Research Needs on the Fire Safety of Subway Stations -Fire disasters, regulations, research efforts and recent smoke movement tests in subway stations in Japan

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Abstract

Fire disasters in underground railway systems, development of related regulations and research efforts on subway fires in Japan are reviewed. Fire safety regulations for stations and trains in underground railway systems were first introduced in the 1970's after the Subway Hibiya-Line fire in 1968 and the JR Hokuriku tunnel fire in 1972. There has been few significant subway fires killing passengers since then, but the general commonness between the Japanese and Korean subway systems suggests considerable risk and potential hazard of subway fires. Experiments using subway stations actually in service in Tokyo in 2003 further revealed considerable difficulty in the conventional operation strategy of smoke control and firefighting in subway stations. Importance of the restriction of heat release rate through either the control of combustibility of lining materials or the automatic fire extinguishments and establishment of alternative evacuation routes on either ends of a platform, and appropriate operation of shutters on the stairs between the platform and the concourse is pointed out.

1. Introduction

The subway train and station fire in Daegu, Korea, on 18 February, 2003, revealed significant hazard of a fire in underground railway systems. While underground railway systems are common in every big city in the world and employ some fire safety measures in general, it is believed that there is only weak sound technical background for the effectiveness of these fire safety measures. Few experiments or modeling works have been conducted on smoke movement, fire growth and human behavior in underground railway trains or stations, although the rather low ceiling and high

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fire load in trains and the connection of a station to tunnels are believed not to be beneficial to the restriction of fire spread or the effectiveness of mechanical smoke control. This should call attention of international transportation authorities and fire experts to the needs to revisit the effectiveness of the current fire regulations on subway systems and establish a functional fire safety measures. It is also important to promote international cooperation on the research and development on the fire safety of underground systems because there is considerable commonness in the features of the related facilities. This paper reviews fire disasters in underground railway systems, regulations and research effort on subway fires in Japan, and introduces recent on-site experiments on the control mechanism of smoke movement in actual subway stations conducted jointly by the authors and Tokyo Fire Department(TFD).

2. Fire experiences in underground railway systems in Japan

While the first subway in Japan was opened as early as in 1928 in Tokyo downtown, construction of the subway network became active only in the1960s when the Japanese economic growth reached a peak and inner-city traffic in big cities encountered significant difficulties. Until the 1960s, Fire Service Law, which specifies requirements of the fire extinguishers and other appliances to help firefighting, was the only fire-related regulation applied to underground railway facilities. The Ministry of Transportation had introduced a guideline for the materials to be used for train cars as early as in 1957, but this guideline was not accompanied by any technical details. However, from the late1960s to the early 1970s, several significant fires causing victims occurred in subway and the then National Railway tunnels (restructured as JR in the late1980s). Among those fires, the Subway Hibiya Line fire(1968) and the JR Hokuriku tunnel fire(1972) are important; the Subway Hibiya Line fire was the first significant subway fire and revealed significance of the combustibility of furnishings and interior lining materials in the development of a train fire, and the JR Hokuriku tunnel fire demonstrated importance of smoke for life safety in tunnel fires. The Nagoya Subway fire in 1983 is also important in that it revealed that even very small cable fire can cause significant difficulty in the smoke management during fire fighting in a subway station. According to the fire records of TFD during the five years from 1998 to 2002, 47 fires in underground railway systems were reported; 26 fires occurred in station facilities, 4 fires were in train cars.

3. Fire safety regulations for subways in Japan

The Subway Hibiya Line fire in 1968 and the JR Hokuriku tunnel fire in 1972 arose strong attention of public to the fire safety of railway systems. It is also important to note that these fires were contemporary with significant building and industrial fires including Osaka Tenroku Subway construction site gas explosion (1970), Osaka Sen-nichi Department Store fire(118 victims, 1972), and Kumamoto Taiyo Department Store fire(103 victims, 1973). Considerable building fires causing multiple deaths had already occurred in the late 1960s, which had led to the revision of the Building Standard Law to introduce requirement of smoke control in newly designed public buildings and high-rise

Table 1 Major Fires in Subways and Underground Railways in Japan

Date	Location	Description	Injuries/deaths
1968, Jan.27	Hibiya Line*, between Roppongi & Kamiyacho Stas.	Passenger car caught fire while running. All passengers evacuated from a station, but one car finally totally burnt and two cars were damaged.	11 fire fighters injured
1969, Mar.20	Joetsu Shinkansen, Oshimizu tunnel (under construction)	Construction site fire due to welding spark. Fire fighters were unable to enter for 11 hours for heavy smoke.	16 construction workers killed
1972, Nov.6	JR Hokuriku tunnel	Dining car caught fire while running in a tunnel and stopped according to the then effective emergency manual.	30 passengers and crew killed. 714 injured.
1982, Feb.25	Marunouchi Line*, Ogikubo Sta	Generator beneath a passenger car caught fire while stopping at the station.	None
1982, Mar.8	Mita Line**, near Kasuga Sta	Heater beneath passenger seat in a passenger car caught fire.	None
1983, Feb.6	Marunouchi Line*, Yotsuya 3-Chome Sta	Break of electrical coil of a generator caused a fire while stopping at the station.	None
1983, July 11	Chiyoda Line*, Yushima Sta	Electrical cable in a machine room damaged by rats caused fire.	None
1983, Aug.16	Nagoya Subway, Sakae-machi Sta	Fire in an electrical room of the station finally caused smoke spread to underground streets.	2 fire fighters killed, 5 injured.
1985, Jan. 25	Ginza Line*, Ueno Sta	Renovation site on the B2 floor caught fire. Smoke spread to whole station.	None
1985, June 19	Hanzomon Line*, Shibuya substation	Electrical substation caught fire. Smoke spreadto whole station.	None
1985, Sep.26	Hanzomon Line*, Shibuya Sta.	Mechanical trouble beneath a passenger car caused fire while stopping at the station. 2000 passengers evacuated.	None
1985, Oct.22	Chiyoda Line*, between Nezu & Sendagi Stas	A motor beneath a passenger car caught fire while running. Passengers evacuated to nearest stations.	None
1988, Sep.21	Kinki Railways, Ikoma tunnel	Power cable caught fire.Trains had to stop in the tunnel. Fire reported to fire dept only 80 minutes after. Abandoned tunnel running parallel used for evacuation.	1 killed, 57 injured.
1992, Aug.19	JR Yokosuka Line, Ofuna Sta.	Generator beneath a passenger car caught fire while stopping at the station.	None
1992, Aug.29	Mita Line**, between Kasuga and Hakusan Stas	Electrical fire beneath a passenger car. Passengers evacuated to the nearest stations.	None
1993, Mar. 17	Ginza Line*, Asakusa Sta	A passenger car was partly burnt by a cigarette thrown from the platform	None
1993, Apr. 23	Keihin Express, Haneda Sta	A passenger car was partly burnt by arson	None
1993, Aug.27	Asakusa Line**, Asakusabashi Sta	Electrical fire beneath a passenger car.	None
1994, Mar.22	Marunouchi Line*, Nakano-shinbashi Sta	Electrical fire due to a break of the cable in the motor beneath a passenger car.	None
1995, Apr. 14	Asakusa Line**, Gotanda Sta	Electrical fire beneath a passenger car	None
1997, Oct.16	Namboku Line*, Akabane Iwabuchi Sta	Fire due to friction at a wheel break	None
1997, Nov.13	Marunouchi Line*, Yotsuya-3Chome Sta	Electrical fire beneath a passenger car, while stopping at the station	None
1998, Jan. 21	Yurakucho Line*, Otakemukaibara Sta	Electrical fire while running. Passenger car was partly burnt.	None
2001, Jan.15	Chiyoda Line*, Kasumigaseki Sta	A passenger car was partly burnt by an arson to the seat	None
2002, Jan.24	Marunouchi Line*, Ikabukuro Sta.	Electrical fire beneath a passenger car	None
2002, Dec. 19	Tohoku Shinkansen, Tunnel in Tokyo	Arson to a seat of passenger car	None
2003, Apr. 9	Yurakucho Line*, between Senkawa and Otakemukaibara Sta	Failure of a connector of passenger cars, the trains were partly burnt. 2500 passengers evacuated to Senkawa Sta.	None

* Subway lines thus marked are operated by Teito Rapid Transit Authority（“Eidan” Subway）.

** These lines are operated by the Tokyo Metropolitan Government（“Toei” Subway）.

buildings in 1969-70. The continuation of significant building fires in the early 1970s further led to the new application of the Fire Service Law to existing buildings in 1975. The Subway Hibiya Line fire resulted in the introduction of the first Japanese fire safety regulation on subway trains in 1969, which is known as the "A-A Standard". The A-A Standard regulates the combustibility of lining materials of trains running in subway tunnels using a simple test with a specimen put beneath a downward 45degree holder above a flame from a small methanol tray. Many of then existing train cars were renovated according to the standard during the following few years. Further in 1975, requirement of mechanical smoke extraction was introduced to subway stations. The specified smoke extraction capability, $1m^3$ per unit floor area per minute, is probably an imitation to the Building Standard Law, which had come into practice five years earlier. Although fires in underground railways have still been repeated since then, it is important that all other fires occurred either in the mechanical appliances beneath a train or in mechanical facilities in tunnels. There has been strong belief in the effectiveness of the A-A Standard for the fire safety of subway trains. In 1987, the A-A Standard became a part of the Ministry of Transportation's guideline for railway trains, and began to be applied to all passenger trains throughout the country.

4. Research efforts on subway fires by public sectors

Since the Subway Hibiya Line fire in 1968, several experimental projects have been organized to verify and improve fire safety measures for underground railway systems. Most of them were sponsored by the transportation authorities and their results do not have been released to public. However since around the late 1980s, firefighting authorities have become alert on the fires in underground transportation systems. This is partly because of the increased interest in the development of underground in urban districts and probably for significant underground fires at Nagoya Subway in 1983 and the Kings Cross Subway Station fire disaster in London in 1987.

(1)Validation of the Subway Hibiya Line fire

In February 1969, two fire tests were conducted using actual train cars to identify the fire growth scenario of the Subway Hibiya Line fire in the previous year and verify the effectiveness of the improvement of fire safety performance of lining materials under the leadership of then Ministry of Transportation. According to the report, the first test with a train car exactly reproduced after the one burned at the fire was started under the estimated scenario and resulted in a notable fire within the passenger car. The second test with the interior linings improved according to the then draft "A-A Standard" did lead to only generation of small amount of smoke. The report was not released to public.

(2)Smoke Tests at Subway Yotsuhashi Station, Osaka

In December 1972, Osaka City Transportation Bureau organized a series of smoke tests at newly built Subway Yotsuhashi Station to see general smoke behavior in subway fires and validate effectiveness of mechanical smoke control. Fire source, a 2,000cc methanol tray, was placed at three locations, on the platform, in the tunnel, and on the concourse. Smoke was visualized with smoke candles. Visual observation and measurement of optical density were conducted. It is not clear if the test results were published, but from the present knowledge on fire and smoke movement, it is questionable if the test program was enough to assess the effectiveness of the smoke control systems.

(3)Smoke Tests at Subway Iidabashi Station, Tokyo

In November 1976, a series of smoke tests were conducted at Yurakucho Line Iidabashi Station and its connecting tunnels under the sponsorship of then Ministry of Transportation. It is said that smoke movement with and without mechanical smoke extraction was monitored through measurement of optical smoke density and velocities. Detail of the tests is not clear because the test result was not released to public.

(4)Train Fire Test at Public Works Research Institute

In March 1992, a series of fire tests were conducted using actual trains by Japan Railway Engineering Society at the Full Scale Tunnel Laboratory, Public Works Research Institute. Under different fire scenarios, it was confirmed that a fire source composed of 600cc ethanol, 400cc kerosene and 80 pages newspaper cause an only limited extent of fire damage to a train car.

(5)Fire Test of Trains and Furnishings by Tokyo Fire Department

Attention to the security against terrorist attack to public transportation began to grow in around the turn to the 1990s. This is partly because of the gradual deterioration of public peace in big cities in Japan. With industrial interest in underground development as background, Tokyo Fire Department(TFD) organized a research project to revisit the fire safety of subway systems by fire tests using actual train cars and combustibility tests on furnishings and interior lining materials of subway trains in 1993. The project pointed out that, even though the then effective fire regulations were effective for accidental fires, the regulations are not enough to deal with arson or terrorist attack which may result in a tragic development of a fire because the A-A Standards is limited to the restriction of the ignitability of train materials under weak heat source. Major results were released to public (ref1).

5. Smoke movement in subway stations

After the Daegu subway fire in 2003, Ministry of Land Infrastructure and Transportation(MLIT) and TFD organized independently experts committees on subway fires. The main author of the present study chairs the TFD’s project, which focused on the fire fighting strategy for underground railway fires. As a part of this project, experiments were conducted to clarify the control mechanism of smoke flow in subway stations using actual stations under the cooperation with the Teito Rapid Transit Authority(TRTA, “Eidan” Subway) and the Transportation Bureau of the Tokyo Metropolitan Government(“Toei” Subway), the two subway operating bodies in Tokyo.

5.1 Test Plans

Smoke movement tests were conducted using simulated fire sources on the platform in three subway stations currently in service in Tokyo in October 2003. Two most typical layouts of platforms in subway stations, single platform sandwiched by tracks(“island” type) and two platforms on both sides of tracks(“bank type”), were chosen; both island type and bank type stations were chosen from an Eidan Subway line, and an island type station was chosen from a Toei Subway line. These stations will be referred to as Island-A, Bank-A(both from

Eidan Subway), and Island-B(Toei Subway) respectively. The platform of each selected station is located on the B-2 level, and is connected by stairways and escalators to a concourse on the B-1 level. Island-A and Bank-A stations utilize the ventilation system for the platform for the smoke extraction by reversing the fan. Smoke extraction fans of these stations have $1.0m^3/m^2h$ capacity according to the A-A standard, while the Island-B station has two $300Km^3/h$ powerful smoke fans. The tests were conducted in midnight to avoid conflicts with the traffic services. While numerous scenarios occur to us on fire and operation of fire safety measures, the contents of the tests were limited to those shown in Table 2 for the extremely restricted time available for each test.

Fires sources were simulated with methanol in 2-6 0.50m square trays, each tray of which is believed to make approximately 80kW heat release rate. This fire source intensity, 160kW for one station and 480 kW for other two stations, was chosen not to cause any damage to the stations according to the anticipated fragility of the each subway stations. Since this heat release rate represents only the early stage of a growing fire, it was planned to use numerical simulations to predict impact by more plausible fires. The present tests were conducted to provide information to verify such model and more directly to study the effectiveness of the smoke control systems designed according to the regulations.

Table 2 Smoke Movement Test Conditions

Series	Fire Source	Smoke Extraction	Shutters on the Stairway between Platform and Concourse
1	off	off	open
2	methanol pans on platform	off	closed, half open, open
3		on, platform level	closed, half open, open
4*		on, both platform and concourse	closed, half open, open

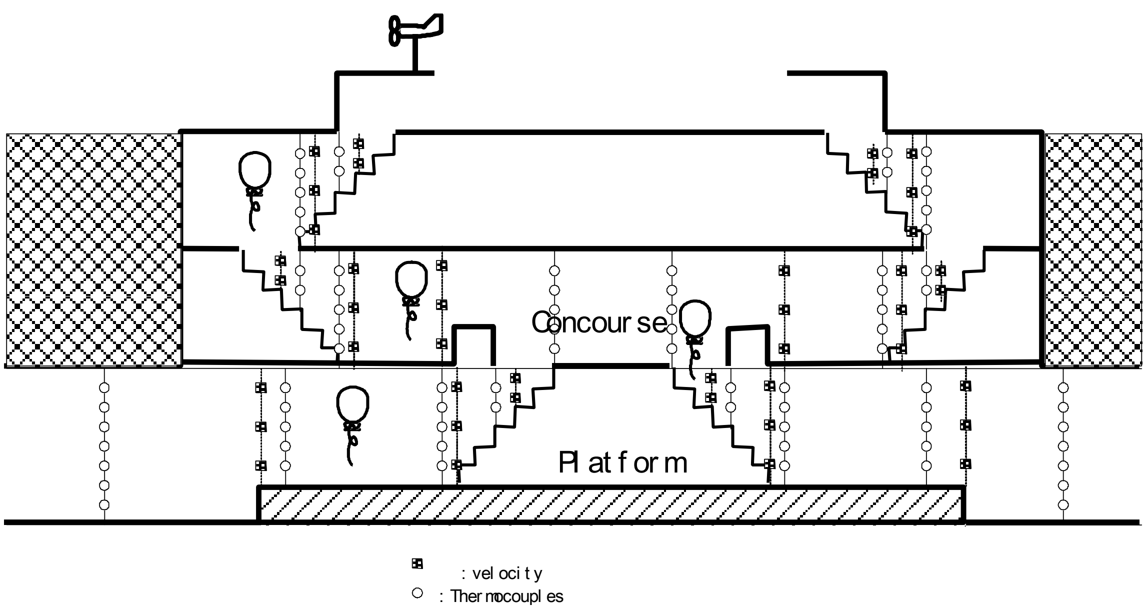

Figure 1 Measurements Layout, Smoke Movement Tests at Subway Stations

Measurements were made on the distribution of temperature, velocity and static pressure throughout the platforms, the tunnel, and the concourse. Thermocouples and other probes had been settled on length-adjustable poles which were brought into the test site just before the test. Hot gas current was visualized with smoke candles. Figures 1 shows a typical measurement layout.

Some interim results of calculation by a 2-zone model will be compared against the test results.

5.2 Experimental Results, Summary

Figures 2, 3 and 4 are a summary of the test results. Number in each circle shows the location of the thermocouple/probe pole whose location is identified in each arrangement map. From the test results, following summaries can be drawn on the general characteristics in the smoke movement and the smoke control performance in a subway station platform.

(1) Operation of shutters causes significant influence on the airflow in the stairways connecting the platform and the concourse. The air flow blowing down the stairway with the shutters open or half-open can prevent smoke penetration from the platform to the concourse, but at the same time, the strong wind through the stairway destabilizes the smoke layer on the platform which significantly let the wide area of the platform be contaminated by smoke. This effect is particularly pronounced when the smoke extraction is operated on the platform.

(2) Influence of the conditions of shutters on smoke movement on the platform level seems to be less significant in a bank type station than in an island type one.

(3) Smoke layer on the platform level was kept stable as long as the shutters were closed. Smoke extraction on the platform level was effective to maintain the smoke layer higher enough to prevent people from being exposed to smoke.

(4) With the smoke extraction on the platform level on and the shutters closed in the island type platforms, smoke layer was restricted within the fire area confined by the stairways. In the bank type platform under the same conditions of smoke extraction and shutters, smoke spread was observed beyond the staircase and other obstacles on the platform.

5.3 Calculation by Control Volume Model

Numerical studies are carried out to reproduce the experiments and then to predict fire hazard and evaluate effectiveness of such fire safety measures as smoke extraction and shutters at the event of more plausible severer fires. A control volume model and a CFD model are being examined. In this report, only interim results of the control volume model applied for the experimental conditions are presented(Figures 5, 6 and 7). The model is essentially based on conventional zone models, but some modifications have been made to deal with the leeward change of the smoke layer depth within the platform and the concourse. The modification includes subdivision of the platform to reproduce gradual development of smoke layer from the fire source to the both ends of the platform. The model was first tuned using the test data on a simplest condition with the shutters closed and the smoke extraction off. The model has been then validated against other test conditions. The calculation and the experiments show good agreement in general for the conditions with shutters closed. However, considerable discrepancy can be seen for the conditions with shutters open; the calculation resulted in higher maximum smoke layer temperature and higher smoke layer interface on the platform than the experiments. This suggests that the adopted control volume model cannot yet appropriately reproduce the impact of the induced air through the stairways on the smoke-air mixing on the platform level.

5.4 Discussions

While calculations on larger fires are not involved in the present report, the following discussions are worth considering in the design and assessment of fire safety for subway stations.

(1) Operation of shutters on the stairway has primary influence on the smoke movement due to a fire on the platform level. Closure of the shutters is generally beneficial not only for saving the concourse from smoke but also for keeping smoke layer on the platform level stable.

(2) If the fire source intensity is controlled and the shutter nearby the fire source is closed, smoke spread on the platform can be confined within certain area. This suggests general importance of the provision of alternative evacuation routes on both ends of a platform.

(3) Restriction of the fire intensity is primarily important. Even if appropriate operation of the shutters and so on may prevent evacuees from being involved by smoke, increase of heat release rate should result in the augmentation of the smoke layer temperature which should further cause evacuation difficulty due to the exposure of evacuees to strong radiation.

Acknowledgments

The experiment introduced in this report was conducted as a part of the Research Committee on the Underground Railway Systems organized by the Tokyo Fire Department(TFD) under the cooperation of Teito Rapid Transit Authority and Transportation Bureau of Tokyo Metropolitan Government. The authors would like to acknowledge cooperation of these organizations and the committee members. The authors are also indebted to Bin Du, Masayuki Hirota, Koji Kagiya, Fumikazu Kishimoto, Ken Matsuyama, Tsutomu Nagaoka, Masatoshi Nakamura, Taku Shimada, Keiichi Suzuki, Takashi Wakamatsu, Architecture Laboratory of Railway Technical Research Institute, TFD's Fire Science Laboratories, and members of Hasemi Lab. Waseda University, who helped greatly the experiments.

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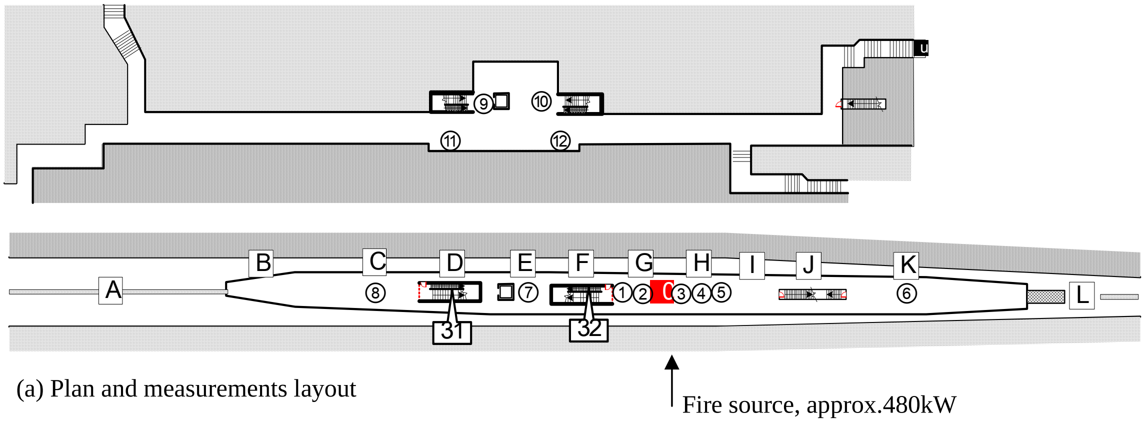
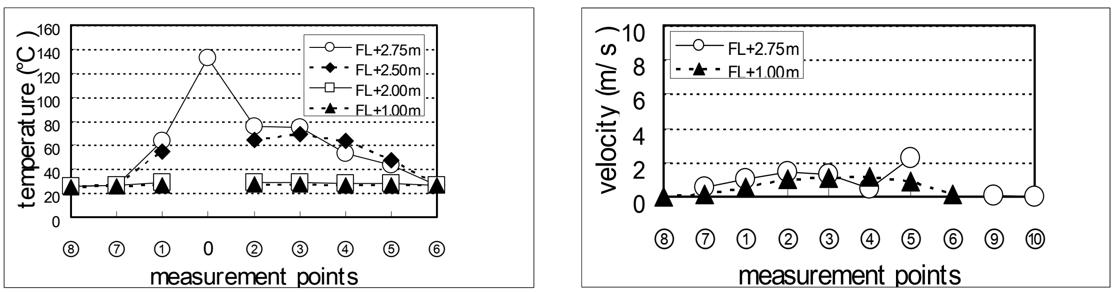
1. Tokyo Fire Department, Report on Full scale experiments and study on railway trains, 1994(in Japanese).
2. Moriyama,S.,Tanaka,S., Yonezawa,M., Hasemi,Y., Nam,D., Ding,W., Okazawa,N., Smoke Movement Behavior in Subway Station Fires, Part 1-3, Kanto Branch Meeting, Fire Safety Section, Architectural Institute of Japan, March 2004(in Japanese).

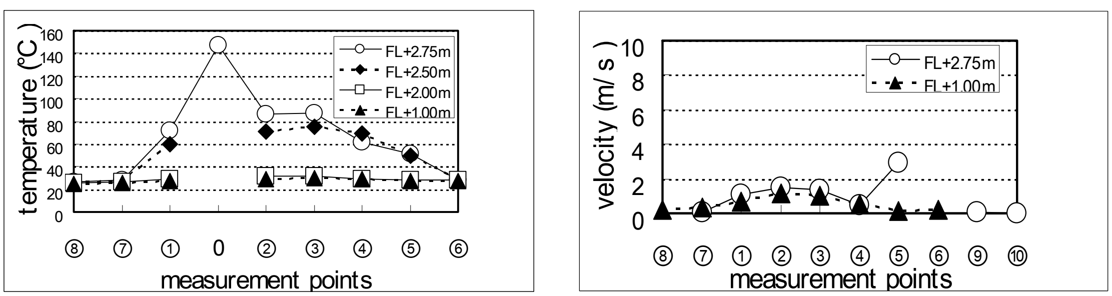
Figure 2 Summary Test Results, Island-A Station



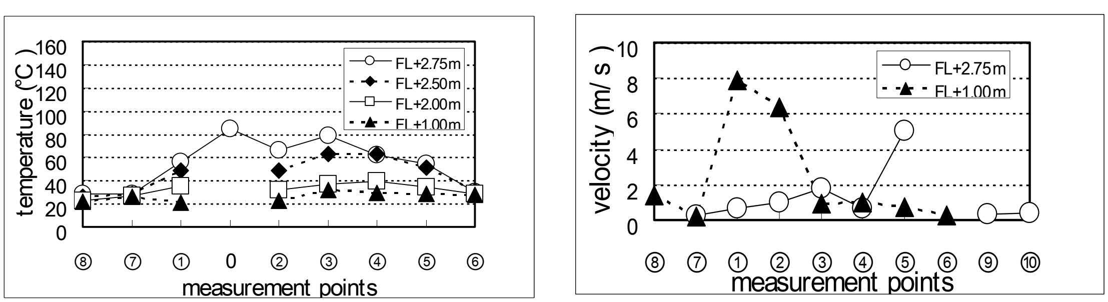
(a) Plan and measurements layout



(b) Temperature and velocity(0: fire source. The numbers in circle denote location, see Fig.2(a))
Shutters CLOSED, Smoke extraction OFF

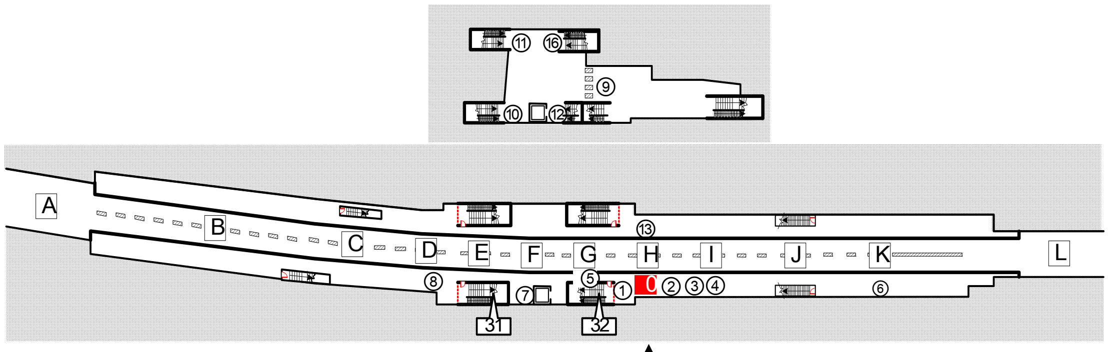


(c) Temperature and velocity, Shutters CLOSED, Smoke extraction ON



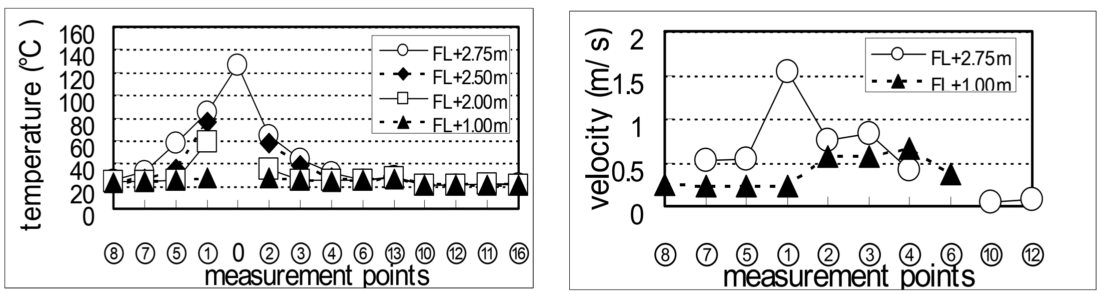
(d) Temperature and velocity, Shutters OPEN, Smoke extraction ON

Figure 3 Summary Test Results, Bank-A Station

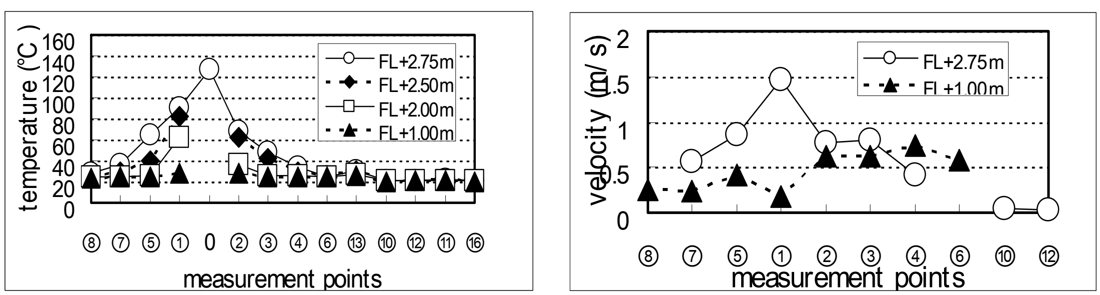


(a) Plan and measurements layout

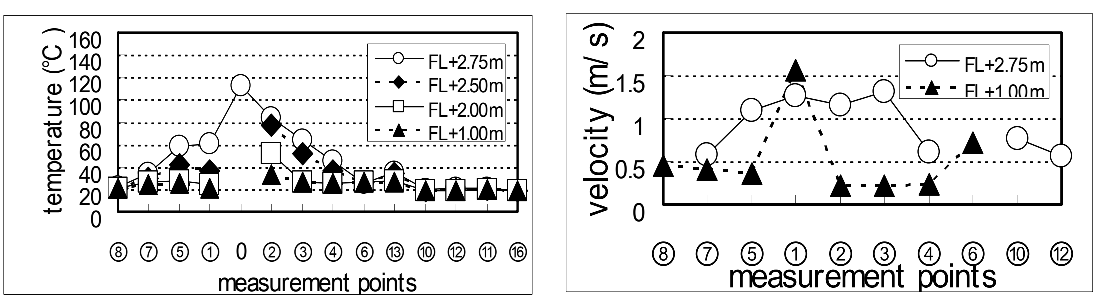
Fire source, approx.480kW



(b) Temperature and velocity(0: fire source. The numbers in circle denote location, see Fig.3(a))
Shutters CLOSED, Smoke extraction OFF

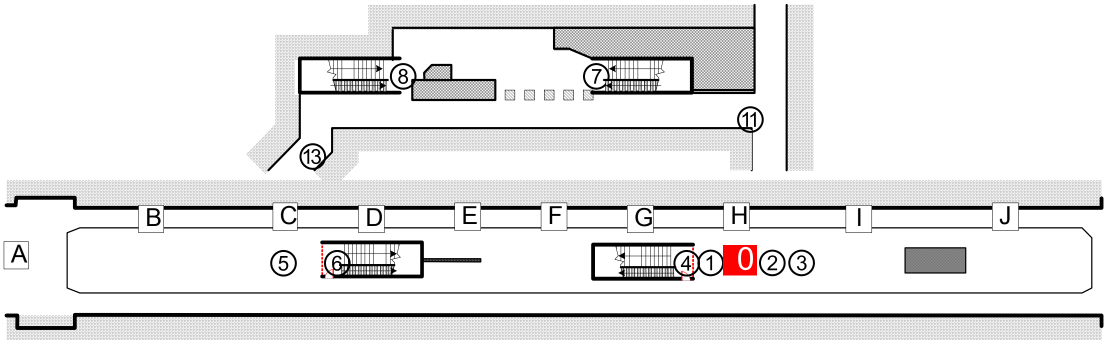


(c) Temperature and velocity, Shutters CLOSED, Smoke extraction ON



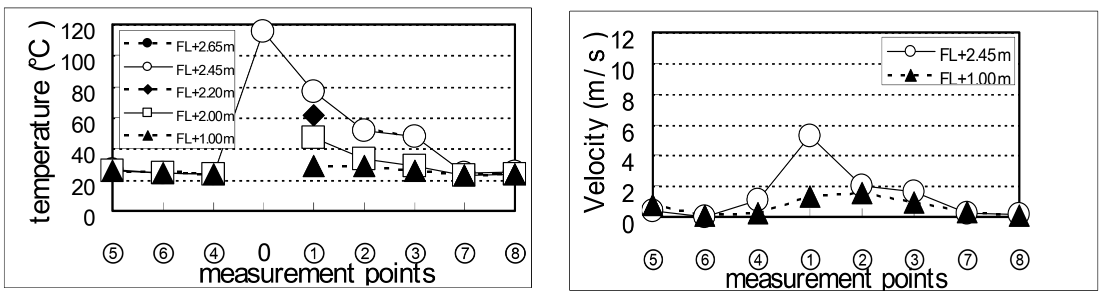
(d) Temperature and velocity, Shutters OPEN, Smoke extraction ON

Figure 4 Summary Test Results, Island-B Station

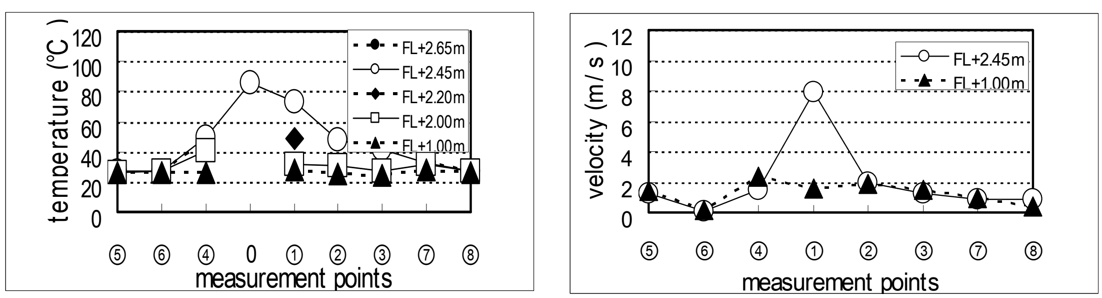


(a) Plan and measurements layout

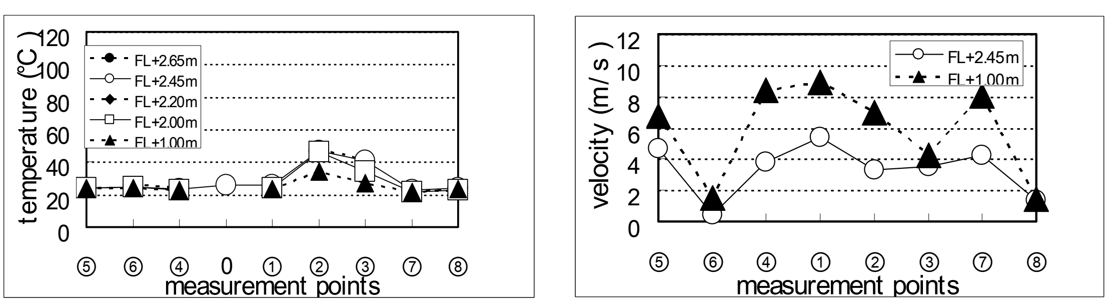
Fire source, approx.160kW



(b) Temperature and velocity(0: fire source. The numbers in circle denote location, see Fig.4(a))
Shutters CLOSED, Smoke extraction: platform ON, tunnel entrance ON

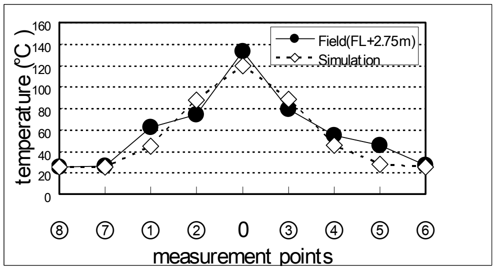


(c) Shutters OPEN, Platform smoke extraction OFF

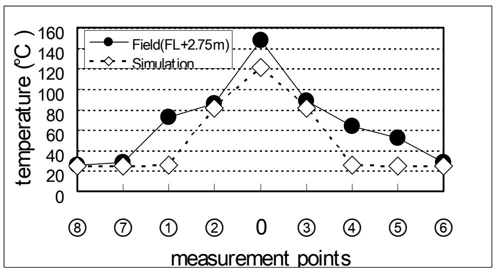


(d) Shutters OPEN, , Smoke extraction: platform ON, tunnel entrance ON

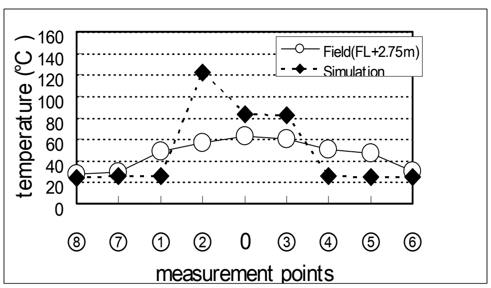
Figure 5 Experimental and Numerical Smoke Layer Temperatures (Island-A Station)



(a) Shutters : CLOSED, Smoke Extraction: OFF

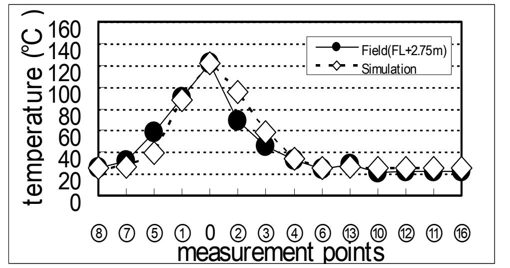


(b) Shutters: CLOSED, Smoke Extraction: ON

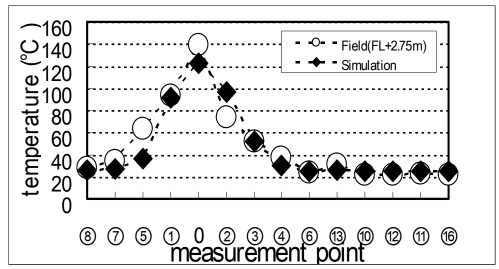


(c) Shutters: OPEN, Smoke Extraction : ON

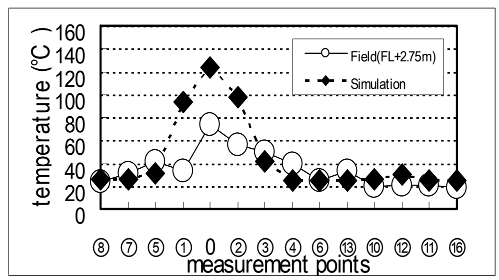
Figure 6 Experimental and Numerical Smoke Layer Temperatures(Bank-A Station)



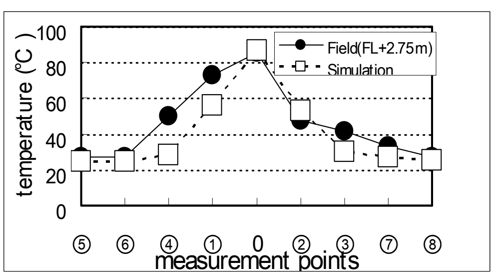
(a) Shutters : CLOSED, Smoke Extraction: OFF



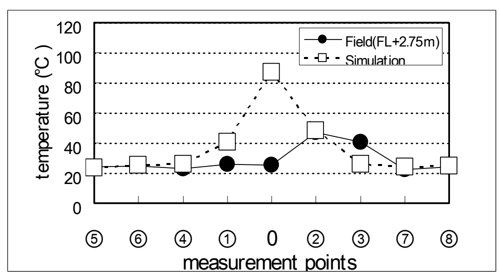
(b) Shutters: CLOSE, Smoke Extraction: ON



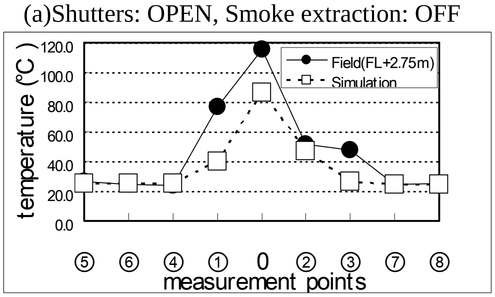
(c) Shutters : OPEN, Smoke Extraction: ON



(a)Shutters: OPEN, Smoke extraction: OFF



(b) Shutters : OPEN, Smoke Extraction: ON



(c) Shutters: CLOSED, Smoke Extraction: ON

Figure 7 Experimental and Numerical Smoke Layer Temperatures (Island-B Station)

Smoke extraction is installed on the ceiling of the platform and at the entrance to the tunnel to both sides.