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SMOKE MANAGEMENT RESEARCH AT NRC

Gary LOUGHEED[1]

ABSTRACT

In recent years, NRC has conducted collaborative research projects to address issues related to smoke management in buildings with ASHRAE and other North American organizations. This includes projects to investigate the effectiveness of smoke exhaust systems in atria, sprinklered fires in retail malls and the effectiveness of duct smoke detectors in HVAC systems. Ongoing projects include investigations of fires involving communication cables in return air plenums and the evaluation of the balcony spill plume correlations used to design atrium smoke management systems. This paper provides an overview of recent and ongoing smoke management research at NRC. It also discusses future research directions.

Keywords: *fire safety, smoke control, smoke management.*

INTRODUCTION

NRC has been involved in research related to smoke movement, smoke management and smoke control since the 1960s. Areas of particular interest have been smoke movement and smoke management in high-rise buildings and in buildings with atria, since, in these cases, smoke potentially poses higher risks to occupants. Prior to 1990, the research was focused primarily on smoke control in high-rise buildings using the NRC ten storey test facility (Figure 1). This research was summarized by Tamura (1994) and was used to develop and verify smoke control methods used in North America (Klote and Milke 2002, NFPA 2000a).

Since 1990, NRC has conducted joint projects with the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) and other North American organizations to address issues related to smoke management in buildings. Completed projects include investigations of shielded sprinklered fires in office buildings, the effectiveness of atrium smoke exhaust systems, sprinklered fires in retail malls and the effectiveness of duct smoke detectors. In addition, there are ongoing projects investigating plenum cable fires and balcony spill plumes in atrium.

Figure 1. NRC ten storey test facility.

In this paper, the issues addressed in recent NRC projects on smoke management are outlined. Also, the results of the projects are provided. In addition, areas for future smoke management research are discussed.

SHIELDED SPRINKLERED FIRES

Smoke management measures in engineering guides such as Klote and Milke (2002), NFPA 92A (2000a) and NFPA 92B (2000b) can be used for both sprinklered and non-sprinklered buildings. In recent years, an increasing number of high-rise buildings constructed in North America are fully sprinklered. For example, in the 1995 edition of the National Building Code of Canada (NRC 1995), automatic sprinklers are mandatory for all buildings

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required to be of non-combustible construction.
North American codes and standards allow for reductions in fire protection requirements for completely sprinklered buildings. For example, the design pressure difference for smoke control systems in NFPA 92A (2000a) is 25 Pa for a non-sprinklered building and 12.5 Pa for a sprinklered building.

The ability of sprinkler systems to control and extinguish unshielded fires is well documented. However, test programs conducted in the 1980s raised concerns about the effect of shielding of the fuel on sprinkler performance (Seattle FD 1984; Klote 1990). As a result of these concern, ASHRAE initiated joint research projects with NRC to investigate the effects of shielded sprinklered fires on the effectiveness of smoke control systems.

Mawhinney and Tamura (1994) conducted an initial study using shielded wood crib fires. Full-scale tests were carried out in a large 1-storey fire compartment as well as on the seventh floor of the NRC ten-storey facility. These tests showed that the sprinklers reduced the heat release rate for the fire. However, the tests conducted in the ten-storey facility indicated there was still a potential smoke problem. Also, these fires consistently produced high levels of CO_2 (9%) and CO (1-1.5%). However, the pressure difference produced by the fire was limited to approximately 7.5 Pa (Tamura 1994). This indicates that the design pressure difference recommended by engineering design guides such as NFPA 92A (2000a) should be sufficient to limit smoke movement for sprinklered buildings (Mawhinney and Tamura 1994).

Figure 2. Open-plan office test arrangement.

A concern with the initial study was the use of shielded wood cribs as the fuel load. As a result, a second project was undertaken to determine if shielded fire scenarios existed in office buildings (Lougheed 1997). As part of this second study, seven full-scale fire tests were conducted using a test arrangement that approximated a standard 3 m by 3 m open-plan office (Figure 2). The impact of various parameters - including the size of the fuel load located under the desks, the location of the test arrangement relative to the sprinklers and the location of the ignition point - was investigated.

For all test scenarios, the first sprinkler was activated between 106 and 220 seconds; it was able to localize the fire under the desks. However, it was unable to stop fire growth and spread to the fuel under adjacent desks and tables. With the continued increase in the heat-release rate, further sprinklers were activated, with up to four sprinklers operating in some tests. The sprinklers were able to control the fire within the limits of the 3 m by 3 m office area.

Peak heat-release rates of up to 800-900 kW were measured for tests in which the fuel under both a table and a desk were ignited by the initial fire source (Figure 3). The highest heat release rates were measured in the test arrangement that was centred within the four sprinklers. Heat release subsequently decayed exponentially with rates of 100-200 kW measured 25-30 minutes after ignition.

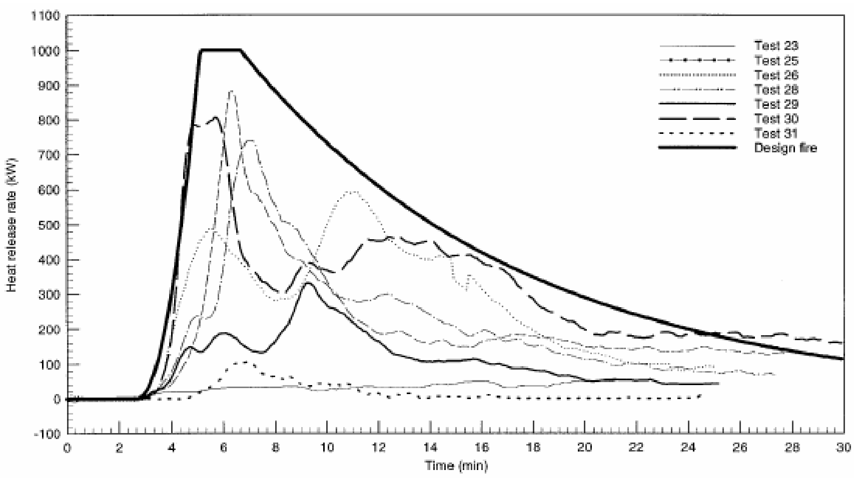

Figure 3. Heat release rate for open-plan office fire tests.

The results of these full-scale fire tests provided technical information on fire spread, fire size (heat-release rate), temperatures, CO concentrations, smoke obscuration and smoke movement for sprinklered open-plan office fires. The design fire shown in Figure 3 is consistent with the steady 1 MW design fire developed by Morgan and Hansell (1985) based on a review of British fire loss statistics and the fire suppression algorithm developed by Madrzykowski and Vettori (1992).

RETAIL MALL FIRES

In North America, it has generally been assumed that communicating spaces connected to an atrium or mall are sprinklered and, as a result, the sprinklers will effectively limit the size of a fire in the adjoining space. As a result, engineering design guides for smoke management systems such as NFPA 92B (2000b) have assumed that the smoke will have minimal effect in the atrium or mall space. However, the design guides do allow for smoke management designs in which the smoke is allowed to spill into the atrium space. With the introduction of performance-based designs for fire protection systems, there has been increasing need to address the potential effects of the smoke in the atrium or mall. One concern was that the smoke cooled by the sprinklers in the retail spaces could travel downward in the mall, where it could endanger people evacuating the building.

In a recent joint study with ASHRAE, NRC investigated smoke movement from fires in sprinklered retail spaces linked to a mall (Lougheed et al 2000 and 2001). To conduct the study, a large-scale test facility was set-up to simulate areas of particular concern: a retail outlet on the second floor of a mall and a section of a pedestrian mall in a shopping centre. Because North American fire statistics indicate that approximately 90% of retail fires activate four or fewer sprinklers (Johnson 1999), four sprinklers were used in the retail portion of the test facility. The mall portion of the test facility included a mechanical smoke exhaust system.

Figure 5. Toy display in shielded area.

The first series of tests used a propane burner shielded from the sprinkler water spray to determine the impact of both fire and sprinkler scenarios typical of retail spaces on smoke movement. In general, these tests showed that for smaller fires (with a heat release rate of less than 1 megawatt) the smoke was cooled to near or below ambient temperature. The smoke was mixed throughout the fire compartment (retail portion of the test facility) and spilled through the opening and descended into lower areas of the mall portion of the facility. Smoke from larger fires (with a heat release rate of more than 1 megawatt) formed a hot layer near the ceiling of the compartment before entering the mall area.

Figure 4. Hot smoke filling upper portion of simulated mall.

The second series of tests simulated fire scenarios with the fuel shielded from direct water spray from the sprinklers. These scenarios were typical of those that occur in retail stores in malls and included clothing and toys in boxes located in display units (Figure 4), and stored or displayed bulk goods, such as paper towels. The resulting fires had three distinct phases: fire growth and sprinkler activation, steady fire, and decay.

During the growth phase, sprinklers typically activated within 5 minutes, and smoke began moving into the mall portion of the test facility. In the steady phase, smoke flowed continuously into the mall section of the test facility (Figure 5). A smoke layer formed in the mall area even though the smoke exhaust system was in use. The density of the smoke layer and its carbon monoxide concentration both exceeded tenability limits. Any accumulation of this smoke in exit routes could limit evacuation. A smoke management system using mechanical exhaust could be used to remove this smoke.

During the decay phase, the smoke cooled and accumulated near the opening between the retail space and the mall space. Visibility in both areas became limited. The rapid mixing of smoke throughout the fire compartment during this phase could trap any occupants still in the area. However, smoke accumulation exterior to the fire compartment occurred in the latter stages of the fire and should pose minimal concerns for occupants.

ATRIUM SMOKE EXHAUST EFFECTIVENESS

Atriums have become popular in commercial, office and residential buildings, providing high marketing value with their environmentally controlled, naturally lit spaces. Such spaces, however, present a challenge for fire protection engineers. The protection of building occupants from smoke in the event of a fire is one of the primary objectives in the design of any fire protection system. Achieving this objective is difficult when dealing with very large spaces, such as an atrium or an indoor sports arena, where a large number of occupants may be present and the compartment geometries may be complex. By interconnecting a number of floor spaces, an atrium violates the concept of floor-to-floor compartmentation, which is intended to limit the spread of fire and smoke from the floor of fire origin to other stories. A fire on the floor of an atrium or in any space open to it can cause smoke to fill the atrium and connected floor spaces. Elevators, open stairs and egress routes that are within the atrium space can also become smoke-laden.

The use of smoke management systems to maintain tenable conditions in egress routes located in an atrium has become common in recent years. One approach is to use a mechanical exhaust system to maintain the smoke layer above the highest egress route. Design information for these systems is available in engineering guidelines (NFPA 2000b; Klote and Milke 2002).

There are a number of situations that may affect the effectiveness of a mechanical exhaust system used for atrium smoke management. One concern, raised by many designers and researchers, is the possibility of fresh air being pulled into the exhaust inlet for systems in which the "headroom" for accumulation of smoke above the highest egress route is minimal. This "plugholing" of the exhaust inlet by the fresh air can decrease the efficiency of the smoke exhaust system and can result in a deeper layer of smoke, to which occupants may be exposed (Figure 6).

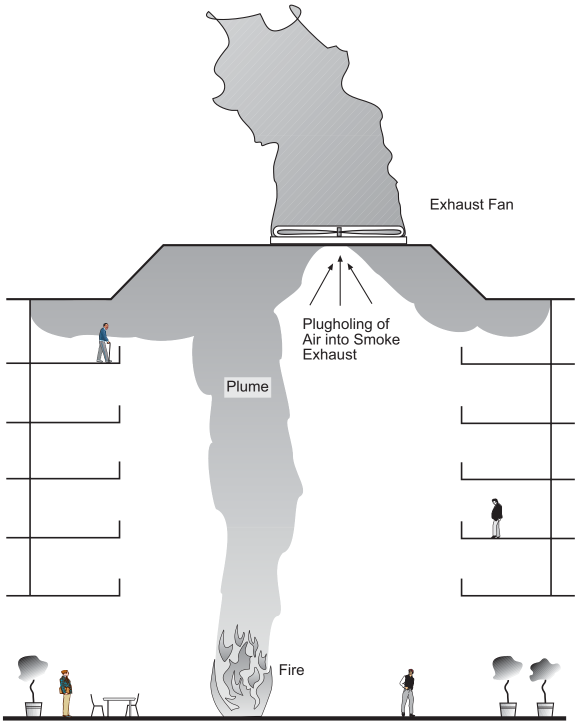

Figure 6. Plugholing of atrium smoke exhaust.

In a research project sponsored by ASHRAE, NRC used full-scale physical model studies combined with CFD modeling to investigate this issue (Hadjisophocleous et al 1999; Lougheed et al 1999). The results demonstrated that a design approach similar to one used in the United Kingdom to prevent plugholing in gravity venting systems could be applied to an atrium mechanical smoke exhaust system. Design equations were included in the 2000 edition of NFPA 92B (2000b).

To minimize plugholing, multiple inlets should be used for the mechanical smoke exhaust system. Also, the maximum mass (volumetric) flow rate through each exhaust inlet must be limited depending on the depth of the smoke layer below the exhaust inlet. In addition to limiting the maximum flow rate through each exhaust inlet, the designer should ensure that there is a minimum separation between inlets to minimize interaction of the smoke flows near the inlets. Appropriate selection of the number of exhaust inlets can minimize the effects of plugholing and improve the efficiency of the exhaust system. Such considerations are particularly important in retrofits or other applications in which the headroom above the highest evacuation route in the atrium is minimal.

EFFECTIVENESS OF DUCT SMOKE DETECTORS

The fire hazards associated with air moving systems in buildings and the underlying approaches for fire safety that limit the effects of HVAC systems were reviewed by Klote (1993). In principle, protection is needed from the spread of fire and smoke due to fires both inside and outside of the HVAC system. The National Board of Fire Underwriters (NBFU 1939) recommended the shutdown of the HVAC system during a fire. For many years, this was the standard approach for preventing smoke transport by the HVAC system. In recent years, the operation of the HVAC system as a smoke control system has become a common alternative (Klote 1993).

North American codes and standards (NRC 1995; NFPA 1999) require that duct smoke detectors be installed in HVAC systems. The purpose of the duct smoke detector is to provide for the shutdown of the HVAC system in the event of a fire to avoid actively re-circulating smoke through a building.

Various issues were raised regarding the effectiveness of duct smoke detectors including the effects of smoke dilution, aging and stratification on detection. There were also concerns regarding the effects of HVAC filters and the efficacy of sampling tubes. The Fire Detection Institute initiated a study to investigate the various issues regarding the application of duct smoke detectors with portions of the project conducted by the University of Maryland (UMD) and NRC. UMD conducted a literature review, small-scale testing and modeling studies. The results of the UMD investigations are provided by Wolin et al (2001).

NRC conducted eight calibration tests and thirty-four preliminary and full-scale fire tests in the ten-storey facility to provide data for use in verifying the findings of the small-scale tests and modeling studies. A test arrangement was set-up to simulate an operating HVAC system in an office building including a section of a corridor on the fire floor and airflow to and from 7 other floors. The shafts used for the supply and return air systems were also included in the test arrangement. All other shafts (stair, elevator, etc.) were sealed and not included in the test arrangement (Lougheed, McCartney and Carpenter 2002). Duct detectors were installed in the return duct on the fire floor and in the main return and main supply ducts in the mechanical room.

The results of the full-scale fire tests indicated that the continued operation of the HVAC system increased the pressure difference that resulted from the fire. The contribution of the HVAC system was in the range of 0-15 Pa and increased with heat release rate. This pressure difference is comparable to that produced by the other mechanisms that produce smoke transport into building shafts. This effect on the pressure difference by the HVAC system indicates that the system should be shutdown during the fire event.

The smoke produced by the fires was diluted by a factor up to 15 times with air mixing in both the corridor on the fire floor and in the main return shaft. Even with this amount of dilution the duct detectors showed good sensitivity to the smoke. Also, by the time the smoke reached the main HVAC system in the mechanical room, it was cooled to near ambient. The primary aging effect on detection that was noted was consistent with the decrease in smoke optical density between measuring stations.

Tests were conducted with no filters as well as two commercially available filters with different dust-spot efficiency. The response of detectors in the main supply duct relative to those mounted in the main return duct were comparable with no filter and with filters with a dust spot efficiency of 10-15%. This would suggest that the decrease in detector response was primarily due to losses to the duct system and other components in the HVAC system. The change in relative detector response was more substantial for tests with filters that had a dust spot efficiency of 30-35%. The combined effect of the filter and other losses in the duct on the photoelectric detector was approximately a factor of two. The filters generally had a lower effect on the relative detector response for the ionization detector. This would suggest that most likely larger smoke particles were removed from the air stream.

A series of detectors were also mounted in a straight section of duct in the main HVAC return air system in the facilities mechanical room to investigate the effects of stratification on detector response. With the limitations posed by the length of duct available, the distances used in the test set-up covered the range of 0-3 duct diameters. This is less than the 6 duct diameters required in standards. However, except for the detectors located close to the two ends of the duct section, there was minimal variation in the results for detectors.

By using measurements in the duct on the fire floor and in the main return and supply ducts in the mechanical room combined with four fan airflow capacities, a wide range of airflow velocities was covered.. Variations in detector outputs could be attributed to changes in both the smoke development and dilution effects with changes in HVAC airflow indicating efficacy of the sampling method over the range of velocities investigated.

PLENUM CABLE FIRES

The use of ceiling voids for unducted return ventilation air is an increasingly common practice in modern commercial buildings (Clarke et al 1993). It is also common practice to route communication cables through hidden voids in buildings: under floor spaces, vertical riser spaces and ceiling spaces. In those cases in which the void space is also used as part of the normal HVAC system, there is the potential, in the case of a cable fire, to spread heat and smoke to occupied parts of the building.

The potential increase in communication cable loads in plenums resulting from the increased use of computers and re-cabling of local area networks (LAN) has raised concerns in the regulatory community (Clarke and Gewain 2000). Specific concerns regarding the potential effect on life safety of cables installed in above-ceiling return air plenums resulted in ASHRAE initiating a joint research project with NRC. The objective of this project was to evaluate the hazard to human life of communication cable fires in return air plenums above ceilings and to develop information that can be used as input to performance test standards and codes.

Figure 7. Cable installation in plenum space.

The project included surveys in North American office buildings to determine the types and quantities of cable in return air plenums and fire scenarios that could potentially ignite the cables. Surveys were conducted in three high-rise buildings in the Baltimore/Washington area by the Fire Protection Engineering Department, University of Maryland. In addition, NRC conducted a limited survey of a high-rise building in the Chicago area as well as surveys in three Canadian office buildings in the Ottawa/Montreal area (Figure 7). For occupied floor levels, two primary fire scenarios were observed. The scenario of particular interest is for cables located in a plenum space with ignition from a fire located in the compartment below. The second scenario is for cables located in a cable closet or computer room with a fire involving stored or miscellaneous items as the ignition source. The first scenario was investigated in the full-scale tests conducted for this project.

Fire tests were performed on communication cables at three scales: small, medium and full. FTIR (Fourier Transform Infrared) spectrometers were used with the tests to obtain data on smoke components including acidic halides for use in hazard assessment.

The small-scale tests were conducted using a cone calorimeter using a heat exposure of 50 kW/m^2. These tests provided an initial evaluation of the fire performance of representative cables including 10 new cables and 14 previously used cables from five buildings. Medium-scale tests were conducted using a modified standard room fire test facility. Tests conducted in this facility were used to determine the behaviour of communication cables with exposure to air heated to 200, 325 and 450°C as well as direct flame impingement. Finally, a series of full-scale fire tests were conducted in a facility set up specifically for this project. Tests in this facility were used to determine the behaviour of communication cables in plenums with fully-developed fires in a compartment below the plenum.

Smoke obscuration and gas concentrations were measured in a target room in the full-scale tests and were used to investigate the potential effect of fires involving cables in plenum spaces on the hazard to building occupants in compartments contaminated by smoke distributed through the building HVAC system. The results indicate that the cables can result in an increased hazard. Some of the factors that can affect tenability include an increase in smoke and CO production. In addition, irritant gases (HCl and HF) were produced in quantities sufficient to affect the ability of occupants to evacuate.

BALCONY SPILL PLUMES

With the introduction of performance-based design approaches, there is an increasing demand for consideration of the smoke produced by a fire located either under an atrium balcony or in a room opening onto an atirum balcony (producing a balcony spill plume). Currently, there are several design methods for estimating the smoke-production rate. They are based on scale-model testing conducted in the U.K. and assume that the fire is

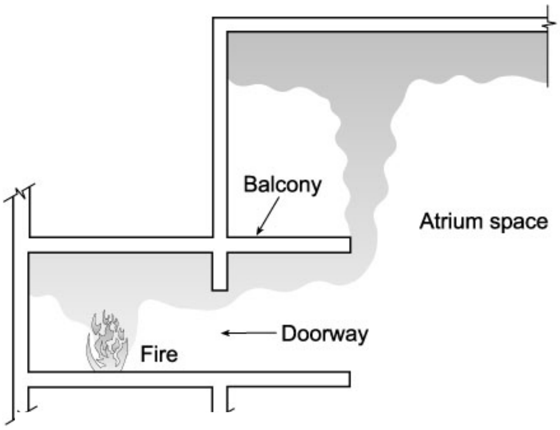

Figure 8. Balcony spill plume.

in an adjacent room (Morgan et al 1999). However, there are considerable differences in the capacity of the required smoke-exhaust system as calculated using these various approaches. These differences become particularly significant when applied to the large atriums often found in North American buildings. While over-sizing the fans can be uneconomical, under-sizing them results in failure to maintain the smoke layer above evacuation routes.

ASHRAE and NRC have recently initiated a joint research project to investigate existing design equations for the balcony spill-plume scenario. The project will include both full-scale testing and CFD modeling, and will also examine the situation where the fire is located under a balcony. At present, there are no design methods that address the latter situation.

FUTURE RESEARCH

Combustion products including smoke and carbon monoxide have major effects on the tenability conditions within the built environment. Currently, codes and standards include prescriptive measures to limit smoke production and inhibit smoke movement with the objective of providing a tenable environment in egress routes and areas of refuge.

With the growth of performance-based codes and standards, there is a growing need to develop techniques to support the appropriate evaluation of fire performance measures for codes and standards. This includes methods for mitigating smoke spread in large buildings and in transportation systems.

Over the next 5 years, NRC will carry out a strategic project to investigate smoke production and spread in the built environment and in transportation systems to determine its effect on life safety. This project will include efforts to verify numerical models for use in investigating smoke movement. In addition, the project will provide methods to evaluate the performance of smoke management systems and other fire protection systems.

ASHRAE has identified two areas for future research. The first project would investigate the maximum velocity that can be used for make-up air for an atrium smoke management system. The intended operation of atrium smoke management systems depends on formation of a plume above the fire to take the smoke upward. Current design guidance (NFPA 2000b) sets a maximum make-up air velocity of 1 m/s to prevent disruption of the plume and the smoke layer. This criterion is based on limited research into the effect of wind on flames. Many designers have stated that meeting this requirement often is costly and presents a hardship. A project is being developed by ASHRAE in which CFD modeling will be used to gain an understanding of the mechanisms of smoke flow in atria when an air jet impacts on a smoke plume or the smoke layer to determine if the 1 m/s make-up air velocity limit is valid, and what tests, if any, are recommended to confirm the assessment.

ASHRAE is also interested in a project to develop an algorithm for smoke modeling in large, multi-compartmented buildings. Traditional two-zone fire modeling has been used with considerable success to simulate smoke transport in the fire compartment and a small number of other rooms. Computational fluid dynamics (CFD) has also been used to simulate smoke transport from building fires when a much higher level of detail is needed. Neither, two zone fire models or CFD are appropriate for simulation of smoke transport in large, multi-compartmented buildings.

Network models are used to simulate airflow in large buildings, and many such programs can model contaminant flow. However, these models assume that each space of a building is a uniformly mixed zone. In addition, the energy equation is not solved. For some applications, an approximate method is sometimes used that uses a two zone fire model for simulation near the fire and a network model for simulation of smoke flow for locations remote from the fire. However, this approach has limitations. A computer model is needed that can simulate smoke flow in large multi-compartmented buildings.

SUMMARY

In this paper, the issues addressed in recent NRC projects on smoke management are outlined. This includes projects to investigate the effectiveness of smoke exhaust systems in atria, sprinklered fires in open-plan office spaces and in retail malls and the effectiveness of duct smoke detectors in HVAC systems. Ongoing projects include investigations of fires involving communication cables in return air plenums and the evaluation of the balcony spill plume correlations used to design atrium smoke management systems. This paper provides an overview of recent and ongoing smoke management research at NRC and the results of the projects. It also discussed future research directions.

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