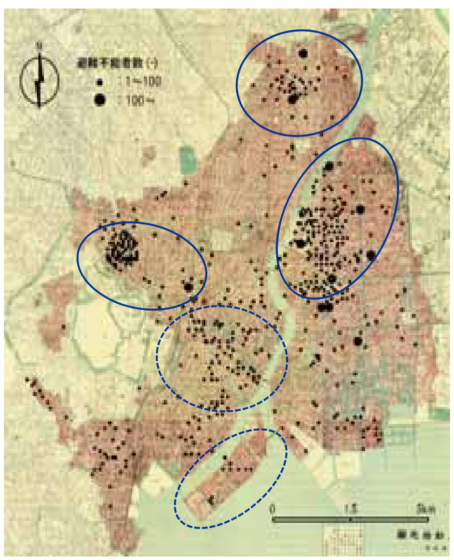




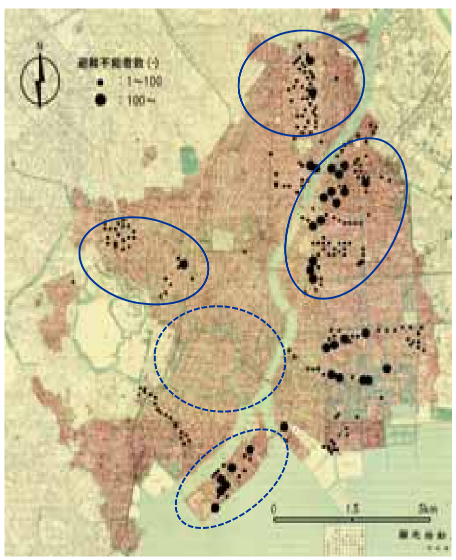
Comparison of Fatalities Number

Constant χ_F	Model	Survey Report
0.0	8,054	
10.0	18,985	
11.0	29,097	27,902 (=65,902-38,000) ※ Except fatalities by fire whirs at Hihukushoato
12.0	36,609	
100.0	179,430	

Comparison of Fatalities Distribution (χ_F=11.0)



27,902 fatalities (Survey Report)



29,097 fatalities (Model)

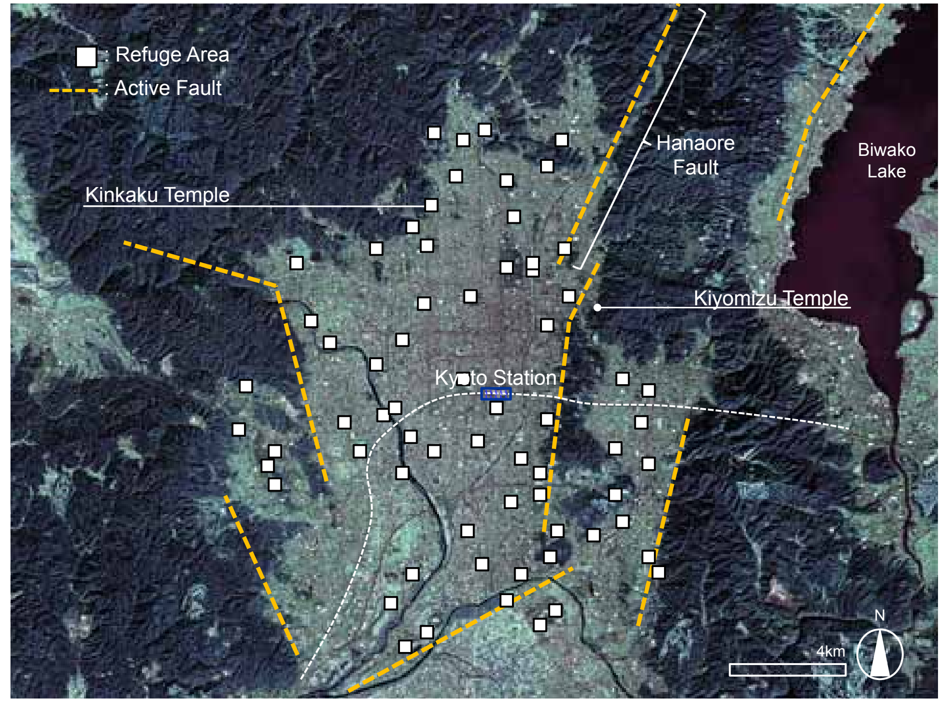
Conclusion

- Modeling of City Evacuation in Conflagration
- Model Validation
  - Kanto Earthquake Conflagration (1923)
- Future Issues
  - Further Refinement of Evacuation Model to be More Realistic
  - Model Application to Future Conflagration

Model Application

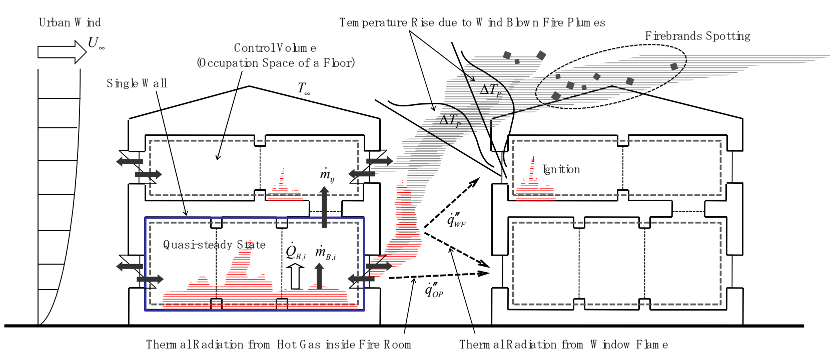
Kyoto Inland Earthquake (20XX)

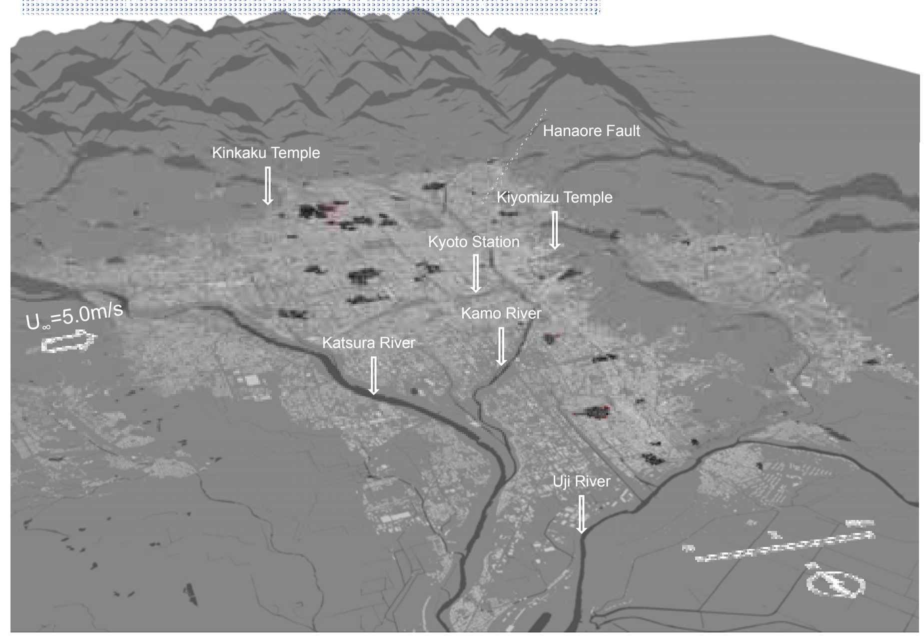
Number of Residents	1,467,313
Number of Buildings	698,386
Anticipated Magnitude	6.3 to 7.7
Anticipated Outbreaks	Max 96 (Winter, 6:00 PM)

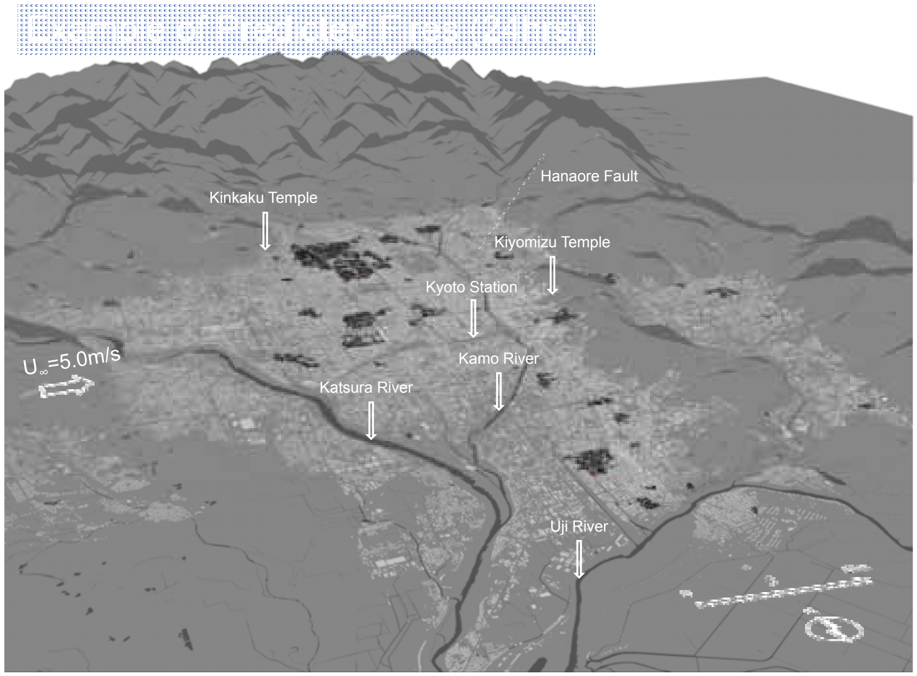


Prediction of Urban Fire Spread

- Fire Origins
  - Random Setting based on Outbreak Ratio VS. Collapse Ratio
- Fire Spread
  - Using a Physics-based Model by Himoto and Tanaka

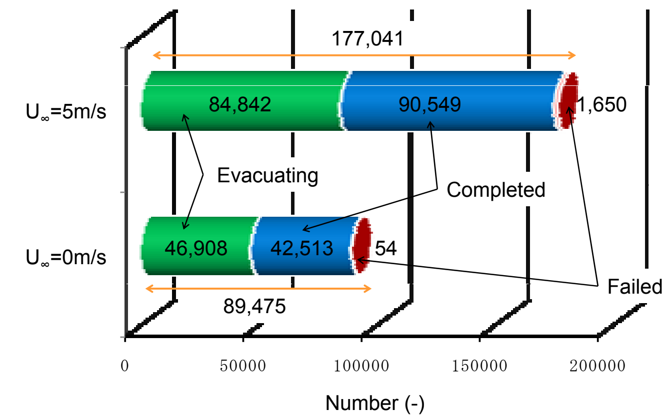


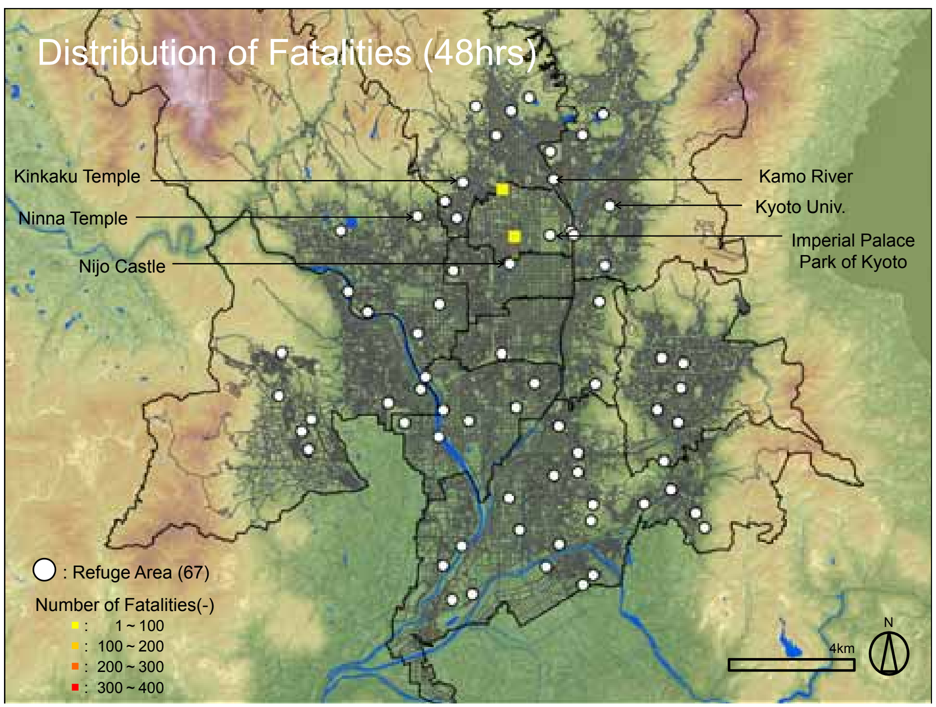


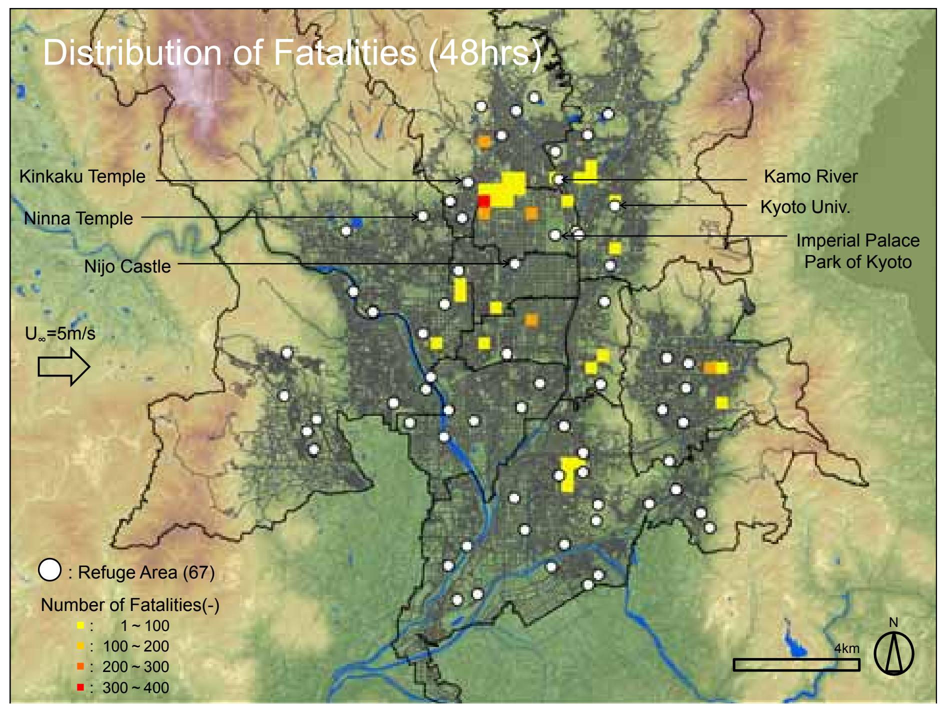


Breakdown of Evacuation State

- 48hrs after the Earthquake







The Interface Fire Problem: An Overview

Workshop on Future Japan/USA Interface Fire Research Collaborations
NIST Engineering Laboratory June 27, 2011 Gaithersburg, MD

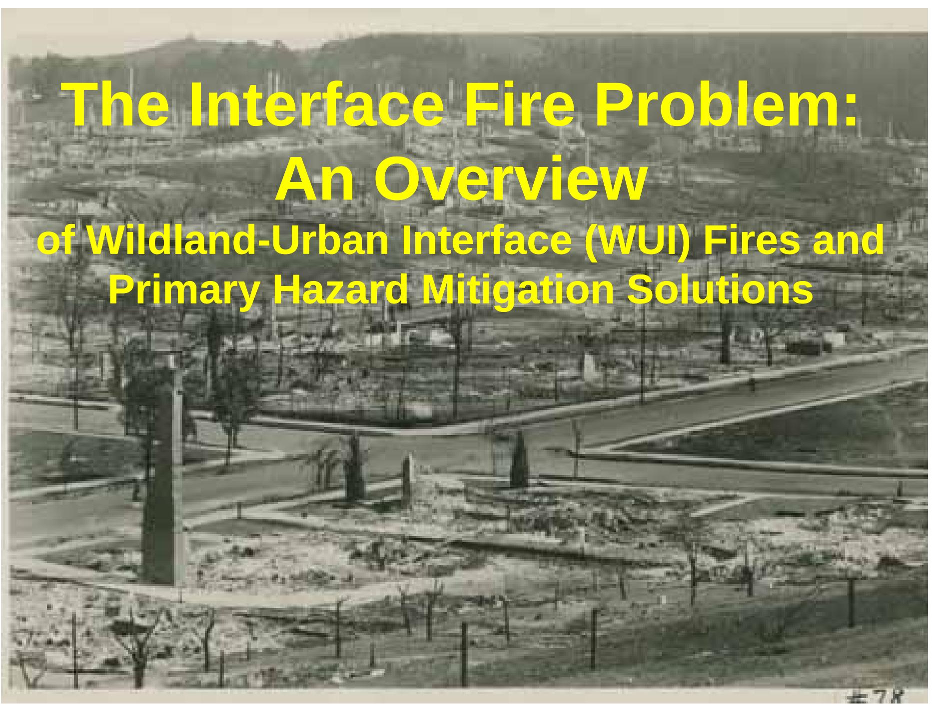
Ethan Foote, Co-Chair
Wildland-Urban Interface Committee

California Fire Prevention Officers
A Section of the California Fire Chiefs Association
Northern Division

Speaker & Contact Information

- State fire officer since 1979.
- County Fire Marshal & California Fire Prevention Officers member in 1994.
- Fire command and damage assessment assignments on major Wildland-Urban Interface conflagrations (1981-2008).
- MS (U.C. Berkeley) and BS (University of Washington) studying WUI fires.
- California/U.S.F.S. Advanced Fire Behavior instructor cadre, ten years.
- Co-chair (2004 & 2009) of advisory committees on California Building Standards Code regulations pertaining to wildfire protection.
- Assistant Chief for *Wildfire Protection Building Construction* with CALFIRE Office of the State Fire Marshal since 2007.
- Lives in Santa Rosa with his wife of 22 years, 16 year old son, and 8 year old daughter.

California Fire Prevention Officers www.firepreventionofficers.org
c/o CALFIRE, Office of the State Fire Marshal
135 Ridgway Ave., Santa Rosa, CA 95401-4318
E-Mail: ethan.foote@fire.ca.gov



The Interface Fire Problem: One of Many Wildfire Problems

- **Large wildland fires** (2002 CA/OR Biscuit fire 500,000ac/2,000 ha < 12 cabins burned)
- **"Fire Siege"** (2,096 lightning fires 2008 1,200,000ac/4,86,000ha & 100 homes in 7 WEEKS)
- **"Mega Fires"** (Nov 2008 1,000 homes in 7 DAYS)
- **"WUI fires"** (Wildland-Urban Interface)

Only One Wildfire Problem

addressed in the

California Building Standards Code

- **Disastrous Loss of Homes**

  (and other major buildings)

  During Wildfires

- Historically known as "Conflagrations"

Wildland-structural Intermix   Exurban Fire Problem

Hillside/wildland Intermix

Urban-Wildland Intermix   **I-ZONE Fires**

After 30+ Years of Confusion
WUI or Interface Fire
is the name of this "Fire Problem"

Rural-wildland Intermix   WUM (Wildland-Urban Mosaic)

SWI (Structural Wildland Interface-Interzone)

Chaparral-urban Interface

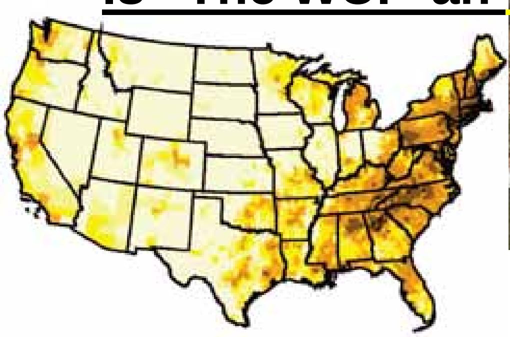
Wildland/Urban Interface/Intermix

WURST (Wildland/Urban/Rural Structural Triage)

View "WUI" Area with Caution!

Total WUI

Is "The WUI" an Area?



2007 Journal of Forestry

It is also a *Fire-Loss Problem* we can solve!

Historic Risk of Loss
An Essential Element of the Interface Fire Problem

- 2009 Santa Barbara
- 2008 SoCal Again
- 2007 SoCal Again
- 2003 Southern Cal.
- 1991 Oakland
- 1990 Santa Barbara
- 1985 Nevada County
- 1980 Napa & San Bernardino
- 1977 Santa Barbara
- 1970 State of Cal.
- 1964 Santa Rosa
- 1961 Los Angeles
- 1947 State of Maine
- 1936 Bandon, OR
- 1929 Mill Valley
- 1923 Berkeley

2009 Australian Black Saturday Fires
173 dead / 2133 houses destroyed

Australia-USA Symposium on Fires at the Interface

17 June 2010 Canberra ACT Australia

Building & Risk Management Breakout Group

Dave Sapsis (CALFIRE-FRAP)
Doug Stone (DHS)
Ethan Foote (CalChiefs)
Greg Buckley (NSWFB)
Jack Cohen (USFS)
Justin Leonard (CSIRO)
Mark Chladil (TFS)
Michele Steinberg (NFPA)
Rob Rogers (NSW RFS)

Australian & U.S Experts Agree on the Problem & Solution

- "Before describing house ignition potential and house vulnerability assessment, ***we must first define the problem*** in terms of house ignition."

The Interface Fire Problem

- "In its simplest terms, the fire interface is any point where the **fuel** feeding a wildfire **changes** from natural (wildland) to man-made (urban) fuel" (C.P. Butler 1974).
- More of a fire-spread problem, less of a geographic description.
- Four distinct elements to the problem:

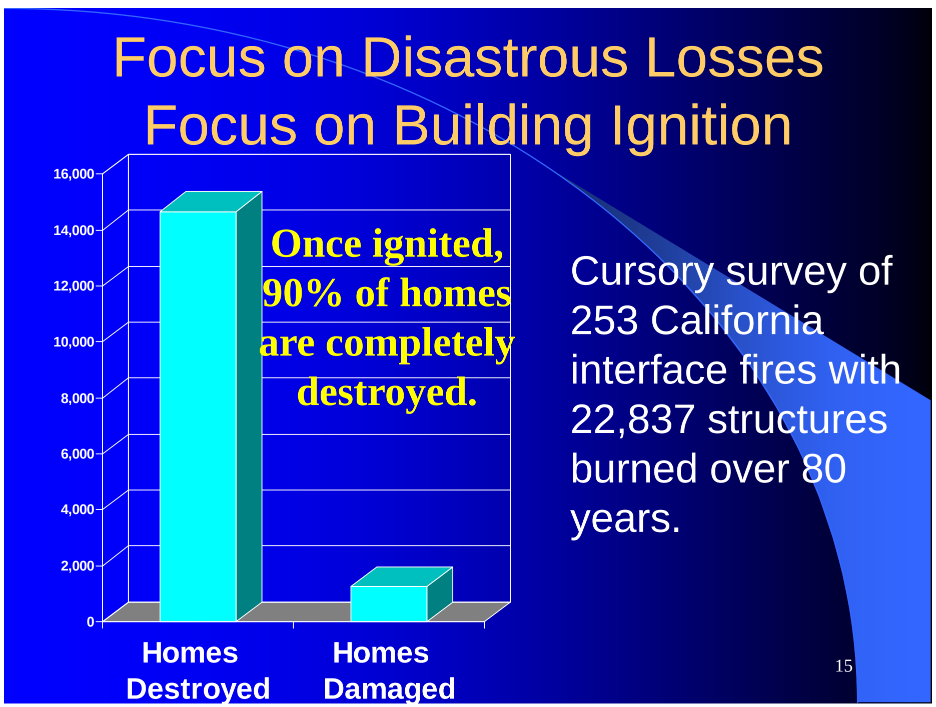
Elements of the Interface Fire Problem:

1) Vegetation Fire Exposure Under Extreme Weather Conditions

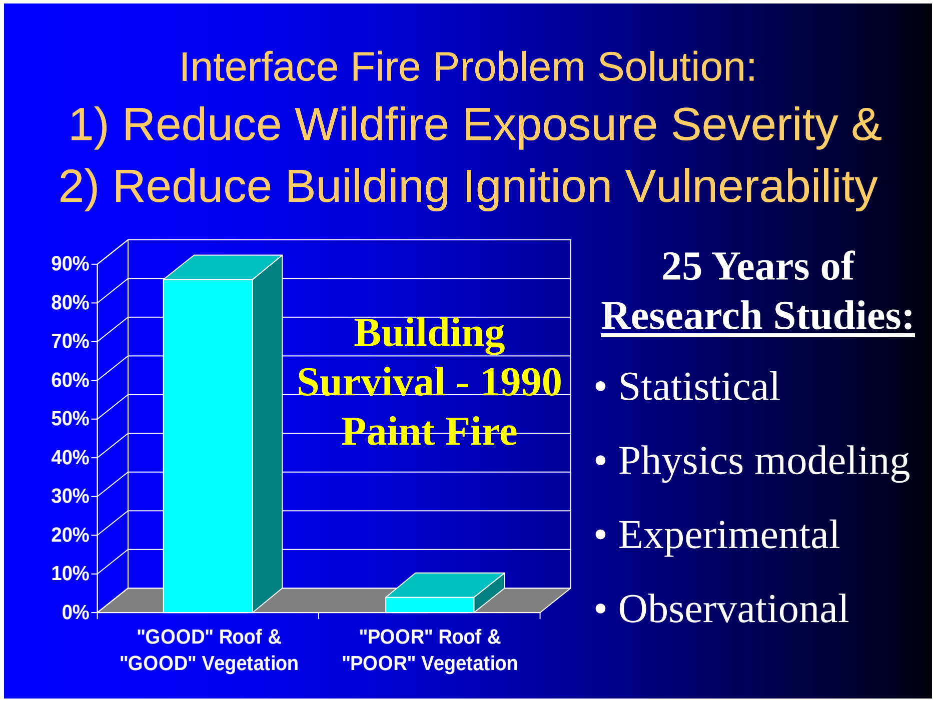
- High Wind
- Low % RH
- Well defined synoptic patterns
  - Foehn/Föhn
  - Post frontal

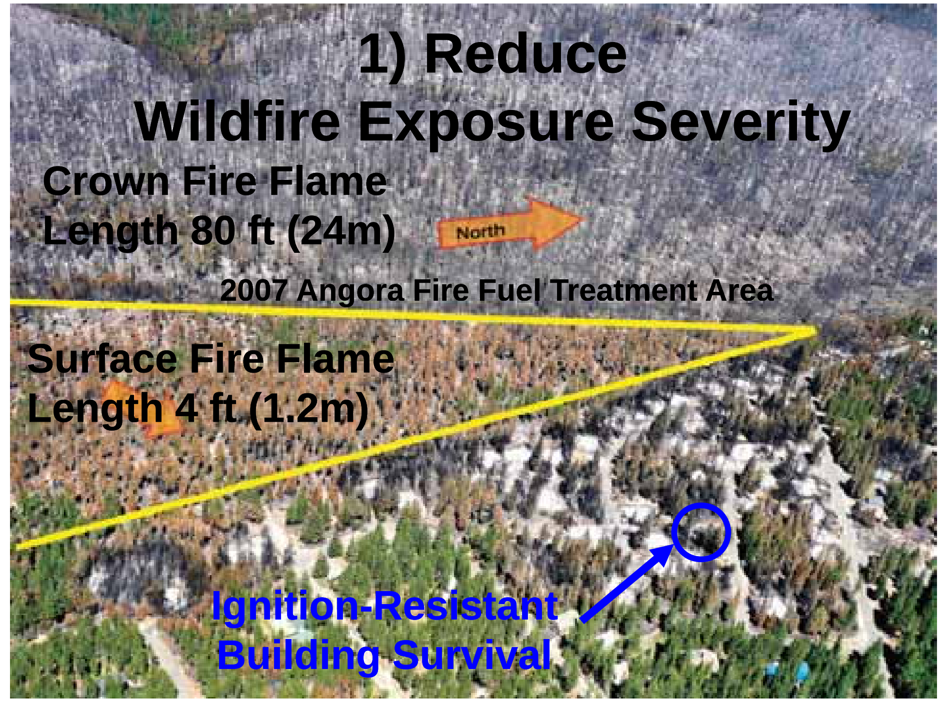

Elements of the Interface Fire Problem :
2) Rapid fire spread to readily ignitable buildings (e.g. untreated wood roofs)

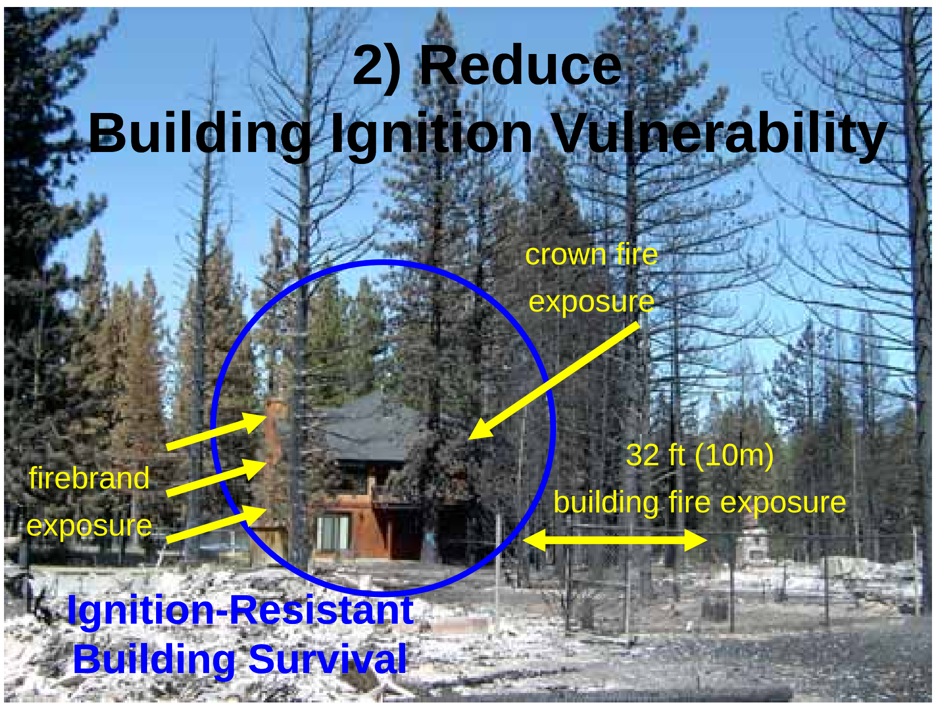

Elements of the Interface Fire Problem :
3) Fire protection overwhelmed
4) Disastrous interface fire losses
Spot fires
What's missing in this picture?

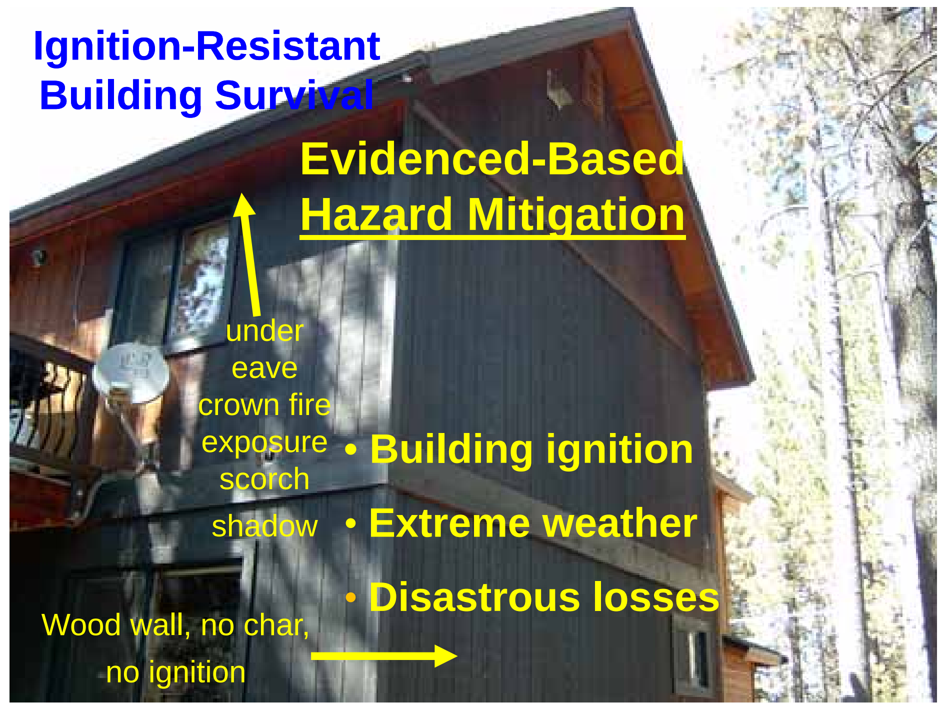

Focus on Disastrous Losses
Focus on Building Ignition
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Once ignited, 90% of homes are completely destroyed.
Homes Destroyed
Homes Damaged
Cursory survey of 253 California interface fires with 22,837 structures burned over 80 years.
15

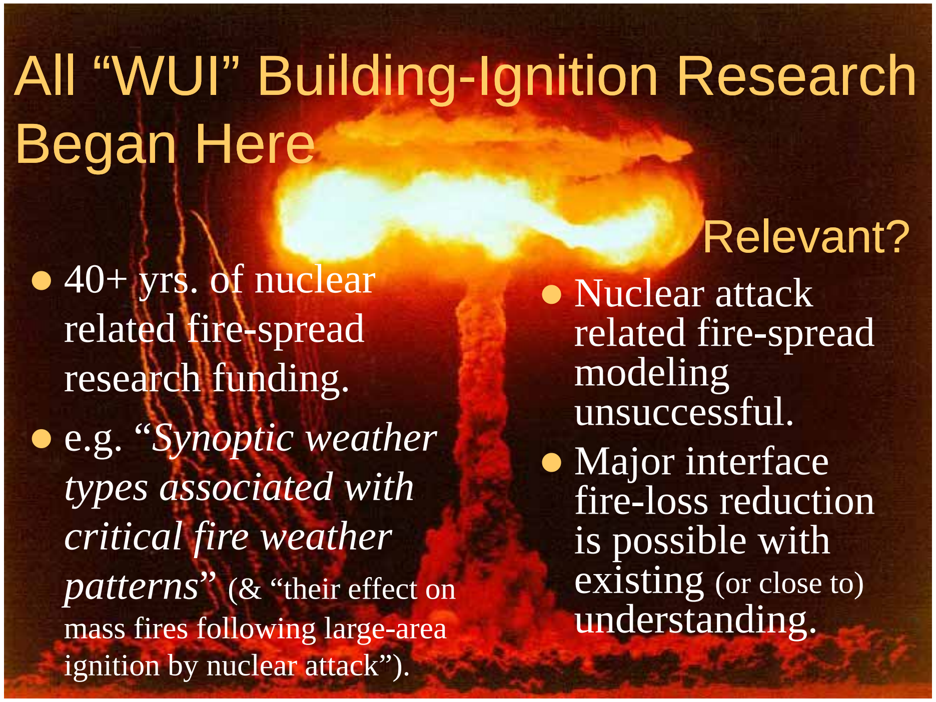

Interface Fire Insanity?
"Insanity … doing the same thing over and over again and expecting different results."
- Albert Einstein
What fire-loss reduction "things" are not solving the Problem
Outdated Paradigms
Fire protection
(1,000 fire engines / DC-10 air tankers)
Fire resistive construction
Wildland fuel management

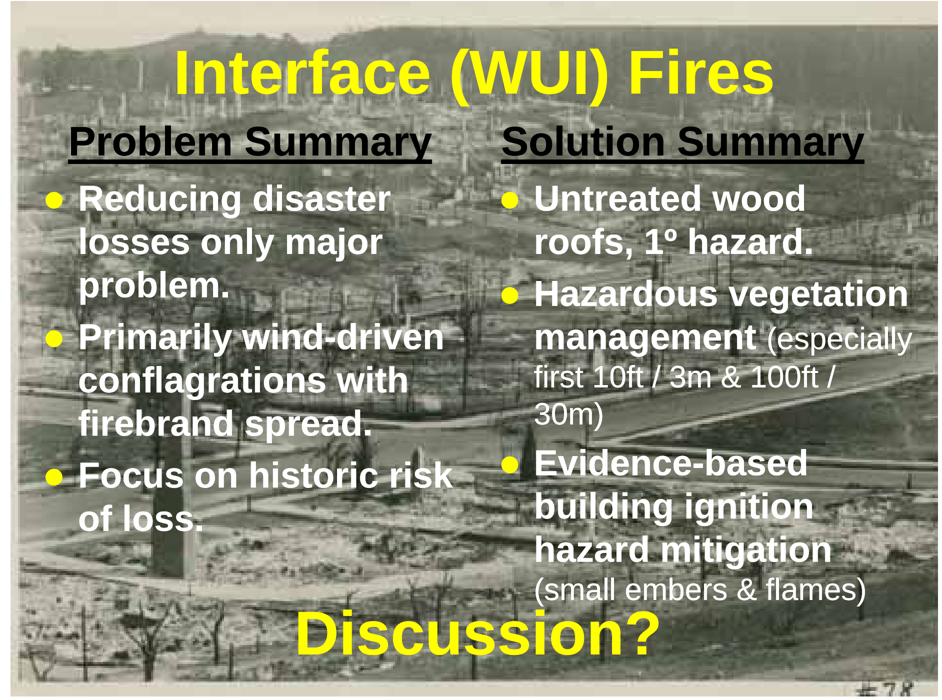

Interface Fire Problem Solution:
1) Reduce Wildfire Exposure Severity &
2) Reduce Building Ignition Vulnerability
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Building Survival - 1990 Paint Fire
"GOOD" Roof & "GOOD" Vegetation
"POOR" Roof & "POOR" Vegetation
25 Years of Research Studies:
• Statistical
• Physics modeling
• Experimental
• Observational


1) Reduce Wildfire Exposure Severity
Crown Fire Flame Length 80 ft (24m)
North
2007 Angora Fire Fuel Treatment Area
Surface Fire Flame Length 4 ft (1.2m)
Ignition-Resistant Building Survival


2) Reduce Building Ignition Vulnerability
crown fire exposure
firebrand exposure
32 ft (10m) building fire exposure
Ignition-Resistant Building Survival


Ignition-Resistant Building Survival
Evidenced-Based Hazard Mitigation
under eave crown fire exposure scorch shadow
• Building ignition
• Extreme weather
• Disastrous losses
Wood wall, no char, no ignition


All "WUI" Building-Ignition Research Began Here
Relevant?
40+ yrs. of nuclear related fire-spread research funding.
e.g. "Synoptic weather types associated with critical fire weather patterns" (& "their effect on mass fires following large-area ignition by nuclear attack").
Nuclear attack related fire-spread modeling unsuccessful.
Major interface fire-loss reduction is possible with existing (or close to) understanding.


Interface (WUI) Fires
Problem Summary
Reducing disaster losses only major problem.
Primarily wind-driven conflagrations with firebrand spread.
Focus on historic risk of loss.
Solution Summary
Untreated wood roofs, 1° hazard.
Hazardous vegetation management (especially first 10ft / 3m & 100ft / 30m)
Evidence-based building ignition hazard mitigation (small embers & flames)
Discussion?

Wildland Urban Interface
A Coupled Problem

Alexander Maranghides and Ruddy Mell*
Engineering Laboratory
National Institute of Standards and Technology (NIST)
Gaithersburg, MD

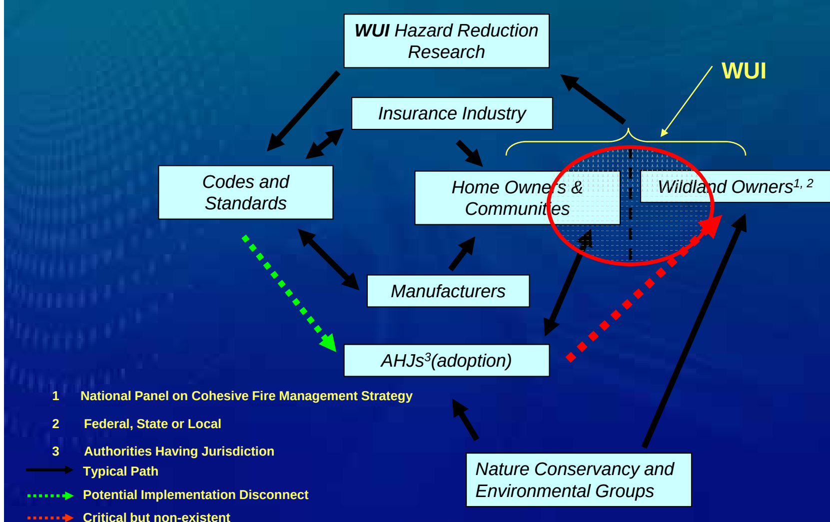
Rancho Bernardo Trails Development – Witch Fire

*** *USFS, Fire and Environmental Research Application (FERA), Seattle, WA***

Outline

- Wildland Urban Interface (WUI): A problem spanning many scales
- The Yardstick: Exposure, Exposure, Exposure
- Field Data Collection – Collecting the RIGHT data
- The NIST Witch/Guejito Case Study
- The Tanglewood Complex Fire (NIST/USFS/TFS partnership)
- Where do we go from here?

The WUI – Still an Orphan?



Hazard Reduction Solutions
From Building Materials to Land Use

- Hazard reduction solutions must be:
  - Targeted and Tested (Research)
  - Implementable (Public)
  - Reliable (Codes and Standards)
  - Cost Effective (Industry)

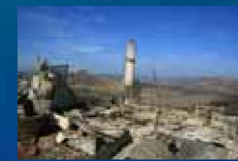
Coupled Problem REQUIRES Coupled Solutions

WUI – Housing Density and Incident Size

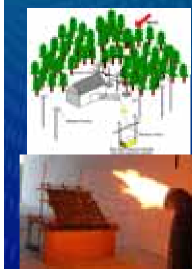
WUI Fires Occur in Different Structure Density Environments

Exposure Exposure Exposure

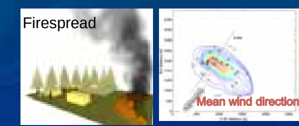
Pre- and Post-Fire Data Collection & Analysis
Texas Forest Service, CAL FIRE, City of San Diego, *Coeur d'Alene Tribe, McNamara Consult., USFS*



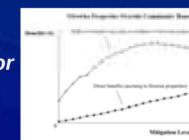
Structure Ignition
USFS, CALFIRE, ASTM, DHS, BRI



Physical Modeling
NOAA, USFS, JFSP, *U Utah. Tribe, McNamara*

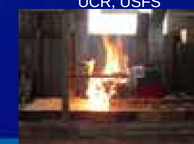


Economic Modeling
USFS, JFSP, DHS



Field Scale Fire Behavior & Wind Measurements
USFS, NOAA, *CU, RIT, SDSU*

Lab Scale Fire Behavior Measurements
UCR, USFS



Collecting Critical Baseline Information

- 16% of destroyed homes had wood shake roofs **+ baseline***
- 100% of homes with wood shake roofs that were exposed to fire were destroyed**

Baseline Info Will Help Focus In On The Problem Areas

* Baseline: all destroyed, damaged and undamaged homes within the fireline

** From NIST Witch/Guejito Fire Report #2 – report in preparation

Witch and Guejito Fires Case Study

- **NIST**
- **CALFIRE – Chief Chamlee**
- **SD Fire Department – Chief Jarman**
- **IAFF Local 145 – Eddie Villavicencio**
- **SD Police Department – Chief Lansdowne**
- **The Trails Home Owner Association – Mr. Steve Arnold**
- **NIST Grantees and Contactors**
- **USGS**

Witch and Guejito Fire Origins, Weather Stations and *The Trails* community

Successful Joint Effort

The NIST Case Study of *The Trails*

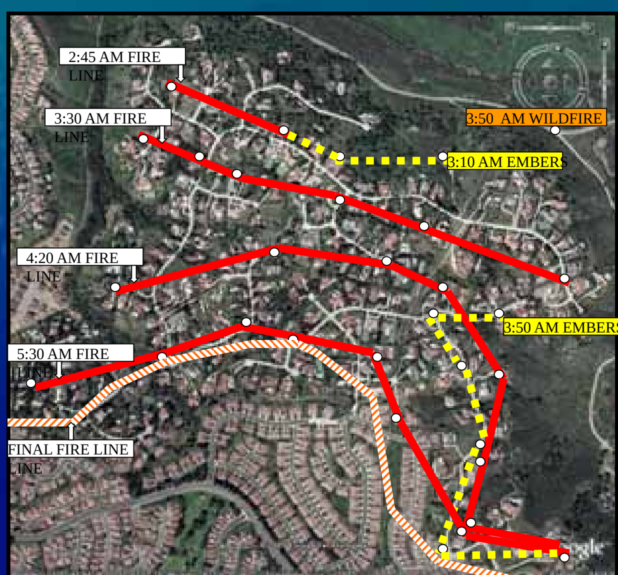
The NIST Case Study was limited to only 5% of the loses from the Witch and Guejito Fires

The Trails

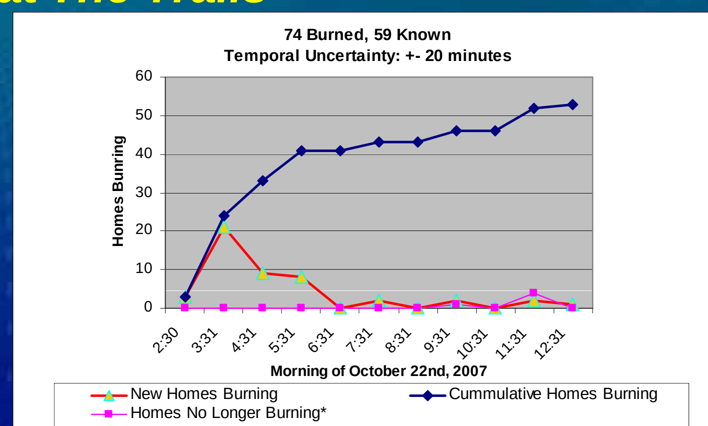
- Identify structure ignitions and fire/ember exposure
- Develop timeline
- Identify suppression actions
- Firewise analysis
- Modeling
- Post fire incident data collection methodology

- 274 residences
- 245 within fire line
- 74 residences completely destroyed
- 16 partly damaged

Fire Line Progression within *The Trails*



Cumulative Homes Burning at *The Trails*



The Trails - Defended Structures

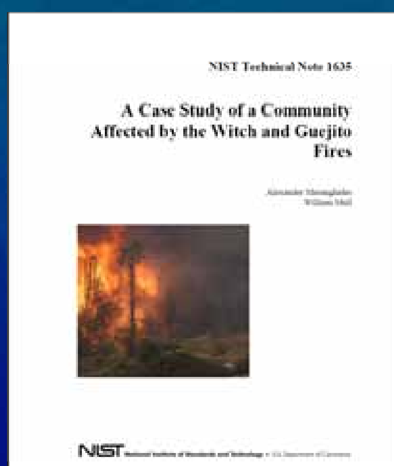
- Actions taken from 2 am until 3 pm October 22nd, 2007
- Spotting/ smoldering fires and reignitions continued after 3 pm

Findings
Structural Loses and Defensive Actions

- The **arrival of the wildland fire front**, not the preceding embers, caused the majority of the damage and **overwhelmed the first responder resources**.
- 70 % of the destroyed homes were not defended.
- 60 % of defended structures on fire were saved.
- Over 50 % of the structures were ignited within 3 hours
- Structure ignitions reached 21 per hour.
- It is estimated that 29 of the destroyed structures (40 %) were burning at the same time.

What did we accomplish to date?

- Fire behavior report - NIST TN1635 - also published in Fire Technology, 2011, Volume 47, Number 2, Pages 379-420
- Firewise-type assessment of community – report in progress
  - Defensive actions
  - Fire and ember exposure
- Methodology for future deployments – successfully used in Amarillo, TX (March 2011)



NIST Technical Note 1635

A Case Study of a Community Affected by the Witch and Guejito Fires

NIST

Field Data Collection –Two Tiered Approach

- WUI 1 Objective: Develop Uniform (Statewide) WUI Fire Losses Database
  - Training: Locally Trained Data Collectors
  - Hardware: Checklist or Pocket PC
  - Participants: NIST/ State/ County/ City
  - Implementation: adapt existing practices
  - Application: across entire Wildland Urban Interface fires
- WUI 2 Objective: Collect High Resolution Fire Behavior Data including timeline reconstruction information:
  - Training: NIST and State Trained Data Collectors
  - Hardware: GIS based system
  - Participants: NIST/ State/ County/ City
  - Implementation: new/ expanded data collection supported in part by NIST
  - Application: selected communities

Collecting Critical Baseline Information

- 16% of destroyed homes had wood shake roofs
  + baseline*
- 100% of homes with wood shake roofs that were exposed to fire were destroyed**

Baseline Info Will Help Focus In On The Problem Areas

* Baseline: all destroyed, damaged and undamaged homes within the fireline

** From NIST Witch/Guejito Fire Report #2 – report in preparation

WUI 1 - Field Data Collection Kit Paper Solution

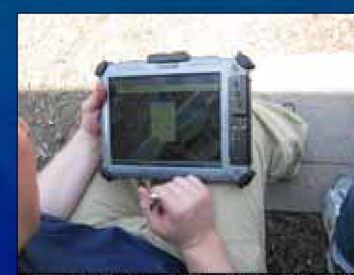

DAMAGE ASSESSMENT REPORT

- Checklist and clipboard
- GPS w/street maps
- Digital Camera
- Batteries and chargers
- Hardware and software cost ~ $400/ kit
- *Advantages*
  - Easy to use checklist
  - Robust system
  - Street maps available in GPS
- *Disadvantages*
  - More time and labor intensive data transfer
  - Impractical for large incidents

WUI 1 - Field Data Collection Kit Electronic Solution

- PDA or Phone with GPS and street maps
- Digital Camera
- Batteries and chargers
- Hardware and software cost ~ $500/ kit
- Advantages
  - Electronic data transfer reducing time and labor
  - Street maps built in
- Disadvantages
  - Harder to read and use in the field
  - Less robust
  - Slightly more expensive

NIST WUI 2 – GIS Data Collection Process



- Pre-fire
  - training
  - kits maintenance
  - GIS data gathering
- During and shortly after fire
  - decision to collect data
  - collect and load GIS data
  - mobilize team
  - field data collection
  - demobilize team
- Post Fire
  - collect first responder and homeowners data
  - data analysis
  - report writing

WUI Assessment System Field Kits

- Equipment
  - Clinometer, Compass, Range Finder, Camera, two-way radio, hand-held GPS, Etc…
  - First Aid, Repellant, Flagging, Batteries, Etc…

- 9 Boxes
  - 7 Field Kits & Extras
- 3 Pelican Cases
  - 7 Tablet PCs
  - 7 Extra Batteries
  - Battery Chargers

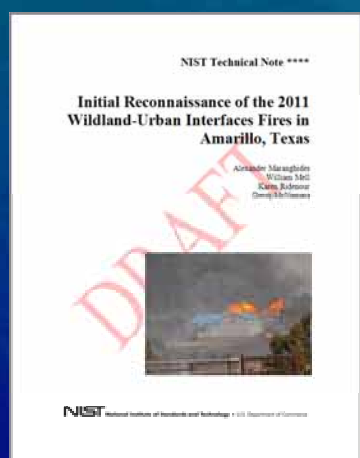
Amarillo Deployment Summary

- Primary focus: Tanglewood Complex Fire
- Secondary focus: Willow Creek Fire
- 21 days
- Two to three WUI 2 Teams
- One WUI 1
- Field data collection initiated within 48 hours of ignition

Locations of fires around Amarillo Texas

Tanglewood Complex Fire

- Over 120 structures documented using WUI 2
- 163 GB of data collected
- Timeline reconstruction data collection (85% completed)
- Summary report of deployment to be issued by NIST in next 2 weeks.
- First technical report to be issued Maranghides, Mell, Ridenour *et al.* in 12-18 months.



NIST Technical Note ****

Initial Reconnaissance of the 2011 Wildland-Urban Interfaces Fires in Amarillo, Texas

Alexander Maranghides
William Mell
Karen Ridenour

DRAFT

NIST

Summary

- The NIST developed two tiered data collection methodology has been successfully field tested as applied to the WUI fire problem
- Training in California (San Diego) and in Region 8 (Location TBD) scheduled for FY12

Thank You for Your Attention

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Ignition of Cellulose Fuel Beds by Hot Metal Particles

Sarah Scott[1], Rory Hadden[2], Ann Yun[1],
Chris Lautenberger[1], A. Carlos Fernandez-Pello[1]

[1]Department of Mechanical Engineering, University of California, Berkeley, Berkeley CA 94720, USA

[2]BRE Centre for Fire Safety Engineering, University of Edinburgh, Edinburgh, UK

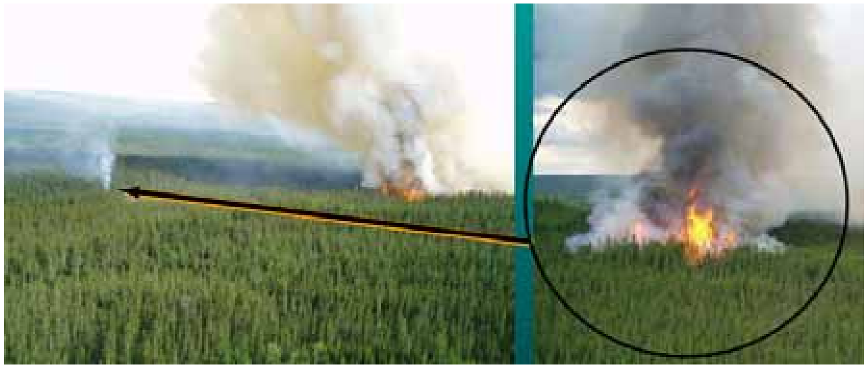
Background

- Regions with long hot dry periods are vulnerable to wide spread wild land fires
  - Western United States
  - Australia
  - Mediterranean

Fire Spotting

- Under dry, hot, and windy conditions (such as Santa Ana winds in California) an important mechanism of wildland fire spread is spotting
- Fire "spotting" is due to the ignition of vegetation by burning embers lofted by the plume of ground fires and transported by the wind ahead of the fire front
- Fire spotting can also be caused by metal particles ejected from arcing power lines or by burning embers generated by power lines contacting trees
- Important to understand spotting to understand fire spread

Spotting in a Forest Fire



An example of spotting

Wildland Fire Urban Inteface

Photo by JOHN GIBBINS / Union-Tribune
Cedar Fire about to engulf the Scripps Ranch residential community

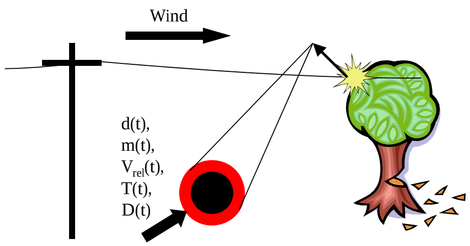
Fire Patterns From Spotting

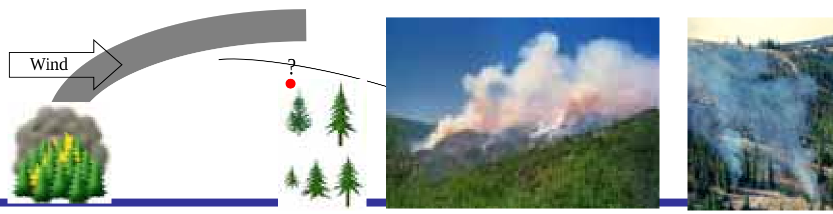
Background: Particles

Fire spotting at the urban/wild land interface

Embers and metal particle generation

- Arcing power lines in high winds-burning ember or metal particle ejected
- Ground fire lofts burning ember
- Burning ember or spark can lead to fire "spotting"
- How is particle carried by wind?
- What is its temperature upon landing?
- Is it burning upon landing?
- Is it capable of igniting vegetation?





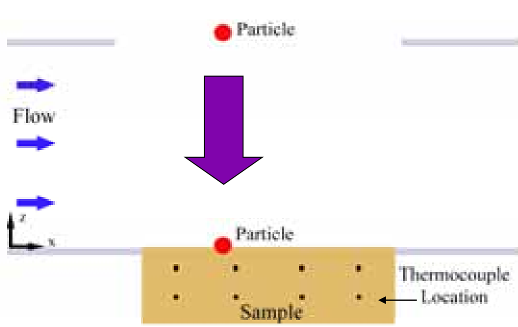
Objectives

- Perform experiments to determine critical temperature and size for a particle to ignite a combustible fuel bed

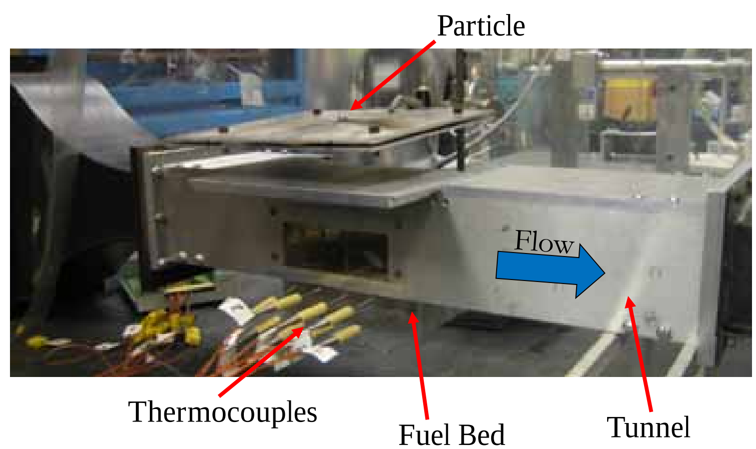
Southern California Fire, October 2007

Spotting Ignition Experiment

- Load sample into small scale wind tunnel
- Heat the particle outside the tunnel
- Set air flow rate
- Drop Particle
- Record Temperature Data
- Record Video Data



Experimental Design

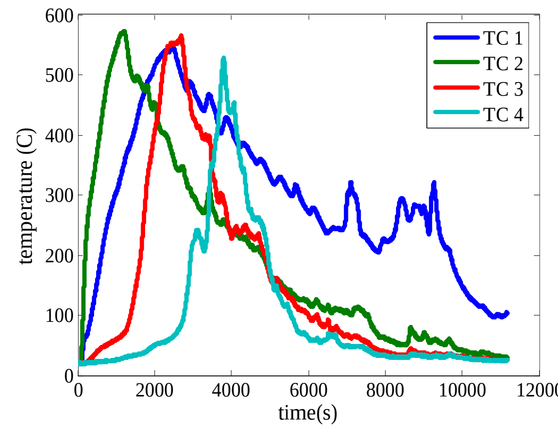


Video of Test Powdered Celllose

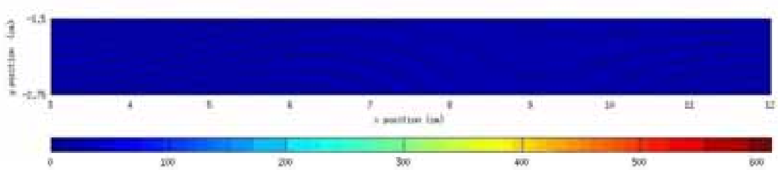
Powdered Cellulose, 1100°C 15mm Steel Sphere, 2 m/s Air Flow from the right (3.1 hour test sped up x512)

Powdered Cellulose

- Sample with sustained smolder
- 15mm Steel Sphere, Heated to ~1100°C, 2 m/s Air Flow
- 1.6 mm/min forward propagation rate



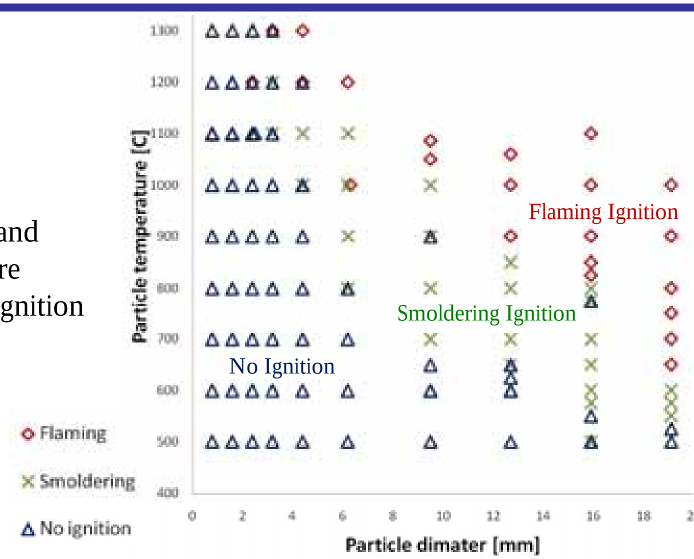
Powdered Cellulose



Temperature map for a sample with sustained smolder (15mm Steel Sphere, ~1100°C, 2 m/s Air Flow from left)

Results

- Both size and temperature influence ignition



Data Correlation

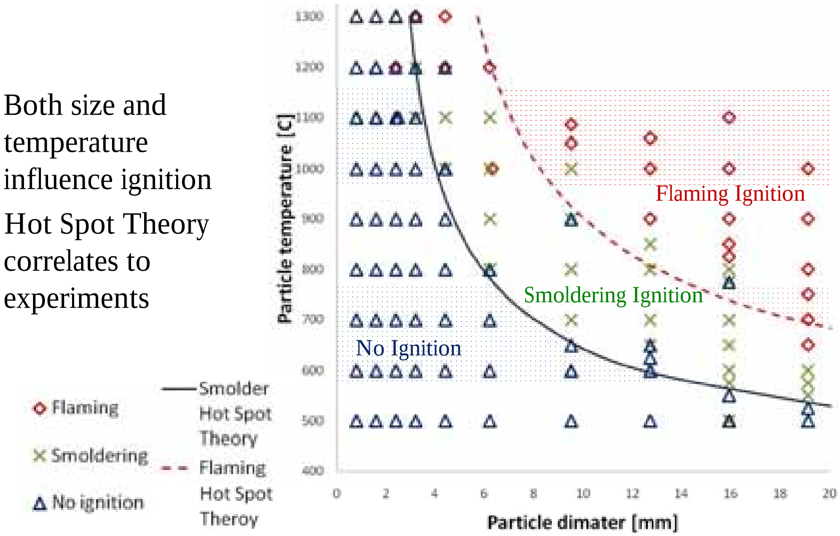
- Hot Spot Theory gives a critical diameter for ignition of the form

$$d_{cr} = C_1 T_p \sqrt{\exp\left(\frac{C_2}{T_p}\right)}$$

- Parameters C_1 and C_2 determined by fitting to data

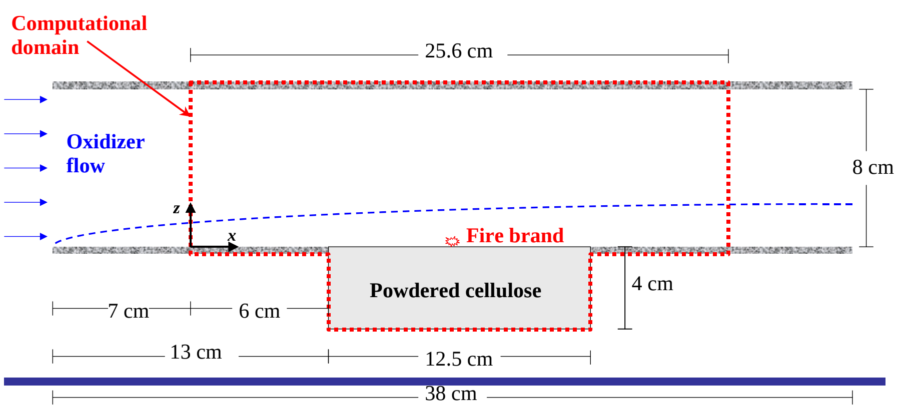
Data Correlation

- Both size and temperature influence ignition
- Hot Spot Theory correlates to experiments



Experimental / Model Schematic

- 2D schematic of experimental wind tunnel and its computer model representation:



Solid-phase Governing Equations (1)

Conservation of solid mass:

$$\frac{\partial \bar{\rho}}{\partial t} = -\dot{\omega}'''_{fg}$$

Conservation of solid species:

$$\frac{\partial (\bar{\rho} Y_i)}{\partial t} = \dot{\omega}'''_{fi} - \dot{\omega}'''_{di}$$

Conservation of gas mass:

$$\frac{\partial (\rho_g \bar{\psi})}{\partial t} + \frac{\partial \dot{m}''_x}{\partial x} + \frac{\partial \dot{m}''_z}{\partial z} = \dot{\omega}'''_{fg}$$

Conservation of gas species:

$$\frac{\partial (\rho_g \bar{\psi} Y_j)}{\partial t} + \frac{\partial (\dot{m}''_x Y_j)}{\partial x} + \frac{\partial (\dot{m}''_z Y_j)}{\partial z} = -\frac{\partial \dot{j}''_{j,x}}{\partial x} - \frac{\partial \dot{j}''_{j,z}}{\partial z} + \dot{\omega}'''_{fj} - \dot{\omega}'''_{dj}$$

Solid-phase Governing Equations (2)

Conservation of solid energy:

$$\frac{\partial(\overline{\rho h})}{\partial t}+\frac{\partial(\dot m''_x h_g)}{\partial x}+\frac{\partial(\dot m''_z h_g)}{\partial z}=-\frac{\partial \dot q''_x}{\partial x}-\frac{\partial \dot q''_z}{\partial z}+\dot Q'''_s+\sum_{i=1}^{M}(\dot\omega'''_{fi}-\dot\omega'''_{di})h_i$$

Conservation of gas energy (thermal equilibrium):

$$T_g = T$$

Pressure evolution equation (from Darcy's law):

$$\frac{\partial}{\partial t}\left(\frac{P\overline{M}\overline{\psi}}{RT_g}\right)=\frac{\partial}{\partial x}\left(\frac{\overline{K}}{\nu}\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{\overline{K}}{\nu}\frac{\partial P}{\partial z}\right)+\dot\omega'''_{fg}$$

Reaction Source Terms

Stoichiometry:

$$1\,\text{kg}\ A_k+\sum_{j=1}^{N}\nu'_{j,k}\ \text{kg gas}\ j\rightarrow\nu_{B,k}\text{kg}\ B_k+\sum_{j=1}^{N}\nu''_{j,k}\ \text{kg gas}\ j$$

Thermal pyrolysis reaction rate:

$$\dot\omega'''_{dA_k}=\left(\frac{\overline{\rho}Y_{A_k}}{(\overline{\rho}Y_{A_k})_\Sigma}\right)^{n_k}(\overline{\rho}Y_{A_k})_\Sigma Z_k\exp\left(-\frac{E_k}{RT}\right)$$

Oxidative pyrolysis reaction rate:

$$\dot\omega'''_{dA_k}=\left(\frac{\overline{\rho}Y_{A_k}}{(\overline{\rho}Y_{A_k})_\Sigma}\right)^{n_k}(\overline{\rho}Y_{A_k})_\Sigma\left[(1+Y_{O_2})^{n_{O_2,k}}\right]Z_k\exp\left(-\frac{E_k}{RT}\right)$$

Reaction Mechanism

- 3-step reaction mechanism developed for white pine:

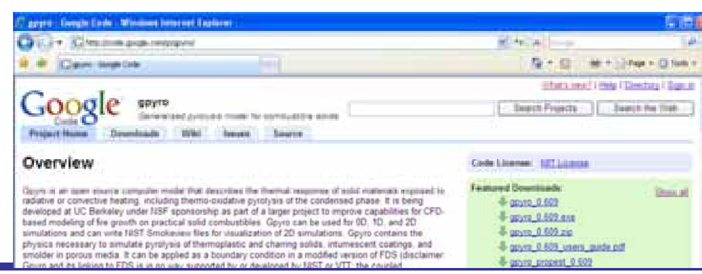
$$\text{cellulose}\ \rightarrow\nu_{\text{char}}\ \text{char}+\nu_{\text{tp}}\ \text{thermal pyrolysate}$$

$$\text{cellulose}\ +\nu_{O_2\text{cell}}\,O_2\rightarrow\nu_{\text{char}}\ \text{char}+\nu_{\text{op}}\ \text{oxidative pyrolysate}$$

$$\text{char}\ +\nu_{O_2\text{char}}\,O_2\rightarrow\nu_{\text{ash}}\ \text{ash}+\nu_{\text{cop}}\ \text{char oxidation products}$$

Computer Code – Solid Phase

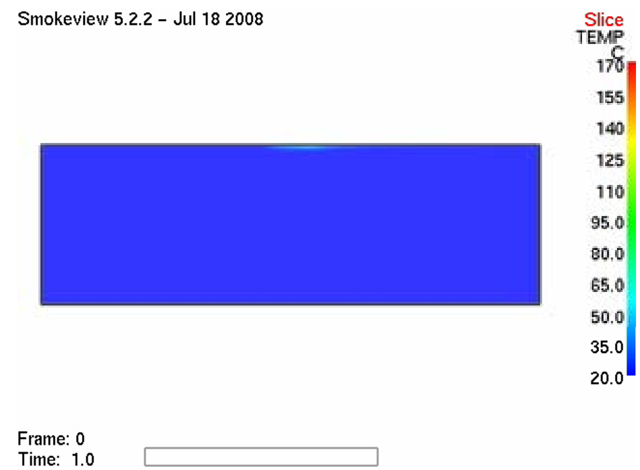
- Gpyro – http://code.google.com/p/gpyro
  - Open source – funded by NSF as part of larger project
  - Conjugate heat transfer in reacting porous media (2D)
  - Solves for pressure and gas/solid species in porous fuel bed
  - Coupled to FDS where it is applied as boundary condition



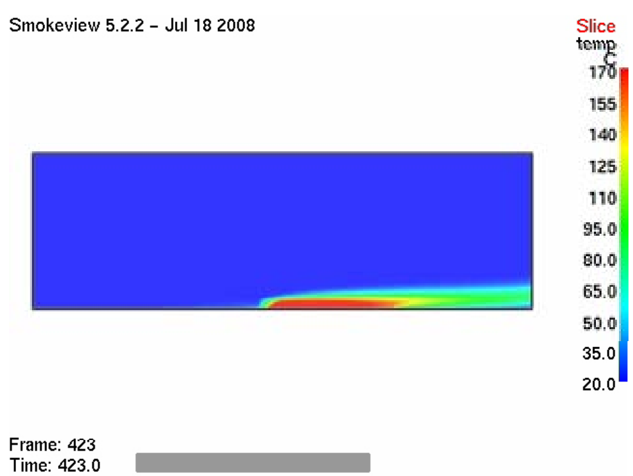
Computer Code – Gas Phase

- Fire Dynamics Simulator (FDS)
  - CFD-based fire model developed by NIST and VTT
  - 2D implementation applied here
  - Single step finite rate combustion reaction
  - Ember modeled as volumetric heat source (4 or 6 MW/m^3)

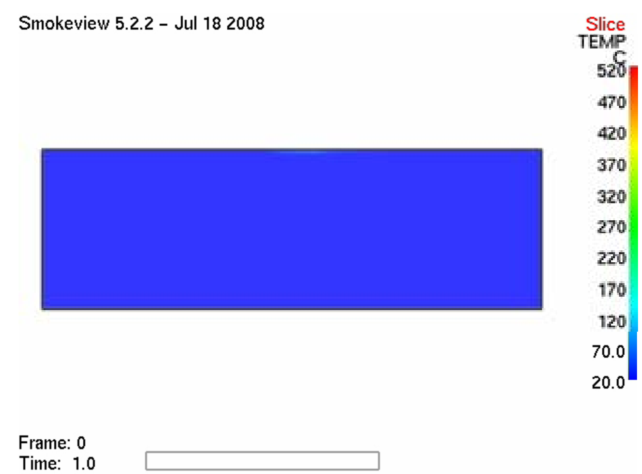
Smoldering Ignition – Solid Temperature



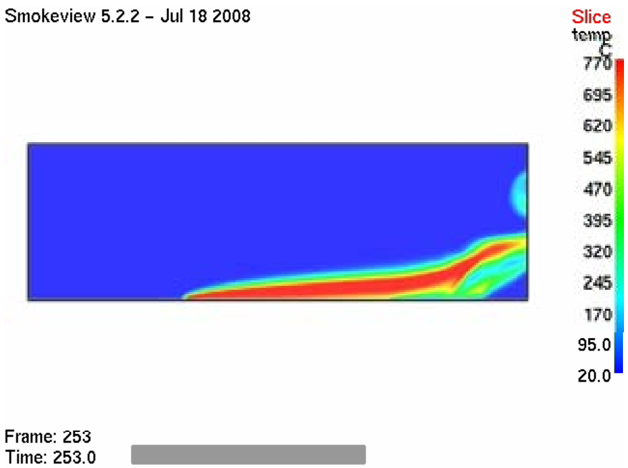
Smoldering Ignition – Gas Temperature



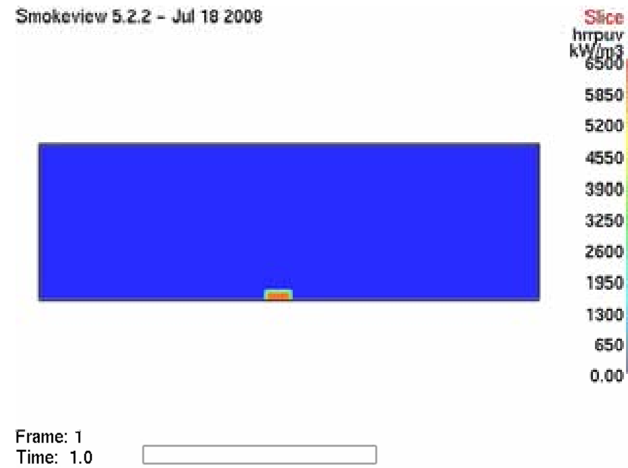
Flaming Ignition – Solid Temperature



Flaming Ignition – Gas Temperature



Flaming Ignition – Gaseous Reaction Rate

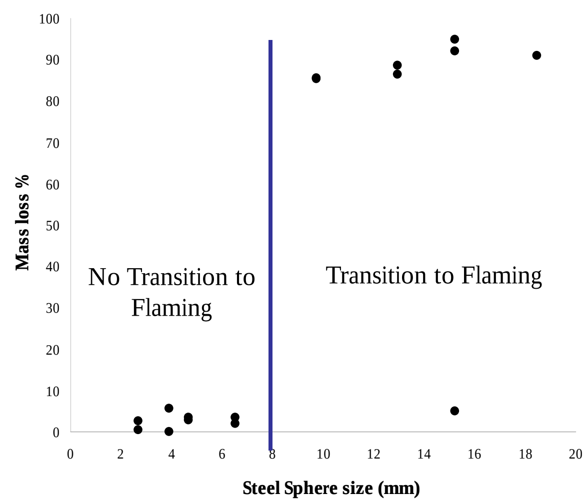


Video of Tests Ponderosa Pine Needles

Ponderosa Pine Needles, ~1100°C 13mm Steel Sphere, 0.54 m/s Air Flow from the right

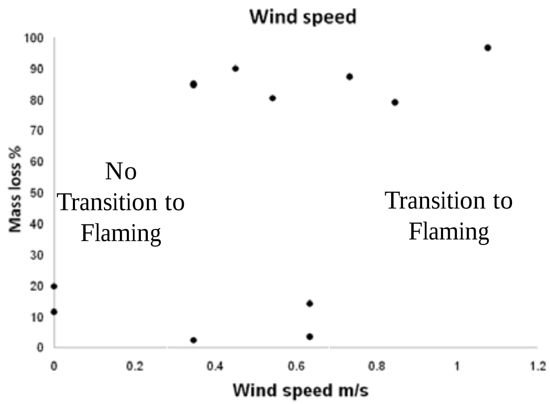
Minimum Particle Size for Ignition

- Mass loss used as indication of burning
- Pine needles are an inhomogeneous sample, causing inconsistent ignition
- Possible minimum particle size for ignition



Minimum Wind Speed for Ignition

- Possible minimum wind speed range for ignition
- Pine needles are an inhomogeneous sample, causing inconsistent ignition
- More testing required



Summary

- Cellulose testing suggest demarked ignition regimes
  - At 1100°C the minimum size for:
    - smolder ignition is 3mm
    - flaming ignition is 9mm
  - At 19.1mm the minimum temperature for:
    - smoldering ignition is 550°C
    - flaming ignition is 650°C
- Pine needles testing suggests a critical steel sphere size
  - At 1100°C the minimum size for ignition is 8mm
- Hot Spot Theory provides a correlation of flaming and smoldering ignition
- Numerical models coupling solid and gas phases provide a better understanding of the ignition controlling mechanisms

An Urban Fire Simulation Model (UFS)

Rachel Davidson (University of Delaware)
with students Sizheng Li (current) and Selina Lee (former)

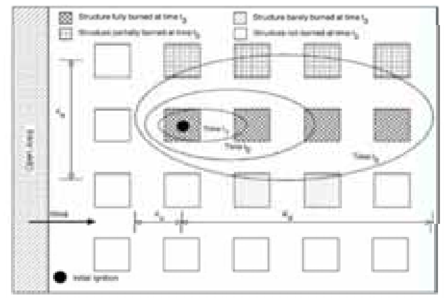
Urban and Wildland-Urban Interface (WUI) Fires:
A Workshop to Explore Future Japan / USA Research Collaborations

NIST, June 27, 2011

Background on (post-eq) urban fire models

Hamada-based models

Macro, empirical



- Scawthorn et al. 1981
- HAZUS-MH (FEMA 1999)

Physics-based models

Micro, physics-based

Spread modes explicit

- Himoto/Tanaka (2008)
- Cousins et al. (2002)
- Iwami et al. (2004)
- ResQ Firesimulator (2004)

(Simplify physics, geometry in different ways)

Urban Fire Simulation (UFS) Model

Applicability

- Involves many buildings
- Possibly many ignitions
- Post-eq and WUI

Components

- Ignition
- Spread
- *Suppression*

Anticipated uses

- Improve understanding, contributing factors, how they interact
- Estimate risk under different circumstances
- Identify, evaluate effectiveness of risk reduction measures
- Identify areas for further study

Presentation Outline

- Introduction
  - Background
  - Uses and applicability of model
- UFS model description
  - Inputs and GIS pre-processing
  - Overview
  - Modules
- Grass Valley case study
  - Inputs
  - Results
- Conclusions and future work

Model Inputs

Building
- Num. stories
- Occupancy type (e.g., single-family, school)
- % exterior wall that's windows
- Cladding, roof type
- Home ignition zone (HIZ) level
- Geometric attributes from building footprint

Region
- NFDRS Ignition Component (IC), Spread Component (SC)

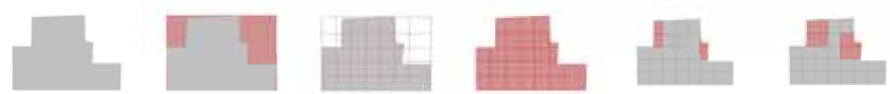
Ignition
- Deterministic. User-specified.
- Probabilistic. Negative binomial regression→mean number of ignitions per census tract for an eq; simulate exact location.

Wind
- Deterministic. User-specified.
- Probabilistic. Sample time series from historical data

GIS Pre-processing

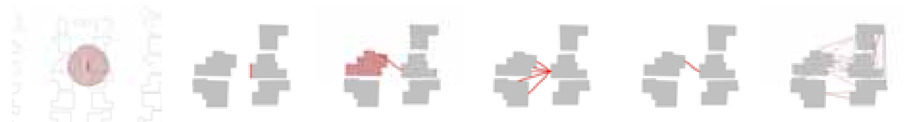
Divide building footprints into rooms

Assume min. room wall length, min. room area



Find "facing wall" for each building wall

Nearest wall of another building s.t. line connecting them doesn't intersect any buildings



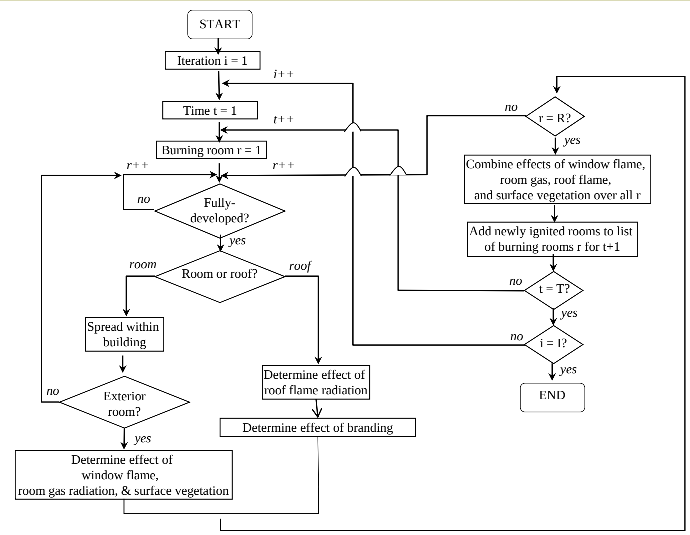
Fire Spread Modules

Evolution of fire within a room or roof

Room-to-room spread within a building
- Doorway
- Burn through walls, ceilings, and floors
- Leapfrogging

Building-to-building spread
- Flame impingement and radiation from window flame and room gas
- Radiation from roof flame
- Branding
- Surface vegetation

Overall Fire Spread Simulation Process



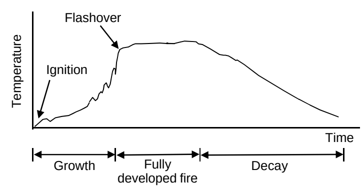
Evolution within a Room or Roof

Temperature-time curves (Law and O'Brien 1981)

- Reasonable results
- Requires only room dimensions, window area, fire load
- Includes other modules → ensures consistency

Rate of burning

- Draft conditions (thru or no)
- Occupancy-dependent fuel load
- Room, window dimensions



Fully developed phase if $0.3<L_t<0.8$

Room-to-Room Spread within a Building

Through doorways (1 door/interior wall)

- If open (p=0.5) → immediate ignition
- If closed (p=0.5) → wall subject to burnthrough

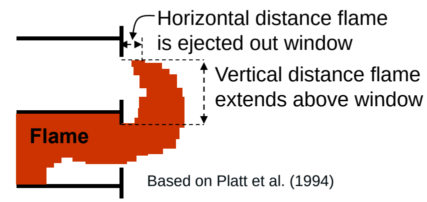
Burn through walls, ceilings, floors

$t_{burnthru} \sim LN(\mu_{FR,barrier}, \sigma)$

$t_{down} = 2t_{up}$

(based on IBC 2006)	Mean time to burnthrough in hours		
	Fire-resisitive	Protected	Unprotected
Interior beaing walls	2	1	0.25
Interior non-bearing walls	0.25	0.25	0.25
Floor-ceiling assemblies	2	1	0.25
Roof-ceiling assemblies	1.5	1	0.25

Leapfrogging



Based on Platt et al. (1994)

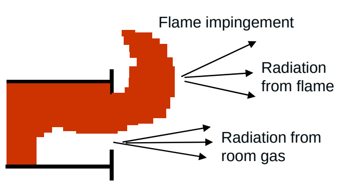
External wall spread

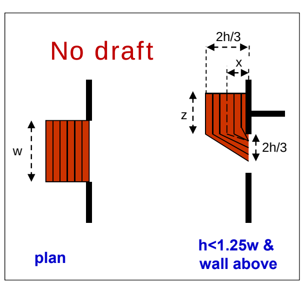
If cladding flammable

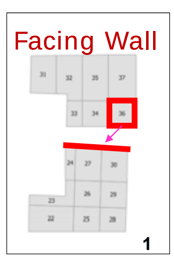
→ $t_{spread} \sim U(2, 10 \text{ min})$

Building-to-Building Spread: FI, Window Flame & Room Gas Radiation

1. Window flame geometry (Law and O'Brien 1981)
2. Configuration factor ϕ
   - Radiator: vertical rectangle (window or flame front)
   - Multiple receivers. Centroids of windows in facing wall on same floor as burning room.
3. Radiation received $I_z = \phi_z \varepsilon_z \sigma \left(T_z^4 - T_a^4\right)$







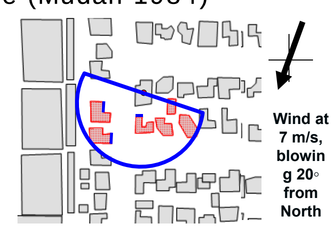
Building-to-Building Spread: Radiation from Roof Flame

Assume roof flame is large, open pool fire (Mudan 1984)

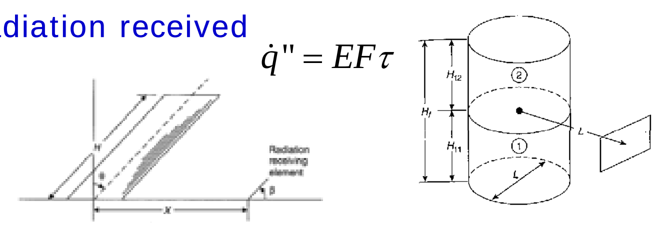
1. Burning rate

   Assume roof is room with N.P. at ceiling.
2. Roof flame geometry
3. Configuration factor, F

   All bldgs. in semi-circle; roofs, windows in flame height
4. Radiation received

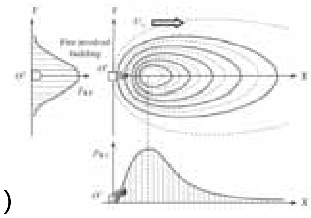


$$\dot{q}'' = EF\tau$$

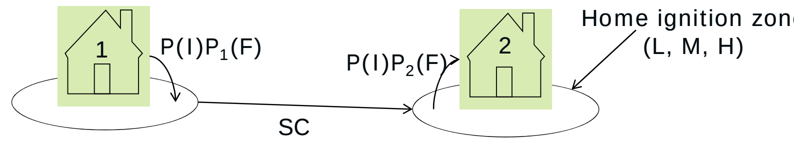


Building-to-Building Spread: Branding

1. Generation
   - Empirical (e.g., Waterman 1969)
   - Depends on wind speed, roof area
   - Size: Fine, medium, coarse
2. Transport (Himoto and Tanaka 2008)
3. Host ignition
   - Empirical (e.g., Waterman and Takata 1969)
   - Depends on roof type



Building-to-Building Spread: Surface Vegetation



P(I) Probability fuel will ignite
f(air temp, moisture content)
(from NFDRS ignition component)

P(F) Probability there is fuel to ignite near home
Based on home ignition zone level (L, M, H)

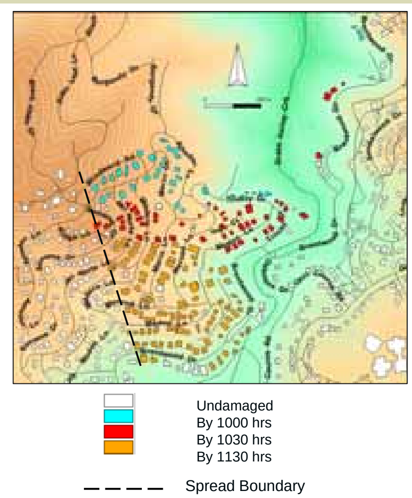
SC Speed of spread
f(wind speed, slope, moisture content, fuel characteristics)
Spread component NFDRS

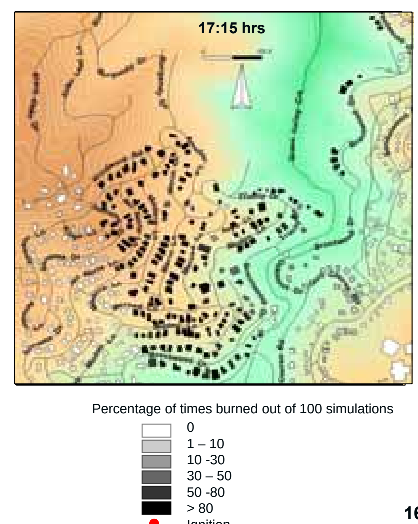
Grass Valley, CA fire

- October 22, 2007
- Part of 23-fire outbreak in So. Calif.
- Burned 1250 acres, destroyed 174 homes, damaged 25
- Steep terrain
- Lots of vegetation (Pine/oak overstory, brush understory, needle/leave/branch surface litter)
- Large 2- to 3-story woodframe SFDs with clapboard siding, wood or asphalt shingle roofs
- Drought, Santa Ana winds N-NE 18 mph, gusts 27 mph, RH=10%
- Suppression. $5.7M, 109 engines, 3 helicopters, up to 1051 firefighters


Cohen and Stratton (2008)

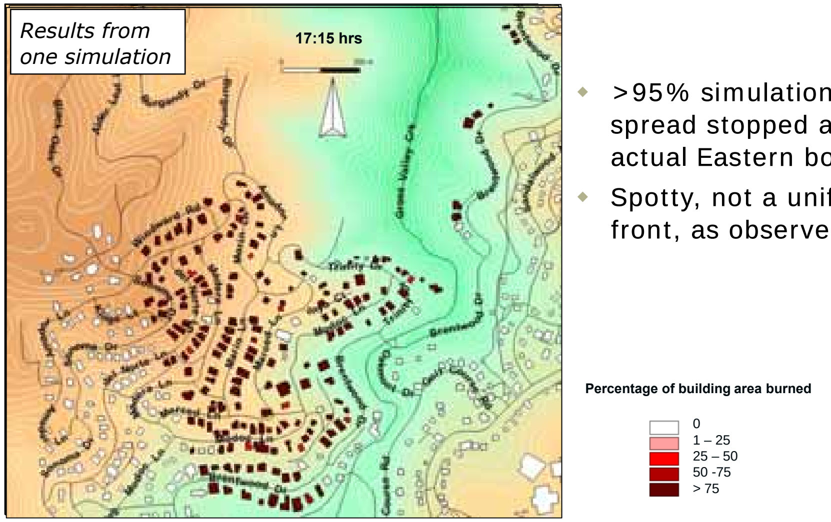
Grass Valley fire spread





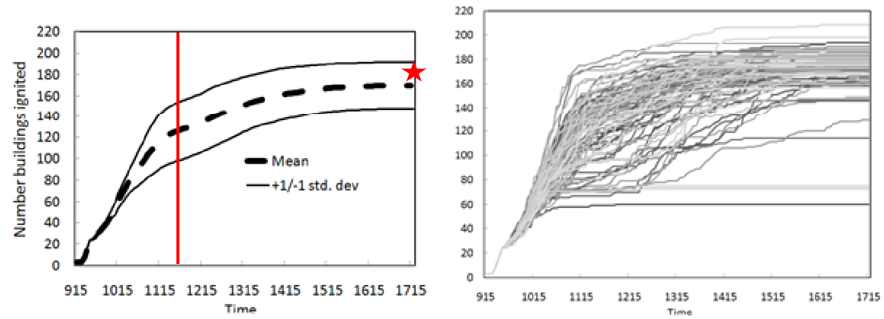
100 iterations
(so CI half-length of mean total burned area=3.6%)

Nature of fire spread



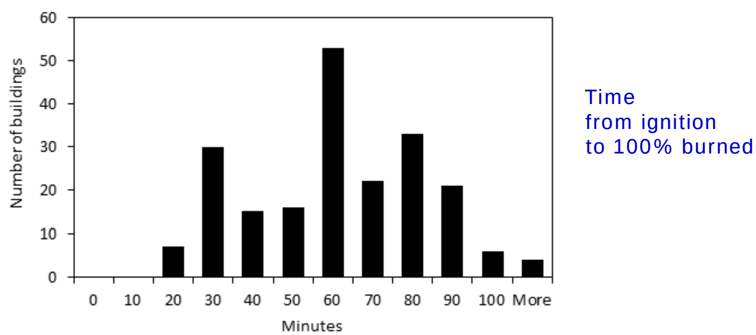
- >95% simulations spread stopped at actual Eastern border
- Spotty, not a uniform front, as observed.

Speed of spread through neighborhood



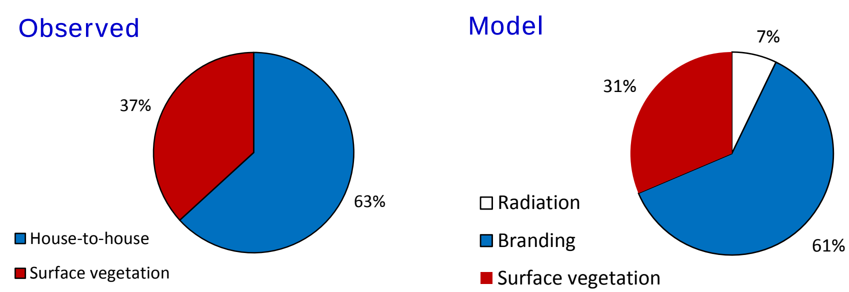
- On avg. 170 bldgs ignited vs. 180 in real life
- At 11:41a, on avg. 125 ignited and 85 >50% burned. vs. 75 to 100 reported destroyed
- High variability as in real life

Speed of spread thru a building



- Mean=57 min
- Consistent with common belief
- Possibly a little fast because of external wall spread

Modes of fire spread



- Similar modes of spread
- Branding and surface vegetation both important
- In reality, difficult to determine mode & may be multiple modes

Key features

- Physics-based with simplified rules
  - Evolution within room based on temp-time curves
  - Room-to-room spread within building by
    - Open doors
    - Burn through walls, ceilings, floors
    - Leapfrogging
  - Building-to-building spread by
    - Radiation from room gas, window flame, roof flame
    - Flame impingement from window flame
    - Branding
    - Surface vegetation
- Use real building footprints
- Room-based spread
- Configuration factors
- Treat roof flame as a pool fire
- Appropriate level of detail
- Quantifies uncertainty
- Ignition model
- No suppression currently

Final remarks

- UFS results match Grass Valley observations well w.r.t. spatial pattern, timing, modes of spread
- Validation is difficult (e.g., Oreskes et al. 1994)
  - Match between observations and model results doesn't prove model is correct
  - Variability and few events to observe
  - Observations incomplete
- Future work
  - Incorporate suppression
  - Improve spread around external walls
  - Incorporate topography

Acknowledgements

National Science Foundation
WHERE DISCOVERIES BEGIN

- Jack Cohen, USFS
- Craig Beyler, Hughes Associates
- Jason Floyd, Hughes Associates
- Charles Scawthorn, UCBerkeley (formerly Kyoto U.)

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Quantifying Structure Vulnerabilities to Ignition from Firebrand Showers

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Japan/USA Workshop
June 27th, 2011

WUI: What is the Problem?

- Post-fire studies – firebrands a major cause of ignition
- Understanding firebrand ignition of structures – important to mitigate fire spread in communities

Improved understanding of structure ignition in WUI fires
  - Major recommendation (GAO 05-380)
  - National Science and Technology Subcommittee on Disaster Reduction
  - Homeland Security Presidential Directive (HSPD 8; Paragraph 11)

2007 Southern California Fire

2003 Southern California Fire

Partnerships

- **BRI - Japan**
- **US Department of Homeland Security**

Who Cares?

- **CALFIRE**
- **ASTM**
- **ISO, ICC, NFPA, Insurance Industry**
- **Homeowners**

International Collaboration BRI (Japan) and EL-NIST (USA)

- **Firebrands: generation, transport, ignition**
- **Research focused on how far firebrands travel for 40 yrs!!**
- **Nice Academic Problem – Not helpful to design structures**
- **Vulnerable points where firebrands may enter structure**
  - **Unknown/guessed!**
- **Difficult to replicate firebrand attack!**
- **Entirely new experimental methods needed!**

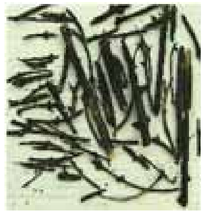
Goals

Science - Building Codes/Standards; Retrofit construction

Design structures to be more resistant to firebrand ignition

Douglas-Fir Tree Burns at NIST

- Firebrand Collection using water pan array
  - Range of crown heights: 2.4 m – 4.5 m
  - Different moisture regimes
- Mass loss using load cells



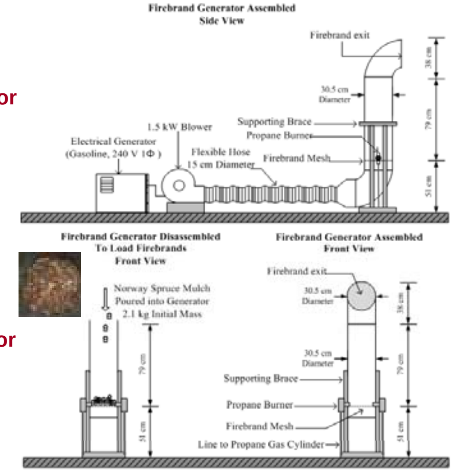
4.5 m Douglas Fir, MC = 25%

Firebrand Generator (NIST Dragon) 龍

Capable of producing controlled and repeatable size and mass distribution of firebrands

Firebrand Generator Side View

Firebrand Generator Front View



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Building Research Institute (BRI)

- Fire Research Wind Tunnel Facility (FRWTF)
- Unique facility – investigate influence of wind on fire
  - Constructed more than 10 years before IBHS wind tunnel

Fire Research Wind Tunnel Facility (FRWTF)

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NIST Dragon 龍

Firebrand size/mass commensurate to full scale tree burns and actual WUI fire (2007 Angora Fire)

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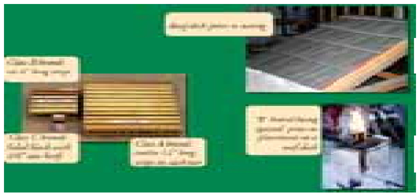
Current Roofing Standards

Roofing test: ASTM E108; UL 790
Does not simulate dynamic firebrand attack!

Japan/USA
Use This Test!



12 mi/hr
(5.3 m/s)

Mitchell &Patashnik [2007] – possible correlation homes ignited in 2003 Cedar Fire with those homes fitted with ceramic tile roofing

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Ceramic Roofing

Aged Roofing Simulated: OSB, then tiles (no tar paper)

U_∞ (m/s)	OSB/TP/CT No Bird Stops	OSB/TP/CT With Bird Stops	OSB/CT No Bird Stops	OSB/CT With Bird Stops
7	SI	NI	SI to FI	SI
9	SI	NI	SI to FI	SI

New Roofing Construction: OSB, Tar Paper, then Ceramic Tiles

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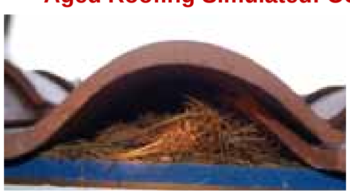
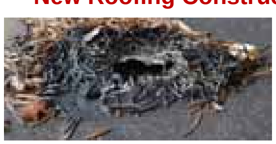
Ceramic Roofing

Aged Roofing Simulated: OSB, then tiles (no tar paper)



U_∞ (m/s)	OSB/TP/CT No Bird Stops	OSB/TP/CT With Bird Stops	OSB/CT No Bird Stops	OSB/CT With Bird Stops
7	SI	SI	SI to FI	SI
9	SI	SI	SI to FI	SI

New Roofing Construction: OSB, Tar Paper, then Ceramic Tiles



Pine Needles/Leaves Under Tiles

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Roofing Tests

- Roofing section constructed for testing
- Gutters filled with needles/leaves
- Firebrands cause SI; then transition to FI

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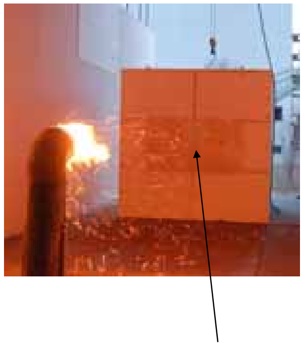
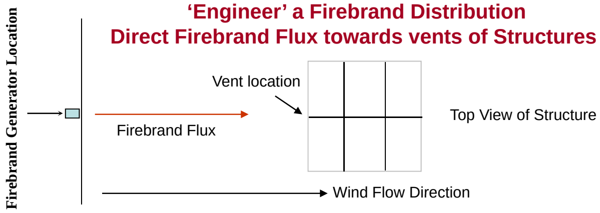
Firebrand Penetration Through Vents

Experiments conducted in 2007





Screen Behind Vent
Three sizes tested 6 mm , 3 mm , and 1.5 mm

Research Plan

- Quantify firebrand penetration through building vents
  - Full scale experiments at BRI
    - Only full scale wind driven testing in the world
  - Compare to new NIST reduced scale tests (Dragon's LAIR)
  - Compare to apparatus developed by ASTM E05.14.06 Vents
    - Wind driven firebrand attack at reduced scale
  - 6 mesh sizes (5.72 mm to 1.04 mm)
  - Four types of ignitable materials behind mesh
    - Cotton,
    - Shredded Paper,
    - OSB – Wood Crevice (filled with shredded paper)
    - OSB – Wood Crevice (bare – no shredded paper)

Manzello/Quarles preparing paper summarizing results

BRI/NIST Full Scale Experiments

20 x 20 mesh (1.04 mm) is shown

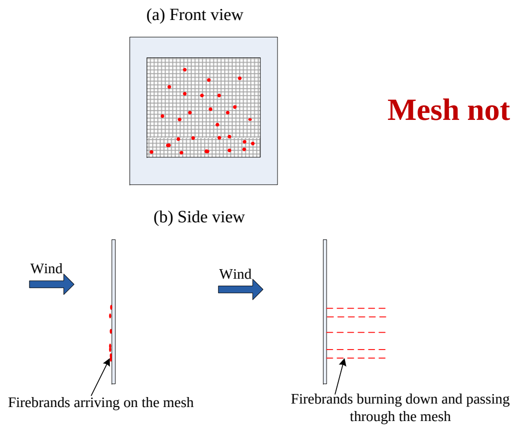
Summary of BRI/NIST Results

- SI – Smoldering Ignition; FI – Flaming Ignition
- NI – No Ignition
- Each case – three repeat experiments

Mesh	Paper	Cotton	Crevice	Crevice with paper
4 x 4 (5.72 mm)	SI to FI	SI	SI	SI to FI (paper) SI (OSB)
8 x 8 (2.74 mm)	SI to FI	SI	SI	SI to FI (paper) SI (OSB)
10 x 10 (2.0 mm)	SI to FI	SI	NI	SI to FI (paper) (SI OSB)
14 x 14 (1.55 mm)	SI	SI	NI	SI (paper) SI (OSB)
16 x 16 (1.35 mm)	SI	SI	NI	NI
20 x 20 (1.04 mm)	Two tests: NI; One test SI	Two tests: SI One Test NI	NI	NI

Mesh Effectiveness

BRI/NIST full scale and NIST reduced scale tests - mesh is not effective



Mesh not effective!

Research Plan

- **Determine siding treatment vulnerability to firebrand showers**
  - **Do firebrands become trapped within corner post/under siding itself?**
- **Determine glazing assembly vulnerability to firebrand showers**
  - **Do firebrands accumulate inside corner of framing of glazing assemblies, and lead to window breakage?**
- **Determine eave vulnerability to firebrand showers**
  - **Do firebrands become lodged within joints between walls/eave overhang?**
- **Determine if fine fuels adjacent to structure can produce ignition**

First experiments ever conducted

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Workshop Held For Testing Input in CA in 2010


NIST Special Publication 1111

Summary of Workshop on Research Needs for Full Scale Testing to Determine Vulnerabilities of Siding Treatments and Glazing Assemblies to Ignition by Firebrand Showers

Samuel L. Manzello
Sayaka Suzuki
Fire Research Division
Building and Fire Research Laboratory

June 2010

U.S. Department of Commerce
Gary Locke, Secretary

National Institute of Standards and Technology
Patrick D. Gallagher, Director

Industry
Fire Service
CALFIRE/OSFM
Building Officials
Code Consultants

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Siding Treatments

- **Corner - believed that firebrands may become trapped within the corner post and under the siding itself**
- **OSB, moisture barrier applied (OSB dried; 11 %)**

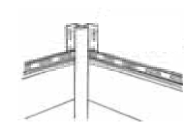

Image of vinyl siding (from bottom) after firebrand exposure at 7 m/s

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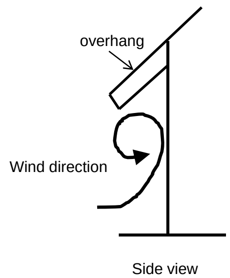
Eave Vulnerability

- A very important, long standing question is whether firebrands may become lodged within joints between walls and the eave overhang
- There are essentially two types of eave construction commonly used in California and the USA
  - Open eave
  - Boxed in eave
- In open eave construction, the roof rafter tails extend beyond the exterior wall and are readily visible
- In the second type of eave construction, known as boxed in eave construction, the eaves are essentially enclosed and the rafter tails are no longer exposed

Firebrand accumulation in eaves
Does this really happen??



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Walls Fitted With Eaves

Images of eave assemblies constructed for testing

Open eave construction is thought to the worst possible situation, this configuration was used

Wall Size: 2.44 m by 2.44 m
Eave Overhang: 61 cm (2 ft)

Vent holes: 50 mm (2”)
fitted with mesh 2.75 mm opening

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Wall Fitted With Eave Exposed to Firebrand Showers

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Wall Fitted With Eave Results

- The number of firebrands arriving at the vent locations increased as the wind speed increased
- Yet was very small as compared to the number of firebrands that bombarded the wall/eave assembly

U_∞ (m/s)	Open Eave With No Vents	Open Eave with Vents
7	No Accumulation	11 Firebrands Arrived at Vents
9	No Accumulation	28 Firebrands Arrived at Vents

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Wall Fitted With Eave Results

- The base of the wall actually ignited due to the accumulation of firebrands (9 m/s)
- It was very easy to produce ignition outside the structure since many firebrands were observed to accumulate in front of the structure during the tests
- Although some firebrands were observed to enter the vents, the ignition of the wall assembly itself demonstrates the dangers of wind driven firebrand showers
- The base of wall assembly ignited without the presence of other combustibles that may be found near real structures (*e.g*. mulch, vegetation)

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Firebrand Accumulation

Wood Boards Placed In Front

Easily Ignited!!!

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Fine Fuels Near Structure

Wall Ignited

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Reentrant Corner

- Firebrand generation from structure Components
- NIST Dragon will produce structure firebrand size/mass

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Recent Impacts

- State of New Jersey using NIST video in training courses
- Worked with CALFIRE as part of a task force (invitation only) to reduce mesh size used to cover building vent openings to lessen the potential hazard of firebrand entry into structures.
  - Changes were formally adopted into the 2010 California Code of Regulations, Title 24, Part 2, Chapter 7A, and are effective January, 2011
- "Your research will certainly further our understanding of the risks of flying embers during a wildfire event, and will help guide us as we make recommendations to our policyholders on how to better protect their home from the threat of wildfires"

  Stan Rivera – Chartis Insurance (http://www.chartisinsurance.com)
- Work has garnered the attention of Australian Government.
  - ABCB is joint initiative of all levels of Australian Government
  - ABCB has requested a formal partnership with NIST to assess Australian Standards to see whether they can account for ignition vulnerabilities observed by firebrands
- IBHS has used NIST's Dragon concept for use in their wind tunnel facility to generate firebrand showers

Summary

- NIST Dragon coupled to BRI's FRWTF
  - Capability to experimentally expose structures to wind driven firebrand showers for first time!
- Structure vulnerability experiments conducted for:
  - Roofing (cermaic/asphalt)
  - Vents/mesh (gable/different mesh sizes)
  - Siding (vinyl, polypropylene, cedar)
  - Eaves (open)
- NIST Dragon's LAIR Facility
  - Capability to expose materials/firebrand resistant technologies to wind driven firebrand showers
  - With newly developed Continuous Feed Baby Dragon, evaluate and compare relative performance

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Special Thanks

- Dr. Sayaka Suzuki (NIST)
- LFL Staff (Dr. Matthew Bundy – Supervisor)
- Dr. Yoshihiko Hayashi (BRI)

Homeland Security

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Future Plans

Determine vulnerabilities of Decking assemblies to firebrand Showers

DELIVERABLE

Report to ASTM and CALFIRE regarding vulnerabilities of decking treatments to firebrand attack; journal publication on testing results

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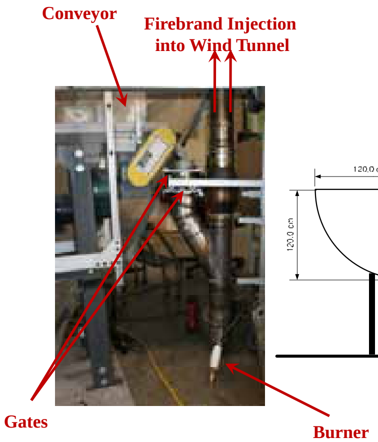
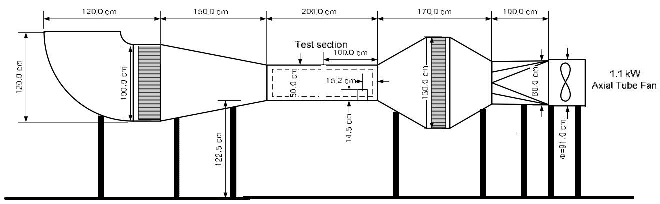
Improved NIST Dragon's LAIR

Expose materials to continuous, wind driven firebrand showers





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Ignition Regime Maps for Materials Exposed to Firebrand Showers Using NIST Dragon's LAIR Facility

Dr. Sayaka Suzuki
Guest Researcher
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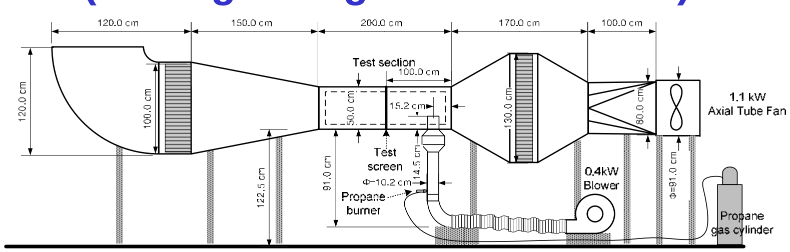
Japan/USA Workshop

Motivation for Dragon's LAIR Facility

- NIST Firebrand Generator (NIST Dragon) shown the vulnerabilities of structures to ignition from firebrand showers for first time
- Full scale experiments are required to observe the vulnerabilities
- Bench scale test methods afford the capability to evaluate firebrand resistant building materials/technologies
- Bench scale test methods may serve as the basis for new standard testing methodologies

NIST Dragon's LAIR (Lofting and Ignition Research)



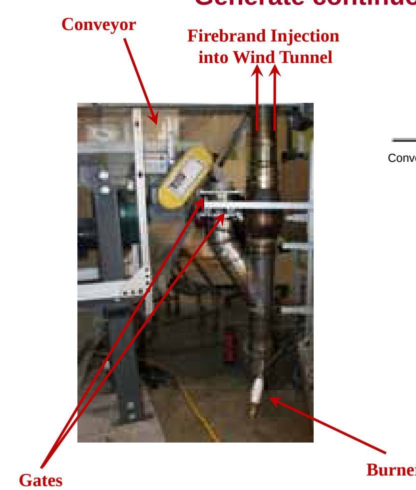
- NIST Reduced Scale Firebrand Generator (NIST baby Dragon) coupled with bench scale wind tunnel
- Reproduced results from full scale tests

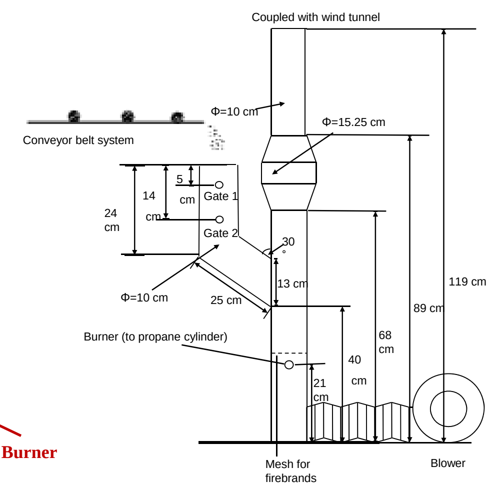
Both NIST Dragon/Dragon's LAIR have limited exposure duration

To develop test methods, it is necessary to generate firebrand showers of varying duration

Continuous Feed Baby Dragon

Generate continuous firebrand showers

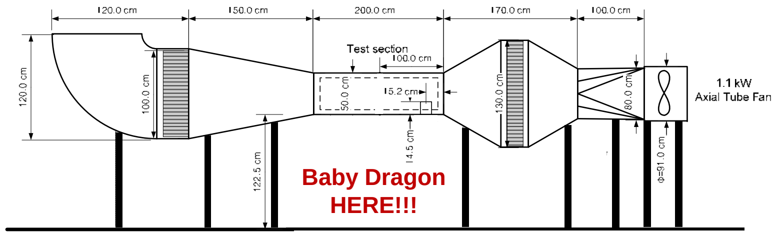




Coupled to Dragon's LAIR

Improved NIST Dragon's LAIR

Expose materials to continuous, wind driven firebrand showers



- **Coupled continuous feed baby dragon with bench scale wind tunnel**
- **Ability to evaluate and compare material performance to firebrand showers**

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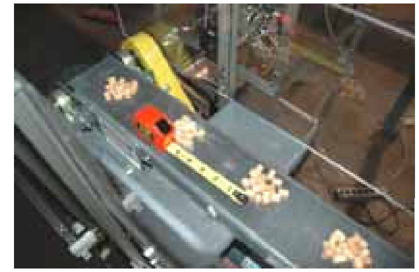
Experimental Conditions

- **Douglas-fir wood pieces with 7.9 mm (H) by 7.9 mm (W) by 12.7 mm (L)**
- **Wood pieces were placed every 12.5 cm and conveyer speed was 1.0 cm/s**
- **Varied loadings of wood pieces**



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Characteristics of Continuous Feed Baby Dragon

- **Varied wood feeding rates to find the optimal feeding rate for constant firebrand showers**
- **Loadings of wood pieces were 15 pieces (34.6 g/min), 30 pieces (69.1 g/min), 35 pieces (81.1 g/min), 40 pieces (91.7 g/min)**
- **Measured number flux and mass flux as a function of feeding rate**
- **It was observed that a feeding rate of 15 pieces (34.6 g/min) provided the most constant and uniform continuous firebrand production**

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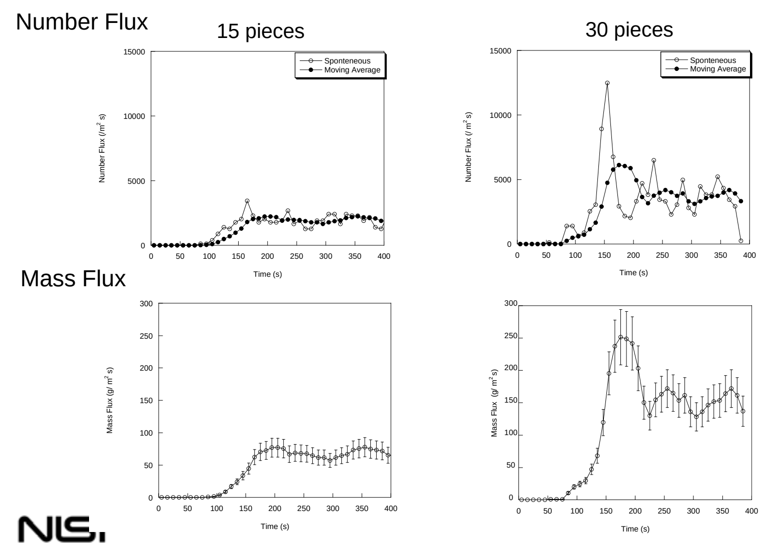
Number Flux & Mass Flux



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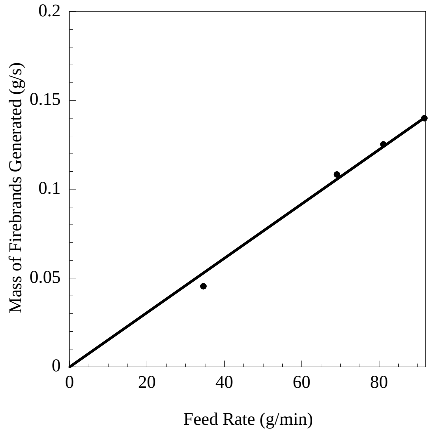
Mass generation rate of firebrands



Generation rate (g/s) was linear and increased with an increase in wood feed rate

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Experimental Conditions for Ignition Regime Map

- **Oven Dried Cedar Crevice and Not Dried Cedar Crevice**

- **Loadings of wood pieces**
  - 5 pieces (11.7 g/min)
  - 10 pieces (23.1 g/min)
  - 15 pieces (34.6 g/min)
  - 30 pieces (69.1 g/min)
  - 40 pieces (91.7 g/min)

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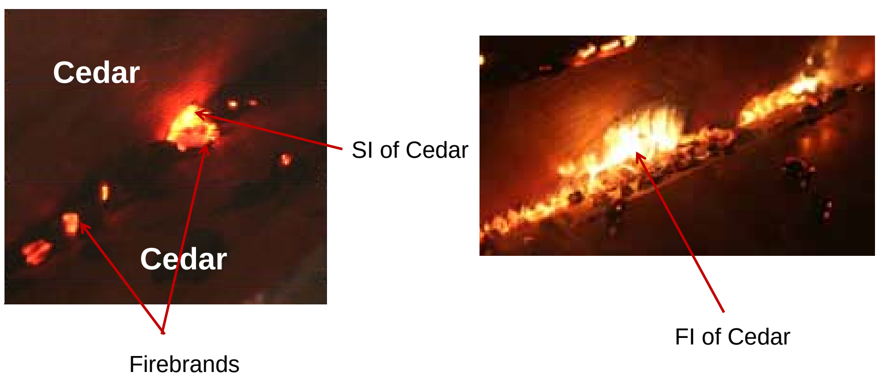
Ignition



Smoldering Ignition

Flaming Ignition

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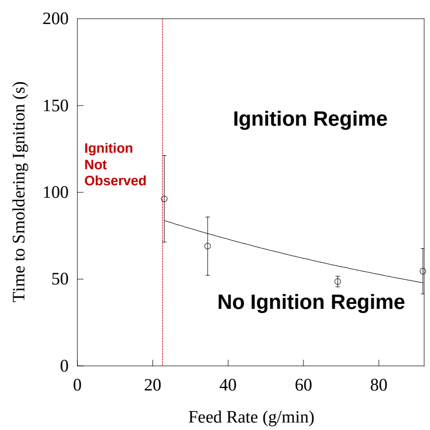
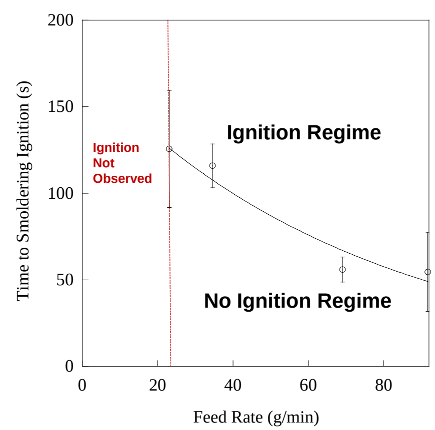
Ignition Regime Map

Oven Dried SI



Not Dried SI



- No SI for 5 pieces (11.7 g/m)
- Ignition delay time was observed to decrease as the firebrand generation rate was increased

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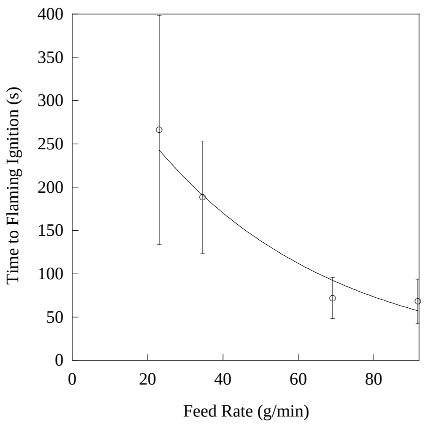
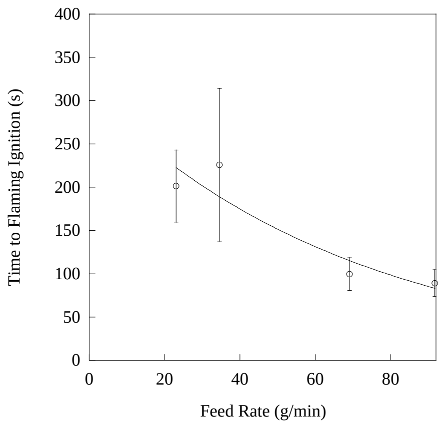
Flaming Ignition

Oven Dried FI



Not Dried FI



•Transition from SI to FI was observed
•Less repeatable

Summary

- A new and improved Dragon's LAIR facility was presented
- Ignition regime maps were determined as a function of glowing firebrand generation rate for fixed wind tunnel speed and two different moisture contents
- For given moisture content and wind speed, the ignition delay time was observed to decrease as the firebrand generation rate was increased
- This facility has the capability to produce a constant firebrand shower in order to expose building materials to continual firebrand bombardment

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Summary

- The time to flaming ignition, after the onset of smoldering ignition, was also measured
- As compared to the time required to reach smoldering ignition, the time to reach flaming ignition was less repeatable
- This work has set the stage to be able to evaluate and compare various building materials resistance to ignition from firebrand showers for the first time
- Feeding concept has been used to develop full-scale continuous feed dragon

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Acknowledgements

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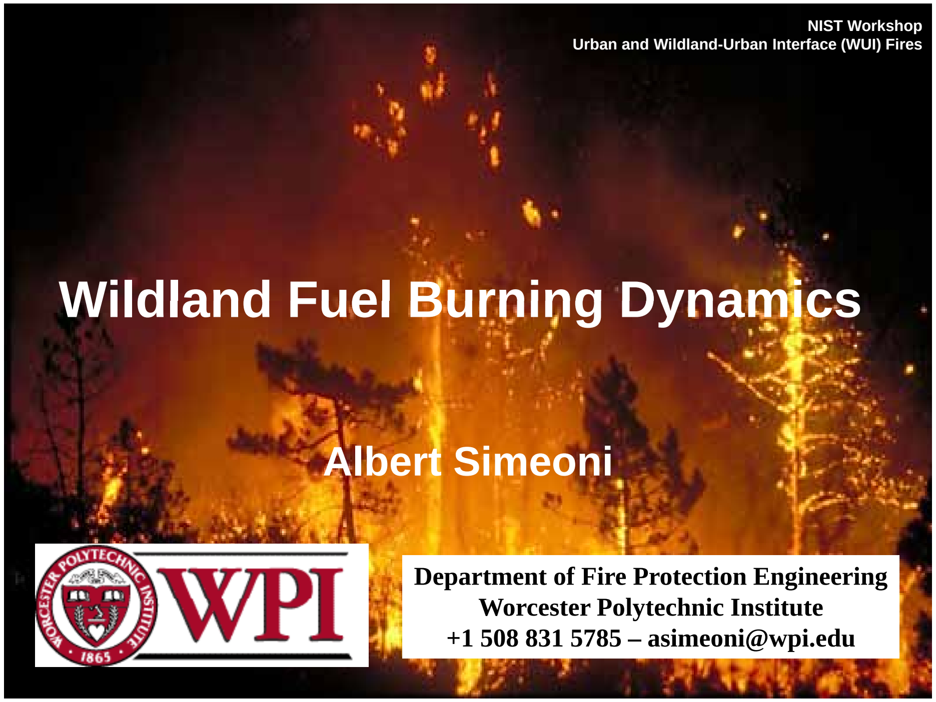

NIST Workshop
Urban and Wildland-Urban Interface (WUI) Fires

Wildland Fuel Burning Dynamics

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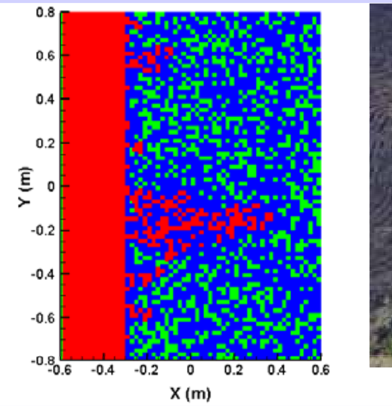
Before starting

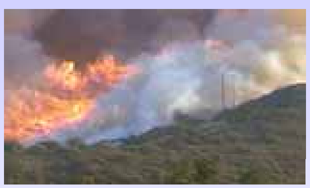
- Heterogeneous fuels

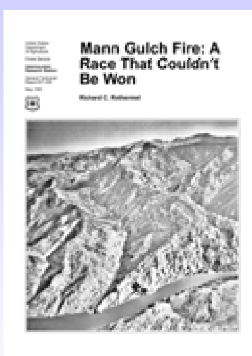


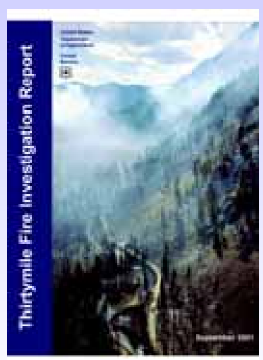
A. Simeoni, P. Salinesi. A study on forest fire spreading through heterogeneous fuel beds thanks to physical modeling. To appear in International Journal of Wildland Fire.

Before starting

- Extreme fire behavior







J. Dold, A. Simeoni, A. Zinoviev, R. Weber. "The Palasca fire, September 2000: Eruption or Flashover?" in Recent Forest Fire Accidents in Europe, D.X. Viegas (Ed.) JRC-IES, European Commission, Ispra, Italy, 2009, ISBN 978-92-79-14604-6.

D.X. Viegas, A. Simeoni. Eruptive behavior of forest fires, Fire Technology, 47(2), 303-320.

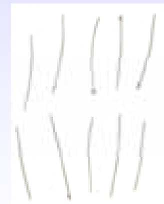
Outline

- Introduction
- Experimental protocol
- Burning dynamics
- Time to ignition
- Bulk properties

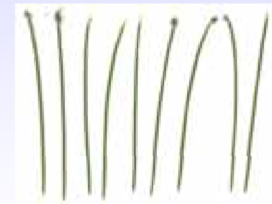
Introduction

- CFD-based fire models are closed thanks to a variety of sub-models
- The accuracy of the models depends on the reliability of the sub models
- Several sub-models are based on empirical data with a lack of understanding of the underlying chemical and physical processes
- This is particularly true for wildland fires because of the complexity of wildland fuels
- This work aims at better understanding the ignition and burning of porous (wildland) fuels

Introduction



The thinnest particles are primarily involved in the fire spread



Pinus Halepensis

L ≈ 8 -10 cm	Ø < 1 mm

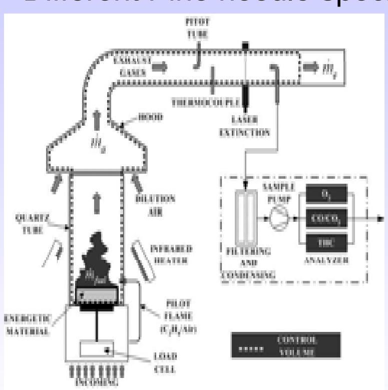
Pinus Pinaster

L ≈ 15 - 20 cm	Ø > 3 mm

Forest fuels are extremely porous (95% porosity for pine needle litters)

Experimental protocol

- Test series used a FM Global FPA
- Different Pine needle species



Specific design of fuel sample holders (porous beds)

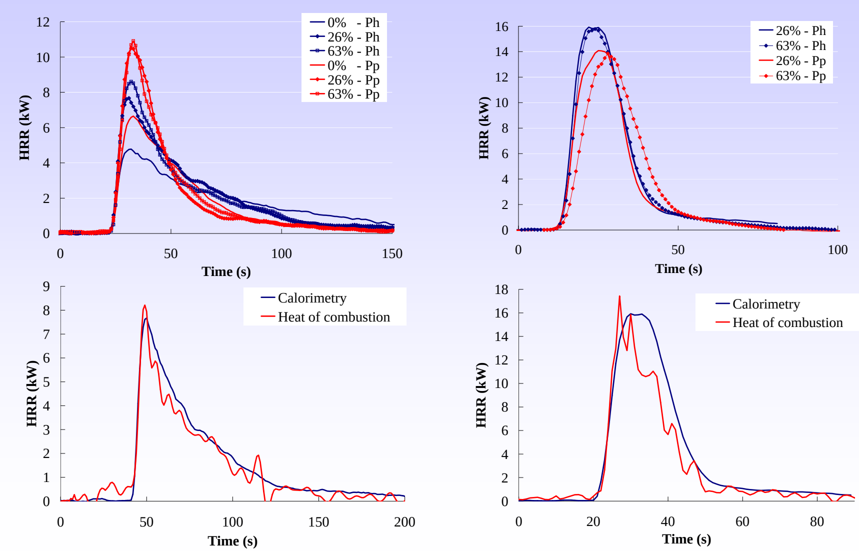
Pinus halepensis
0% basket

Pinus pinaster
63% basket

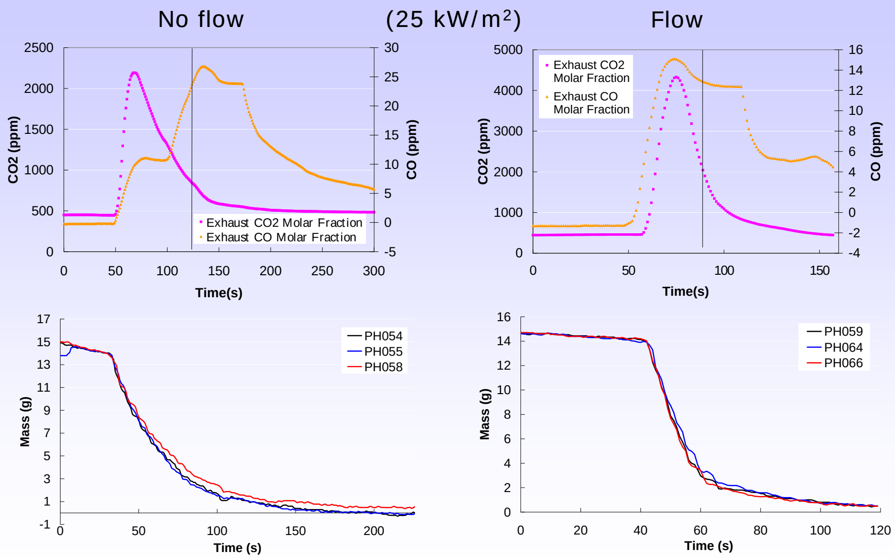
- Moisture content: 4.9-6.4%
- mass: 15 g, fuel bed porosity: 95%
  - No flow (natural convection)
  - Different levels of forced flow
  - Heat fluxes from 8 to 50 kW/m²

Burning Dynamics

No flow (25 kW/m²) Flow



Burning Dynamics



Burning Dynamics – Conclusions

- CO concentration profiles are a good indicator of the dynamics of the combustion process
- HRR, time to ignition and time to reach peak HRR indicated a strong dependence on flow conditions within the fuel bed
- Transport processes have a significant impact and seem to be the rate limiting phenomenon for the combustion process in these porous fuel beds

Time to Ignition

Two different models:

- Solid fuel model: 1D, thermally thick, semi-infinite solid:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha_T}\frac{\partial T}{\partial t} \qquad \text{BC: } x = 0, -k\frac{\partial T}{\partial x} = \dot{q}_S''(0,t), \quad t = 0 \quad x \to \infty \quad T = T_\infty$$

$$\dot{q}_S''(0,t) = a\dot{q}_e'' - h_T(T(0,t) - T_\infty)$$

Global parameters representative of the ignition process

- Porous fuel model: 1D, thermally thick, thermal equilibrium:

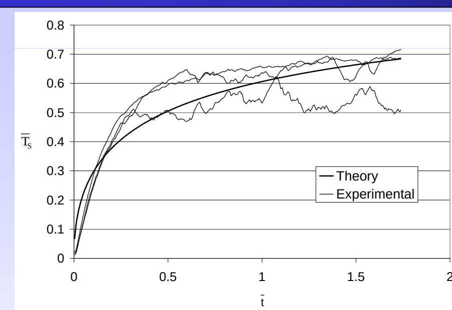
$$\alpha_s\rho_s c_{ps}\frac{\partial T}{\partial t} + \alpha_g\rho_g c_{pg}V_{g,x}\frac{\partial T}{\partial x} = k_R\frac{\partial^2 T}{\partial x^2} + \dot{\bar{q}}_e'' K e^{-Kx}$$

$$K = \frac{\alpha_s \sigma_s}{4}$$ (attenuation coefficient)

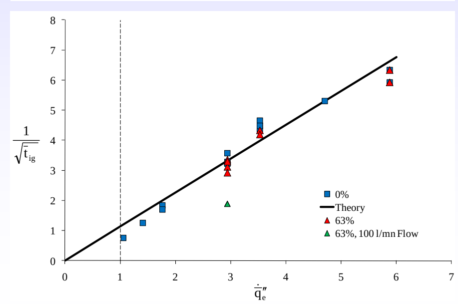
Parameters come from literature or from measurements

ρ_s [kg/m^3]	σ_s [m^{-1}]	α_s [m^3/m^3]	a_s	C_{ps} [J/kg K]
789	7377	0.0492	1	3100

Time to Ignition – No Flow

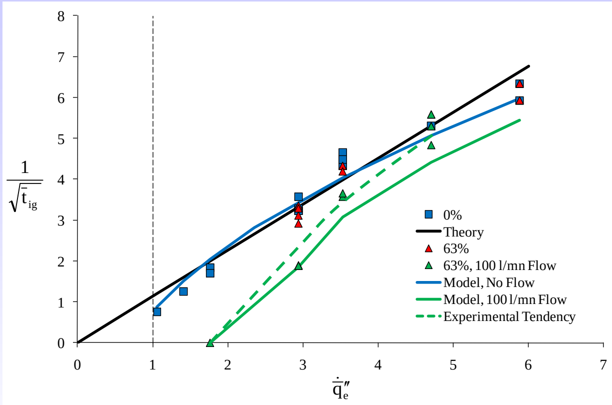


- Only overall agreement
- Relevant temperature for long times
- Bigger discrepancies for high values of the flux



- 53 experiments (some discarded)
- Closed basket displays a good agreement with theory (!!)
- Natural convection induces more scattering but similar results

Time to Ignition – Flow



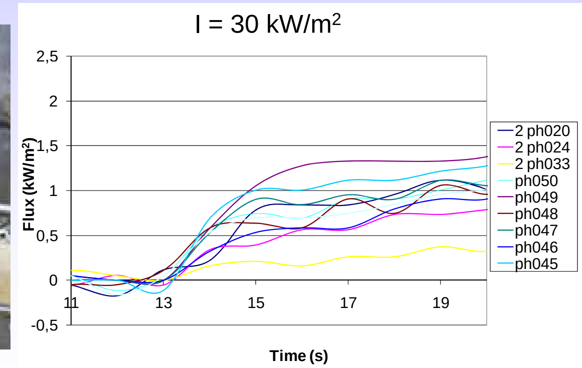
- K fitted to obtain the best agreement (K = 167 m^{-1} instead of 91 m^{-1})
- $V_{g,x}$ set to 50 mm/s (estimated at 30 mm/s by PIV)
- Good agreement for low flows
- For high flows, the times get closer to the no-flow conditions
- When the pyrolysis gas production is massive, dilution is decreased

Time to Ignition

Coefficient of attenuation??

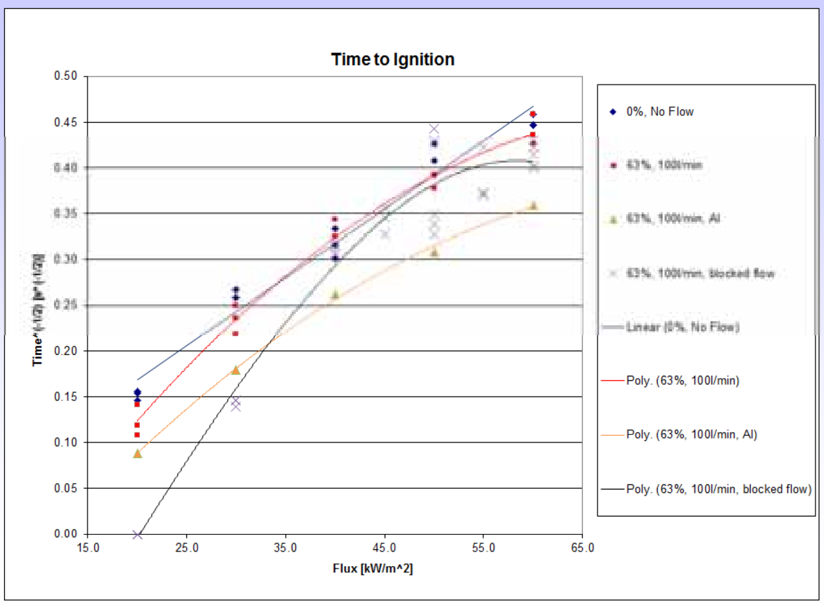
$$\vec{e}.\vec{\nabla}\left(\alpha_g L_g^\Omega\right)=\alpha_g a_g\left(\frac{\beta T_g^4}{\pi}-L_g^\Omega\right)+\sum_k\left[\left(\frac{\alpha_k\sigma_k}{4}\right)\left(\frac{\beta T_k^4}{\pi}-L_g^\Omega\right)\right]$$

Beer-Lambert law: $I = I_0 e^{-KL}$



- If I = 1 kW/m^2, K = 170 m^{-1} and δ = 5.88 mm
- Very consistent with the value used in the model (167 m^{-1} and 6 mm)

Time to Ignition – High Fluxes



Time to Ignition – Conclusions

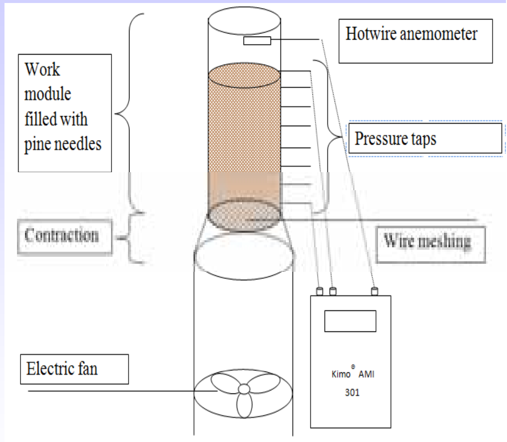
- If the flow is blocked, the fuel bed behaves like solid fuels and classical theory is sufficient to describe times to ignition
- If the flow is allowed
  - Natural convection induces more scattering
  - Forced convection induces a cooling of the fire front but mixing is likely to be important for high flows
- The coefficient of attenuation of the pine needle beds is higher than the one currently estimated in fire spread models

Bulk properties

Characterization of the fuel beds

Permeability of the porous medium estimated using Darcy's law:

$$\nabla P = -\frac{\mu}{K} v$$



Experimental parameters

- Basket opening (0% , 63%)
- Incoming flow (Natural Flow (NF), 100 *L.min*-1 (LF), 200 *L.min*-1 (HF)
- Use of different fuel species
- Variation of fuel bed permeability

Bulk properties

Characterization of the pine needles

Three pine species were studied: *Pinus halepensis (PH)*, *Pinus laricio* (PL) and *Pinus pinaster* (PP). *Samples* collected from the fuel layer across the forest floor. Dead needles not conditioned prior to testing

- **Surface to volume ratios and densities of the three pine needle species**

	Surface to volume ratio (m^{-1}) with relative uncertainty	Density ($kg.m^{-3}$) with relative uncertainty	Mean diameter (mm)	Mean thickness (mm)
Ph	7377 (2.4%)	789 (2.4%)	0.7003	0.5045
Pl	4360 (3.3%)	485 (8.1%)	1.1234	0.7998
Pp	3057 (1.3%)	511 (6.6%)	1.8519	1.1569

- **Ultimate analysis (mass fraction) and low heating value of the three forest fuels**

	C	H	O	N	LHV ($kJ.kg^{-1}$)
Ph	49.17	6.75	39.14	1.19	21202
Pl	50.39	6.72	39.65	0.3	21328
Pp	49.87	6.72	40.16	0.26	20411

The main differences between the species are linked to their geometry and specifically to their SVR

Bulk properties

Characterisation of the fuel beds

Experimental results: Fuel beds permeabilities

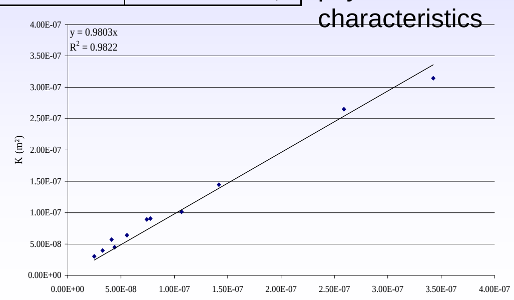
Equivalent mass load ($kg.m^{-2}$)	Permeability (m^2)		
	Pinus halepensis	*Pinus pinaster*	*Pinus laricio*
0.8	-	$2.64.10^{-7}$	$3.14.10^{-7}$
1.2	$9.06.10^{-8}$	$1.01.10^{-7}$	$1.45.10^{-7}$
1.6	$5.70.10^{-8}$	$6.39.10^{-8}$	$8.91.10^{-8}$
2	$3.02.10^{-8}$	$3.96.10^{-8}$	$4.48.10^{-8}$

The fuel beds permeability depends upon:
- their compactness,
- the pine needles geometrical and physical characteristics

Empirical law derived from the experiments

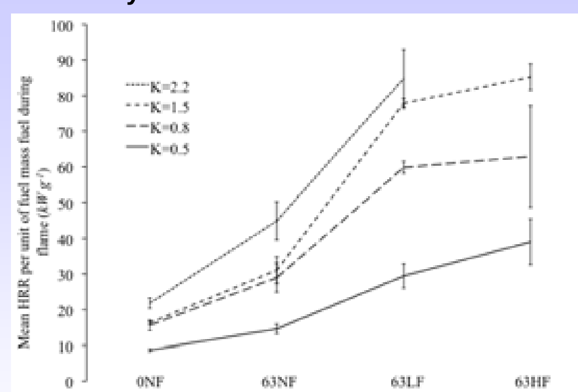
$$K = \frac{1}{20}\frac{\varepsilon^3}{\left(\alpha * \sigma * \left(D/E\right)^2\right)^2}$$

K: permeability
α: fuel volume fraction
ε: porosity
σ: SVR
D: diameter
E: thickness



Fuel bed effects

Permeability

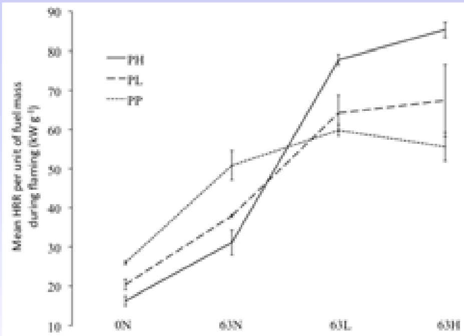


Mean HRR during flaming (global heat of combustion)

- Energy released increases with permeability: combustion enhanced
- Slopes of curves increase with permeability
- Inflexion for high flows: limiting effect of air supply (but higher peak)
- Influence of mean path of radiation

Fuel species effect

Mean heat of combustion (flaming)



- No and natural flow: Heat released increases with flow (*Pinus pinaster*: lowest LHV but more flammable gases and attenuation of radiation)
- Forced flow: tendency is changing. PH more influenced than PL: high surface-to-volume ratio and more oxygen at the particle surface
- Inflexion for the two species when a high flow (HF) is applied and decrease for PP (flow enhancement reaches a maximum)

Bulk properties – Conclusions

- Taking into account fuel composition improved HRR calculations
- Permeability is an important parameter driving the burning dynamics of forest fuel beds
- Mean free path of radiation is important too (for same permeability)
- For a given permeability, species have an influence but does not seem to be due to the chemistry
- *Pinus pinaster* displayed a specific behavior

Acknowledgements

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  University of Edinburgh
  - Pauline Bartoli
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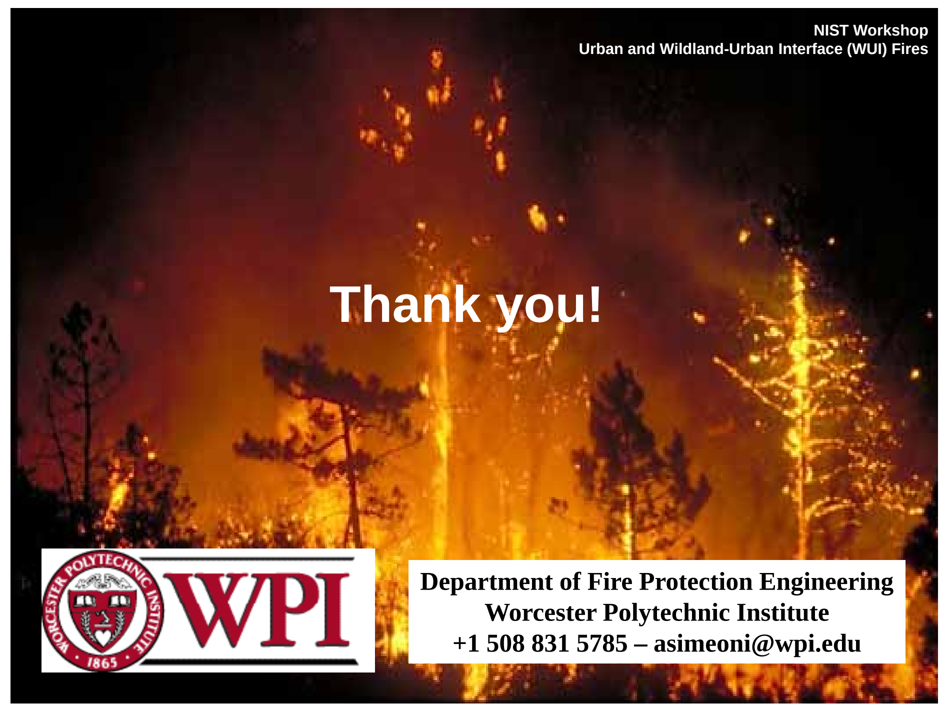
  - Jan Thomas
    WPI
  - FM Global: Donation of the FPA



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Future Collaborations / Workshops

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For the Future Workshop

- Intervals
  - Associated with IAFSS meeting
  - Associated with Asia-Oceania IAFSS meeting
  - Others
- Topics
  - Large fires
  - Relatively emerging topics
  - Other
- Size
  - 30 people : less or more ?
  - One day or more ?

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For the Future Workshop (continued)

- Who
  - Invitation only ?
  - US/Japan or International ?
- Focus
  - Research oriented ?
  - With focus of application (e.g., revision of standards) ?
  - Difference between other meeting ?

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