Our ref 131211-19/jja

ARUP

955 Massachusetts Avenue
4th floor
Cambridge
MA 02139
United States of America

t +1 617 864-2987
d +1 617 349 9214
f +1 617 864-6178

jarrod.alston@arup.com
www.arup.com

Mike Garz
Downtown Design Partnership
100 Broadway, 3rd Floor
New York, NY 10005

August 23, 2011

Dear Mike

World Trade Center Transportation Hub
Structural Fire Engineering Analysis – Follow-Up

On 16 august 2011, the Downtown Design Partnership (DDP) presented the *Whitepaper on Fire Resistance of Above Grade Oculus Steel* to the New York City Department of Buildings (DOB). While the DOB expressed general agreement with the analytical approach taken in evaluating the thermal exposure to the above grade Oculus steel for a fire occurring at the Transit Hall level (elevation 274'), there were also expressions of concern relative to alternate uses of the facility and the resultant impact on fuel load.

Principally, the Transit Hall level is for the circulation of PATH transit passengers and patrons of the adjacent retail spaces. As such, a retail kiosk fire with a maximum heat release rate of 2 MW has been considered by DDP to be a maximum credible design fire scenario for the purpose of designing the emergency ventilation systems within the Transit Hall. The same 2 MW fire served as the basis of evaluation of the above grade oculus steel. However, it was acknowledged by DDP that there is a developing plan for "special event" use of the Transit Hall by the building operator. "Special events" could involve displays or exhibits, including automobile displays or showcases. Consequently, it was deemed necessary to evaluate the response of the above grade Oculus steel to a larger fire event involving a passenger vehicle.

An appropriate credible maximum fire size for a passenger vehicle can be identified from literature including:

- *NFPA 502 – Standard for Road Tunnels, Bridges, and Other Limited Access Highways* (NFPA)
- *Fire and Smoke Control in Road Tunnels* – PIARC Technical Committee 5 – Road Tunnels (PIARC)

- *Fire in Tunnels Thematic Network – Technical Report Part 1 – Design Fire Scenarios* (FIT)
- *UPTUN – Work-package 2 Fire Development and Mitigation* ("Cost effective sustainable and innovative UPgrading Methods for Fire Safety in existing TUNnels")
- "Design Fires in Tunnels", H. Ingason
- *Comparison and Review of Safety Design Guidelines for Road Tunnels*, SP Report 2007:08

The data from PIARC's *Fire and Smoke Control in Road Tunnels* has been widely reference by the developers of standards and guidelines, including the National Fire Protection Association (NFPA). The vehicle fire heat release rates cited in *Fire and Smoke Control in Road Tunnels* have been utilized widely in the design of road tunnels throughout the world. According to the PIARC data, excerpted below, characteristic heat release rates can be determined by vehicle type: a small passenger car will have a representative peak heat release rate of 2.5 MW; a large passenger car will have a representative peak heat release rate of 5 MW.

• 1 small passenger car	2.5 MW
• 1 large passenger car	5 MW
• 2-3 passenger cars	8 MW
• 1 van	15 MW
• 1 bus	20 MW
• 1 lorry/truck with burning goods	20-30 MW

Source: *Fire and Smoke Control in Road Tunnels*

It is assumed that there is potential for displaying multiple cars wherein a fire involving one vehicle could result in the ignition of adjacent, closely spaced cars. Therefore, a representative credible maximum fire size for an automobile display is 8 MW.

Previous analysis of the 2 MW kiosk fire demonstrated close agreement between results obtained via computational fluid dynamics (CFD) modeling and that obtained via hand calculations. Therefore, hand calculations are sufficient for evaluating the thermal exposure to the lowest point of above grade Oculus steel that is proposed to be unprotected. The methodology adopted for this analysis is summarized as follows:

1. Determine the shortest height above the Transit Hall floor (elevation 274') at which the above grade Oculus steel is proposed to be unprotected.
2. Estimate the convective exposure to the steel based on centerline plume temperature calculations at the aforementioned height.
3. Estimate the radiative exposure to the steel based on a point-source approximation at the aforementioned height.
4. Estimate steel temperature rise of the steel assuming uniform conditions based on the previously determined maximum convective and radiative exposures.
5. Estimate the percentage of the maximum yield strength retained by the steel at the estimated steel temperature.

The proposed approach is highly conservative for the following reasons:

- the exposure calculated for the *lowest* portion of the steel above the fire is applied to the entire element although temperatures and radiant fluxes at higher elevations will be significantly lower;
- the lineal steel weight has been assumed to be comprised of only the portion of the steel interior to the building glazing neglecting the significant mass of steel exterior to the building glazing (the lighter the structure the more rapid the temperature rise and vice versa);
- the lineal weight is based on the thinnest portion of the structure that occurs at the lowest elevation proposed to be left unprotected;
- conduction along the height or across the width of element to the exterior, which would serve to distribute heat and effectively cool the steel, is neglected;
- the convective exposure is based on the plume centerline temperature, neglecting the temperature profile across the plume which would result in a lower average thermal exposure at a given elevation;
- the radiant flux to the steel is assumed to be uniform at a given elevation, neglecting effects of view factors and shading;
- design fires are assumed to attain their maximum heat release rate instantaneously; neglecting characteristic growth rates;
- design fires are assumed to burn indefinitely, neglecting effects of burnout and finite quantities of fuel; and
- design fires are assumed to burn uninterrupted, neglecting the effects of sprinklers or fire dept intervention.

The convective exposure to the steel is based on estimates of the centerline plume temperature as determined from the correlation proposed by McCaffrey[1].

$$\boldsymbol{T_p - T_0 = 1.5\frac{T_0}{2g}\left(\frac{z}{Q^{2/5}}\right)^{-5/3}} \qquad \textbf{Equation 1}$$

In the above expression, Q is the fire heat release rate and z is the height above the fire source or the distance above the Transit Hall floor (elevation 274').

The incident radiant flux to structure is approximated from a point-source formulation:

$$\boldsymbol{q''_{r,i} = \frac{Q_r}{4\pi z^2}} \qquad \textbf{Equation 2}$$

In the above expression, Q_r is the radiative component of heat release rate which is taken to be 1/3 of the total, typical for many common fuels.

The temperature rise of the steel can then be approximated from the following expression:

[1] McCaffrey, B. J., "Purely buoyant diffusion flames: some experimental results." NBSIR 79-1910, National Bureau of Standards, Washington, D.C., 1979.

$$\Delta T_s = \frac{\Delta t}{c_s(W/D)}\left[h(T_p - T_s) + \varepsilon(q''_{r,i} - \sigma T_s^4)\right]$$ **Equation 3**

where c_s is the temperature dependent specific heat of steel, (W/D) is the ratio of the lineal steel weight and wetted perimeter, h is the convective heat transfer coefficient (25 W/m^{2}K), and ε is the surface emissivity of the unprotected steel.
Based on the resultant temperature of the steel element, the percentage of the maximum yield strength or the percentage residual strength can be estimated from:

$$\frac{\sigma_{y,T_s}}{\sigma_{y,T_0}} = 1 + \frac{T_s}{900\ln(T_s/1100)} \quad \text{for } 0 < T_s \leq 600$$ **Equation 4**

The above set of equations has been applied to determine the maximum steel temperature after 1-1/2 hours of exposure to:

- a 2 MW fire, representative of the nominal kiosk design fire;
- a 5 MW fire, representative of a large passenger car fire; and
- a 8 MW fire, representative of a fire involving 2 to 3 passenger cars.

The resulting maximum steel temperatures and residual strength are summarized here:

Table 1: Steel temperature and percent residual strength after 1.5 hours of thermal exposure

	2 MW Kiosk Fire	5 MW Large Passenger Car Fire	8 MW 2 – 3 Passenger Car Fire
Max. Steel Temperature at 1.5 Hours	66 °C	115 °C	155 °C
Percent Residual Strength at 1.5 Hours	98%	95%	93%

Based on the results of the analysis, up to 93% of the maximum steel strength is expected to be retained after 1.5 hours of exposure to fires of hypothetical infinite duration. Even at exposures of 4 hours, the residual strength of the steel does not drop below 90% for any of the design fires considered. For reference, the American Institute for Steel Construction's (AISC) *Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings*[2] limits the maximum permissible design stress to approximately 50 or 60 percent of the yield strength, which corresponds to steel temperatures on the order of of 550 °C.

Based on the analysis discussed herein, the strength of the steel portal frame members is not expected to be significantly reduced as a result of any of the calculated fire exposures considered, whether it is the nominal 2 MW kiosk design fire or the multiple car, four times the magnitude. For all fire scenarios considered, the residual steel strength is not predicted to drop below 90%. The current analysis, taken in conjunction with that described in Arup's letter report to DDP dated 25 February 2011, justifies the omission of applied fire protective coatings on the above grade portions of the steel portal frames which reside more than 33' to 47' above the Transit Hall elevation of 274'.

[2] *Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings,* American Institute for Steel Construction, New York, 1978.

Yours sincerely

Jarrod Alston
Associated

Enc
Attachment A – Predicted Centerline Plume Temperatures
Attachment B – Estimated Steel Temperatures and Percent Residual Strength
Attachment C – "World Trade Center Transportation Hub Structural Fire Engineering Analysis", February 25, 2011

Attachment A

Predicted Centerline Plume Temperatures

The chart below depicts air/smoke temperatures at a range of elevations directly above a fire located on the Lower Concourse (274'-0" elevation). The structural members for which omission of applied fireproofing is proposed begin between 10.0 and 14.5 m above the Lower Concourse and extend upward from there. The temperatures at the lowest elevation (10.0 m) have been highlighted for clarity. It is worth noting that the gas temperatures at the exposed steel do not exceed 213 °C, a temperature at which the steel would not be expected to lose sufficient strength to cause structural failure.

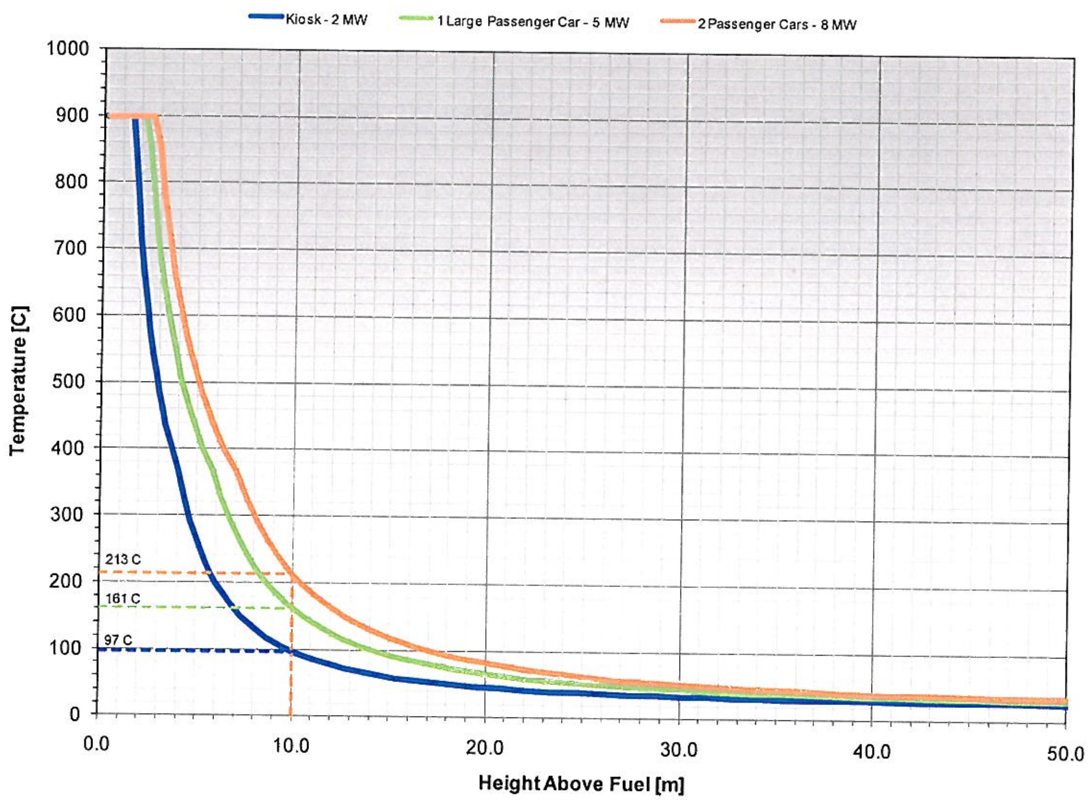

Figure A1 - Predicted centerline plume temperatures above a 2 MW kiosk fire, 5 MW large car fire, and 8 MW multiple (2 to 3) car fire located at the Transit Hall elevation 274' level

Attachment B

Estimated Steel Temperatures and Percent Residual Strength

The charts below depict the predicted steel temperatures and percent residual steel yield strength based on the analysis methodology. The analysis considers an element immersed in conditions predicted at 10.0 m above the Lower Concourse (274'-0" elevation) based on a range of design fires located at the Lower Concourse. The analysis considers fires of infinite duration. Results have been summarized at 1-1/2 hours, corresponding to the required fire-resistance rating for columns in buildings of Type 1C construction according to the 1968 Building Code of the City of New York.

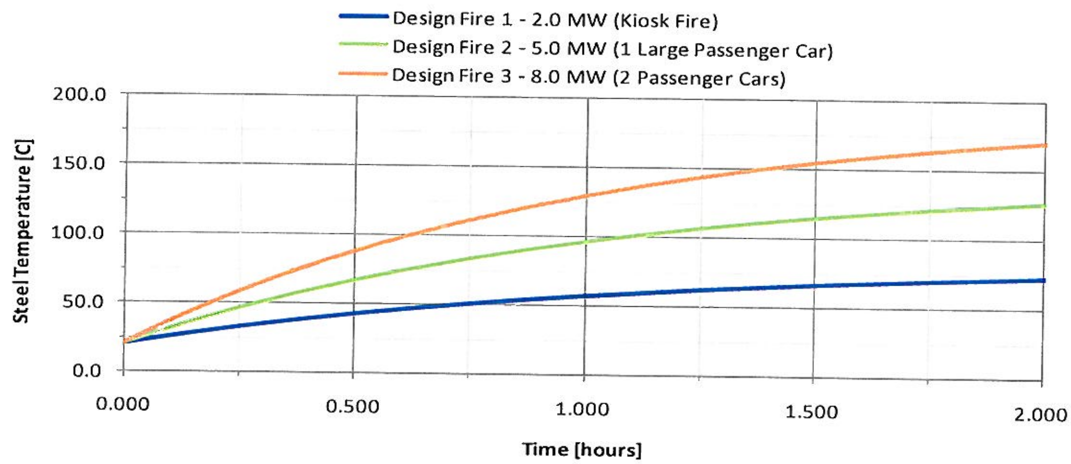

Figure B1 - Predicted steel temperatures based on infinite and uniform thermal exposure conditions 10.0 m above a 2 MW "kiosk" fire, 5 MW "large car" fire, and 8 MW "multiple (2 to 3) car" fire located at the Transit Hall 274' level

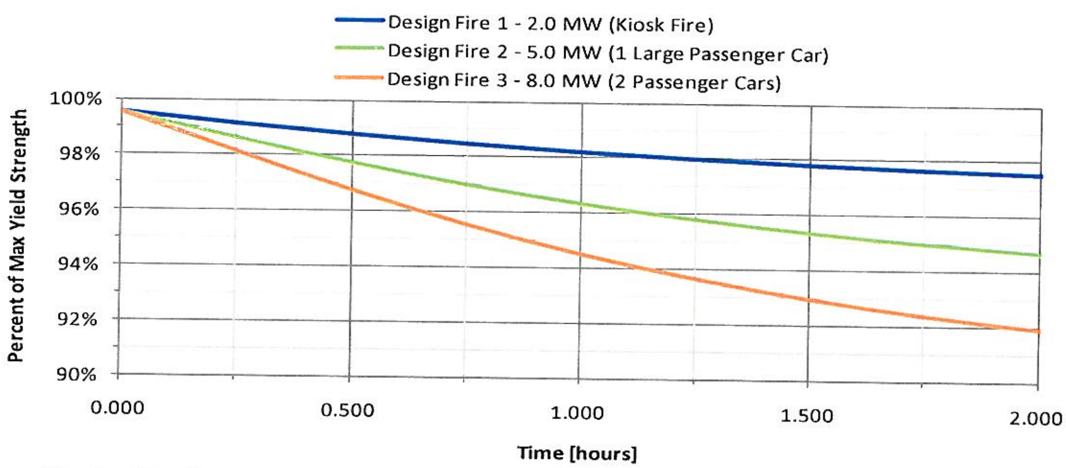

Figure B1 - Predicted percent residual steel strength versus time for members immersed in infinite and uniform thermal exposure conditions 10.0 above a 2 MW "kiosk" fire, 5 MW "large car" fire, and 8 MW "multiple (2 to 3) car" fire located at the Transit Hall 274' level

Table A1: Steel temperature and percent residual strength after 1.5 hrs of estimated thermal exposure

	2 MW Kiosk Fire	5 MW Large Passenger Car Fire	8 MW 2 – 3 Passenger Car Fire
Max. Steel Temperature at 1.5 Hours	66 °C	115 °C	155 °C
Percent Residual Strength at 1.5 Hours	98%	95%	93%

Attachment C

"World Trade Center Transportation Hub Structural Fire Engineering Analysis" February 25, 2011