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Summary of workshop for fire structure interaction and urban and wildland-urban interface (WUI) Fires–*operation Tomodachi–fire research*

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ABSTRACT

A workshop, known as "*Operation Tomodachi—Fire Research*" was held in Tokyo, Japan from July 1 to July 4, 2012. Tomodachi means friendship in Japanese. This workshop, under the direction of Dr. Samuel L. Manzello of EL-NIST and Dr. Tokiyoshi Yamada of the University of Tokyo, was conducted in partnership with the Japan Association of Fire Science and Engineering (JAFSE). The objective was to: (1) develop scientific knowledge and translate it to building codes and standards that will be of use to both countries to reduce the devastation caused by unwanted fires, (2) provide a forum for next generation researchers to present their work in order to develop new research collaborations, (3) and allow USA participants a chance to visit excellent large-scale research facilities available in Japan that are of use to the research topics of this workshop. This is a formal continuation of the kickoff meeting held at NIST's Engineering Laboratory (EL-NIST) in June 2011. USA presentations were delivered from: NIST, Purdue University, University of Texas-Austin, Michigan State University, University of Michigan, Insurance Institute for Business and Home Safety (IBHS), Worcester Polytechnic Institute (WPI), University of California-Berkeley, California Polytechnic University (CALPOLY), Underwriters Laboratories (UL), and the University of Delaware (organizations are listed based on the order of oral presentation). Japanese presentations were delivered from: The University of Tokyo, Building Research Institute (BRI), Takenaka Corporation, Center for Better Living, Shimizu Corporation, Tokyo University of Science (TUS), National Institute for Land and Infrastructure Management (NILIM), Kyoto University, National Research Institute of Fire and Disaster (NRIFD), Yamagata University, and Kobe University (organizations are listed based on the order of oral presentation). All of the presentations are documented in a recent NIST Special Publication (NIST SP 1137). The present paper provides a detailed summary for the need of this workshop as well as the findings obtained from the event. It is desired that this activity will motivate the next generation of researchers to explore and develop research collaborations related to emerging areas of fire safety science. The authors are hopeful that new and exciting activities specific to other countries may come out of this type of event.

1. Introduction

Research in the area of fire safety science has grown tremendously over the past 50 years. To this end, there are numerous international meetings within the fire safety science community to disseminate research findings (e.g. International Association of Fire Safety Science Symposium, Interflam, Fire and Materials, Structures in Fire, etc). In addition, in 1991, the International Forum of Fire Research Director was established to provide a path for research exchange between organizations engaged in fire safety science research and testing [1].

Due to the large number of paper submissions at International meetings focused on fire safety science, a need exits to hold many simultaneous parallel sessions. While many parallel sessions afford the opportunity to allow more papers to be presented,

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it greatly limits opportunities for in depth discussion and collaborative research. From 1976 to 2000, the United States Japan Natural Resources Panel (UJNR) on Fire Research and Safety allowed for more in depth, and detailed discussion of shared research findings between both countries. The interested reader may refer to any of the proceedings; see [2] for the 6th UJNR Panel on Fire Safety Research and Safety. A review of the proceedings from the UJNR activities suggests that with each subsequent meeting, focus was lost. As a result, it was decided to no longer continue the UJNR activities since it became a mirror image of fully developed conferences within the fire safety science community. At the final UJNR meeting in 2000, it was recommended that future activities be focused on small workshops related to topics of great interest to specific countries [3]. It is important to keep in mind that in 1976, when the first UJNR panel on fire research was established, the International Association for Fire Safety Science (IAFSS) had not yet been established and UJNR was really the first mechanism for research exchange among countries actively engaged in fire safety science research.

As a result, while there are numerous venues to exchange information in the fire safety science area, it became apparent that the opportunities to interact and establish joint research on areas of great mutual interest between researchers in different countries needs to be enhanced. More importantly, with growing pressures on research budgets worldwide the field fire safety science is in need of stronger research ties across the 'next generation' of researchers to share and pool resources to conduct research on important emerging topics of great need to certain countries. Large outdoor fires are a good example of an emerging research topic in severe need of coordinated and collaborative research activities. Large outdoor fires present risk to the built environment yet many building codes intended to mitigate the risk of such fires are based on anecdotal evidence or best guesses not based on scientific rigor or experimentation. Two important examples of such large outdoor fires are urban fires, a concern in Japan, and wildfires that spread into communities, commonly referred to as Wildland–Urban Interface Fires (WUI), which is a concern in several countries including the USA. In the field of fire protection engineering, significant research has been focused on fires inside buildings; such fires may be thought of as compartment fire research. Compared to large outdoor fire research, compartment fire research is far more advanced with significant understanding obtained from years of focused research conducted internationally in a collaborative nature. On the contrary, little understanding exists on how to contain and mitigate the hazard associated with urban and WUI fires. These topics are extraordinarily challenging and present the next frontier in fire safety engineering.

Although urban and WUI fires have been termed differently, there are substantial phenomenological similarities between these fires. However, research on urban fires in Japan and WUI fires in the USA has been conducted in each country independently, with little chance of constructive research collaboration. To this end, a kick-off 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 goal of this workshop was to open a dialog to embark on new research collaborations in an effort to begin develop scientifically based building codes and standards that will reduce the devastation caused by urban and WUI fires. While the focus of this kick-off meeting was on urban/WUI fires, participants were invited from the USA and Japan from diverse organizations with a key interest in this topic as well as the overall idea of the meeting: a workshop that allows in depth discussion and interaction on research topics of great interest. Selected papers from this kick-off workshop were published in a recently released special issue in *Fire Safety Journal* guest edited by two of the co-authors of this paper. The interested reader is referred to this issue for more information as well as a summary report of presentations given at the workshop [4,5].

It was decided to continue the activity but provide a more formalized frame work to hold these types of workshops in the future. To this end, NIST's Engineering Laboratory (EL) signed an agreement with the Japan Association for Fire Science and Engineering (JAFSE) to hold two more meetings. During the preparation of this agreement, it was decided to permit each workshop to be targeted on two specific research areas. The continuation workshop, and the reason for writing this paper, known as "*Operation Tomodachi—Fire Research*" was held in Tokyo, Japan from July 1 to July 4, 2012. Due to the importance of urban and WUI fires in Japan and the USA, and in light of the recent Great East Japan Earthquake that occurred on Mach 2011, this topic was expanded and considered in more depth than the kick-off event described above.

There was considerable thought placed on what the additional topic should be for the next, formalized workshop. The topic of Fire Structure Interaction (FSI) was added as the second major topic for "*Operation Tomodachi—Fire Research*." FSI is a topic of great interest in the fire safety science research community as the performance of structural/non-structural elements is not known under realistic fire exposures. Fire resistance testing in the United States has been based upon ASTM standard E119, "Standard Test Methods for Fire Tests of Building Construction and Materials" [6]. A similar international standard is ISO 834 [7]. In these tests, building components are subjected to a constantly increasing furnace temperature intended to represent a standard fire. The components are then rated, with units of time, on their ability to withstand the exposure up to a criterion that is defined as a failure point. Clearly, there are limitations to this approach in providing a known degree of fire safety for structures. There have been several recent reviews that highlight such limitations and the interested reader is referred elsewhere [8]. Clearly, FSI is an important research topic worldwide and of particular importance to Japan and the USA.

Consequently, the present paper provides a detailed summary of the findings from "*Operation Tomodachi—Fire Research*." The objective of the workshop was to: (1) develop scientific knowledge and translate it to building codes and standards that will be of use to both countries to reduce the devastation caused by unwanted fires, (2) provide a forum for next generation researchers to present their work in order to develop research collaborations, (3) and allow USA participants a chance to visit excellent large-scale research facilities available in Japan that are of use to the research topics of this workshop. This is an important aspect of this activity and involved laboratory tours at the Building Research Institute (BRI) and the National Research Institute of Fire and Disaster (NRIFD). There was also an optional laboratory tour held at the Tokyo University of Science (TUS) the evening before the official commencement of the meeting. Providing the participants the opportunity to see these experimental facilities was intended to generate the potential to embark on shared use of facilities and research exchange of staff since budgets for fire research appear to be diminishing worldwide. Individuals from a diverse set of backgrounds joined the event. Thirteen researchers from US and 36 researchers from Japan participated in lively discussions during the event. Senior researchers also joined in the event to provide their valuable experience on the development of fire safety science research. Fig. 1 is the complete program from the workshop.

2. Urban/wildland urban interface (WUI) Fires

Wildland–Urban Interface (WUI) fires have caused significant destruction to communities in Australia, Greece, Portugal, Spain,

July 2nd	At Building Research Institute (BRI)
10:00 - 10:10	Workshop Objective Coordinator Yamada, T. (University of Tokyo, Japan) Manzello, S. (National Institute of Standards and Technology, USA)
I. Fire-Structure Interaction Session Chair: Kohno, M. (Tokyo University of Science, Japan) Jeffers, A. (University of Michigan, USA)	
10:10 - 10:30	Suzuki, J. (Building Research Institute, Japan) Effect of Deformation of Structural Frame on Fire Resistance of Compartmentation
10:30 - 10:50	Varma, A. (Purdue University, USA) Experimental Evaluation of Column Stability and Its Influence on Overall Structure Collapse under Fire Loading
10:50 - 11:10	Nishimura, T. (Takenaka, Corporation) Fire Safety of Curtain Wall Spandrel -Proposal for Curtain Wall Spandrel Board Supported by Structural Members-
11:10 - 11:30	Coffee Break
11:30 - 11:50	Engelhardt, M. (University of Texas, USA) Barriers to Performance-Based Structural Fire Safety Design
11:50 - 12:10	Mizukami, T. (Center for Better Living, Japan) Calculation methods for Temperature Rise of Compartment Walls Exposed to Fire Heating
12:10 - 12:30	Morita, T. (Shimizu Corporation, Japan) An Experimental Study on Fire Resistance of Composite Structure Consisting of Steel Beam and Partition Wall
12:30 - 13:40	Lunch
13:40 - 14:00	Garlock, M. and Kodur, V. (Princeton University/Michigan State University, USA) Performance and Research Needs for Bridges Subject to Fire
14:00 - 14:20	Kohno, M. (Tokyo University of Science, Japan) Strategic Measure for Ensuring Fire Safety of Buildings after An Earthquake
14:20 - 14:40	Jeffers A. (University of Michigan, USA) Response Sensitivity and Reliability Analysis of Structures in Fire
14:40 - 15:00	Coffee Break
15:00 - 15:20	Manzello, S (National Institute of Standards and Technology, USA) National Fire Research Laboratory
15:20 - 15:40	Nii, D. and Yoshioka H. (National Institute for Land and Infrastructure Management, Japan) Full-scale Fire Test for Wooden 3-Story School Building (Preliminary Test)
15:40 - 16:20	Discussion (Structural Fire) Adjourn

July 3rd	At Building Research Institute (BRI)
II. Urban/Wildland-Urban Interface (WUI) fires - 1 Session Chair: Himoto, K. (Kyoto University, Japan) Suzuki, S. (National Institute of Standards and Technology, USA)	
10:00 - 10:20	Himoto, K. (Kyoto University, Japan) Urban Fire Spread Modeling and Loss Prevention Planning
10:20 - 10:40	Manzello, S. (National Institute of Standards and Technology, USA) Overview of NIST's Wildland-Urban Interface (WUI) Fire Research
10:40 - 11:00	Shinohara, M. (National Research Institute of Fire and Disaster, Japan) Fire Whirls Caused by Urban Conflagration
11:00 - 11:20	Coffee Break
11:20 - 11:40	Quarles, S. (Insurance Institute for Business and Home Safety, USA) Evaluating the Vulnerability of Buildings to Wildfire Exposures
11:40 - 12:00	Simeoni, A. (Worcester Polytechnic Institute, USA) Wildland Fire behavior: Combustion and Dynamics
12:00 - 12:20	Suzuki, S. (National Institute of Standards and Technology, USA) Determining Firebrand Production from Full Scale Structures and Building Components
12:20 - 13:30	Lunch
13:30 - 13:50	Fernandez-Pello, C. (University of California, Berkeley, USA) Effect of Physical Properties on the Capability of Hot Particles to Ignite Vegetation
13:50 - 14:10	Kuwana, K. (Yamagata University, Japan) Scale-model Experiment of Large-scale, Wind-aided Fires
14:10 - 14:30	Discussion (WUI + Post-EQ fire #1)
14:30 - 14:45	Coffee Break
14:45 - 15:00	Introduction of Laboratory Tour #1 Ohmiya, Y. (Tokyo University of Science, Japan) Introduction of Center for Fire Science and Technology, TUS
15:00 - 15:15	Hagiwara, I. (Building Research Institute, Japan) Introduction of Research Laboratory, BRI
15:15 - 16:15	Laboratory Tour #1 (Building Research Institute) Adjourn

July 4th	At National Research Institute of Fire and Disaster (NRIFD)
II. Urban/Wildland-Urban Interface (WUI) fires - 2 Session Chair: Hirokawa, Y. (National Research Institute of Fire and Disaster, Japan) Fernandez-Pello, C. (University of California, Berkeley, USA)	
9:30 - 9:50	Tamura, H. (National Research Institute of Fire and Disaster, Japan) Investigation and its Characteristic of Post Earthquake Fire at the 3.11.
9:50 - 10:10	Dicus, C. (California Polytechnic State University, USA) Fuel Treatment Impacts to Fire Behavior and Ecosystem Services in the Wildland-Urban Interface.
10:10 - 10:30	Nishi, H. (National Research Institute of Fire and Disaster, Japan) Fires and Damages of Oil Tanks Caused by the 3.11 Earthquake
10:30 - 10:50	Matsuyama, K. (Tokyo University of Science, Japan) Experimental Study on the Possibility of the Vehicles Fire in Urban and Tsunami Fire - About the Burning Behavior for Motorcycles -
10:50 - 11:10	Coffee Break
11:10 - 11:30	Iwami, T. and Kagiya, K. (National Institute for Land and Infrastructure Management, Japan) Fires in Non-inundated Area Following the 3.11 Earthquake
11:30 - 11:50	Fabian, T. (Underwriters Laboratory, USA) Fire Exposure of Roof-Mounted Photovoltaic Systems
11:50 - 12:10	Nishino, T. (Kobe University, Japan) Qualitative Aspect of the Fires Fueled by the Combustibles Arriving in the Vicinity of the Tsunami Refuge Buildings
12:10 - 12:30	Davidson, R. (University of Delaware, USA) Statistical Modeling of Post-earthquake Ignitions
12:30 - 13:00	Discussion (WUI + Post-EQ fire #2)
13:00 - 14:00	Lunch
14:00 - 15:10	Future Collaboration and Workshop Coordinator Manzello, S. (National Institute of Standards and Technology, USA) Nakamura, Y. (Hokkaido University, Japan)
15:10 - 15:20	Introduction of Laboratory Tour #2 Wakatsuki, K. (National Research Institute of Fire and Disaster, Japan) Introduction of Research Laboratory, NRIFD
15:20 - 15:30	Coffee Break
15:30 - 16:45	Laboratory Tour #2 (National Research Institute of Fire and Disaster)

Fig. 1. Detailed Program of *Operation Tomodachi—Fire Research*.

and the USA. The 2003 Cedar Fire in California resulted in $2B in insured losses and destroyed more than three thousand homes. The 2007 Southern California Fire displaced more than 300,000 people, destroyed over 1000 structures, and resulted in $1B paid by insurers in 2007 alone [9]. WUI fires continue to burn in the USA and are rapidly getting worse; most recently in Texas in 2011 and Colorado, California in 2012. In 2009, fires in Victoria, Australia caused the death of more than 100 people, destroying more than one thousand structures. The 2007 Fires in Greece destroyed several hundred structures and caused the deaths of more than 70 people.

From a pragmatic point of view, the WUI fire problem can be seen as a structure ignition problem [9]. Historically, fire safety science research has spent a great deal of effort to understand fire dynamics within buildings. Research into WUI fires, and how to potentially mitigate the loss of structures in such fires, is far behind other areas of fire safety science research. This is due to the fact that fire spread in the WUI is incredibly complex, involving the interaction of topography, weather, vegetation, and structures. As described below, a majority of the presentations from USA were focused on developing the needed scientific understanding to lessen structure ignition in WUI fires.

Japan does not have a documented problem of fires spreading from the wildlands to communities, such as the WUI fire problem in the USA. Rather, Japan experiences many earthquakes due to its geographical location. After large earthquakes, many fires simultaneously occur that easily overwhelm fire-fighting resources. Since many Japanese cities are densely populated, severe fire spread occurs within these urban areas. As a result, both Japan and the USA can benefit from sharing knowledge; in the case of WUI fires, once the fire reaches the community, the structures become involved and the fire spread mechanism from structure to structure in WUI communities in the USA and urban areas in Japan are similar. The idea of this workshop was to bring these research communities together. A summary of on-going research in these areas in presented below.

2.1. WUI fires—structure ignition studies

Samuel Manzello reported on the WUI fire research being conducted at NIST to collect fire behavior/structure ignition data from actual WUI fires. These data together with the experimental information of ignition of structures by firebrands will be used to develop strategies for reducing WUI structure losses. Particularly significant is the data collected in two reports from NIST, one describing the Witch and Guejito fires in Southern California [10] and the other the Amarillo fire in Texas [11]. These reports provide extensive information about the development of these fires, the effect of the suppression efforts conducted, and damages caused by the fires.

Manzello provided an overview of the efforts being conducted at NIST and the Building Research Institute (BRI) in Japan on the ignition of structures by firebrands, a major fire spread mechanism in both WUI and urban fires. He first presented work conducted to characterize firebrand sizes both in laboratory experiments at NIST and data from a California wildland fire (Angora fire) [12]. He reported on the development at NIST of the Firebrand Generator (NIST Dragon) to generate controlled showers of firebrands. The firebrands are directed to different sections of the structure (roof, vents, wall corners, etc) to analyze their ignition characteristics and capabilities. Manzello presented results of studies conducted on the ignition by firebrands of ceramic roofs by the firebrands penetrating the roof between the ceramic tiles and the supporting wood structure, and the penetration of firebrands into the structure through the attic vents. Also interesting were the studies of the potential effect of the accumulation of firebrands in wall corners, siding, or eve overhangs [13]. Finally, Manzello presented the development of two versions of the firebrand generator, a "Full Scale Continuous Full Feed Dragon" and the NIST

"Dragon's" LAIR Facility (Lofting and Ignition Research) [14]. The former is a generator of continuous firebrand showers and the latter a generator of wind driven firebrand showers at bench scale. Both devices will allow the exposure of materials to continuous firebrand showers.

Sayaka Suzuki presented results from a study to characterize the size and mass distribution of firebrands generated during WUI fires [15,16]. The data is to be used in the operation of the NIST firebrand generators. Burning of building components such as walls and re-entrant corner assemblies under varying wind speed were obtained in a laboratory scale. The data was compared with data from an actual full scale structure burn conducted by NIST in Dixon, California. The size distribution of firebrands from the assemblies was similar to those from the full scale structure. The results are significant because they indicate that tests with individual building components can provide insight from firebrand generation from full scale structures.

Steve Quarles in his presentation "Evaluating the Vulnerability of Buildings to Wildfire Exposure" described the Insurance Institute for Business and Home Safety (IBHS) collaboration with Savannah River and Oak Ridge National Laboratory and the USDA Forest Service to develop the Wildfire Ignition Resistance Home Design (WIRHD) program with the goal to develop a home evaluation tool that could assess the ignition potential of a structure subjected to wildfire exposure. He also provided a detailed overview of another important testing facility, the IBHS Research Center, to study natural hazards. The test facility can house a medium scale structure and expose its surfaces to a radiant flux provided by gas burning radiant panels, and showers of firebrands (generated based on the NIST Dragon described above), in a relatively high speed wind (up to 50 m/s) provided by an array of 105 fans of 1.7 m diameter. The results from the tests are used to provide material property data to a software code named the Wildfire Ignition Resistance Estimator (WildFIRE) Wizard [17]. The software allows the user to create a building using software tools and specify vegetation and other components surrounding the building. Quarles described some of the tests conducted in the facility including ember testing to document vulnerability associated with near building vegetation, vents, roof covering, decks, and other design features [18].

Additional challenges are present for WUI communities due to advances in new construction technologies applied to sturctures. Thomas Fabian reported on a study of the flammability of roof mounted solar photovoltaic (PV) modules. The motivation for the work is that current flammability tests such as the UL790/ASTM E108, are ordinarily performed individually on each component and there is a need to investigate the combined effect of PV modules and roof coverings as a system when exposed to fire. Fabian presented results of flame spread tests with different class rated roofs and PV panels, different roof slopes and different mounting between module and roof. The results showed that PV modules mounted on a roof have an adverse effect on the fire performance of the roof regardless of the fire rating of the roof or the class rating of the PV panel. The magnitude of the effect depended of the geometry of the assembly, including the gap size between the panel and roof, the setback distance of the panel from the roof leading edge, the angle of the module relative to the roof and the type of roofing system. UL has released a recent report highlighting additional experiments that have been conducted [19].

2.2. WUI fires—vegetation ignition studies

Understanding fire spread in the wildlands is needed to determine exposures that WUI communities experience in these devastating fires. The subject of ignition of natural fuels by an external radiant flux was addressed by Albert Simeoni in contribution entitled "Wildland Fire Behavior: Combustion and Dynamics". In his presentation Simeoni described experiments on the ignition of pine needles using a modified Fire Propagation Apparatus experiments, specifically time to ignition versus applied heat flux (up to 60 kW/m^2). He also presented a model of ignition delay of pine needles using semi-infinite heat transfer model with solid properties obtained from literature and experiments. Two models were developed, one considering an air flow through the porous pine needle bed to simulate the effect of wind and another without air flow. The comparison of model results and experiments showed that if flow of air is allowed to pass through the pine needle fuel bed a porous fuel model will be necessary to predict the experiments [20]. However in the absence of flow that fuel bed can be treated as a solid fuel. Simeoni also presented a model of the ignition of a polymeric solid exposed to a radiant flux that grows linearly with time. The objective of the analysis is to understand the ignition of structures by an approaching fire. The work represents a successful application to wildland fire modeling approaches and techniques for fire safety studies.

Carlos Fernandez-Pello presented recent work, using the experimental apparatus presented elsewhere [21], on the capabilities of hot metal particles to ignite natural fuels. Hot metal particle from power line clashing in high winds, or other spark generation events (welding, grinding, electrical short circuiting) can initiate wildland fires when landing on vegetation. This mechanism has been the cause of some of the wildland fires in California and Texas. Results were presented of the capability to ignite powder cellulose by steel and brass spheres of different diameters and temperatures. The results showed ignition boundaries in terms of type of metal, particle diameter and temperature, and fuel bed moisture. Particle energy and temperature appear to determine the potential for the particles to ignite natural fuel beds.

2.3. WUI fires—ecological considerations

Christopher Dicus presented another important component of the WUI problem not addressed by other speakers in the WUI area at this workshop. Specifically, land management strategies must be developed that minimize both fire risk to communities and also the residual impact to the ecosystem services (carbon sequestration, vegetative air pollution removal) that distinct vegetation types provide [22]. To this end, he discussed ongoing research into how various WUI fuel treatments in shrub- and forest-dominated ecosystems simultaneously impact potential fire behavior and environmental benefits provided by vegetation. Multiple scales, including stand- and landscape-levels, were evaluated.

2.4. Urban fires—2011 great east Japan earthquake

The 2011 Great East Japan Earthquake Disaster (Tohoku Earthquake Disaster) was a historical disaster which devastated a wide range area of eastern Japan. Most fatalities in this disaster were caused by the gigantic tsunami which struck the Pacific coast of Japan shortly after the earthquake. However, the damage due to fire following tsunami was not at all small. It is reported that the number of earthquake- and tsunami-induced ignitions observed in this disaster was as many as 330 [23], some of which developed and became conflagrations. A fire-related disaster of such a scale has not occurred ever since the 1995 Kobe Earthquake Disaster at which the number of ignitions was 293. The experience of the Tohoku Earthquake Disaster will affect the direction and focus of future fire research activity in Japan; considerable effort was devoted on earthquake-related fire researches after the Kobe Earthquake Disaster, such as those on earthquake-induced ignitions, fire following earthquake, or firefighting activity in an earthquake-struck city area, and so forth. The workshop was held a little over a year after the Tohoku Earthquake Disaster, and not surprisingly, five out of eight presentations in the urban fire research area were on fires in the Tohoku Earthquake Disaster.

Masahiko Shinohara, in his presentation entitled "Fire Whirls Caused by Urban Conflagration", reported on a fire whirl observed in the tsunami-struck city of Kesennuma. The result of the field survey suggested that the height of the fire whirl was at least 70 m, and the estimated diameter was between 55 m and 130 m which is equivalent to the size of a city block. The combustibles of the fire were tsunami-generated debris which filled roads and empty lots within the city blocks. One of the presumed generation mechanisms of the fire whirl is the horizontal shear flow over the burning area which is caused by wind speed differential between debris field and river adjacent to the burning area.

Hiroyuki Tamura, in his presentation entitled "Characteristics of Post-Earthquake Fires in 311", reported some of the results of the field survey at 9 tsunami affected municipalities conducted by the National Research Institute of Fire and Disaster in Japan (NRIFD) [24]. He demonstrated several characteristic causes of tsunami-induced ignitions such as those from tsunami-drifted vehicles and drifted liquefied petroleum gas cylinders for household use.

Haruki Nishi, in his presentation entitled "Fires and Damage of Oil Tanks Caused by the 3.11 Earthquake", reported that the way of damage of oil tanks and hazmat facilities were different by their locations. As for those by the Pacific coast, damages were caused mainly by the strike of the tsunami or liquefaction of the foundation ground following strong ground motion. On the other hand, as for those by the coast of the Japan Sea at which no significant tsunami arrival was observed, damages were caused by the earthquake generated sloshing of liquid contained in large oil storage tanks. Although the sloshing did not cause any ignition in the 311 earthquake, there were several cases which accompanied ignition in the past such as those in the middle of Japan Sea earthquake in 1983, and the off the coast of Tokachi earthquake in 2003.

Tatsuya Iwami, in his presentation entitled "Fires in Non-Inundated Area Following the 3.11 Earthquake" reported that there was not much difference in the major causes of ignition in the non-inundated area in comparison with the previous earthquake-generated ignitions. Ignitions include those by shaking induced contact of heating appliances with combustible, misuse of open flame in the blackout, or short-circuit of damaged electric appliances at the recovery of electricity. However, ignition ratio in the non-inundated area of the 2011 Tohoku Earthquake Disaster was approximately 1/4 of the 2004 Chuetsu Earthquake Disaster and 1/12 of the 1995Kobe Earthquake Disaster. Unlike the 1995 Kobe Earthquake Disaster, damages of fires in the non-inundated area were limited, i.e., fires were extinguished before they got large because the fire services were effectively functioning in the non-inundated area.

Tomoaki Nishino, in his presentation entitled "Qualitative Aspect of the Fires Fueled by the Combustibles Arriving in the Vicinity of the Tsunami Refuge Buildings", reported on a case of fire occurred in the vicinity of a tsunami refuge building which were sheltering a number of evacuees inside. Although the fire approached to the refuge building, evacuees were unable to escape to another safer building, because the refuge building was isolated among seawater and tsunami generated debris. For the same reason, fire-fighting was not conducted. Fortunately, this fire did not cause any casualties. However, the refuge building was exposed to severe heating of the flame above the drifted debris. Evacuees trapped in the refuge building were forced to change their locations in the building in order to maintain their safety.

2.5. Urban fires—role of vehicles to phyiscs-based models of urban fire spread

The remaining presentations were on the status report of research started in advance of the 2011 Tohoku Earthquake. Ken Matsuyama, in his presentation entitled "Experimental Study on the Possibility of the Vehicle Fire in Urban and Tsunami Fire", reported on the full-scale burn experiment of twelve motorcycles which are considered as one of the triggers of the tsunami-induced fires. The result showed that the maximum heat release rate (HRR) was dependent more on the type of motorcycle, rather than the engine displacement or initial total mass. Additional experiments were conducted to investigate fire spread behavior between two motorcycles parked side by side. The maximum HRR of the heat-receiving motorcycle was about 1.8 MW, which was higher than that of the heat-source motorcycle of about 1.2 MW.

Kazunori Kuwana, in his presentation entitled "Scale-Model Experiment of Large-Scale Wind-Aided Fires", discussed difficulties in designing scale-model experiments of large-scale wind-aided fires, which could be seen in both urban fire and WUI fires. He proposed a method to relax the scaling requirement and was validated by reconstructing the fire whirls that occurred in the 1923 Great Kanto Earthquake and the wildland fire whirl that occurred in Brazil in 2010. The result showed appropriateness of use of the flame-height-based Froude number as the scaling dimensionless parameter for a scale model experiment of fire whirls [25,26].

Keisuke Himoto, in his presentation entitled "An Analysis on the Burn-Down Probability of Historic Temple and Shrine-Structures in Kyoto City in the Case of Fires Following Earthquake", reported on the result of fire spread simulation analyzing the burn-down probability of 2131 historic temple and shrine-structures which may be involved in fires following an earthquake in Kyoto city. This fire spread simulation in urban area is conducted using a physics-based model formerly developed by the authors [27]. The result showed that over 30% of the national treasures and the important cultural properties will be damaged in the worst expected scenario. The result also showed that the post-earthquake fire safety of designated and registered historic buildings is generally higher than that of undesignated and unregistered historic buildings.

Rachel Davidson presented a new rigorous approach to statistical modeling of post-earthquake ignitions and data compilation for such modeling [28]. The primary objective of the work is to improve statistical models to estimate number and geographical distribution of post-earthquake ignitions. Davison provided an overview of the data collection approach and emphasized the need to define the characteristics of the type of ignition considered and the region that the data was collected for. She presented a comparison of several models of data analysis including Poisson regression, Negative Binominal (NB) regression and Poisson Generalized Linea Mixed Model (GLMM). Generalized linear models (GLMs) and generalized linear mixed models (GLMMs) were used to estimate the number of ignitions in several areas in California. A comparison with observations shows good results of the modeling approach to predict number of ignitions. Suggestions were also given on how the models could be applied in a predictive mode for hypothetical earthquakes. Current efforts to apply this ignition modeling approach in Japan were also discussed.

3. Fire-structure interaction (FSI) research

Structural and non-structural components must be designed to withstand fire for a long enough period of time to allow occupants to exit the building safely and to enable fire rescue personnel to extinguish the fire. Structural fire resistance is traditionally satisfied by a prescriptive design approach, which involves rating components and assemblies based on a standard fire test (e.g., ISO 834 [2]). While the standard fire test continues to serve as a benchmark for evaluating the performance of structural elements in fire, the fire safety community has placed greater emphasis in recent years on an *engineered* approach to structural fire design, in which fire resistance experiments not only qualify a component or assembly but also provide an understanding of the thermal and mechanical actions that develop in the structure at extreme temperatures [29]. In light of the recent paradigm shift, the standard fire test has been augmented by many researchers to include better measurements of temperatures, forces, and deformations [30]; to account for more realistic boundary conditions, including expanding the test method to frame assemblies [31–33]; and to consider more natural types of fire exposures [30]. Engineered structural fire resistance has also prompted the development and increased use of sophisticated modeling approaches for understanding the thermo-structural response of systems exposed to fire [33]. As a result of the extensive experimental and analytical research that has been conducted over the past few decades, performance-based structural fire design has been implemented in building codes in a number of countries (the most notable example being the Eurocodes that have been adopted across Europe and the U.K.).

The trend towards engineered structural fire safety is evident in Japan and in the U.S. although both countries lag behind regions (e.g. Europe) where performance-based structural fire design is well-established. To understand the outcomes of the U.S.–Japan workshop, it may be useful to understand the context of structural fire design in each of the respective countries.

In Japan, the fire resistance verification method was introduced into the Building Standards Law of Japan in 2000 as performance based codes [34]. The fire resistance verification method of Japan has enabled building designers and engineers to evaluate the fire performance of structures under respective fire conditions of the buildings. Adoption of the fire resistance verification method aimed at giving freedom in building design with the opportunity to reduce cost without loss of safety. In recent years, unfortunately, in terms of fire resistance, there have not been many buildings in Japan designed by performance based codes compared to prescriptive codes. There have been moves to improve the situation in the Japanese fire protection engineering community.

In the United States, building codes (e.g., [35]) still continue to emphasize a prescriptive design approach, although recent code developments have allowed more flexibility for engineered structural fire safety. For example, an appendix was added to the AISC *Specification for Structural Steel Buildings* [36] to provide a means for designing steel structures for fire based on non-prescriptive measures. The movement towards engineered structural fire safety has enabled innovations in building system design that would not be permissible under the prescriptive code, such as the use of unprotected steel in buildings [37]. Similar to the situation in Japan, the fire safety community in the U.S. is working to address limitations that are preventing the widespread use of performance-based measures for structural fire design, which include code reform, education and training of structural engineers, and pursuing fundamental research.

The similarities between Japan and the U.S. led to the emergence of several of common themes that spanned the area of structural fire resistance. The discussions and research presentations at the workshop ranged from component-level fire resistance tests to natural fire tests on full-scale building systems. The following summarizes key research areas that were identified in the workshop.

3.1. Continuous improvement in the fire resistant design of buildings

The current practice of structural fire engineering places greatest emphasis on continually improving the fire resistance of buildings through the identification and improved understanding of the sources of weakness in existing building systems, as well as

Specification	Existing Laboratory	New Expansion
Total Floor Area	10,800 sq. ft.	21,400 sq. ft.
Fire Capacity	1 MW (small hood) 3 MW (medium hood) 10 MW (large hood)	20 MW
Strong Floor/Strong Wall	None	60 ft. x 90 ft. x 4 ft. thick strong floor and 60 ft. x 30 ft. x 4 ft. thick strong wall.
Structural Loading	None	Reconfigurable hydraulic loading system, 55-215 kip actuators; 30 inch stroke

Fig. 2. Overview of NIST's new National Fire Research Laboratory (NFRL).

the exploration of new materials and structural configurations for enhanced fire resistance. For example, Toshihiko Nishimura explained that observations of the poor performance of curtain wall spandrel beams made of aluminum prompted researchers at Takenaka Corporation to develop an improved design that prevents the loss of protective boards under extreme temperatures, which is necessary for preventing the vertical spread of fire in buildings. In a similar vein, experimental and analytical research was conducted by Amit Varma and co-workers at Purdue University to better understand the behavior of steel perimeter columns and their role in the resistance of building systems to fire-induced collapse [38]. These types of research provide fundamental understanding of structural performance in fire and can lead to improvements of building codes and standards.

Due to recent advances in testing methods, fire resistance experiments can more accurately simulate the response of building elements when they are part of a structural system. For instance, Jun-ichi Suzuki of the Building Research Institute of Japan and Takeshi Morita of the Institute of Technology at Shimizu Corporation presented novel experimental tests of partition walls that considered the interactions between partition walls and structural frames to account for the potential loss of integrity that may arise due to large deformations in an adjoining frame structure. The approach is somewhat analogous to fire resistance tests on columns that seek to account for partial restraint by the surrounding structure [39,40]. In this manner, some of the limitations of the standard fire test can be overcome by expanding the methodology to include interactions between structural elements that would naturally exist in building systems. It is acknowledged that, while this approach may simulate more realistic mechanical boundary conditions, it does not overcome the thermal limitations to the standard fire test.

Advances in the numerical analysis of structures exposed to fire can also lead to improvements in the fire resistant design of structures by providing enhanced understanding and enabling simulations to extend the findings from experimental research to a broader range of parameters. For example, Tensei Mizukami presented a simple calculation method for predicting temperatures in mud-plastered walls exposed to heating. Similarly, Ann Jeffers of the University of Michigan presented an extension of the perturbation-based stochastic finite element method for quantifying the reliability of structures threatened fire [41]. In addition to enhancing understanding, the quantification of structural reliability can facilitate the performance-based design of structures by allowing comparisons to be made between alternative designs in an objective manner.

3.2. Full-scale building systems under natural fire hazards

While most on-going research is limited to component-level behavior, there is an obvious trend towards understanding the behavior of full-scale building systems subjected to natural fire hazards. The motivation for considering system-level behavior is due largely to limitations in component-level tests, which fail to capture important aspects of the response such as the interactions between structural elements [42]. In addition, compartment fire exposures that assume stationary, uniform heating are limited to relatively small compartments and do not account for the integration of passive and active fire protection systems and the overall building's performance [43]. To address this need, the National Institute of Standards and Technology in the US is currently constructing the National Fire Research Laboratory (see Fig. 2), a full-scale testing facility that allows mechanical loading as well as a hood system to handle fires with HRRs up to 20 MW [44]. As explained by Samuel Manzello, the unique capabilities of being able to measure fire properties as well as the thermo-structural response of full-scale building systems is expected to yield new insight that is beyond the current level afforded by component level tests. Fig. 5 displays an image of the facility under construction along with expected capabilities.

Full-scale testing of building systems can also lead to a holistic understanding of fire safety that could allow stringent limitations imposed in the prescriptive codes. For example, the National Institute

Fig. 3. Overview of Experimental Facilities at the Building Research Institute (BRI). (Fire Research Wind Tunnel Facility (FRWTF), Wind Speeds Up to 10 m/s, Wind Cross-Section: 4.0 m (High) by 5.0 m (Wide), Test Section Length: 15.0 m).

for Land and Infrastructure Management in Japan is in the midst of conducting a series of full-scale tests on large (i.e., three-story) wooden school buildings, as described in a presentation by Daisaku Nii and Hideki Yoshioka. The Japanese Building Standard Law prohibits the use of such large buildings constructed of timber. However, it is believed that adequate fire resistance can be attained using fire safety engineering principles to control the spread of fire and the ensure adequate egress times for building occupants.

3.3. *The expanding scope of structural fire safety*

While most of the research being done in the area of structural fire engineering aims to improve the fire resistance of buildings, it is clear that the scope of the discipline is expanding beyond the traditional areas of focus. For example, Venkatesh Kodur explained that there have been a number of bridge failures in the U.S. that have resulted from vehicular fires, but the subject has received very little attention to date. The problem has prompted a collaborative effort between Princeton University and Michigan State University to assess the fire resistance of steel bridge girders, which are generally designed to be unprotected against fire despite the threat of vehicular fires [45].

In his presentation "Barriers to Performance-Based Structural-Fire Safety Design," Michael Engelhardt identified the limitations to compartment fire exposures used in structural fire design and advocated for research to better understand the resistance of structures to moving fires in large, open floor plans. The study of structural performance under spreading fires inherently requires a close collaboration between fire scientists and structural engineers.

The US and Japan also have significant interest in ensuring the safety of buildings threatened by multihazard load effects, particularly fires following earthquakes. According to research conducted at the Tokyo University of Science, buildings damaged by earthquakes may exhibit reduced fire performance even if structural damage is minor. For example, compartmentation may be compromised due to damage to non-structural elements such as partition walls. Mamoru Kohno explained that, because the threat of fire is increased following earthquakes, it is important that communities in earthquake prone regions have the appropriate action plans in place to prevent injury and loss of life due to fires that occur following earthquakes.

4. Laboratory Tours

One of major focuses of this activity was to encourage or facilitate collaboration amongst attendees. Shared use of facilities and exchange of staff has decreased as fire research budgets are decreasing worldwide. After workshop attendees had toured full-scale experimental facilities in Japan, it was apparent that many were not aware of these facilities and their capabilities. Fig. 3 and 4 display the range of facilities visited by the attendees. Specifically, the research facilities at BRI consist of a full-scale fire test laboratory capable of measuring the HRR of burning vehicles and it is also used to investigate smoke movement through corridors (see Fig. 3). BRI also maintains a suite of furnaces to expose building components to standard fire exposures. Of particular importance is BRI's Fire Research Wind Tunnel Facility (FRWTF). This facility was designed to allow investigation of wind effects on fire. The FRWTF can apply wind speeds up to 10 m/s and full-scale structures can be exposed to wind during combustion (see Fig. 3). While there are many wind tunnels in the world, most are constructed from wood and not designed to investigate the influences of wind on fire since the wind tunnel is combustible. At NRIFD's research campus, there are two experimental facilities

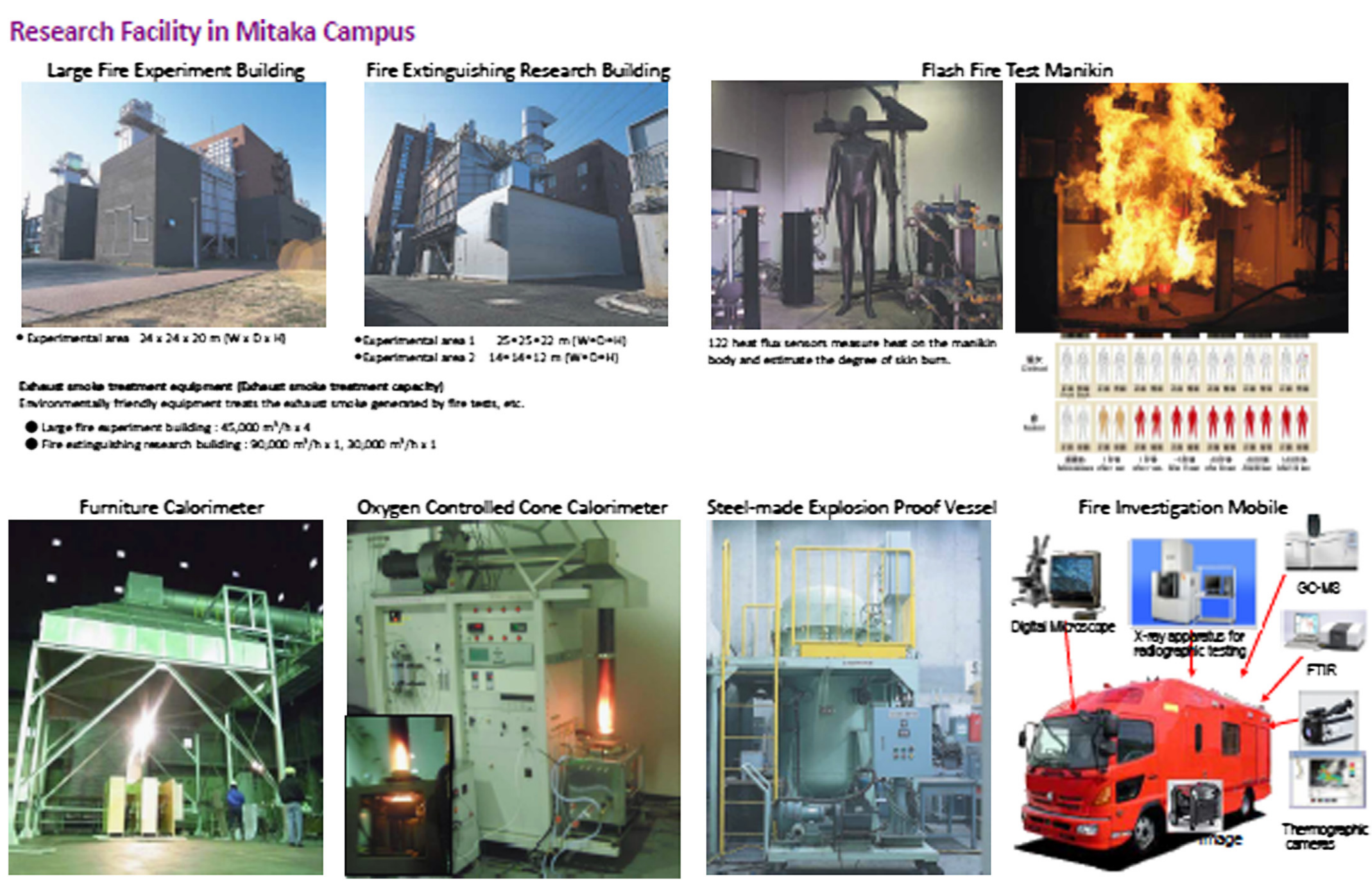
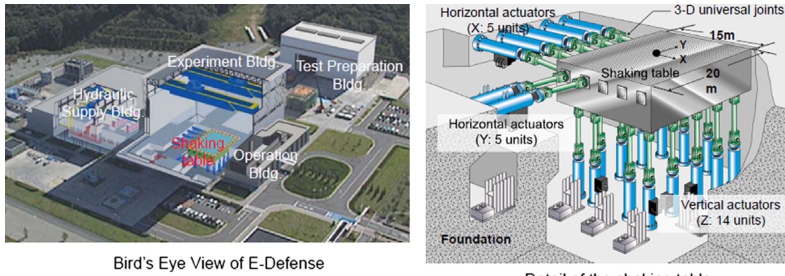


Fig. 4. Overview of Experimental Facilities at National Research Institute of Fire and Disaster (NRIFD).



Bird's Eye View of E-Defense

Detail of the shaking table

Fig. 5. Overview of E-Defense (NIED).

to study full-scale fire experiments. These consist of the Large Scale Fire Experiment Building and the Fire Extinguishment Research Building (see Fig. 4).

Research being conducted by Japanese construction companies, using their own unique facilities, was presented as well. Even though these industrial facilities were within the Tokyo area, tours of those facilities were not possible in the interest of time. Other unique facilities in Japan were introduced at the workshop via poster presentation. One very unique facility that was not possible to visit due to its location in the Kansai region of Japan is E-Defense, a 3D-full scale earthquake testing facility operated by National Research Institute for Earth Science and Disaster Prevention (NIED see Fig. 5). This facility allows entire multi-story structures to be placed on a 15 m by 20 m shaking table to simulate earthquakes. The maximum horizontal displacement is ± 1 m in the horizontal (X–Y) direction and ± 0.5 m in the vertical direction (Z). The follow-on meeting at NIST is intended to allow Japanese attendees to tour facilities within the USA.

5. Summary

This paper has attempted to summarize the findings of *Operation Tomodachi—Fire Research*, a workshop that was held in Tokyo, Japan from July 1 to July 4, 2012. The research topics considered were urban/WUI fires and Fire-Structure Interaction (FSI). The objective was to: (1) develop scientific knowledge and transfer it to building codes and standards that will be of use to both countries to reduce the devastation caused by unwanted fires, (2) provide a forum for next generation researchers to present their work in order to develop lasting research collaborations, (3) and allow USA participants a chance to visit excellent large-scale research facilities available in Japan that are of use to the research topics of this workshop. Based on discussions with those that attended, it would appear the objectives were met. In particular, collaborative discussions between UL and NRIFD resulted directly after the close of the meeting. In the interest of providing a succinct summary, details of the presentations may be found elsewhere; the interested reader may refer to [46], the NIST report provides all the presentations delivered at this event. As mentioned, there will be a follow on workshop in 2014 to be held at NIST. The topics are in the process of being decided. It is desired that this activity will motivate the next generation of researchers to explore and develop research collaborations related to emerging areas of fire safety science. The authors are hopeful that new and exciting activities specific to other countries may come out of this type of event.

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