Friend or Foe, Wind at Height

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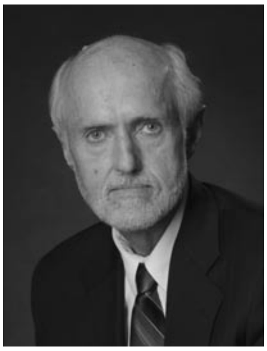

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Peter Irwin

Peter Irwin joined the company back in 1980 and became the President of RWDI in 1999, a position he still holds. His experience in wind engineering dates back to 1974 and includes extensive research and consulting in wind loading, aero-elastic response, wind tunnel methods, instrumentation as well as supervising many hundreds of wind engineering studies of major structures since joining RWDI.

Examples of tall building projects he has worked on are the Petronas Towers in Kuala Lumpur, the Taipei 101 building in Taipei, Two International Finance Centre in Hong Kong and the Burj Dubai tower in Dubai. Peter earned his Ph.D. in Mechanical Engineering from McGill University. He is a Registered Professional Engineer in the Provinces of Ontario, Alberta and British Columbia and is a Fellow of the ASCE and CSCE.

He has published over 120 papers and won several awards for his work, including the Jack E. Cermak Medal, American Society of Civil Engineers, 2007 and the Canadian Society for Civil Engineering's Gzowski Medal in 1995. He serves on several committees for codes and standards, such as the Standing Committee on Structural Design for the Canadian Building Code, and the wind committees of theASCE 7 and ISO standards.

John Kilpatrick

John Kilpatrick joined Rowan Williams Davies & Irwin Inc. in 1996. His experience in wind engineering includes research on the behaviour of tall buildings under wind loading, and consulting on the response of tall buildings, bridges, and stadia. John recently earned his Ph.D. in Civil Engineering from the University of Western Ontario, validating model-scale predictions of tall building performance using full-scale measurements of tall buildings in Chicago. He is a registered engineer in the Province of Ontario, and has been the Head of Structures in the UK office of RWDI Anemos since relocating to the UK in 2005.

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Abstract

Wind is often regarded as the foe of tall buildings since it tends to be the governing lateral load. Careful aerodynamic design of tall buildings through wind tunnel testing can greatly reduce wind loads and their affect on building motions. Various shaping strategies are discussed, aimed particularly at suppression of vortex shedding since it is frequently the cause of crosswind excitation. The use of supplementary damping systems is another approach that takes the energy out of building motions and reduces loads. Different applications of damping systems are described on several buildings. Wind also has some potential beneficial effects particular to tall buildings. One is that, since wind speeds are higher at the heights of tall buildings, the potential for extracting wind energy using wind turbines is significantly improved compared with ground level. The paper explores how much energy might be generated in this way relative to the building's energy usage. Other benefits are to be found in judicious use of natural ventilation, sometimes involving double layer wall systems, and, in hot climates, the combination of tailored wind and shade conditions to improve outdoor comfort near tall buildings and on balconies and terraces.

Keywords: Wind loads, tall buildings, building motions, wind tunnel testing, sustainability, human comfort

Introduction

The economics of constructing tall buildings are greatly affected by wind as their height increases. To counteract wind loads and keep building motions within comfortable limits can require robust structural systems that drive up costs. Both the loads and motions are often subject to dynamic amplification in both the along wind and crosswind directions. These effects are heavily dependent on shape. Hence the current trend towards considering the aerodynamics of the shape very early in the design of the very tall towers. The curtain wall loads also tend to increase with height primarily due to the fact that wind speeds in general increase with height, and the winds at ground level and on terraces or balconies are increased. All these effects are familiar to experienced developers and designers of tall towers and can be categorized as potential problems to be solved through the use of wind tunnel testing. Wind is the foe.

However, there are also some effects of wind that can make it a friend. One example is the possible use of the building as the platform for wind turbines for generating energy. With the available wind power increasing as wind velocity cubed, the higher winds at the upper levels of tall towers present a potential opportunity to access greater wind energy than is available at ground level. There is also in principle an opportunity to use the amplified winds around tall towers to naturally ventilate the building. In hot climates the increased winds around the tower's base can, in conjunction with shading, provide opportunities to improve the thermal comfort around the building.

This paper will examine situations where wind is the foe and measures that can be taken to frustrate the foe. It will also look at situations where it is a friend and look at how far one can go in enlisting the help of this friend.

Wind as the Foe

Influence of Shape and How to Confuse the Foe

One of the critical phenomena that effect tall slender towers is vortex excitation, which causes strong fluctuation forces in the crosswind direction. This is probably the main behaviour that distinguishes tall towers from mid-rise buildings. The well-known expression of Strouhal gives the frequency N at which vortices are shed from the side of the building, causing oscillatory across-wind forces at this frequency.

$$N = S\frac{U}{b} \qquad (1)$$

where S = Strouhal number, U = wind speed, b = building width.

The Strouhal number is a constant with a value typically in the range 0.1 to 0.3. For a square cross-section it is around 0.14 and for a rough circular cylinder it is about 0.20. When N matches one of the natural frequencies N_r of the building, resonance occurs which results in amplified crosswind response, as illustrated in Figure 1. From Equation 1 this will happen when the wind speed is given by

$$U = \frac{N_r b}{S} \qquad (2)$$

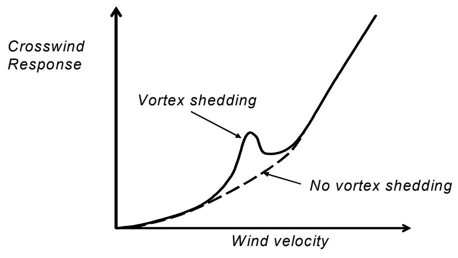

Figure 1. Effect of Vortex Shedding on Response

The peak in the response in Figure 1 can be moved to the right on this plot if the building natural frequency is increased and if it can be moved far enough to the right the wind speed where the peak occurs will be high enough that it is not a concern. This is the traditional approach of adding stiffness but this approach can become extremely expensive if the peak has to be moved a long way to the right. However, the height of the peak is sensitive to the building shape and, with astute aerodynamic shaping, the peak can be substantially reduced or even eliminated. There are several directions that one can go in developing an aerodynamically favourable shape, Figure 2.

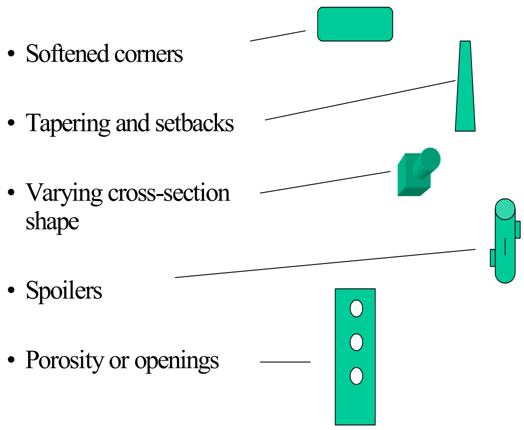

Figure 2. Shaping strategies

- **Softened Corners: -** Square or rectangular shapes are very common for buildings and experience relatively strong vortex shedding forces. However, it is found that if the corners can be "softened" through chamfering, rounding or stepping them inwards, the excitation forces can be substantially reduced. The softening should extend about 10% of the building width in from the corner. The corners on Taipei 101 where stepped in order to reduce crosswind respond and drag, resulting in a 25% reduction in base moment, Irwin (2005).
- **Tapering and Setbacks: -** As indicated in Equation 1, at a given wind speed, the vortex shedding frequency varies depending on the Strouhal number *S* and width *b*. If the width *b* can be varied up the height of the building, through tapering or setbacks, then the vortices will try to shed at different frequencies at different heights. They become "confused" and incoherent, which can dramatically reduce the associated fluctuating forces. Burj Dubai, Figure 3, is a classic example of this strategy.

Figure 3. Burj Dubai spiralling set backs

(photo courtesy Skidmore Owings & Merrill)

- **Varying Cross-Section Shape-** A similar effect can be achieved by varying the cross-section shape with height, e.g. going from square to round. In this case the Strouhal number *S* varies with height, which again, in accordance with Equation 1 causes the shedding frequency to be different at different heights. This again results in "confused" vortices.
- **Spoilers: -** One can also reduce vortex shedding by adding spoilers to the outside of the building. The most well known form of spoilers is the spiral Scruton strake used on circular chimneystacks. Architecturally and practically, the Scruton strake leaves something to be desired for circular buildings, but other types of spoiler could be used that might be more acceptable, such as vertical fins at intervals up the height.
- **Porosity or Openings: -** Another approach is to allow air to bleed through the building via openings or porous sections. The formation of the vortices becomes weakened and disrupted by the flow of air through the structure.

While vortex shedding is the principal culprit causing undesirably high crosswind motions, another cause is buffeting by turbulence cast off from upstream buildings. This is less easy to deal with through the building shape since the origin of the turbulence is not the building itself. However, some cross-sectional shapes, e.g. a lens shape, are more prone to across-wind buffeting because their streamlined shape causes them to act somewhat like a vertical aerofoil, generating high crosswind force variations for relatively small changes in angle of attack of the wind. Shape changes that make them less like an aerofoil can help in this situation. The best tool for assessing shape effects is the wind tunnel. Irwin et al (1998) describe wind tunnel experiments with different shapes. However, though hundreds of tall buildings are tested annually in commercial wind tunnel laboratories around the world, there is only limited feedback received about the actual performance of these tall buildings.

Recent comparisons of wind tunnel predictions with the long-term measured wind-induced accelerations of tall buildings in Chicago (Kilpatrick 2007) reaffirm the validity and effectiveness of wind tunnel model methods to predict the response of tall buildings to wind. A comparison of the predicted accelerations of a 344m tower with measured data acquired during a winter 2003 wind storm is given in Figure 4.

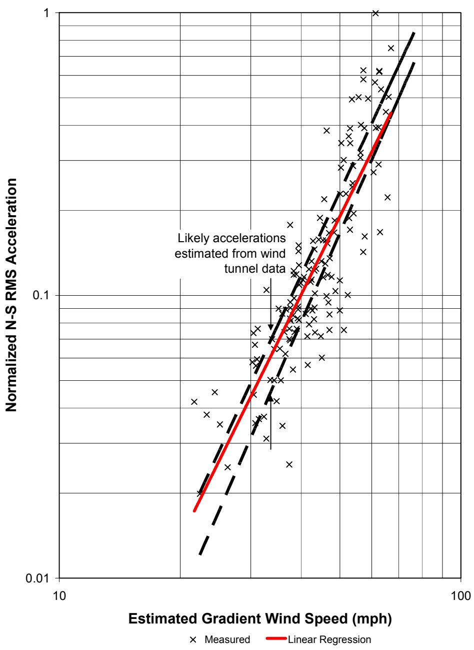

Figure 4. Comparison of RMS Accelerations

On average, the measured data compare favourably with the wind tunnel predictions. Linear regression curves fitted to the measurements indicate that total damping ratio increases with wind speed, likely including an amplitude-dependant structural damping component, in addition to a positive aerodynamic damping component in the along-wind direction. Some data suggested negative aerodynamic damping in the across-wind direction, re-inforcing the need for aeroelastic model tests for super-tall buildings.

Supplementary Damping Systems

A tall tower under the action of wind tends to act as an energy storage device. The fluctuating wind forces cause the tower to move and the motions gradually build up, alternately exchanging kinetic energy with stored elastic energy as the building sways to and fro. The limit on these motions is set by the ability of the tower to dissipate energy faster than the rate at which the wind feeds energy in. A measure of the tower's energy dissipation ability is its damping ratio: the higher the damping ratio, the better. For the purpose of determining building accelerations the inherent damping ratio in tall buildings is usually assumed to be in the range of 0.01 to about 0.02. However, there is considerable uncertainty as to its exact value and it appears possible that it might be significantly lower than 0.01 in some buildings.

The approach of adding supplementary damping to the structure therefore has two benefits: a) it clearly can reduce motions by increasing the towers ability to dissipate energy; and b) it greatly reduces the uncertainty as to what the building damping actually will be. As described by Irwin and Breukelman, 2001, there are a variety of types of damping system that can be used.

- Tuned Mass Damper (TMD) systems which are passive
- Active Mass Damper (AMD) systems
- Tuned Liquid Dampers (Liquid Column, Sloshing)
- Distributed Viscous Dampers
- Visco-elastic Damping

The optimum choice for any given project will depend on a variety of factors: the amount of damping needed, space available, the number of modes of vibration involved, accessibility for maintenance etc.

The Tuned Mass Damper has been quite popular. The principle is illustrated in Figure 5, it being that a small mass m is attached to the main mass of the tower M via a "spring" and viscous damping system, the natural frequency of the small mass-spring system being tuned to close to that of the main system. The Taipei 101 TMD, Figure 6, is a prominent example of this type, the "spring" in this case being based on the gravity stiffness provide by the pendulum principle. The mass m is a 660 tonne steel ball suspended high in the tower. The Taipei 101 application is unusual in that the TMD has been used as a special feature and attraction of the tower, being visible to visitors as illustrated in Figure 7. As the building period becomes longer the simple pendulum type TMD does require plenty of vertical space. Where vertical space is not available, more complex pendulum devices can be used such as the compact compound pendulum TMD used in the Bloomberg tower in New York, Figure 8. AMD systems can provide more damping for the same mass, being driven by active control systems, and can handle more than one mode of vibration. However, they are more complex and, although the mass may be smaller, some of the saved space is used up by the larger stroke requirements.

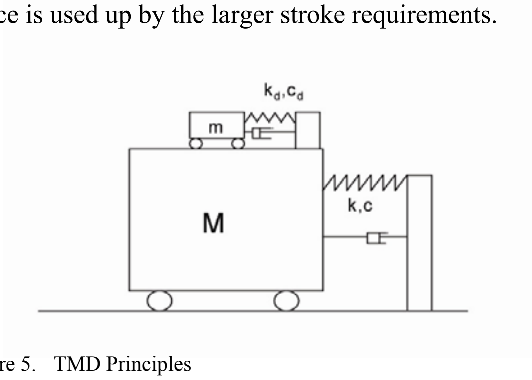

Figure 5. TMD Principles

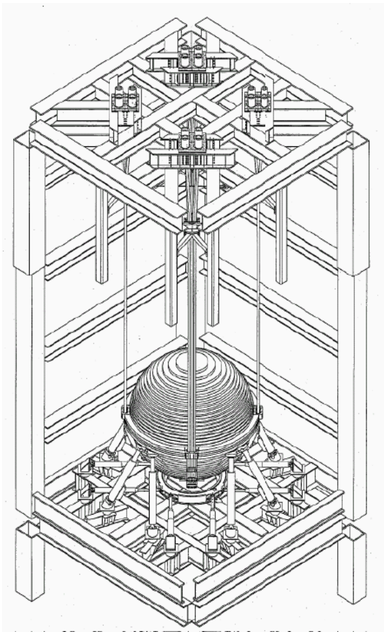

Figure 6. Schematic of Taipei 101 Simple Pendulum TMD

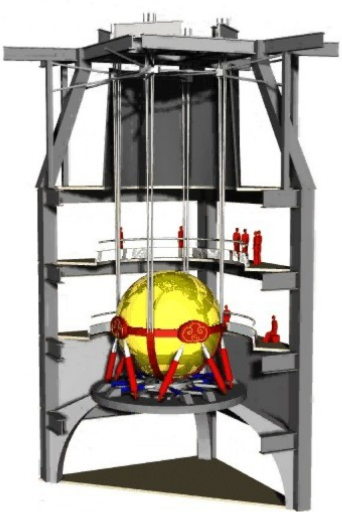

Figure 7. Taipei 101 TMD as an Attraction

Distributed viscous or viscoelastic dampers can be effective but there are a number of practical issues to solve in integrating them into the structural system. Care is needed to make sure that the dampers will be effective at the operational amplitudes involved (Irwin and Breukelman, 2001).

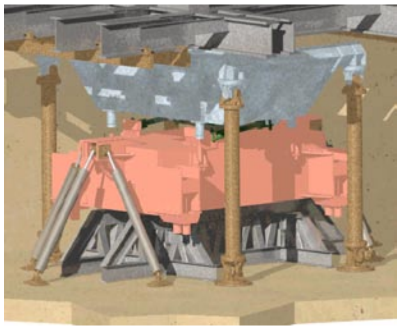

Figure 8. Compact Compound Pendulum TMD

Bloomberg Tower, New York

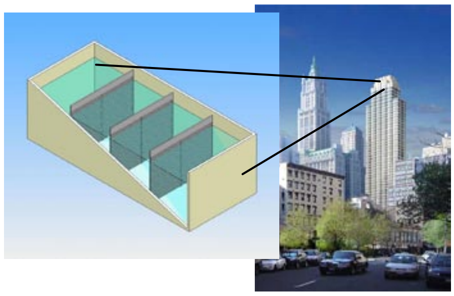

Figure 9. Tuned Sloshing Damper

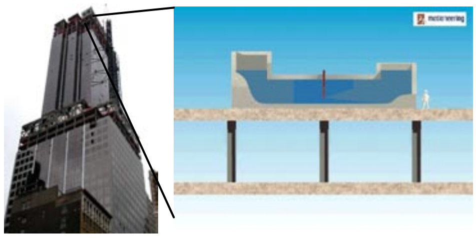

Figure 10. Tuned Liquid Column Damper

Random House, New York

Wind as the Friend

Wind Turbines

The simplest place conceptually to put a wind turbine on a tall building is right on top, high enough above the roof to be free of the disturbed airflow in the separation zone close to the roof. Provided there are no other tall towers of similar height nearby this gives the wind an uninterrupted path to the turbine for all wind directions. It is interesting to examine how much power one can obtain from such a turbine, assuming it can turn to face any wind direction, in comparison to the typical power consumption of the building. As a reference extreme case we will examine the situation where the turbine diameter is the same as the maximum width of the building.

The building selected is one tested by RWDI in its wind tunnels. It is a 41-floor, 137 m high, rectangular tower with side dimensions of 52 m by 23 m. It is assumed to be in a climate similar to that of Rochester, New York, where the average wind speed at 10 m height in open terrain is 4.5 m/s.

Assume the turbine center is 30 m above the roof with a diameter equal to the larger building dimension of 52 m. This is a massive turbine but we are looking to gain an impression of what it takes to obtain significant wind power. Assuming the building is located in a suburban environment the average wind speed $\overline{V}$ at the turbine height is estimated to be $\overline{V} = 5.79$ m/s. The available power per square meter of approaching wind may be calculated from

$$P = \tfrac{1}{2}\rho\overline{V^3}T \qquad (3)$$

where $\rho =$ air density (about 1.2 kg/m3), $\overline{V^3}$ = average of the cube of wind velocity, and T = numbers of hours per year. Assuming the wind speed distribution is approximately Rayleigh in form, then $\overline{V^3}$ may be estimated using $\overline{V^3} \approx 1.91\overline{V}^3$. Also $T \approx 8766$ hours. Therefore the available power in the wind at turbine height is calculated to be

$$P = 1{,}945 \text{ kWh/(yr.m}^2\text{)} \qquad (4)$$

To calculate the energy extracted by the turbine the available wind power *P* is multiplied by the turbine area and the turbine efficiency. Even an ideal turbine cannot exceed about 59% efficiency (the so-called Betz efficiency) because much of the airflow tends to deflect around the turbine due to the turbine drag. Real turbines typically do not achieve overall efficiencies above about 40%. Assuming 40% efficiency the 52 m diameter turbine will therefore extract the following energy *E* from the wind.

$$E = 1945 \times 2123 \times 0.4/1000 = 1.65 \text{ MWh/yr} \qquad (5)$$

Assuming the building uses approximately 300 kWh/(yr.m^2) and that the used floor area is about 45,000 m^2, its energy consumption will be 13.5 MWh/yr. Comparing this figure with the energy from the wind turbine it is estimated that the turbine can produce about 12% of the building's energy requirements. However, this is with a very large 52 m diameter turbine, which could pose many design problems to mount on top of a building. Smaller turbines will clearly produce much less power. For example a more modest 10 m diameter turbine would produce less than ½ % of the building's requirements in the wind zone we have selected. Clearly wind power needs to be considered as just one component in a series of measures to reduce a towers dependence on external sources of energy, since the incremental improvement it provides is unlikely to come close to meeting the total demand.

Figure 11a. Pearl River Tower

(photo courtesy of Skidmore Owings & Merrill)

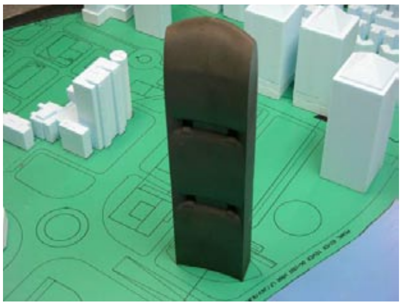

Figure 11b. Wind Tunnel Model of Pearl River Tower

Schemes that involve locating the turbines lower in the building than on the roof have been used in some designs. There are additional complexities to be examined for these schemes, primarily caused by the disturbed airflows created by the surrounding structure of the tower. In one of the designs considered for the Freedom Tower in New York, the approach was taken of having a very open cable structure in the upper portions to reduce these disturbances. Such structures at altitude can attract significant ice accumulations under certain meteorological conditions (in cloud icing), and the potential hazards of falling ice need to be dealt with. Another example of turbines located lower in the tower is the Pearl River Tower, designed by Skidmore Owings Merrill, Figures 11a and 11b. In this case the wind speeds at the turbine locations were increased through aerodynamic shaping of the entrance channels. The shaping of the channels also increased the ranges of wind directions where the turbines were able to operate.

RWDI's experience on several projects is that, because of the wind speed cubed relationship for wind power, it is very important to evaluate the aerodynamic interference of the wind caused by surrounding structures since they can have a large impact on available wind energy.
Natural

Ventilation and Connection to the Outdoors

Sustainable high-rise buildings that provide comfortable, healthy and efficient work-life environments are clearly desirable as the densification of living space for the world's increasing population proceeds. One component of this is the provision of fresh air and a connection to the outdoors, which can be achieved through natural ventilation, using operable windows, double facades, ventilation stacks, balconies, patios, terraces and gardens. There can be multiple benefits to these types of building components. Large amounts of fresh air can be provided to the spaces without the need for power-consuming ventilation equipment. Occupants can control and increase the fresh air provision as needed. Depending on the climate, cooling loads may be removed without the need for mechanical conditioning, or at least ventilation loads can often be reduced. Building elements such as balconies can also help to reduce solar gains through shading. High-rise residential units that provide access to the outdoors combine the feel and the advantages of living in smaller, sub-urban communities with the advantages of central, high-rise living.

Natural ventilation concepts as well as outdoor spaces at higher elevations need to address the potentially high winds at higher elevations. Unlike wind power potential, which typically falls short of the building's needs, the wind can provide ventilation far in excess of the building's needs. This can be controlled by using smaller openings or operable windows than on lower structures. As well, not uncommon in moderate-height residential towers, balconies, patios and similar structures, frequently experience winds that are too strong from a comfort perspective. Though there is some research into providing improved natural ventilation to residential towers, for example see Priyadarsini et al. (2004), most of the efforts to naturally ventilate tall buildings has been focused on office buildings. Over the last years a number of naturally ventilated towers have been built and evaluated (see Pasquay 2004) using the concept of double facades. Double shells protect operable windows at higher elevations from high wind speeds and solve acoustical problems from operable windows at the same time. One early example of such a building is the Commerzbank building in Frankfurt. The building features a double façade, with operable windows in the interior shell. To control stack effect, the building is subdivided into independent segments which also include 4-storey atria with gardens. The building and wind tunnel model are shown in Figures 12 and 13.

Figure 12: Commerzbank Building in Frankfurt, Germany

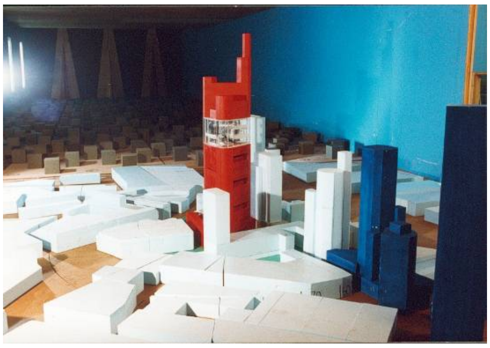

Figure 13. Wind Tunnel Model used for Natural Ventilation Studies of Commerzbank

For future buildings, careful wind engineering can be used to go beyond double facades and create semi-enclosed spaces at high elevations, providing building occupants with sheltered outdoor spaces. Lattices, screens, glazing and wall elements could be used to create desirable, wind-protected and shaded patios and terraces in a high-rise environment.

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