Resilience of Critical Infrastructure to Extreme Fires – Gaps and Challenges

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Abstract

This report provides the results of the study conducted by NRC on the protection and resilience of critical infrastructures against extreme fires, e.g. fuel storage or tanker fires. The 9/11 World Trade Centre building collapse and the MacArthur Maze Bridge collapse on April 27, 2007, a critical bridge in the San Francisco area, are two examples of such extreme fire threats to critical infrastructures. The main goal of this study was to develop a better understanding of the threats from extreme fires to critical physical infrastructures. Furthermore, the studies attempted to identify and prioritize the gaps and challenges of the prevention, response and recovery from such incidents.

The study included a literature review of the gaps and research needs for the assessment and protection of critical infrastructures to enhance their resilience against extreme fire. Critical border crossing bridges/tunnels, embassies and government buildings are examples of critical infrastructures. An advisory board with 25 members from different government departments, industries and regulatory bodies discussed these research needs and provided inputs on their priorities. This project also included two demonstration fire tests conducted using a new testing facility at the National Research Council Canada (NRC). As an example of a bridge/building structural element, two reinforced concrete columns were successfully tested based on two standards; an extreme fire, ASTM E1529, and a typical building fire, ASTM E119. The results demonstrated that 1) extreme fire conditions could be produced using the NRC furnace facility and 2) fire endurance/resilience of critical infrastructures can be tested and evaluated using this facility.

This report presents the outcomes of the review study on the gaps and priorities as well as the results of the two fire tests.

Résumé

Le présent rapport fournit les résultats de l’étude menée par le Conseil national de recherches du Canada (CNRC) sur la protection et la résilience d’infrastructures essentielles exposées à des incendies très violents, p. ex., des incendies d’entreposage de carburants ou de véhicule-citerne. L’effondrement des tours du World Trade Centre, le 11 septembre 2001, et celui de l’échangeur du pont MacArthur Maze, le 27 avril 2007, pont névralgique de la région de San Francisco, sont deux exemples des conséquences que peuvent avoir de tels incendies très violents sur des infrastructures essentielles. Le principal objectif de cette étude était de développer une meilleure compréhension des menaces que représentent les incendies très violents pour les infrastructures physiques essentielles. En outre, les études ont tenté d’identifier et de prioriser les lacunes et les défis en matière de prévention de ces incendies, d’intervention lorsqu’ils éclatent et de récupération subséquente.

L’étude comprenait une analyse documentaire des lacunes et des besoins en matière de recherche pour l’évaluation et la protection des infrastructures essentielles en vue d’améliorer leur résistance aux incendies très violents. Les ponts/tunnels de zones frontalières névralgiques, les ambassades et les édifices gouvernementaux sont des exemples d’infrastructures essentielles. Un conseil consultatif formé de 25 membres provenant de divers ministères, industries et organismes de réglementation s’est penché sur ces besoins en matière de recherche et a fourni des suggestions quant à leurs priorités. Ce projet comprenait également deux (2) essais d’incendie de

démonstration menés au moyen d’une nouvelle installation d’essais du CNRC. À titre d’exemple d’un élément structural de pont/bâtiment, deux (2) colonnes de béton armé ont été mises à l’essai avec succès suivant deux normes précises : un incendie très violent, selon la norme ASTM E1529, et un incendie d’immeuble type, selon ASTM E119. Les résultats révèlent que :

1) des conditions d’incendie très violent peuvent être produites au moyen du four d’essais du CNRC;

2) la résistance au feu/résilience des infrastructures essentielles peut être mise à l’essai et évaluée au moyen de cette dernière installation.

Le présent rapport expose les résultats de l’examen des lacunes et des priorités ainsi que les résultats des deux essais d’incendie réalisés

Executive summary

Background: Recent gap analyses and studies on effects of fire on critical infrastructures by the National Research Council Canada, Transport Canada, Federal Highway Administration and National Institute of Standards and Technology [1, 6, and 14] showed that fire is a considerable threat to the safety and security of critical infrastructures such as critical bridges, tunnels, and buildings. Collapse of the World Trade Centre buildings and several bridges across North America indicated that these infrastructures are vulnerable to fire and the current design and protection practice would need to include tools to more effectively mitigate such threats. As a result, NRC, Transport Canada and DRDC formed this research project to develop a better understating of the fire threats to critical infrastructures, the research needs and methodologies to search for feasible solutions.

The research needs and gaps, identified by previous research [1], were mainly based on literature reviews and studies of previous incident reports. To ensure that these gaps and findings are also recognized by the communities of practice, e.g. owners and operators, regulatory bodies, policy makers, first responders and construction industries, an Advisory Board (AB)with members from these communities was formed. The main role of the advisory board was to review and recommend the research needs and priorities on the resilience of critical infrastructure to extreme fires. Members of the AB were experts from Transport Canada, Defence Research and Development Canada, Ministry of Transportation – Ontario, Ministry of Transportation–Quebec, Ottawa Fire Service, Department of Foreign Affairs and International Trade, Public Works and Government Services Canada, Royal Canadian Mounted Police, National Energy Board, Federal Highway Administration, Seattle Fire Services, National Fire Protection Association (NFPA), NFPA 502 committee, Fyfe Co. LLC, BASF, Lafarge, Sika Canada, and SNC Lavalin. NRC and Transport Canada provided the AB members with the required information and coordinated and moderated the AB meetings. This report includes the outcomes of the review and recommendations extended by the AB members.

The second objective of this project was to demonstrate facilities that could be used in the future to fill the gaps and seek solutions for the recommended research needs. To Pursue R&D on the resilience of critical infrastructures in extreme fire, it is essential to have access to the necessary testing labs with fire testing and research competencies. One of the unique fire labs in the nation, and worldwide, is the NRC fire lab that is equipped with full-, intermediate- and small-scale furnace testing facilities as well as a large real scale burn hall. However, these facilities have been used in the past mostly for normal building fires rather than extreme fires, which are more applicable to the critical infrastructure fires. This project demonstrated that in addition to normal fires these facilities could be upgraded and used for producing extreme fires and tests of critical infrastructure elements, e.g. a reinforced concrete column, in extreme fires.

Results: Among the main recommended gaps and research needs identified through this project are:

1) Develop methods and technologies for property protection of critical infrastructures, in addition to the current life safety requirements, since fast recovery of CIs after an incident is vital, and,

2) Study safety of first responders during and after fire with respect to potential structural failure and their role in reducing the fire damage to CIs.

The test results of this project demonstrated that 1) an extreme fire could be produced in a lab environment 2) tests of critical infrastructure elements in extreme fire could be performed using the NRC fire testing facilities. Additional results, obtained from these tests, are: 1) Substantial loss of load capacities of the infrastructure examples were observed due to the fires, hence effective solutions need to be developed to mitigate such capacity losses for CIs during fire incidents 2) Temperatures in concrete elements continued to increase hours after the stop of the fires. Such phenomenon has not been included in the current design and further studies are needed on infrastructure safety and life safety of both users and first responders after the fire until the structure reaches a reasonable and reliable stability.

Significance: The outcomes of this project are expected to improve awareness and provide a better understanding of the threat to critical infrastructures from extreme fire and the gaps and challenges in the prevention, response and recovery from such incidents. This knowledge will help and support decision making that targets priorities for R&D investments to efficiently enhance structural integrity, safety and security of critical physical infrastructures in extreme fires.

Future plans: Using the demonstrated fire testing lab facility and competencies, NRC will assist Transport Canada, DRDC, other OGDs, and industries to fill the identified gaps. These includes: to identify available materials and technologies for protection of critical infrastructures (CIs) against and to develop methods and technologies to assess and mitigate risk of fires to CIs and to enhance their resilience to such threats.

Sommaire

Contexte : Les récentes analyses des lacunes et les études sur les effets des incendies sur les infrastructures essentielles (IE) réalisées par le Conseil national de recherches du Canada (CNRC), Transports Canada, la Federal Highway Administration (États-Unis) et le National Institute of Standards and Technology (États-Unis) [1, 6, et 14] ont révélé que les incendies représentent une menace de taille pour la sécurité du public et la sécurité matérielle d'IE telles que les ponts névralgiques, les tunnels et les bâtiments. L'effondrement des tours du World Trade Centre et de plusieurs ponts en Amérique du Nord indique que ces infrastructures sont vulnérables aux incendies et que la pratique actuelle dans les domaines de la conception et de la protection devrait englober des outils permettant d'atténuer plus efficacement cette menace. En conséquence, le CNRC, Transports Canada (TC) et Recherche et développement pour la défense Canada (RDDC) ont mis sur pied ce projet de recherche en vue de développer une meilleure compréhension de la menace que représentent les incendies pour les IE, des besoins en matière de recherche et des méthodologies permettant d'en arriver à des solutions réalisables.

Les besoins en matière de recherche et les lacunes, identifiés par la recherche menée précédemment [1], étaient essentiellement basés sur les analyses documentaires et les études des rapports d'incidents antérieurs. Afin de garantir que ces lacunes et ces constatations soient reconnues également par les réseaux d'échange de pratiques, soit les propriétaires et les exploitants, les organismes de réglementation, les responsables des politiques, les premiers intervenants et les industries de la construction, un Conseil consultatif (CC) dont les membres proviennent de ces réseaux a été mis sur pied. Le rôle principal du CC était d'examiner et de recommander les besoins en matière de recherche et de priorisation sur la question de la résistance des IE aux incendies très violents. Les membres du CC sont des experts provenant de TC, de RDDC, du ministère des Transports de l'Ontario, du ministère des Transports du Québec, du Service des incendies d'Ottawa, du ministère des Affaires étrangères et du Commerce international, de Travaux publics et Services gouvernementaux Canada, de la Gendarmerie royale du Canada, de l'Office national de l'énergie, de la Federal Highway Administration, de Seattle Fire Services, de la National Fire Protection Association (NFPA), du comité NFPA 502, de Fyfe Co. LLC, de BASF, de Lafarge, de Sika Canada et de SNC-Lavalin. Le CNRC et TC ont procuré aux membres du CC l'information requise et ont coordonné et présidé les réunions du CC. Ce rapport inclut les résultats de l'examen et les recommandations apportées par les membres du CC.

Le second objectif de ce projet était de faire la démonstration des installations pouvant être utilisées à l'avenir pour combler les lacunes et générer des solutions relativement aux besoins recommandés en matière de recherche. Aux fins de la R. et D. sur la résistance des IE aux incendies très violents, il demeure primordial d'avoir accès aux laboratoires d'essais requis dotés de capacités en essais de tenue au feu et en recherche connexe. Le laboratoire de recherche en incendie du CNRC, l'un des laboratoires ainsi spécialisés les plus notoires au pays et dans le monde entier, est doté d'installations d'essais au four pleine grandeur, en grandeur intermédiaire et à petite échelle, ainsi que d'une salle d'essais de combustion grande échelle (grandeur réelle). Toutefois, ces installations ont été utilisées antérieurement surtout pour l'étude des incendies d'immeuble ordinaires et non des incendies très violents, lesquels peuvent viser plus particulièrement les IE. Ce projet a permis de démontrer que ces installations pouvaient être améliorées aux fins de l'étude, en plus des incendies ordinaires, des incendies très violents, et être utilisées pour produire de tels incendies expérimentaux et des épreuves de résistance à ces incendies d'éléments d'IE, p. ex., une colonne en béton armé.

Résultats : Parmi les principaux besoins recommandés en matière de lacunes à combler et de recherche ayant été identifiés au fil de ce projet, notons les suivants :

1) développer des méthodes et des technologies aux fins de la protection des biens d'IE, en plus des exigences actuelles en matière de sécurité des personnes, la récupération rapide des IE après un incident demeurant vitale;

2) étudier la sécurité des premiers intervenants pendant et après les incendies par rapport à la défaillance structurale potentielle et relativement au rôle que jouent ces intervenants dans la réduction des dommages aux IE causés par le feu.

Les résultats des essais dans le cadre de ce projet révèlent :

1) qu'un incendie très violent peut être produit en conditions d'essai en laboratoire;

2) que des essais d'éléments d'IE exposés à un incendie très violent peuvent être réalisés à l'aide des installations d'épreuves de tenue au feu du CNRC.

Les résultats supplémentaires obtenus de ces essais sont les suivants :

1) une perte substantielle des capacités de charge maximales des échantillons d'infrastructure en raison de l'incendie a été notée; il est donc nécessaire de mettre au point des solutions efficaces pour limiter de telles pertes de capacité des IE exposées au feu;

2) les températures observées dans les éléments de béton continuent d'augmenter plusieurs heures après l'extinction de l'incendie. Ce phénomène n'est pas pris en compte dans les pratiques de conception actuelles, et il sera nécessaire de mener des études plus poussées sur la sécurité des infrastructures et la sécurité après l'incendie tant des usagers que des premiers intervenants jusqu'à ce que la structure soit parvenue à une stabilité raisonnable et fiable.

Pertinence : On s'attend à ce que les résultats de ce projet améliorent la reconnaissance et la compréhension de la menace aux IE que représentent les incendies très violents et des lacunes à combler et des défis à relever dans la prévention de tels incidents, l'intervention durant ceux-ci et la récupération subséquente. Cette meilleure connaissance favorisera et appuiera des prises de décision visant les priorités en matière d'investissement en R. et D. en vue d'améliorer avec efficacité l'intégrité structurale, la sécurité des personnes et la sécurité matérielle des IE exposées à des incendies très violents.

Prospective : Au moyen de ses installations d'essais de démonstration en laboratoire et tablant sur ses capacités, le CNRC aidera TC, RDDC, d'autres ministères et les industries visées à combler les lacunes identifiées, dont les suivantes : identifier les matériaux et les technologies disponibles aux fins de la protection des IE contre les incendies et développer des méthodes et des technologies permettant d'évaluer et d'atténuer ces risques et d'améliorer la résistance des IE à ces incendies

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1 Introduction

The current practice of fire resistance design and fire safety design of structures is based on mainly designing structures/infrastructures to meet the required level of life safety. Based on such performance requirement the structures are designed so that their collapse is prevented during fires. There is minimal consideration on the response and recovery of the structures after the fire incident. For instance, building codes require design of buildings (mid- to high-rise) to ensure a safe evacuation and to prevent buildings from collapse during fires. However, there is limited information or requirement in the design for property protection or structure recovery after the fire.

For critical infrastructures such as a critical bridge or a critical government building, in addition to life safety, it would be very crucial to ensure that the infrastructure could recover its service/operation with no or with minimal repair rapidly after the incident. In other words, protection of property or asset could be an important requirement for Critical Infrastructures (CIs) to mitigate the impact on the community as the result of its damage due to the fire. One of the critical infrastructure examples, for which asset protection is a vital requirement, is a border crossing infrastructure. At Canadian ports of entry every day 1.8 billion dollars of goods and services cross the border using critical transportation infrastructure. Major incidents or disruptions not only pose a high risk to the safety of the users and first responders but also could result in significant economic impact to the country. Rapid recovery is always a vital factor for such critical infrastructures. Even one day delay in the restoration of a critical infrastructure could have a substantial economic impact on the community. For instance, closure of a critical bridge in San Francisco (MacArthur Maze Bridge in April 2007) due to a fuel tanker fire accident resulted in $90 million cost with a $6M/day economic impact estimate.

Therefore, the scope of this study was primarily set on how to protect and recover critical infrastructure assets during and after a fire incident; to mitigate the incident impact and consequences.

2 Purpose

The main objectives of this project were:

- To study gaps in the resilience of critical physical infrastructure to extreme fires, establish priorities regarding structural resilience, protection, restoration and recovery and explore challenges.

- To demonstrate, a new competency, an extreme fire in a lab environment and testing simulation of critical structural elements of an infrastructure, e.g. a bridge or a building, and their performance in fire.

3 Methodology

The main methodology employed for the implementation of this study includes technical reviews and experimental assessments. This chapter describes the applied methodology in five sections. The first section reviewed and defined different types of critical infrastructures, those which the results of this study would be applicable to. The second section, Section 3.2, described different communities of practice which could be affected by an extreme fire threat to Critical Infrastructures, those who could be considered as the end-users of this study. Gaps and research needs related to the resilience of critical infrastructures to extreme fires have been identified previously using a literature review study [1]. These identified gaps and research needs were updated for this study and summarized in the third section. Section 3.4 provides results of the gaps reviewed by the advisory board members of this project. AB members were experts from the identified community of practices. This section includes recommendations of the AB members on research needs and priorities for future R&D. Finally, Section 3.5 provides the assessment approach and results for the demonstrated tests. This includes producing extreme fires and testing critical infrastructure elements in two different fires. More details of the test results are provided in Appendix B.

3.1 Infrastructures Vulnerable to Extreme Fire

Different types of Critical Infrastructures (CIs) related to the objectives of this study are presented in this section, including critical bridges, tunnels, and buildings.

3.1.1 Bridges

Previous studies [1, 6] reviewed the state of knowledge and practice on vulnerability, assessment and design of bridges for fires. One of these studies was carried out by the National Research Council Canada and Transport Canada [1]. The study reviewed more than 35 bridge fire incidents. Another study was carried out by the Federal Highway Administration [6] in which more than 100 bridge fire incidents were reviewed. Both projects looked into different previous bridge fire incidents, e.g. fuel tanker fires, mainly in North America and how such fires could damage the bridge structures. The outcomes of these two studies indicated that bridges are not typically designed for fire and that they are vulnerable to fire. As an example of the previous incident study, the review summary on the Overpass I-75 Fire, Hazel Park, Michigan in 2009 is provided here [1].

- Overpass I-75, Hazel Park, Michigan

  At about 8:00 p.m. on July 15, 2009, a car spun out of control along an overpass bridge on I-75 near Hazel Park close to Detroit, Michigan. This caused the crash of a tanker truck travelling behind the car, which subsequently led to a major fire (see Figure 1). The overpass bridge collapsed as a result of the fire. The tanker was carrying more than 13,000 gal of gasoline. A report indicated that approximately 4,000 gal of the fuel was left in the tanker when it exploded (more likely a large deflagration) under the overpass and that the high intensity heat of the fire made the overpass collapse onto the freeway within 30 min. The overpass was completely removed and reconstructed later. The 9 Mile Road Bridge had recently been restored as part of a $16.5 million Michigan Department of Transportation project to restore 16 overpasses

Figure 1: Collapse of the overpass bridge on I-75 due to tanker fire.

- Discussion
  - Structural Response: The bridge deck consists of a concrete deck and steel girders. No information was found describing the collapse mechanism of the overpass bridge. The fire was completely extinguished by 4:00 a.m. However, the bridge collapsed 30 minutes after the large deflagration. It is not clear whether loss of strength in the steel of the main girders initiated the collapse or if it was the thermal expansion of the deck and the girders which resulted in a structural buckling and failure. Currently the bridge design standards do not include requirements to avoid premature collapse due to a fire scenario.
  - Fire Load: Compared to incidents described earlier in this report, the fire load created in this incident is relatively high. The tanker truck carried 13,000 gal of fuel (likely gasoline). Since the fire was exactly under the overpass, a large fire load was imposed on the bridge, resulting in structural failure. A report also indicated involvement of another truck, a tractor-trailer carrying produce.
  - First Rescue/Response: The drivers of the passenger car, the fuel tanker and a third tractor-trailer involved in the incident were able to escape with only minor injuries. Fire departments were able to control the fire after 8 hours.
  - Explosion/BLEVE: An explosion was reported by the media after the tanker lost 9000 gal of its fuel. However, no official report or information was found to indicate a possibility of BLEVE in this incident.
  - Security-Deliberate Scenario: One of the main differences between this accidental fire scenario and a deliberate fire is the time of the incident. In the case of an accidental truck fire speeding and losing control of the vehicle has been evidenced in most of the cases. Speeding is more likely to occur when there is low traffic volume. In a deliberate scenario, the fire incident would be directed to rush hours to increase the damage and casualties.

3.1.2 Tunnels

More studies have been carried out on the fire safety of tunnels than that of bridges. Perhaps one of the main reasons is the higher risk of casualties in a tunnel fire than a bridge fire. According to statistics, significant fatal accidental fires in tunnels have occurred almost every year in the past decade [9]. Efficiency of the ventilation system plays a major role in the fire safety of tunnels during the response and rescue missions to reduce the casualties. Studies have been carried out to develop emergency ventilation strategies in the events of tunnel fires [10].

Although some research data and information are available on the protection of tunnel assets against fire, more emphasis has been extended to life safety. NFPA 502 [2] "Standard for Road Tunnels, Bridges, and Other Limited Access Highways" is one of the most prominent tunnel fire safety design standards worldwide. Although this standard also includes information about fire safety of bridges, the document is more focused on the requirements for tunnels fire safety. For asset protection, the standard recommends fire tests for tunnel linings to limit damage, e.g. concrete spalling during fires. An example of the time-temperature curve used for such a fire test is the RWS curve [5]. More research and studies are needed to enhance the resilience of tunnels to extreme fire, e.g. developing concrete lining with minimal spalling during fire or develop more efficient fire protection materials to protect tunnel structures in the event of extreme fires.

3.1.3 Buildings

Buildings have been required by the building codes to have a minimum fire safety. National Building Code of Canada [11] has three main objectives in the design of buildings for fire.

- OS1 Fire Safety

An objective of the 2010 NBC is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to fire.

- OP1 Fire Protection of the Building

An objective of the 2010 NBC is to limit the probability that, as a result of the design or construction of the building, the building will be exposed to an unacceptable risk of damage due to fire.

- OP3 Protection of Adjacent Buildings from Fire

An objective of the 2010 NBC is to limit the probability that, as a result of the design or construction of the building, adjacent buildings will be exposed to an unacceptable risk of damage due to fire.

Although buildings have been designed for fire safety and protection, the requirements are mainly for reducing the risk of injury due to a fire. OP1 requires property protection; however, for most of the buildings currently being designed this is to prevent collapse of structures during the fire rather than minimising the damage or protecting the asset. Protection of asset is more pronounced in OP3 which is for protection of adjacent building rather than the building itself. Furthermore, buildings are designed mainly for typical building fuel fire rather than extreme fires. Therefore, the solutions provided by the NBC for fire protection and design of buildings would not be applicable for buildings that are exposed to risk of extreme fires.

Examples of extreme fires in buildings are the 9/11 World Trade Centre buildings or Pentagon building Fires. Other buildings with risk of extreme fires are parking garages building or buildings with an underground parking garage. An example of a previous parking fire is the Nov. 24, 2007's underground car park fire incident in northern Switzerland. In the incident, the fire resulted in the collapse of the parking ceiling [12]. Seven Swiss firefighters were killed due to the collapse of the parking ceiling. Other buildings with risk of extreme fires are government buildings such as embassies abroad. These buildings would have high vulnerability to fire since the buildings may not be properly designed depending on the location of the building and the fire safety requirements of the country that the building is located in. Furthermore, they would be exposed to a higher risk of terrorist attack, deliberate fire, compared to buildings located in Canada. Border building facilities may also have a high risk of deliberate extreme fire threats.

3.1.4 Other Infrastructures

Other types of critical infrastructures include nuclear power plants, airport facilities, pipeline facilities, and telecommunication and facilities. Further studies would be needed to better identify and include these facilities in future research.

3.2 The Communities Affected by An Extreme Fire Threat - Roles and Responsibilities

Main communities affected by an extreme fire threat identified by this project include owners and operators of the CIs, regulatory bodies and policy makers, first responders, and construction industry.

3.2.1 Owners and Operators

Owners and operators of critical infrastructures (CIs) would have the main role in the decisions of what is the required level of life safety and property/asset protection required for the critical infrastructures. For instance, if a bridge is located in a county area with low volume of traffic, it may not require a fire design for its asset protection, if a slow restoration of the bridge would not significantly impact the community. However, if it is a major border crossing bridge and any delay in its restoration after a fire could have significant disruptions and impact on the community, a decision could be made to design the bridge for a rapid recovery and property protection after a potential extreme fire incident. Owners and operators of critical infrastructures are among the main end users of studies related to the protection of CIs in fire such as this study. In this project, representatives from Transport Canada, for international and national transportation infrastructures, Public Works and Government Services Canada (PWGSC), for government buildings and infrastructures, Foreign Affairs and International Trade Canada (DFAIT), for embassies and their other infrastructures, Ministries of Transportation, Ontario (MTO) and Quebec (MTQ), for provincial infrastructures, the US Federal Highway Administration (FHWA), for international infrastructures, and the National Energy Board (NEB), for other energy related infrastructures, provided input on the gaps for future studies as members of the advisory board.

3.2.2 Regulatory Bodies and Policy Makers

Regulatory Bodies and Policy Makers set requirements and priorities for studies; what are the main requirements which need to be developed for enhancing the resilience of critical infrastructures to extreme fires, or which area of research or study would have a higher priority. Representatives from National Fire Protection Association (NFPA) for standards and design requirements, and Defence Research and Development Canada (DRDC) for priorities of research, provided input in the outcomes of this study as members of the advisory board.

3.2.3 First Responders

First responders play major roles not only in rescuing the victims in extreme fire incidents and minimizing the casualties but also in mitigating damage to the critical infrastructures during the fire. Efficient firefighting strategies could help firefighters control and extinguish the fire with minimal damage to the critical infrastructures. A fire emergency responder's safety guideline could reduce the risk of injury to the first responders. Representatives from Fire Services (Ottawa and Seattle), and RCMP, for emergency responders, are participating in this study and providing input as members of the advisory board.

3.2.4 Construction Industry

Construction industry plays a main role in developing and providing solutions for enhancing resilience of critical infrastructures to extreme fire. This will be through supporting and performing research and study for developing tools/technologies and materials that could be employed for enhancing fire endurance of existing critical infrastructures and new critical infrastructures. For instance, developing and producing a fire protection material for CIs to reduce the effects of fire on critical infrastructures or to develop a concrete mix design that could increase the fire resistance of concrete used in construction of critical infrastructures. Representatives from the construction industry in this project are Fyfe Co. LLC, BASF, Lafarge, Sika Canada and SNC Lavalin, as members of the advisory board.

National Research Council of Canada, as a research body, carried out this study with coordination of Transport Canada, other above OGDs and Industries, and under sponsorship of the DRDC-Canadian Safety and Security Program.

3.3 Gaps and Research Needs

NRC and TC carried out a study on "Vulnerability of Bridges and other Critical Transportation Infrastructure to Extreme Fire and BLEVEs" in 2011[1]. This paper will provide a summary of the gaps and needs identified in this report and those identified later (the full report is available on request from ron.cowalchuk@tc.gc.ca of Transport Canada). The research needs are sorted according to two main categories: 1) Gaps related to design and construction of new critical infrastructures and 2) research needs related to existing critical infrastructures. The second category itself is divided into two subcategories i) gaps related to assessment, protection and strengthening of existing constructions and ii) research related to inspection, repair and recovery of existing infrastructures after an incident.

The gaps listed in this paper address the needs for enhancing the resilience of critical infrastructures by means of assessment/inspection, strengthening, protection, retrofitting and repair of the main structure.

The scope of this study is limited to the physical critical infrastructures such as critical bridges, tunnels, buildings, e.g. government buildings, and ports of entry facilities' structures mainly constructed with, but not limited to, concrete and steel.

3.3.1 New Infrastructure Constructions

This section includes research needs related to the design and construction of new critical infrastructure. For instance, how we can modify structural materials, e.g. concrete mixtures, to enhance their resilience to extreme fire, e.g. when building a new tunnel with concrete. Although the impact of such a solution on the overall resilience of the country's critical infrastructure will only be evident in the long-term the results would have a beneficial impact on the country's resilience.

Below is the list of identified gaps in this category:

- Develop construction materials that could withstand extreme fire

Examples: Previous incidents and experimental studies indicated concrete spalls, sometime explosive, in extreme fire; a new concrete design/mix, e.g. with a reinforcing fibre, could reduce damage to the infrastructure in such an event. Another example is to develop a fire protection material coated on the concrete surface, e.g. on a tunnel lining or under a bridge deck, however this would create an obstruction to maintenance inspections, therefore the design of a coating should include a solution to facilitate the inspection of the concrete structure during the operation of the infrastructure.

- Develop a risk-based design tool for new critical infrastructure

Examples: Buildings are currently designed to withstand typical building fuel fire. Not even the most critical buildings such as the 9/11 World Trade Centre, are designed for extreme fire, moreover bridges are not designed for fire of any type. Some work related to the design of infrastructure against extreme fire is underway for tunnels but the research is still under development (NFPA 502). Developing a risk-based design tool for critical infrastructure would help engineers to design new critical infrastructure to counter this threat, based on the associated risk.

3.3.2 Existing Infrastructures

Research gaps related to existing infrastructure is provided separate from the new constructions, since their impacts may need to be addressed according to the long-, intermediate- or short-term requirement. As for new structures, the research gaps are divided into two categories.

- Protection and Strengthening

These are research gaps related to mitigation measures for enhancing the resilience of the existing critical infrastructures, such as protection and strengthening of structures, against extreme fire threats. The results of this research could have an intermediate term impact on enhancing the resilience of the country's critical infrastructure. This section does not include response and recovery.

- Develop a risk-based inspection tool to assess the resilience of the existing critical infrastructures to extreme fire:

  Examples: Some of the existing critical infrastructures, critical bridges, international port of entry facilities, critical government buildings, e.g. embassies, might be vulnerable to the extreme fire. Currently, authorities/owners/operators of these critical infrastructures would need a reliable inspection tool to help them in their decision making, for example, whether the resilience of the existing critical infrastructure would be sufficient or needs to be enhanced for the associated risk of an extreme fire.

- Develop protection and strengthening material/system:

  Examples: Fire protection materials/systems, e.g. fire insulation materials, could be developed to enhance the resilience of existing critical infrastructures, e.g. tunnels and bridges that are subjected to the risk of extreme fire. In many cases of existing critical infrastructure, not only do they need to be protected from the risk of the extreme fire but they also need to be retrofitted to compensate for deterioration due to ageing, e.g. corrosion. In such scenarios, the solution should include both problems.

- Repair and recovering

This section includes gaps in response to an extreme fire and recovery of existing critical infrastructures after the incident. Due to the significant associated cost, not all critical infrastructures could be retrofitted or protected against extreme fire. An efficient preparedness plan for extreme fire threats might be a short term solution. This could be achieved by developing a cost-effective rapid response and recovery plan for critical infrastructures in the events of extreme fires. During an incident, the role of firefighters is vital in order to control the fire and damage to the critical infrastructure. A rapid cost-effective inspection, repair and recovery protocol would reduce the economic impact due to the incident. For instance, when a critical bridge is damaged due to a fire, a rapid restoration of the bridge would reduce the interruption to the traffic which could result in substantial savings.

- Developing inspection methods to assess residual resilience of critical infrastructures after an extreme fire incident:

  Examples: Previous studies by NRC, Transport Canada and the Federal Highway Administration identified that more than 100 extreme fire incidents have occurred in the past few years which resulted in substantial damage to the infrastructures, e.g. bridge fuel tanker fires. After many of these incidents, due to less reliable inspection tool/information available, a decision was made to demolish the infrastructure and to reconstruct it entirely. Each day a critical infrastructure is not operational could pose a substantial economic burden to the community. For instance, in the case of the 2007 MacArthur bridge fire, near San Francisco, a $6 million per day economic impact was estimated due to the bridge failure. Developing a more reliable inspection tool could help decision makers answer the critical question after an extreme fire incident: "would the critical infrastructure be: 1) non-repairable 2) repairable or 3) not require any repairs?

- Developing fast cost-effective and efficient repair methods for recovery of critical infrastructures from an extreme fire incident:

  Examples: Protection of all infrastructures or even the most critical infrastructures in a short time would be economically unfeasible. Therefore, a short term solution would be to develop recovery plans for the critical infrastructure after an extreme fire. For instance, rapid and cost-effective repair/retrofitting materials/systems could be developed to restore the strength and resilience of the critical infrastructures after an extreme fire.

- Developing a guideline that helps first responders, e.g. firefighter and police, to assess potential infrastructure failure during their operation:

  Examples: Studies on previous incidents showed that an infrastructure, e.g. a bridge, might collapse due to an extreme fire in a very short time, this could be as little as half an hour, depending on the extent and intensity of the fire and the protection of the critical infrastructure. This could cause a safety hazard during rescue and firefighting operations. It is critical for first responders to have reliable estimates of how long structures can resist fires before collapsing. Developing a first responders' guideline would assist them in decision making to better predict structural collapse during their response operations and to better plan their firefighting strategies for minimizing the damage to the infrastructure during a fire.

3.4 Review of Research Needs and Priorities

This section provides information on the Advisory Board formed for this project. It includes the outcomes of their review, discussions during two meetings and their input and recommendations on the gaps and research needs.

3.4.1 Advisory Board

An Advisory Board was formed to review the outcomes of the literature review provided in section 3.3 of this report. The advisory board members consisted of experts/representations from policy makers/regulatory bodies, first responders, and industries. The primary goal of the advisory board was to review and provide comments/input to the project on the identified research needs and priorities for resilience of critical infrastructure to extreme fires. The advisory board committee consisted of a chair, a secretary and members. The Chair was responsible for chairing the meetings and a secretary for preparing the meeting Minutes and communicating with the members. List of the advisory board members are provided in Appendix C as part of the project team.

3.4.2 Advisory Board Meeting 1

The first meeting was held on Thursday, February 7, 2013, 1:30 p.m. – 3:30 p.m. (Eastern Time) at the National Research Council Canada. The main purpose of this meeting was to provide an introduction to the project objectives and tasks as well as review and comment on the identified gaps. Minutes for this meeting are provided in the Appendix.

- A summary of the meeting outcome is provided here
  - Future research on extreme fires needs to include different structural system/materials, e.g. pre-stressed concrete and cast-in-place concrete, high strength concrete, ultra high performance concrete, and concrete with polypropylene (PP) fibres.
  - Inspection/protection of Critical infrastructure should include consideration of risk and threat assessments, level of required performance, criticality/importance of the Critical infrastructure and the impact analysis.
  - Bridge design needs to be balanced with life safety and criticality, especially for tunnels vs. Bridges, life safety needs to be considered differently and the categorization of bridges needs to be based on the impact of the injury to the occupants.
  - When protection is not feasible, design needs to consider potential replacement of the bridge.
  - There is a need to find out the inherent fire resistance rating of bridge elements such as columns, beam and slab based on current practices of bridge construction.
  - There is a need to develop fire resistance requirements based on a classification system for critical infrastructures against extreme fire.
  - There is a need to develop approaches and tools for assessment and quick repair and recovery of the critical infrastructure after an extreme fire. The assessment needs to include the age/deterioration effects of infrastructure.
  - Risk of fires in buildings with parking garages inside should be assessed with consideration for extreme fire.

- Studies are needed on safety assessment during (first responders) and after extreme fires.
- There is a need for a roadmap of priorities and where investments in research should be made.

3.4.3 Advisory Board Meeting 2

The second meeting was held on Thursday, March 7, 2013, 1:30 p.m. – 3:30 p.m. (Eastern Time) at the National Research Council Canada. The main purpose of this meeting was to provide a summary on the test results, final review of the gaps and provide comments on priorities for future research. Minutes for this meeting are provided in the Appendix.

- A summary of the meeting outcome is:
  - The main objective of the study could be property protection of the critical infrastructures however life safety also needs to be considered as an important objective. Note: current fire protection objective for buildings does not include asset protections. This would be a very important objective for CIs for recovery after the incident
  - The main challenge is to find a solution that could enhance fire protection of existing structures so they can be protected from the fire without damage or with minimal reparable damage.
  - Priority first goes to protection of existing structures and then to new constructions, since there are usually more options available to protect new constructions.
  - Studies need to include real fire scenarios, critical structural elements, e.g. beams, columns cables, deterioration and aging of critical infrastructures, reinforcing details, and confinements.
  - Studies could include a combination of tests and numerical analysis.
  - Different materials and technologies should be studied, e.g., ultra high performance concrete, epoxy coated reinforcements, GFRP and FRP reinforced concrete, spray on fire protection materials, etc.
  - Safety of the first responders during and after the fire, in respect to potential structural failure, needs to be investigated. This includes studies on increase of temperatures in structures even after the stop of the fire.
  - A guideline could be developed for firefighters to enhance available approaches for more efficiently reducing the fire damage to structures during the firefighting practice.

3.5 Research Capabilities

Identification and demonstration of facilities and capabilities for extreme fire research were part of the 2nd objective of this study. This section describes the existing facility that can be used for tests of critical infrastructures to extreme fire and demonstrate how such a facility could be used to test critical infrastructures in extreme fires.

3.5.1 NRC Fire Lab

One of the main resources required for any fire resistance testing is a furnace facility. In Canada, few labs have such facilities; however, perhaps none is equipped to the extent of the NRC fire testing facilities. NRC has three full-scale furnace testing facilities; for testing walls, Fig. 2, for testing floors/beams, Fig. 3, and for testing columns , Fig. 4, and one smaller scale furnace for testing intermediate-scale specimens, Fig. 5. Some of these facilities, e.g. NRC column furnace, are unique in North America and perhaps worldwide.

These facilities, as those of other labs around the globe, could mainly be used for the testing of building systems/materials in normal building fires. A new upgrade program has been planned and started by NRC to equip these furnaces for performing extreme fire tests, e.g. tunnel fires, bridge fires and extreme fires such as 9/11 WTC fires. To date, the intermediate-scale furnace has been upgraded and used for simulating a tunnel fire using the RWS time-temperature curve [5]. Furthermore, the column furnace has been upgraded for simulation of hydrocarbon fire [3, 4].

Two main steps were taken to demonstrate research capacities in this section: 1) producing extreme fire 2) testing two critical infrastructure elements in fire.

Figure 2. NRC full-scale wall furnace for testing load and non-loaded walls.

Figure 3. NRC full-scale floor furnace for testing slabs/beams.

Figure 4. NRC full-scale column furnace for testing loaded columns.

Figure 5. NRC intermediate-scale furnace for testing walls/floors/slabs.

3.5.2 Extreme Fire

Typically, hydrocarbon fires [3, 4] are being used for testing refinery facilities and offshore structures, mainly steel elements in a fuel fire. UL 1709 [3] and ASTM E1529 [4] are the two main standards employed for such fire endurance assessment. Currently there is no standard, other than NFPA 502 [2], in North America for design/assessment of critical infrastructures, e.g. bridges, in fire. Even for bridges, NFPA 502 does not provide the required information for test/assessment of such infrastructure in fire. Among available standards, ASTM E1529 seems to be representing more or being used for simulation of a critical infrastructures fire such a bridge fire [13]. Therefore, for the purpose of the test demonstration of this study, the extreme fire test was simulated based on ASTM E1529 standard.

Series of tests were first carried out to ensure the requirements for producing an extreme fire are met according to ASTM E1529 [4]. These are the two main requirements by this standard:

- The test setup will provide an average total cold wall heat flux on all exposed surfaces of the test specimen of 158 kW/m^2 ± 8 kW/m^2. The heat flux shall be attained within the first 5 min of test exposure and maintained for the duration of the test.
- The temperature of the environment that generates the heat flux of procedures in 6.2 shall be at least 815°C after the first 3 min of the test and shall be between 1010°C and 1180°C at all times after the first 5 min of the test.

After a couple of test attempts using the column furnace, requirements for both temperature and heat flux were met as shown in Fig. 6 and Fig. 7. ASTM E1529 requires a calibration test to be carried out using a prototype protected steel column. However, this was found to be less applicable for test of concrete specimens. In case of steel column, neither the calibration column nor the real column would absorb as much heat as concrete does. One of the main reasons would be due to the protections provided for steel. That means calibration test, for steel specimens, provide a reasonable representative of the real test. However, for the concrete column tests, concrete absorbed large amount of heat during the tests, since no protection was provided for the specimens in this study. Therefore, a protected steel column, required by the standard, could not represent the concrete column tests. The furnace required generating larger amount of heat to produce the required amount of heat flux. Therefore, in this study, a real full-scale concrete column without protection was used also during the calibration tests.

Fig. 5 shows a little overshooting of heat flux. However, this was obtained based on meeting the temperature requirement. A lower heat flux could be achieved by reducing the temperatures within the limits required by the standard.

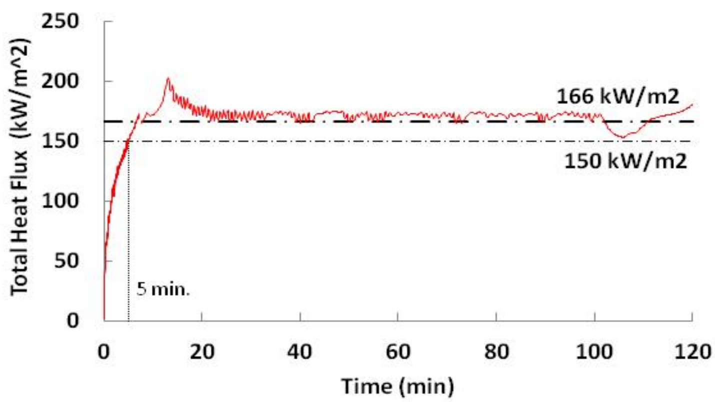

Figure 6. Heat flux measured during the test using Directional Flame Thermometer (DFT).

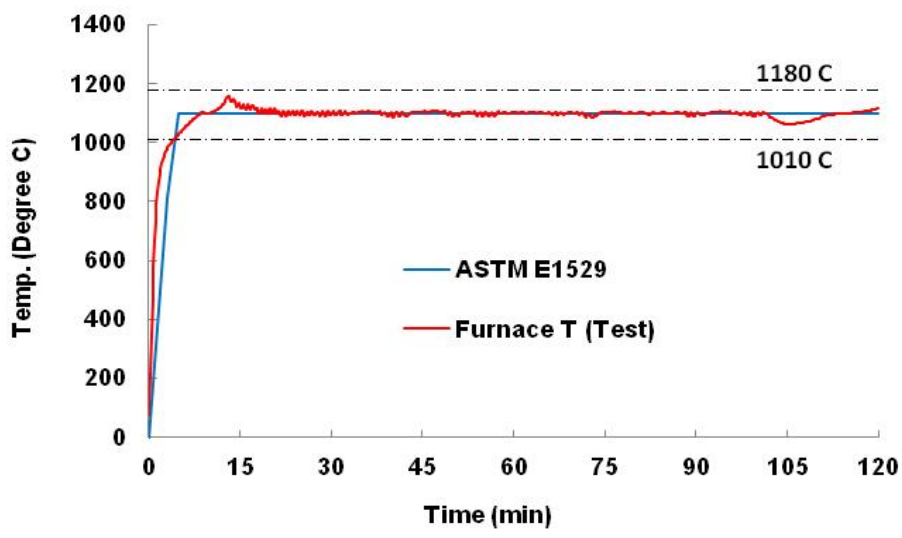

Figure 7. Furnace temperature measured during the test.

3.5.3 Test Demonstration of an Infrastructure Element in Extreme Fire

Two reinforced concrete columns, as examples of critical elements of a critical infrastructure, building/bridge, were tested; one demonstrating a normal building fire test [14, 15] and one simulating a hydrocarbon fire test [4]. Figure 8 shows the details of reinforcements and dimensions of the columns as well as one of the columns in the furnace just before the fire test. Both column specimens were designed identical in detail. Their concrete was cast at the same time, November 17, 2010.

More information on the specimens and test data are provided in the Appendix B. Here the summary of the main test process and outcome is provided. Fig. 9 shows time-temperature curves used for the two fire tests.

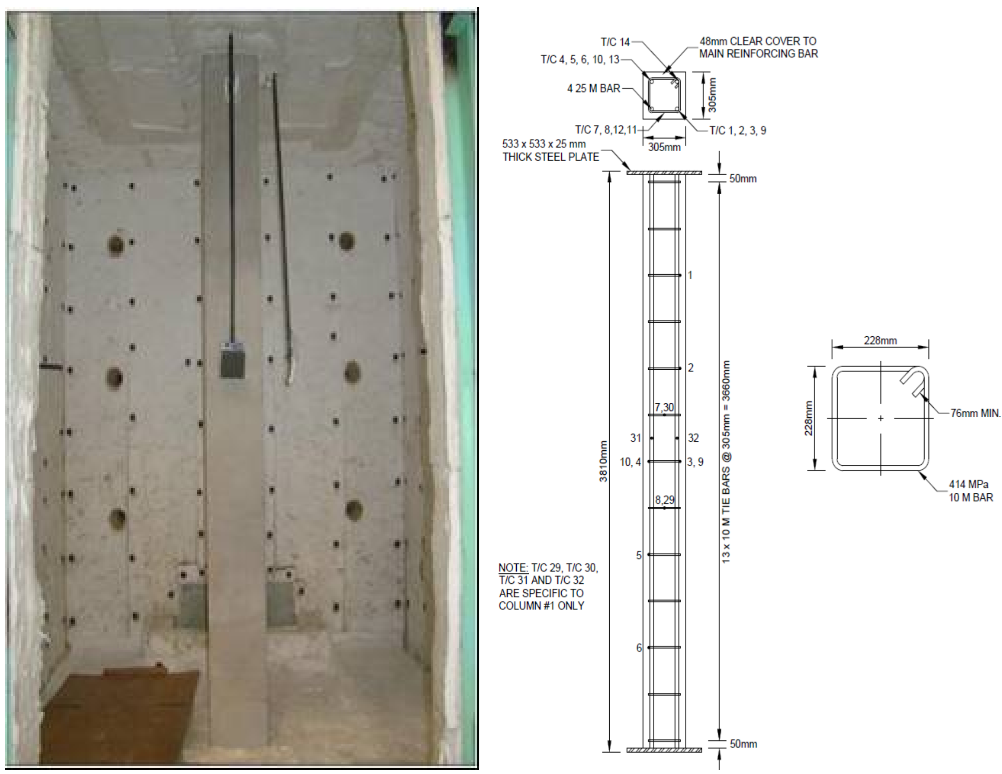

Figure 8. A column specimen in the column furnace before the test, on the left, and drawing of the specimen on the right.

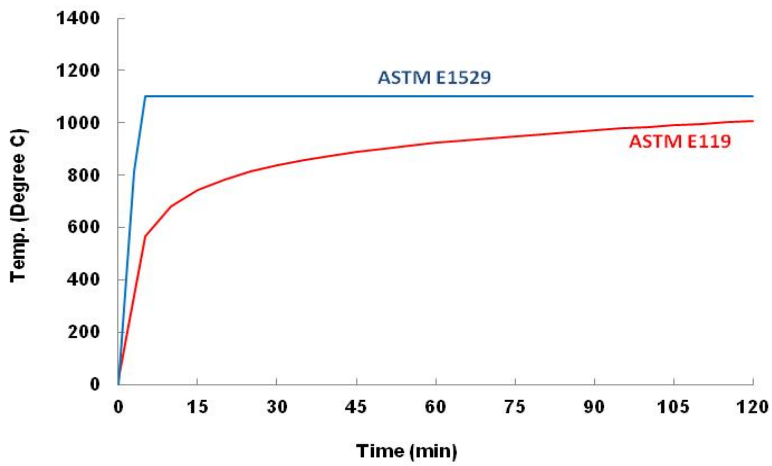

Figure 9. Time-temperature curves for ASTM E119 and ASTM E1529.

In both tests, the columns were loaded at least half an hour before fire tests. Here are the main steps executed for the two tests.

- Pre-load: the initial axial load of the column was applied.
- Fire test: Specimens were exposed to the fires under the applied load for 2 hours.
- Cooling phase: The cooling phase was about 20 hours for each specimen. That was until the temperature at the center of the concrete section reached the ambient temperature. A small load was applied on the column during this period. The hydraulic system was shutdown however; the small load was employed by bolting up the column.
- Failure load test: Finally, the initial axial load was reapplied and then increased until the column failure was achieved.

Temperatures, at different locations in the concrete section, axial load and deformation were recorded for all the above 4 main steps, for the two specimens. Fig. 10 shows the temperature at the center of the concrete cross section for both tested specimens. One interesting finding was that the column temperature, at the section centre, continued to increase up to about 2 to 3 hours after the stop of the fire and it took several hours (18 to 20 hours) for the column centre to come back to the ambient temperature. This means that structural collapse could be "a potential threat" to the first responders and the users of the critical concrete infrastructures even hours after extinguishing the fire. Fig. 11 shows the pictures of the two columns after failure load tests.

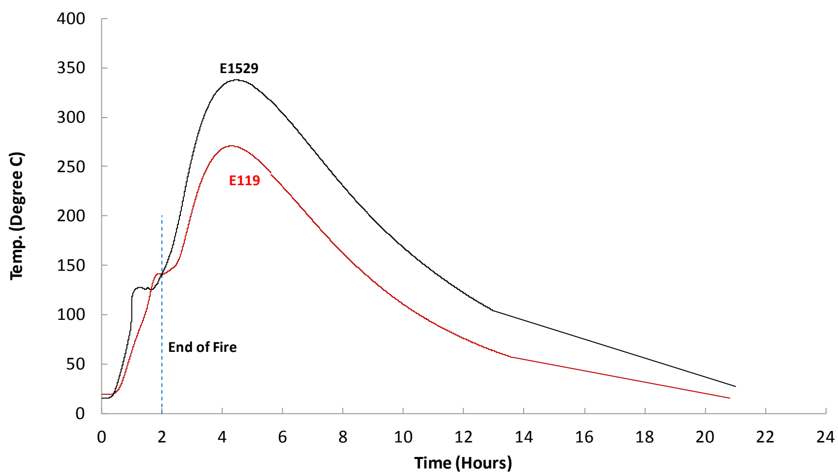

Figure 10. Temperatures at the centre of the two columns' cross section during the tests.

Figure 11. The two column specimens after testing for failure loads; column tested for E1529 on the left and column tested for E119 on the right.

Here are the main outcomes of these two tests:

- An extreme fire was successfully demonstrated using the NRC Column Furnace facility.
- Two tests of critical infrastructures in fire were demonstrated; one according to ASTM E1529 and one based on ASTM E119.

The main purpose of these two tests was to demonstrate the feasibility of resilience assessment of Critical Infrastructures in fire. Since the number of test specimen was small, no general conclusion can be made. Therefore, the following additional outcomes are only applicable for the two tested column specimens. Further study is required to produce more conclusive results. Here are the additional results for these two tests:

- Large spalling (a vertical shear failure) occurred for the specimen tested based on E119 a few minutes after the start of the fire. This could be due to higher moisture content of this specimen, however, further studies needed to investigate such failure.
- In both tests, temperatures in the centre of the column cross-section continued to increase for up to about 2 to 3 hours after the stop of the fire. It took several hours (18 to 20 hours) for the concrete to come back to the ambient temperature.
- In both tests, the columns could carry only up to about 40% of their original load capacity, almost the same failure load, after the fire exposure. A higher failure load was expected for the E119 test. This could be due to the initial large spalling of the E119 test specimen.
- Spalling was also observed a few minutes after the start of the ASTM E1259 test.

4 Results

The intermediate outcome of this project is relevant to the Resilience Infrastructure community of practice: "Enhanced resilience of the physical and cyber infrastructure domains is risk and evidence based". The immediate outcome of this study is related to "Regionally based analyses and assessments of risk and vulnerability help shape national approaches to infrastructure risk mitigation investments" and "Emerging and emerged risks to Canada's infrastructure are rapidly assessed and inform action".

- Impact and relevance to the identified priority and gap addressed by the project

The results of this study are expected to improve awareness and provide a better understanding of the gaps and research needs related to threat from extreme fire to critical infrastructures and priorities for future R&D to help decision making in response to and recovery from such incidents.

- Lessons Learned and implementation plan of the Lessons Learned

This study showed that there are important gaps and research needs related to the resilience of critical infrastructures to extreme fires. It was found that property protection is a vital requirement for critical infrastructures after a fire incident, of which very limited information is provided by the current codes and standards. The future plan is expected to develop tools/materials that could address more efficiently asset protection and fast recovery after fire.

The test demonstrations showed that 1) fire could cause substantial damage to critical infrastructures and therefore future studies are needed to develop methods for reducing such risks 2) it may take several hours for infrastructures, e.g. concrete specimens tested in this study, to cool down and reach the ambient temperature, after fire being extinguished. Even increase of temperatures, up to three times, were observed for several minutes/hours after eliminating the fire exposure. This information would be particularly useful for first responders and decision-makers during the response operation to reduce the risk of casualties due to potential structural collapse hours after the incident. Note that these two lessens leaned based on only two demonstration tests of this project, which were not intended as objectives of this study. Therefore, further studies needed to confirm these outcomes.

- New capabilities, partnerships and networks created through the horizontal work of the project

The outcome of this project showed that an extreme fire could be produced in a lab environment using the NRC fire test facility. Using such capability, it was also demonstrated that the resilience of a critical infrastructure could be evaluated in extreme fires. These new competencies will enable the communities of practice, on critical infrastructures, to develop methods and tools for enhancing resilience of CIs against extreme fires. Forming the advisory board of this project with 21 members, provided the opportunity to create a network among the related different government departments, regulatory bodies and industries, from North America, which will enable the team to first disseminate directly the outcomes through the communities of practices and to develop future research plan more efficiently.

5 Transition and Exploitation

- Transition to End Users:

The end users of the outcome of this project are transportation infrastructures, government buildings and facilities, regulatory bodies, first responders and construction industries. The advisory board of this project included representatives and experts from these end users. The results of this study were shared with and disseminated to these end users, after including their input. Two presentations were prepared and delivered during the advisory board meetings, one on Feb. 7, 2013 and one on March 7, 2013, at the NRC, on the results of this study. At least one paper will be produced from the outcome of this study and will be presented in a related conference. Finally, this report will be shared with the end users through DRDC.

- Follow-On Commercial Development or R&D Recommended:

NRC continues to upgrade its other facilities for extreme fire testing of critical infrastructures. Currently, two research projects are carried out by NRC to develop fire protection materials for tunnels. Two study proposals have been developed and submitted to the CSSP program to fill the gaps identified in this project. Manufactures are interested in supporting and funding part of these proposals for developing protection materials and technologies for enhancing resilience of critical infrastructures to fire.

- Intellectual Property Disposition:

The IP produced by this study vests in the Crown.

- Public Information Recommendations:

The recommendations produced by this study are intended to be used by the end users.

6 Conclusion

This study reviewed gaps and research needs on resilience of critical infrastructures (CIs) to extreme fires and demonstrated examples for tests of CIs in two different fires. The following conclusions can be made based on the outcome of these works.

Objective I – Gaps:

- The current fire protection practice has very limited information/technology on how to protect infrastructures' asset in fire incidents for a fast recovery/restoration.
- One of the main challenges is to find solutions for enhancing resilience of existing critical infrastructures to fire so that they can be restored rapidly after the fire with or without minimal reparable damage.
- Priority would go to protection of existing structures and then to new constructions, since there are usually more options available to protect new constructions.
- Studies need to include real fire scenarios, critical structural elements, e.g. beams, columns, cables, different important factors, e.g. deterioration and aging of critical infrastructures, reinforcing details, and confinements.
- Numerical analysis, in addition to the experimental studies, could be employed to include large size critical infrastructures.
- Fire resistance/resilience of different materials and technologies should be studied, including, but not limited to, ultra high performance concrete, epoxy coated reinforcements, GFRP and FRP reinforced concrete, and spray on fire protection materials.
- Safety of the first responders and critical infrastructures' users, during and after fire, in respect to potential structural failure, needs to be investigated. This includes studies on the increase of temperatures in structures even after extinguishing fire.
- A guideline could be developed for firefighters on approaches for reducing the fire damage to structures during the firefighting practice.

Objective II – Demonstration:

- An extreme fire was successfully demonstrated using the NRC Column Furnace facility. The furnace is now capable of producing a hydrocarbon (extreme) fire.
- It was also demonstrated that the NRC column furnace facility could be used for fire resistance/resilience assessment of critical infrastructure elements.

The following additional outcomes are only applicable for the two demonstration tests, the two concrete column specimens. Further study is required to produce more conclusive results. Here are the additional results for these two tests:

- Temperatures at the centre of the column cross-section continued to increase for up to 2 to 3 hours after eliminating the fire exposure. In addition, it took several hours (18 to 20 hours) after the fire for the concrete to reach the ambient temperature. The current fire safety design practice has very limited information on the effects of temperatures in structures after the fire.

- Spalling was observed during the two fire tests starting a few minutes after the start of the fire. This could be due to the amount of moisture content of this specimen. However, further studies are needed to investigate more efficient approaches to mitigate concrete spalling in the critical infrastructures.
- In both tests, the columns lost more than 50% of their original load capacity after the fire exposure. Studies needed to assess larger size specimens to explore the size effects on the resilience of the structures after fire.

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Annex A Advisory Board Meetings Minutes

A.1 Advisory Board Meeting 1

Time: Thursday, February 7 2013, 1:30pm – 3:30pm (Eastern Time).

Location: NRC building M-59, 1200 Montreal Road, Ottawa, Ontario - 2nd Conf. Room

ATTENDEES

AB Members: Kathleen Almand (NFPA), Barbara Di Bacco (TC), Darek Baingo (DRDC), William Connell (NFPA 502), Ron Cowalchuk (TC), Alexandre Debs (MTQ), Gary English (Seattle Fire), Steve Ernst (DOT), Simon Foo (PWGSC), Ed Fyfe (Fyfe), Richard Garber (NEB), Roxanne Halverson (RCMP), David Lai (MTO), Daniel MacEachern (BASF), Pierre Meunier (DRDC), Vic Perry (Lafarge), Marc Roy (DRDC), Rick Sherping (Sika), Trevor Stewart (DFAIT), Sean Tracey (Ottawa Fire), Adel Zaki (SNC-Lavalin).

NRC Research Team: Ahmed Kashef, Cam McCartney, Mohamed Sultan, and Hossein Mostafaei

MEETING ITEMS

Item 1: Welcome to Advisory Board (AB)

Ron welcomed members to the meeting and briefly reviewed the role of the advisory board members. It was emphasized that the advisory board will provide comments on report, not contribute material or sections.

Introduction and welcome address by Ron Cowalchuk (Chair):

Welcome Address to the Advisory Board to the Research Study into "Resilience of Critical Infrastructure to Extreme Fires"

In today's busy world it is not often that one has such a pleasant opportunity to thank persons for their voluntary contribution of time and knowledge. All of you in attendance deserve to be recognized for your dedication by your participation in the introductory teleconference meeting regarding the study of "RESILIENCE OF CRITICAL INFRASTRUCTURE TO EXTREME FIRES" in order to examine gaps and challenges. It is indeed a pleasure to recognize your commitment to making the world a better place by giving freely of your time so that projects that are of benefit to all are as complete, accurate and thorough as possible.

I would also like to extend a special recognition and thank you to the sponsor of this study, Defence Research and Development Canada's Centre for Security Sciences who's funding makes the study possible and the centre's project manager for critical infrastructure protection, Pierre Meunier for his unwavering support.

I believe that everyone in attendance expects that they will review and provide comments/inputs to the project thus helping to provide guidance and direction to this study. There is no expectation or obligation or commitment to produce part of the report or to make any decisions regarding the resolution of issues that may be identified during the course of the study. However, everyone is asked to be as prepared as feasible due to their individual circumstances.

At this point I would like to introduce myself to the members of the Advisory Board that are in attendance. As you are aware I am Ron Cowalchuk and I have been involved in security for the Canadian government since leaving Architecture School at Carleton University in 1977. That totals up to over 35 years involved in security, first as an Architectural Security Consultant working for the Royal Canadian Mounted Police. At that time the RCMP was mandated to provide security advice and guidance to all Federal Departments that were constructing or renovating new accommodation, therefore I have provided security advice to lot of departments over the years. For the last 10 years I have been the Chief of Security Technology Research and Development at Transport Canada and been involved in many research projects related to transportation critical infrastructure.

I will now ask each of you to introduce yourself and perhaps you can share with the other members of the Advisory Board a couple of words regarding your background and experience.

Two reinforced concrete columns, as examples of critical elements of a critical infrastructure, building/bridge, were tested; one demonstrating a normal building fire test [14, 15] and one.

Ron then asked attendees to introduce themselves.

Item 2: Members Individual Introductions

All the attendees introduced themselves.

Item 3: Project plan (Resilience of Critical Infrastructure to Extreme Fires) & Overview of fire tests

Hossein delivered a presentation on the objective and task plan of the project. Slides of presentations were provided to the AB members (Appendix C).

Item 4: Summary of Report, "Vulnerability of Bridges and Other Critical Transportation Infrastructure to Extreme Fire and BLEVE"

Ron presented a summary of the findings of the previous research project on Vulnerability of Bridges and Other Critical Transportation Infrastructure to Extreme Fire and BLEVE. Most of the findings are provided in Appendix D in addition to those identified since completion of this study. It was observed that the population is increasing and therefore the density of traffic and congestion is on the rise. Also as the economy continues to improve the amount of hydrocarbons transported on our highways will increase. These increases in traffic will most likely result in more accidents and hydrocarbon fires that will be offset to some amount by the introduction of intelligent transportation systems, however at least for the short term an increase in hydrocarbon fires on our highways will rise. There is also a growing concern in the intelligence sector that terrorists may seek to find new avenues of attack, such as improvised incendiary devices. Further our critical highway infrastructure is deteriorating and due to the spalling of concrete on bridges and overpasses more reinforcing bar is being exposed thus it is more susceptible to failure from a hydrocarbon fire. It is my belief that for these reasons the work we are undertaking is valid and of growing importance.

Item 5: Discussion and comment regarding the report

Vic Perry: fibre-reinforced concrete was developed within last 20 years therefore design codes don't consider them. Lafarge has developed an ultra high performance concrete and tested it against hydrocarbon fires without any spalling. Most work was done in France about 15 years ago. North American focus is for bridges, but not for fire performance. Some testing has been done on wall panels.

Marc Roy: How is it that the study is in the US while the work seems to have been performed in France?

Adel Zaki: Performed work on railway bridges (open/Ballast decks) to increase protection against dangerous goods. Many bridges were constructed with 2 girders that were protected/strengthened with wood beams attached to the steel girder that had problems due to fires started by sparks/friction from trains and the creosote also had environmental issues.

Mohamed Sultan: NRC developed low-shrinkage concrete for a Quebec bridge which could be an alternative to FRP.

David Lai: Current project uses Polypropylene (PP) fibre for tunnels to enhance its fire resistance and reduce explosive spall. Concern is that PP melting in fire may produce toxic fumes, add fuel to fire and a bigger issue: the concrete after fire would have no PP fibre left for the next potential fire.

Marc Roy: In case of extreme fires, it is most likely required to replace the concrete.

Ahmed Kashef: Concrete spall is acceptable when exposed to a regular fire, but different (more vulnerable) when exposed to extreme fires. There is a big difference in results with small changes in fibre percentage. Gap is a tool to measure remaining strength in damaged concrete.

William Connell: It is important to define what we are trying to protect, is it the public or is it the structure, that will impact how structure should perform and level of acceptable damage.

Adel Zaki: The prime goal is protection of public, like earthquake. Second goal, provide redundancy to the structure for residual functionality.

William Connell: PP fibre provides spall protection, but doesn't prevent heat from affecting rebar and inducing collapse. Suggest division of life safety from protection of asset. Frankly, life safety due to extreme fires is an unlikely event, so more important to focus on asset protection.

Vic Perry: The study needs to include risk assessment considerations. Codes look at earthquake based on category of the event and performance expectation. This allows for identifying proper solutions and protection for non-critical vs. critical infrastructure.

Ron Cowalchuk: Transport Canada is developing requirements for international bridges and tunnels by diving them into 3 different categories/classifications.

David Lai: Some "lifeline" bridges must remain in-service after extreme events. Ontario is using a risk based approach that takes account of the criticality of the bridge.

Marc Roy: Depending on the threat assessment protection requirements would have a risk-based dependency.

Gary English: The gap may be a lack of fire rating for bridges, tunnels, etc. Having a value rating system would establish the criteria that could be used to confirm when life safety in an extreme event is no longer relevant due to immediate casualties.

William Connell: TSA commissioned USACE to conduct a vulnerability assessment of bridges and tunnels.

Steve Ernst: They have assessed 37 bridges, 7 tunnels, including robust, component-level analysis for bridges. Tunnels' analysis has been divided into structural and operational. Good system for looking at risk in these facilities. It is still at secret level. There could be a suggestion of fire hydrants on bridges as a simple approach but there is owner resistance. Replacement should be a consideration during the design phase.

William Connell: NFPA 502 defines these requirements, as well as alarms. NFPA 502 is seen as a roadway tunnel document, but also applies to bridges. Fire may be underrepresented especially regarding asset protection and repair. Tools for forensics and repair assessment protocols may be a gap.

Gary English: Japanese approach is to rate tunnels based on length and volume of traffic (i.e. economic importance).

Marc Roy: Suggest using other countries' standards as a starting point.

Sean Tracey: Unlikely that NBCC would accept changes related to protection of critical infrastructure. Trevor Stewart: Ask if Simon Foo could describe work with (CSA 851) on assessment of blast-affected structures, and design of buildings for protection against blast, including first responders. Buildings are to be included, will look at blast mitigation and design to assure resilience of the building. Will evaluate design criteria including embassies, provide guidance for rating for the facility and special events to ensure continuity of operations, fire is one aspect of this system.

Simon Foo: Guidance to the design of buildings for protection against blast loads is given in CSA-S850; blast mitigation leads to resilience of the building. CSA-S851 provides guidance on post-blast safety evaluation of buildings, including the guidance for the determination of the safety rating of a building after a blast event – which would affect the continuity of operations.

Marc Roy: A review can be performed to study works done by others e.g. European.

Adel Zaki: For fire hazards one of the existing practices is to have a quick replacement of the bridge after fire. There is a guide for evaluation of bridge condition for safety and bridge rehabilitation, post-incident evaluation/assessment guide, but does not assess fire.

David Lai: The existing guide does not include assessment after fire and there is a need to develop such a post-fire inspection/repair guide for bridges.

Ahmed Kashef: Evaluation is needed both after events and during events (e.g. for first responders) for both short-term and long-term repair.

Darek Baingo: For the post event inspection the relation to aging/deterioration's effect on lowering current capacity pre-event need to be considered.

Adel Zaki: Currently we have some rapid bridge replacement technologies (not a gap).

Gary English: Senior designer for Seattle wants design criteria for bridges to withstand extreme fire without collapse. Propose that column is less likely to fail than beams, connections.

Adel Zaki: May be difficult to improve protection for existing bridges.

Gary English: Will project test beams?

Hossein Mostafaei: Not at this phase, the tests are primarily to demonstrate lab capabilities.

David Lai: Fire protection may need to be different for pre-cast concrete elements. Work need to be done for classification of infrastructures, light bridges, and multi span structures.

Mohamed Sultan: There is a need to find out the inherent fire resistance rating of bridge elements such as columns, beam and slab based on current practices of bridge construction.

Follow-up Comments

Trevor Stewart: Note that neither document (S850 or S851) has little information related to fires (i believe S851 may make a 1 line statement about potential fire damage after an explosion). Further efforts could be welcome as we are developing suicide lobbies that should limit the amount of internal damage due to an internal IED. On parking structures: believe (fire is) a minor concern. Personally, unaware of any incident in any of our underground parking structures.

Item 6: Concluding Summary and Next Steps

- The differences between the behavior of pre-stressed and cast-in-place concrete to extreme fire should be investigated.
- High strength concrete has different properties and the effects of extreme fire on it are under investigation but at this point there is limited North American research underway.
- More investigation is needed on the efficiency of the new materials such as PP fibers for protection of concrete in fire.
- Inspection/protection of Critical infrastructure should include consideration of risk and threat assessments, level of required performance, criticality/importance of the Critical infrastructure and the impact analysis.

- Bridge design needs to be balanced with life safety and criticality, especially for tunnels vs. bridges life safety needs to be considered differently and the categorization of bridges needs to be based on the impact of the injury.

- When protection is not feasible, design need to consider potential replacement of the bridge.

- There is a need to find out the inherent fire resistance rating of bridge elements such as columns, beam and slab based on current practices of bridge construction

- There is a need to develop fire resistance requirements based on a classification system for critical infrastructures against extreme fire.

- There is a need to develop approaches and tools for assessment and quick repair and recovery of the critical infrastructure after an extreme fire. The assessment need to include the age/deterioration effects of infrastructure.

- Risk of fires in buildings with parking garages inside should be assessed with consideration for extreme fire.

- Studies are needed on safety assessment during (first responders) and after extreme fires

- There is a need for a roadmap of priorities and where investments in research should be made.

A.2 Advisory Board Meeting 2

Time: Thursday, 7 March, 1:30pm – 3:30pm (Eastern Time).
Location: NRC building M-59, 1200 Montreal Road, Ottawa, Ontario - 2nd Conf. Room

ATTENDEES

AB Members: Kathleen Almand (NFPA), Darek Baingo (DRDC), William Connell (NFPA 502), Ron Cowalchuk (TC), Gary English (Seattle Fire), Steve Ernst (DOT), Simon Foo (PWGSC), Ed Fyfe (Fyfe), Roxanne Halverson (RCMP), David Lai (MTO), Daniel MacEachern (BASF), Pierre Meunier (DRDC), Vic Perry (Lafarge), Trevor Stewart (DFAIT), Sean Tracey (Ottawa Fire), Adel Zaki (SNC-Lavalin).

NRC Research Team: Ahmed Kashef, Cam McCartney, and Hossein Mostafaei

MEETING ITEMS

Item 1: Brief on the 2nd meeting objectives

Chair thanked the AB members for their participation and contributions to the first AB meeting which made it such a success. He then welcomed members to the meeting and briefly explained the objectives of the second meeting are to determine and discuss any unidentified gaps that remain and to determine the AB's recommended order of priority for research to resolve those gaps.

Item 2: Confirmation of Attendees

Chair then conducted a role call and asked for confirmation of attendance.

Item 3: Outcomes of the two Fire Tests

Hossein delivered a presentation on the outcomes of the two tests on concrete columns that were performed at the NRC for the purpose of verifying that their test furnace could accurately and reliably reproduce the fire curve and loading associated with an extreme fire. Slides of the presentation were provided in advance of the meeting and are replicated in Appendix B. Comments were extended that the increase of temperatures in the concrete hours after the stop of fire would be a new finding and that such phenomenon could compromise the first responders safety after the fire. Spalling of the columns was noted and there was some discussion regarding the cause, such as the diameter/mass concrete type/mixture, and the moisture content. Also noted that this test did not apply to other material such as steel, however it was noted that the purpose of the tests were to confirm the performance of the furnace, not the columns.

Item 4: – Summary of identified gaps discussed during the last meeting

Chair read the summary of the gaps discussed during the previous meeting reprinted in (Appendix C) and then posed the following two questions of the of the members:
1- Gaps: Aside to the gaps identified, is there any other research need related to Resilience of CIs to Extreme Fire that might have been missed?
2- Priority: which of the identified gaps would need to be addressed first?

Item 5: Inputs and discussions by AB members

FIRST ROUND: GAPS

Sean Tracey: Started off by reiterating that some studies on the increase of internal concrete temperatures after a fire is an important phenomenon that could affect the safety of first responders entering the structure (buildings) following a fire.

Kathleen Almand: The first requirement is to study the fire scenarios for bridges. Other critical elements, e.g. cables, need to be included and investigated. Scenarios that led to bridge fires also require further research.

Darek Baingo: The investigation should include deterioration and aging of structures. Existing infrastructures could not carry loads as well as new structures following a fire.

William Connell: A listing of potential materials and products (in addition to PP fibers) should be developed and investigated as to potential use in this application and their ability to improved fire performance for both steel and concrete existing and/or new structures. Possible examples include cemetitious spray, fire board, high temperature ceramic coatings, intumescent paint, etc. Potential protection materials and/or methods need to be identified and evaluated in terms of how they satisfy the intention of asset/property protection.

Ron Cowalchuk: Agreed with Kathleen that the objective of research needs to be bounded by today's reality, for example how long a pool fire will burn to establish the fire necessary rating for the structure, what is the likelihood that a tanker accident will happen, etc..

Gary English: Posed the question, would adding water to cool down the structures (by firefighters) help? A guideline for first responders would be useful.

David Lai: Water could impose a thermal shock on concrete; therefore it is import to study its effects on heated concrete.

Steve Ernst: Confinement of concrete has proven to be very effective for columns under seismic or blast loads. Could this be important for fire resistance too? Ratio of lateral reinforcement, reinforcement size and hook enhancement and method of tying could be a benefit to be studied.

Simon Foo: More priority is on protection of existing structures and how it can be applied.

Roxanne Halverson: Not sure how RCMP can contribute to this project. RCMP is interested in the outcome of the study, regarding measures for entering structures during or after a fire.

David Lai: Bridge concrete columns are normally large in size and the effect of fire on them would be less compared to the small columns. Steel elements are more vulnerable to fire and more studies needed on them. A combination of fire tests and finite elements analysis could be performed to study large scale elements/structures. Three types of reinforcements should be studied: epoxy coated reinforcing steel (possible loss of bond), GFRP and FRP reinforcements.

Daniel MacEachern: Specimens could be conditioned by preheating to reduce the moisture. New fire protection materials could be studied.

Pierre Meunier: Finite element modeling could be used for the study, using available software. Spalling will be a challenge for the modeling software.

Trevor Stewart: Increase of temperatures in concrete after fire is important to study further. Confinement and reinforcing details and their effects on fire resistance could be studied. Item 7 (Appendix C) need to include not only bridge but also tunnels and buildings. Buildings with parking garages might not have high risks for fire; however floor slabs have collapsed after the fire has been contained.

Darek Baingo: Studies showed that parking structures have been affected greatly by corrosion. In 10 years they could lose half of their load capacity due to corrosion/bond loss. Corrosion of concrete after fire could be studied.

Adel Zaki: This study could have added value to bridge codes. Study need to include and addresses approaches and specific recommendations for the design codes.

Vic Perry: High strength concrete is different from steel fiber or ultra performance concrete. These materials need to be studied. Moisture contents are different in different regions based on their climates.

SECOND ROUND: PRIORITIES

William Connell: The term "fire protection" as applied in this study should be specifically clarified as intended to mean protection of the asset rather than the life safety of its users. A scale for determining level of importance – or criticality – of an asset should be considered. This could be used to determine the level of fire protection necessary and an order of priority of those gaps that must be addressed.
Ahmed Kashef: New materials need to be studied e.g. their fire durability and resistance

Darek Baingo: There are differences between environmental fire and controlled fire. Such differences need to be investigated.

Steve Ernst: Develop methods for post-disaster assessments to make sure that systems are strong enough to restore.

Simon Foo: Methods to evaluate the risk and to mitigate the risk to an acceptable level.

Vic Perry: Form a matrix to set the priority and include the most important issues, different materials etc. Matrix might include priority setting from differing perspectives, i.e. procedures/guidelines, structural protection, life safety factors, etc.

Item 6: Concluding Summary

- The main objective of the study could be property protection of the critical infrastructures however life safety needs to be considered also as an important objective.

- Note: current fire protection objective for buildings does not include asset protections. This would be very important objective for CIs for recovery after the incident

- 2. The main challenge is to find a solution that could enhance fire protection of existing structures so they can be protected from the fire without damage or with minimal reparable damage.

- 3. Priority first goes to protection of existing structures and then to new constructions, since there are usually more options available to protect new constructions.

- 4. Studies need to include real fire scenarios, critical structural elements e.g. beams, columns cables, deterioration and aging of critical infrastructures, reinforcing details, and confinements

- 5. Studies could include a combination of tests and numerical analysis

- 6. Different materials and technologies should be studied e.g., ultra high performance concrete, epoxy coated reinforcements, GFRP and FRP reinforced concrete, spray on fire protection materials etc.

- 7. Safety of the first responders during and after fire in respect to potential structural failure need to be investigated. This includes studies on increase of temperatures in structures even after the stop of the fire.

- A guideline could be developed for firefighters to enhance available approaches for more efficiently reducing the fire damage to structures during the firefighting practice.

Annex B Tests Data

B.1 Column Specimens

Column specimens were constructed on November 17, 2010. The column specimens moist cured in their forms for approximately seven days. They were more than three years of age when tested in fire in this project. The concrete compressive strength was obtained based on three cylinder compression tests (with diameter = 100mm and height = 200mm). The concrete strength result at 28 days was 44.5 MPa and that just before the first tests was 55 MPa.

The internal relative humidity of the column concrete was measured before the tests, which was 76.1% at 15.9 (degree C) for E1529 specimen and 81.2% at 18.5 (degree C) for the E119 specimen.

The column specimens were 3810 mm long from end plate to end plate and were of square cross-section with dimensions of 305 mm × 305 mm. Figure 12 shows the layout of one of the column specimens and the reinforcements.

Figure 13 shows locations of the thermocouples on a column cross section, at the centre height of the column. Figures 14 and 15 show the layout of the thermocouple locations on the height of a column and reinforcements.

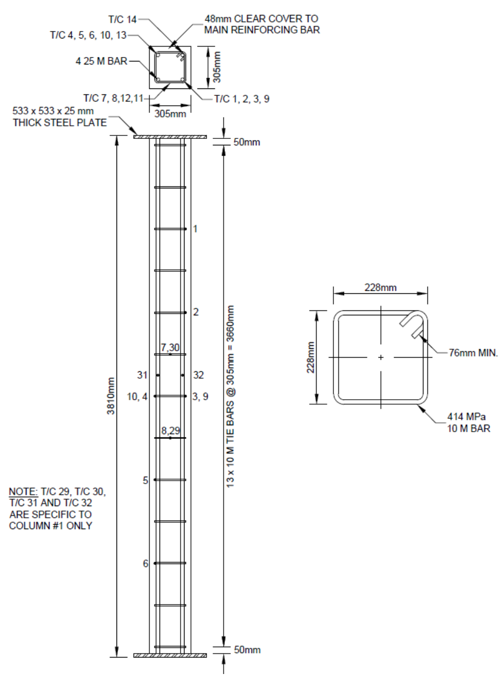

Figure 12. Layout of the column specimens.

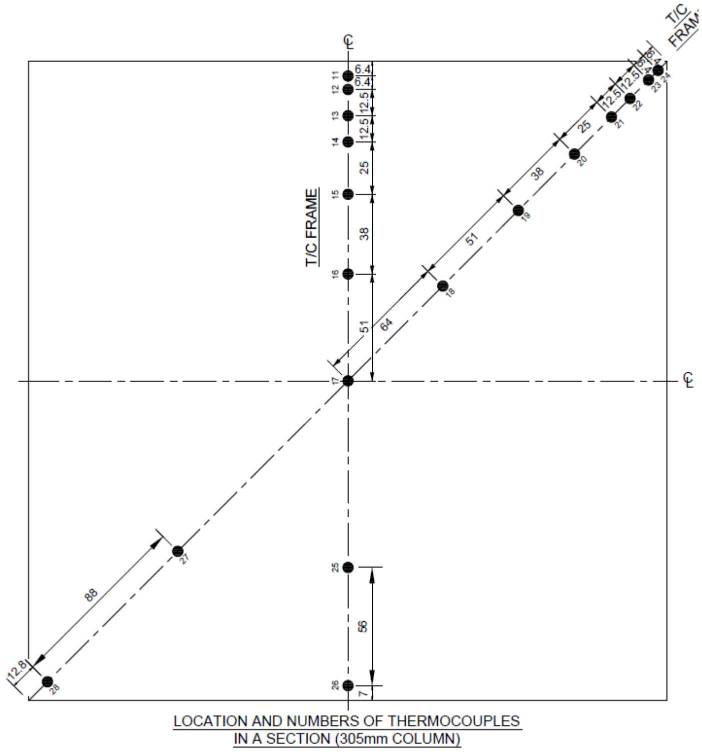

Figure 13. Columns' Cross-Section and Location of Thermocouples.

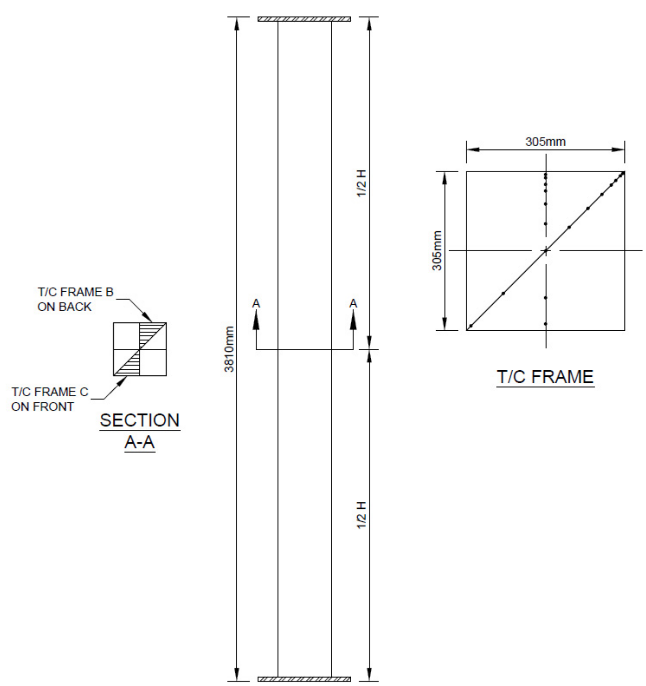

Figure 14. Thermocouples layout.

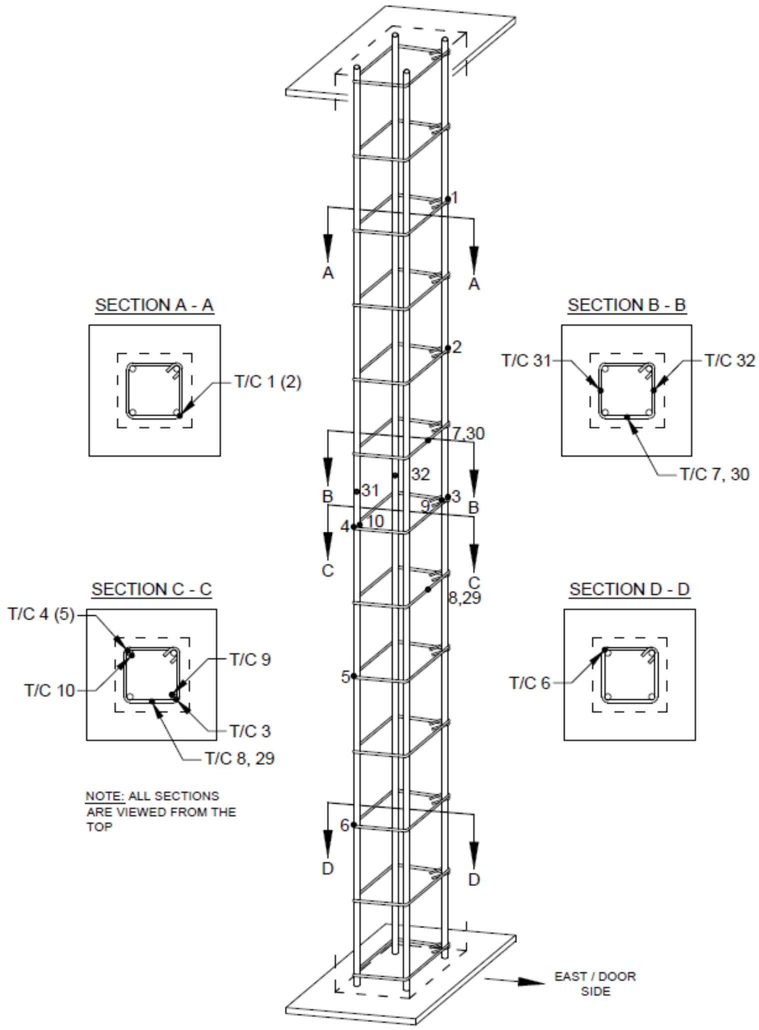

Figure 15. Thermocouples on reinforcing bars.

B.2 Column Facility

The test was carried out using the NRC's full-scale column furnace facility in Ottawa. The furnace is capable of applying axial loads up to 9790 kN (2200 kips), lateral loads up to 110 kN (25 kips) in a North-South direction, lateral loads up to 310 kN (70 kips) in a East-West direction and e-centric loading. E-centric hydraulic jacks are placed one at the top and one at the bottom of the column at a distance of 508 mm from the axis of the column. The capacity of the top hydraulic jack is 587 kN and the bottom hydraulic jack is 489 kN. Further details are provided by Lie, T.T. (1980). Figure 15 shows the column furnace facility. In this study, only the axial loading capability of the column was used.

Figure 16. NRC's Column Furnace Facility.

During the test, axial load was controlled by servocontrollers and measured with pressure transducers. The pressures then converted into load based on a calibration test result. The loading system has ~4.0 kN accuracy at lower load levels and relatively better accuracy at higher loads.

The furnace chamber has a floor area of 2600 x 2600 mm and height of 4300 mm. The chamber is insulated from inside to efficiently transfer the heat to the column specimens. Part of the column specimens at the top and bottom are insulated to keep the heat away from the test apparatus. Therefore, only 3175 mm of the column specimen is exposed to fire during the test. The furnace has 32 propane gas burners arranged at different elevations, each with four burners. The pressure in the furnace chamber is monitored during the test.

Eight Type K chromelalumel thermocouples, located 305 mm from the column specimen at different heights, measure the furnace temperatures during the tests. The furnace temperature is controlled based on the average of the temperatures measured by these thermocouples.

B.3 Load and support conditions of the specimen

A zero rotation and lateral displacement were employed in the furnace for the column specimens at the top and bottom ends. An axial load of 1590 kN was applied on the column in both tests. The axial load was determined based on a previous test specimen for the purpose of a comparison. The load was applied before the fire started, gradually reaching its value in about 30 minutes.

B.4 Data recording during the test

Temperatures in the furnace and designated locations in concrete and steel bars, axial displacement and axial load of the column specimens, and time were recorded during the entire test. The test results are provided in the following sections.

B.5 Test results

- Observations during the ASTM E1259 test

During the test, the main actions were recorded and the column specimen was observed closely for spalling or any damage. Here are some of the observations taken during the test (Feb 21, 2013, Times are in Eastern Time - Ottawa, Canada):

- Pre-Load Phase:

  Required load = 1590 kN

  Required pressure, from calibration = 444 psi

  Preload set points are: (111, 222, 333, 444) psi

  Relative humidity of specimen during preload = 76.1% RH @ 15.9C

  Displacement was zeroed at 111 psi

  Displacement gauge was not zeroed before 111 psi, so ignore them

- Fire Test:

  Spalling was heard at an elapsed time of 4 min 30 sec

  Displacement was 0.6 mm after 20.5 min

  The gas pressure was slowly decreased from 18.5 psi to 11 psi by 33 min elapsed

  At ~ 103 min, a strip fell off the North, West & South faces (spalling)

- Cooling Phase:

  None.

- Load failure Phase:

  The specimen's pressure was increased from 444 psi at a rate of 20 psi/min, and later 30 psi/min, and 10 mm/min

  The specimen failed, with a bang, after 1 hr 8 min 12 sec

- Post failure data:

  Relative humidity of specimen after failure = 4.5% @ 19.8C

- Observations during the ASTM E119 test

During the test, the main actions were recorded and the column specimen was observed closely for spalling or any damage. Here are some of the observations taken during the test (Feb 27, 2013, Times are in Eastern Time - Ottawa, Canada):

- Pre-Load Phase:

  Required load = 1590 kN

  Required pressure, from calibration = 444 psi

  Preload set points are: (111, 222, 333, 444) psi

  Relative humidity of specimen during preload = 81.2% RH @ 18.5C

  Lab conditions are 30.5% RH @ 18C

  Outdoor temperature is ~ 0C

- Fire Test:

  Potential spalling herd at 13 min 15 sec elapsed time

  At ~ 23 min potential spalling heard

  At 24 min a long 2 m crack was seen along both the South and West faces

  At 1:12:00 it was observed that 2 long cracks along West face, one along North face, and 1 deep one on South face

  At 1 hr 51min the South/West corner has seperated from specimen and there is now a horizontal crack there

- Cooling Phase:

None.

- Load failure Phase:

  Displacement at 100 psi = -7.57 mm and was -13 mm @ 444 psi

  Pressure increased from 444 psi, @ 20 psi/min

  @ 595 psi, back piece fell.

  Main fracture occurred immediately thereafter

- Post failure data:

  Specimen humidity = 17.3% RH @ 19.1C

- Columns' failure

  Figure 17 illustrates the column specimens after the fire test stopped and the furnace door was opened. Figure 18 illustrates the spalling patterns on the cross section of the two specimens around the final load failure locations. Based on the remaining cross section area the residual concrete strengths after fire, compared to their original strengths were calculated. Results: the residual concrete load capacity for the E1259 specimen was 46% of its original capacity and the E119 specimen was 50% of its original capacity.

Figure 17. Column Specimens just after shutting down the burners of the furnace; E1529 test on the left and E119 test on the right.

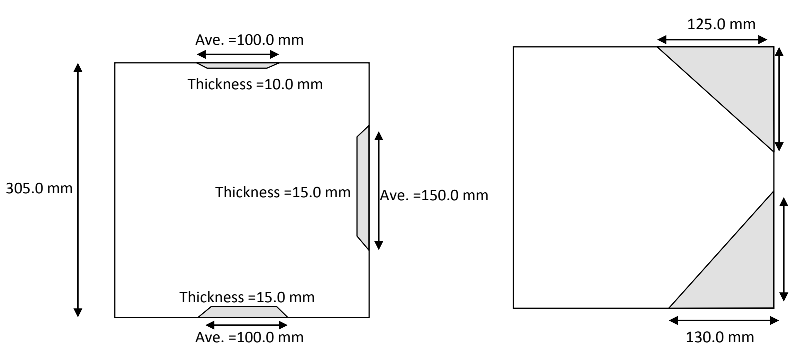

Figure 18. Spalling of the concrete column during ASTM E 1259 test on the right, and major spalling (vertical shear failure) of the concrete column during the ASTM E119 on the left.

- Furnace and Thermocouple Temperatures

Table 1 and Table 4 provide the standard temperatures and the furnace temperatures during the E1259 and E119 tests, respectively. Temperatures were measured in concrete and steel bars during the tests. Tables 2 and 5 provide the test data for these temperatures, during the E1259 and E119 tests, respectively. Note that the data in these tables also includes the cooling phase of the test.

- Axial Displacement/Load

During the fire test, axial load of 1590kN was kept constant however during the failure load phase it was increased until the column failure was achieved. Axial deformation and load of the columns were measured. Table 3 and Table 6 provide axial load and deformation data of the columns during the E1259 and E119 tests, respectively.

Table 1. Furnace Temperature - E1529 Test.

Time	E1529 Standard Temperature	Furnace Temperature
min.	°C	°C
0	20	75
1	285	667
2	550	914
3	815	978
4	958	1006
5	1100	1029
6	1100	1051
7	1100	1074
8	1100	1091
9	1100	1103
10	1100	1101
15	1100	1131
20	1100	1115
25	1100	1099
30	1100	1096
35	1100	1106
40	1100	1093
45	1100	1104
50	1100	1088
55	1100	1092
60	1100	1105
70	1100	1099
80	1100	1098
90	1100	1097
100	1100	1101
110	1100	1082
120	1100	1118
130	20	194
140	20	119
150	20	89
160	20	74
170	20	64
180	20	57
300	20	30
1350	20	12

Table 2. Thermocouples Temperatures - E1529 Test.

Time	E1529 Standard Temperature	Furnace Temperature	Thermocouple Temperature						
			TC-01	TC-02	TC-03	TC-04	TC-05	TC-06	TC-07
min.	°C	°C	°C	°C	°C	°C	°C	°C	°C
0	20	75	14	15	17	16	19	20	15
1	285	667	14	15	17	16	19	20	15
2	550	914	14	15	17	17	19	20	15
3	815	978	15	16	19	19	20	20	16
4	958	1006	18	19	21	24	22	22	17
5	1100	1029	25	27	29	31	29	25	20
6	1100	1051	37	44	46	40	39	31	24
7	1100	1074	45	55	65	49	51	39	29
8	1100	1091	54	64	79	59	67	46	35
9	1100	1103	66	73	88	69	80	58	40
10	1100	1101	85	82	93	79	94	70	46
20	1100	1115	109	115	119	133	123	116	101
30	1100	1096	151	163	166	192	181	175	111
40	1100	1093	210	222	223	254	240	240	155
50	1100	1088	265	280	275	311	296	300	201
60	1100	1105	315	330	318	362	345	352	239
70	1100	1099	359	374	362	405	388	397	275
80	1100	1098	398	413	405	442	425	435	309
90	1100	1097	432	448	442	475	457	469	339
100	1100	1101	463	479	473	502	485	498	367
110	1100	1082	491	506	501	522	511	523	393
120	1100	1118	515	530	524	543	534	544	417
130	20	194	536	549	543	558	550	562	439
140	20	119	533	548	544	550	546	563	444
150	20	89	512	531	529	530	529	549	436
160	20	74	487	507	506	505	506	528	424
170	20	64	460	481	482	479	482	504	410
180	20	57	434	456	457	453	458	480	397
240	20	38	320	339	343	337	348	362	332
300	20	30	258	273	278	273	286	293	286
360	20	22	216	225	233	224	242	248	250
420	20	18	184	188	199	186	208	216	218
600	20	12	115	115	128	115	140	153	139
780	20	9	71	70	80	71	95	111	85
1290	20	5	19	18	22	21	34	46	20
1350	20	12	16	15	20	18	31	44	18

Time	E1529 Standard Temperature	Furnace Temperature	Thermocouple Temperature						
			TC-08	TC-09	TC-10	TC-11	TC-12	TC-13	TC-14
min.	°C	°C	°C	°C	°C	°C	°C	°C	°C
0	20	75	18	17	16	19	18	18	17
1	285	667	18	17	16	24	21	18	17
2	550	914	18	17	16	52	38	20	17
3	815	978	19	17	16	110	81	28	18
4	958	1006	20	18	17	112	104	42	19
5	1100	1029	23	20	20	113	106	54	22
6	1100	1051	27	26	24	140	110	67	26
7	1100	1074	32	33	29	167	127	78	31
8	1100	1091	36	44	36	191	145	83	36
9	1100	1103	41	56	43	211	163	86	41
10	1100	1101	45	68	51	227	178	90	45
20	1100	1115	93	104	102	394	327	155	85
30	1100	1096	115	115	109	494	427	239	114
40	1100	1093	147	157	156	553	489	302	149
50	1100	1088	183	197	208	595	534	352	188
60	1100	1105	216	231	258	626	569	392	224
70	1100	1099	248	272	309	652	598	427	258
80	1100	1098	279	316	353	674	622	457	289
90	1100	1097	310	356	389	692	642	483	319
100	1100	1101	339	392	423	708	661	508	348
110	1100	1082	366	423	454	717	673	529	374
120	1100	1118	390	451	481	735	691	549	399
130	20	194	412	476	504	621	617	549	421
140	20	119	420	493	513	516	521	503	426
150	20	89	417	493	505	456	463	464	418
160	20	74	409	483	489	414	422	432	407
170	20	64	399	467	470	382	391	407	396
180	20	57	389	450	449	357	366	387	385
240	20	38	335	349	344	277	286	314	336
300	20	30	295	287	282	234	242	270	295
360	20	22	261	243	235	205	212	236	259
420	20	18	231	208	196	178	185	207	227
600	20	12	159	133	121	117	121	135	148
780	20	9	107	84	75	74	77	86	93
1290	20	5	34	23	21	22	23	24	26
1350	20	12	31	21	19	20	21	22	23

Time	E1529 Standard Temperature	Furnace Temperature	Thermocouple Temperature						
			TC-15	TC-16	TC-17	TC-18	TC-19	TC-20	TC-21
min.	°C	°C	°C	°C	°C	°C	°C	°C	°C
0	20	75	16	16	15	16	17	18	19
1	285	667	17	16	16	16	17	19	20
2	550	914	16	16	15	16	17	19	29
3	815	978	17	16	16	16	17	23	106
4	958	1006	17	16	16	16	17	31	124
5	1100	1029	17	16	16	16	18	44	122
6	1100	1051	17	16	16	16	20	58	117
7	1100	1074	18	16	16	16	25	71	114
8	1100	1091	18	16	16	16	31	83	127
9	1100	1103	20	16	16	17	37	96	148
10	1100	1101	21	16	16	17	45	108	169
20	1100	1115	43	23	17	34	96	190	397
30	1100	1096	69	37	29	51	98	329	544
40	1100	1093	89	54	47	68	102	430	637
50	1100	1088	107	71	68	87	116	500	696
60	1100	1105	121	88	117	108	138	549	736
70	1100	1099	132	106	127	128	175	589	764
80	1100	1098	153	126	127	129	233	622	785
90	1100	1097	182	124	126	138	280	648	803
100	1100	1101	209	131	126	156	321	669	817
110	1100	1082	234	142	131	180	357	686	827
120	1100	1118	259	158	142	204	389	700	836
130	20	194	284	178	153	229	418	707	791
140	20	119	307	200	168	255	441	665	667
150	20	89	323	224	189	280	450	606	572
160	20	74	334	246	212	300	450	551	500
170	20	64	342	266	238	316	442	501	445
180	20	57	347	285	260	328	431	459	402
240	20	38	345	337	332	349	356	303	255
300	20	30	317	329	332	326	300	229	189
360	20	22	282	299	304	291	257	183	149
420	20	18	248	265	267	254	221	152	123
600	20	12	160	170	168	161	142	95	78
780	20	9	100	106	104	100	89	60	49
1290	20	5	27	28	27	27	25	20	17
1350	20	12	24	25	24	24	22	17	16

Time	E1529 Standard Temperature	Furnace Temperature	Thermocouple Temperature						
			TC-22	TC-23	TC-24	TC-25	TC-26	TC-27	TC-28
min.	°C	°C	°C	°C	°C	°C	°C	°C	°C
0	20	75	22	26	31	16	23	16	25
1	285	667	49	126	256	16	137	16	171
2	550	914	124	263	495	16	253	16	314
3	815	978	183	398	640	16	359	16	440
4	958	1006	257	499	726	16	907	16	527
5	1100	1029	326	575	787	17	940	17	597
6	1100	1051	388	636	838	19	970	17	652
7	1100	1074	445	686	876	22	993	19	698
8	1100	1091	495	729	909	27	1039	22	738
9	1100	1103	539	767	936	35	1057	25	771
10	1100	1101	579	795	956	44	1059	29	794
20	1100	1115	775	932	1058	129	1088	80	915
30	1100	1096	839	980	1063	194	1086	100	948
40	1100	1093	877	1003	1067	248	1066	132	974
50	1100	1088	906	1022	1076	291	1077	164	993
60	1100	1105	930	1036	1048	318	1094	203	1013
70	1100	1099	951	1047	1039	342	1092	245	1023
80	1100	1098	965	1053	1059	363	1094	285	1033
90	1100	1097	976	1056	1061	386	1101	323	1038
100	1100	1101	987	1061	1072	409	1099	358	1045
110	1100	1082	978	1041	1059	430	1078	391	1031
120	1100	1118	1001	1073	1107	448	1117	419	1066
130	20	194	694	566	458	449	193	444	563
140	20	119	515	410	335	417	127	460	449
150	20	89	421	336	277	395	102	461	385
160	20	74	362	290	240	380	89	454	341
170	20	64	319	257	213	370	85	443	306
180	20	57	286	231	193	362	78	430	279
240	20	38	176	142	119	326	57	351	182
300	20	30	128	103	87	288	49	296	137
360	20	22	99	79	67	246	14	252	89
420	20	18	82	66	56	209	12	213	71
600	20	12	53	43	37	130	8	133	45
780	20	9	34	27	24	81	4	83	28
1290	20	5	14	12	26	23	2	23	12
1350	20	12	15	15	23	20	18	21	14

Table 3. Axial load and displacement ASTM E1529.

Time	Axial Displacement	Axial Load
min.	mm	kN
0	0.000	1585
2	0.004	1586
3	0.043	1589
4	0.055	1586
5	0.058	1584
6	0.060	1584
7	0.074	1586
8	0.133	1586
9	0.209	1590
10	0.287	1583
20	0.587	1583
30	0.861	1585
40	1.062	1587
50	1.125	1586
60	1.128	1584
90	1.079	1586
100	0.682	1586
110	0.100	1581
120	-0.614	1582
140	-3.148	1585
150	-4.266	1589
160	-5.173	1585
170	-5.978	1589
180	-6.726	1588
240	-10.055	1583
300	-11.905	1585
1310	-19.412	1583
1320	-19.485	1583
1330	-19.518	1587
1340	-19.546	1587
1342	-19.955	1710
1344	-20.895	1926
1346	-22.144	2131
1347.33	-23.146	2277
1348	-26.204	1440
1350	-36.320	644
1352	-56.410	418

Table 4. Furnace Temperature - E119 Test.

Time	E119 Standard Temperature	Furnace Temperature
min.	°C	°C
0	20	50
1	333	115
2	426	188
3	487	250
4	533	457
5	568	552
6	598	588
7	623	612
8	645	638
9	664	669
10	680	675
20	785	783
30	839	826
40	875	881
50	902	912
60	924	933
70	942	941
80	957	957
90	972	962
100	984	974
110	996	992
120	1007	1000
130	20	171
140	20	108
150	20	75
160	20	61
170	20	52
180	20	45
240	20	31
300	20	22
600	20	14
1380	20	17

Table 5. Thermocouple Temperatures - E1529 Test.

Time	E119 Standard Temperature	Furnace Temperature	Thermocouple Temperature						
			TC-01	TC-02	TC-03	TC-04	TC-05	TC-06	TC-07
min.	°C	°C	°C	°C	°C	°C	°C	°C	°C
0	20	50	18	19	19	19	20	20	19
1	333	115	18	19	19	19	20	20	19
2	426	188	18	19	19	19	20	20	19
3	487	250	18	19	19	19	20	20	19
4	533	457	19	19	20	20	20	21	20
5	568	552	19	20	20	20	20	21	20
6	598	588	20	20	21	21	21	21	22
7	623	612	21	22	22	22	22	23	24
8	645	638	23	24	24	24	24	25	27
9	664	669	25	26	26	27	27	27	32
10	680	675	28	29	29	30	29	30	36
15	743	744	54	55	52	55	48	49	68
20	785	783	102	101	95	96	90	86	88
25	815	805	126	132	126	104	106	110	125
30	839	826	133	133	130	98	102	105	129
40	875	881	155	158	149	102	104	119	147
50	902	912	197	205	186	131	123	130	191
60	924	933	245	253	229	189	173	179	227
70	942	941	289	297	272	252	224	222	260
80	957	957	328	336	308	310	271	260	291
90	972	962	363	370	339	363	314	295	320
100	984	974	394	400	370	403	353	330	346
110	996	992	422	428	403	452	388	362	371
120	1007	1000	448	454	434	503	421	393	397
130	20	171	469	474	458	485	448	420	420
140	20	108	477	481	466	454	453	434	420
150	20	75	466	471	457	421	442	431	406
160	20	61	447	451	440	390	424	418	389
170	20	52	423	428	420	361	402	402	373
180	20	45	398	405	398	334	380	384	358
240	20	31	281	290	291	234	276	293	285
300	20	22	217	227	227	186	219	240	235
600	20	14	89	89	91	66	95	126	102
1380	20	17	14	12	14	13	21	33	13

Time	E119 Standard Temperature	Furnace Temperature	Thermocouple Temperature						
			TC-08	TC-09	TC-10	TC-11	TC-12	TC-13	TC-14
min.	°C	°C	°C	°C	°C	°C	°C	°C	°C
0	20	50	20	19	19	20	20	19	19
1	333	115	20	19	19	21	20	19	19
2	426	188	20	19	19	23	21	20	19
3	487	250	20	19	19	26	22	20	20
4	533	457	20	19	19	31	25	21	20
5	568	552	20	20	19	43	30	22	20
6	598	588	21	20	20	57	38	24	21
7	623	612	22	20	20	72	48	27	22
8	645	638	23	21	21	90	59	32	23
9	664	669	24	22	21	108	72	37	26
10	680	675	26	23	23	116	85	44	28
15	743	744	40	38	36	173	121	80	49
20	785	783	62	75	68	240	172	101	70
25	815	805	88	127	91	296	217	125	89
30	839	826	124	129	86	344	259	131	107
40	875	881	127	128	105	425	331	183	128
50	902	912	156	153	115	485	384	232	157
60	924	933	195	192	140	530	429	274	192
70	942	941	231	233	192	562	463	310	224
80	957	957	263	272	241	588	492	342	254
90	972	962	294	304	287	612	518	371	282
100	984	974	324	336	322	631	540	397	308
110	996	992	352	372	373	650	559	421	332
120	1007	1000	378	415	422	666	578	444	355
130	20	171	400	437	444	576	542	455	375
140	20	108	403	450	432	475	471	431	378
150	20	75	393	450	411	413	419	402	369
160	20	61	380	438	387	368	379	377	357
170	20	52	365	420	363	335	350	357	345
180	20	45	351	401	340	310	327	339	334
240	20	31	284	295	245	228	247	272	283
300	20	22	238	230	195	187	204	230	242
600	20	14	108	91	71	82	89	100	106
1380	20	17	18	14	13	15	15	15	15

Time	E119 Standard Temperature	Furnace Temperature	Thermocouple Temperature						
			TC-15	TC-16	TC-17	TC-18	TC-19	TC-20	TC-21
min.	°C	°C	°C	°C	°C	°C	°C	°C	°C
0	20	50	19	20	19	19	19	20	19
1	333	115	19	19	19	19	19	20	19
2	426	188	19	20	19	19	20	20	20
3	487	250	19	19	20	19	19	20	23
4	533	457	19	19	19	19	20	20	26
5	568	552	19	19	19	19	20	21	32
6	598	588	19	19	19	19	20	23	42
7	623	612	20	19	19	19	20	26	55
8	645	638	20	19	19	19	20	30	70
9	664	669	20	20	19	19	21	35	85
10	680	675	20	20	19	20	21	41	101
15	743	744	25	20	19	20	32	87	157
20	785	783	34	21	19	22	56	126	223
25	815	805	45	23	20	27	91	136	288
30	839	826	58	28	22	35	118	168	346
40	875	881	83	44	31	57	126	255	439
50	902	912	102	62	47	74	120	324	515
60	924	933	120	78	63	85	148	381	573
70	942	941	132	92	78	98	183	428	621
80	957	957	147	107	92	113	213	469	655
90	972	962	166	121	107	131	238	500	682
100	984	974	186	133	130	140	268	527	703
110	996	992	206	141	141	146	309	553	722
120	1007	1000	226	141	141	155	342	579	740
130	20	171	247	148	142	167	367	597	712
140	20	108	268	161	144	187	390	575	611
150	20	75	283	179	149	208	399	530	525
160	20	61	292	196	157	228	398	483	454
170	20	52	297	213	174	246	390	442	399
180	20	45	299	228	194	260	379	404	356
240	20	31	289	279	266	286	298	259	214
300	20	22	259	269	263	264	240	189	152
600	20	14	113	118	114	113	98	71	56
1380	20	17	15	15	14	15	15	15	15

Time	E119 Standard Temperature	Furnace Temperature	Thermocouple Temperature						
			TC-22	TC-23	TC-24	TC-25	TC-26	TC-27	TC-28
min.	°C	°C	°C	°C	°C	°C	°C	°C	°C
0	20	50	19	22	24	19	22	19	21
1	333	115	21	29	35	19	29	19	27
2	426	188	25	41	53	19	38	19	37
3	487	250	31	57	73	19	49	19	49
4	533	457	40	87	121	19	86	19	71
5	568	552	58	132	178	19	120	19	115
6	598	588	80	171	226	19	148	19	147
7	623	612	105	210	272	20	175	19	180
8	645	638	123	248	319	20	204	20	215
9	664	669	141	285	359	21	232	20	250
10	680	675	161	316	388	22	254	21	283
15	743	744	263	451	524	33	358	29	416
20	785	783	357	548	610	48	445	47	514
25	815	805	431	609	662	63	510	71	132
30	839	826	488	652	701	78	556	82	113
40	875	881	575	725	773	105	639	92	----
50	902	912	644	771	818	129	696	107	----
60	924	933	695	813	847	146	739	126	----
70	942	941	729	832	863	169	762	153	----
80	957	957	755	850	889	195	786	180	----
90	972	962	775	858	903	217	802	209	----
100	984	974	791	863	918	235	813	233	----
110	996	992	807	873	934	265	825	263	----
120	1007	1000	821	881	945	293	841	302	----
130	20	171	710	602	513	320	546	343	----
140	20	108	561	451	382	340	430	363	----
150	20	75	464	370	316	345	362	364	----
160	20	61	397	316	271	341	316	357	----
170	20	52	346	276	238	332	283	345	----
180	20	45	308	246	214	322	259	331	----
240	20	31	183	146	128	262	178	257	----
300	20	22	130	106	94	219	141	210	----
600	20	14	49	41	38	81	42	78	----
1380	20	17	15	16	16	13	14	13	----

Table 6. Axial Load and Displacement E119 Test.

Time	Axial Displacement	Axial Load
min.	mm	kN
0	0.000	1582
7	0.000	1585
8	0.013	1586
9	0.042	1582
10	0.087	1587
15	0.415	1580
20	0.807	1584
25	1.204	1586
30	1.295	1584
40	1.476	1589
50	1.671	1588
60	1.795	1586
90	1.833	1585
100	1.834	1585
110	1.803	1585
120	1.445	1585
130	0.590	1587
140	-0.342	1582
150	-1.138	1583
160	-1.826	1585
170	-2.459	1586
180	-3.028	1585
240	-5.601	1584
300	-7.048	1581
1360	-12.971	1587
1370	-13.004	1588
1380	-13.028	1583
1390	-15.122	2077
1390.83	-15.519	2143
1391	-15.706	1474
1392	-23.266	578
1393	-32.803	420
1394	-38.124	341
1395	-30.560	341

Annex C Project Team

Pierre Meunier, Head, Boader and Critical Infrastructure Resilience, S&T, Defence R&D Canada- Centre for Security Science, was the Cluster/CoP lead of this project and contributed greatly in the development and implementation of the research plan.

Hossein Mostafaei, PhD, P.Eng., a Research Officer of the Fire Research of the National Research Council Canada led and managed this project.

Ron Cowalchuk, Chief, Security Technology, Research and Development, Surface and Intermodal Security of Transport Canada, was the Chair of the advisory board. He also contributed greatly in development of the study proposal, tasks and reviewing the reports of this project.

- The advisory board members:

Kathleen Almand, Executive Director of the Fire Protection Research Foundation of the National Fire Protection Association.

Barbara Di Bacco, Chief, Research Development, Promotion and Coordination, Research, Evaluation and Systems, Transport Dangerous Goods Directorate, Transport Canada

Darek Baingo, Security Operations Research Analyst, Operation Research, Defence R&D Canada

William Connell, Chairman of the Technical Committee for NFPA Standard 502 for Road Tunnel, Bridges and Limited Access Highways and Assistant Vice President for Parsons Brinckerhoff.

Ron Cowalchuk, Chief, Security Technology, Research and Development, Surface and Intermodal Security of Transport Canada

Alexandre Debs, Chef du Centre intégré de gestion de la circulation, Ministry of Transportation – Quebec

Gary English, Assistant Fire Marshal – Special Projects, City of Seattle Fire Department and member of the NFPA 502

Steve Ernst, Senior Engineer - Safety and Security, Federal Highway Administration

Simon Foo, Senior Engineer, Risk Management, Public Works and Government Services Canada

Ed Fyfe, President and founder of Fyfe Co. LLC / Fibrwrap Construction.

Richard Garber,Group Leader, Security at the National Energy Board, before joining NEB, Rick was Senior Advisor of the Critical Infrastructure Protection- DRDC Centre for Security Science.

Roxanne Halverson, Senior Planning Analyst, Emergency Management, RCMP

David Lai, Head of Bridge Rehabilitation, Ministry of Transportation – Ontario

Daniel MacEachern, Bridge and Power Specialist, BASF

Pierre Meunier, Head of Border and Critical Infrastructure Resilience S&T, Defence R&D Canada (DRDC) - Centre for Security Science (CSS)

Vic Perry, Vice-President & General Manager - Ductal®, Lafarge North America, Inc.

Marc Roy, Portfolio Manager Explosives/Forensic, Directorate S&T Public Security (DSTPS), Defence R&D Canada, Centre for Security Science (CSS)

Rick Sherping, Application Field Manager / Structural Strengthening and Anchoring Systems, Sika Canada Inc

Trevor Stewart, Senior Physical Security Engineer, Physical Security Abroad, Security & Intelligence Bureau, Department of Foreign Affairs and International Trade

Sean Tracey, Assistant Deputy Chief Community Standards, City of Ottawa, Ottawa Fire Service

Adel R. Zaki, Chief Engineer - SNC-Lavalin, Construction and Infrastructures, Road and Bridges Division

Hossein Mostafaei was the secretary of the advisory board.

- NRC Research team contributed in study on gaps, priorities and technical challenges:

Ahmed Kashef, Acting Director, Fire Safety, National Research Council Canada

Cam McCartney, Research Officer, Fire Safety, National Research Council Canada

Mohamed Sultan, Senior Research Officer, Fire Safety, National Research Council Canada

Noureddine Benichou, Senior Research Officer, Fire Safety, National Research Council Canada

Hossein Mostafaei, Research Officer, Fire Safety, National Research Council Canada

- NRC Technical Officers contributing in the test demonstration:

Patrice Leroux (Chief Technical Officer), Robert Berzins (Technical Officer), Eric Gibbs (Technical Officer), Joe Hum (Technical Officer) and Roch Monette (Technical Officer).

Annex D PROJECT PERFORMANCE SUMMARY

PROJECT PERFORMANCE SUMMARY

Technical Performance Summary:

This project had two main objectives:

Objective 1: Study gaps in the resilience of critical infrastructure to extreme fires, establish priorities regarding structural resilience, protection, restoration and recovery and explore challenges. The focus will be on how to enhance building resilience, safety and minimize the negative economic impacts.

This objective was fully achieved. Research needs and gaps are provided in Section 3.3 of this report. These results were reviewed by the advisory board (AB). The AB's inputs and recommendations are provided in Section 3.4. The Research Team then summarized the gaps and priorities and provided the outcome in the conclusion section.

Objective 2: Demonstrate new methods and competencies to test critical structural elements of an infrastructure, e.g. a bridge or a building, and their performance in extreme fire.

This objective was also fully achieved. First, an extreme fire was produced successfully using the NRC furnace facility. Then, two full-scale structural reinforced concrete columns were tested in the produced fire using the same facility. The outcome exceeded the expectations and further useful outcomes were provided from these two tests. Section 3.5 and Appendix B provide full details of the demonstration tests.

- Technology Readiness Level of Deliverable (TRL)

A TRL of 6 could be assigned from the outcome of this project. The new testing system was demonstrated in a relevant high-fidelity environment.

- Estimated Time to Reach TRL7 Maturity (months)

Studies could be continued for a 24 to 36 months period through which different available fire protection materials could be identified and tested. The results would provide practical methods for enhancing resilience of CIs to extreme fires.

- Advantages Over Existing/Competing Technologies

Objective 1: To date, most of the research efforts have been extended in developing methodologies and tools to reduce the risks of casualties during a fire. Perhaps that is why no fire protection design is required for bridges. This project focused more on property/asset protection. This was because of critical infrastructures (CIs), it is essential to have a fast recovery of the CIs after the incident. This project provided recommendations for future R&Ds on property/asset protection.

Objective 2: Currently, the majority of fire resistance tests are performed using typical building standard fires. In some of the fire scenarios, e.g. fuel tanker fires, such fire tests could not be applicable and a more severe fire needs to be produced. This project demonstrated that an extreme fire could be produced and tests of CIs in such fires could be performed in a lab environment.

Schedule Performance Summary: No time delay was experienced for this project. All tasks were completed as planned in the schedule.

Cost Performance Summary:

The budget of this project was managed according the initial cost estimate and budget plan. The estimated in-kind contribution by NRC, Transport Canada, other OGDs and Industries were achieved.

Annex E Publications, Presentations, Patents

This project includes the following productions:

- The present research report
- Two presentations were delivered to the advisory board members
- A conference paper will be produced and presented

List of symbols/abbreviations/acronyms/initialisms

AB	Advisory Board
CI	Critical Infrastructure
DFAIT	Foreign Affairs and International Trade Canada
DRDC	Defence Research & Development Canada
FHWA	US Federal Highway Administration
MTO	Ministries of Transportation, Ontario
MTQ	Ministries of Transportation, Quebec
NEB	National Energy Board
NFPA	National Fire Protection Association
NRC	National Research Council Canada
PWGSC	Public Works and Government Services Canada
RCMP	Royal Canadian Mounted Police
R&D	Research & Development
TC	Transport Canada