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TORNADO STRUCTURE INTERACTION: A NUMERICAL SIMULATION

Tim Wilson

May 20, 1977

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TORNADO STRUCTURE INTERACTION: A NUMERICAL SIMULATION

Abstract

We examine the effects of tornadoes on buildings to determine the wind forces on structures. The American National Standards Institute (ANSI) has developed guidelines for building code requirements for the minimum wind loads a building must be designed to withstand. We attempt to evaluate the conservatism or non-conservatism on the ANSI approach by simulating tornado-structure interaction numerically with a two-dimensional fluid dynamics computer code and a vortex model. Only

external pressures are considered. The computer calculations yield the following percentages of the ANSI design pressures: rigid frame, 50 to 90%; individual wall panels, 75 to 200%; and wall corners, 50 to 75%. Although the computer program does have its limitations, we conclude that the ANSI approach is a justifiable method for determining reasonable building design loads. In addition, a margin of safety does exist when buildings are designed with this method.

Introduction

The most violent of all atmospheric phenomena are found in the short-lived swirling storms known as tornadoes. Although they occur in all parts of the world, the vast majority of tornadoes are found in the eastern half of the United States, occurring most frequently in late spring and early summer. Approximately 700 tornado strikes are reported each year in this country.

Our primary interest is the effects of tornadoes on buildings. The nuclear power community is currently addressing the problem of tornado-structure interaction (TSI) to

design facilities to reliably withstand a tornado strike. To calculate tornado-induced loads, the structural engineer must be provided with the significant physical properties of a tornado and with an acceptable method to arrive at resulting forces incident on a structure. Tornado properties constitute a Design Basis Tornado (DBT), to be discussed later.

In general, wind forces on structures are calculated using the guidelines in the American National Standards Institute (ANSI) publication, "Building Code Requirements for Minimum Design Loads in Buildings

and Other Structures," (ANSI A58.1-1972) or in ASCE paper No. 3269, "Wind Forces on Structures," (1961). It is important to note that neither publication addresses tornadic winds. The ANSI Standard approach (see Appendix A) involves the conversion of a mean-velocity profile in a straight, quasi-steady wind field to a design load using the wind-velocity pressure and empirically defined pressure coefficients for the building shape in question. The extension of the ANSI approach to tornado winds has been made by several investigators; (see McDonald, et al., 1975; Rotz, et al., 1974; and Shanahan, 1976).

Here, we have attempted to evaluate the conservatism or nonconservatism in an ANSI approach to calculations of tornado-wind loadings. This is accomplished by simulating tornado-structure interaction numerically with a two-dimensional fluid dynamics computer code (BBC) and a suitable vortex model. In this regard, only

external pressures are considered. Seven cases of numerical TSI are examined. In each case, the vortex flow field is allowed to engulf the structure long enough for the important fluid-dynamic effects to develop.

To place these calculations in proper perspective, we must consider the tornado phenomenon as a whole. The next two sections give a brief meteorological description of the phenomenon we are trying to model. Current engineering practice to determine tornado design-wind loading is discussed in a third section. Because our knowledge of tornadoes is far from complete, there remains considerable question over what constitutes a tornado flow field. Any attempt to model a tornado vortex must address this question and we consider this problem in a separate section. Previous efforts at modeling tornadoes theoretically, numerically, and experimentally are also discussed.

Tornado Characteristics

A precise description of the tornado, its cause, or source of energy and rotation has yet to be developed. In general, tornadoes are spawned from thunderstorm systems. The energy source is generally believed to be buoyant potential energy that is derived from condensing water vapor

in an unstable atmosphere (Lilly, 1969; Fulks, 1962). The mature tornado is an intense vortical storm characterized by a rapidly rotating, central air column known as the "core" and an outer region of essentially irrotational flow which extends radially away from the core.

Typically, the core region is a few hundred yards in diameter with peak tangential wind speeds of approximately 200 mph.

Physically, the tornado is most frequently seen to extend downward from the parent cloud, being made visible by the condensation of water droplets. This visible funnel cloud may take on a wide range of appearances from a nearly vertical cylinder to a long ropelike pendant to the more familiar, tapering funnel. At times, a tornado may exhibit no visible funnel (e.g., the Xenia, Ohio,

tornado of April 3, 1974). The majority of tornadoes last only a few minutes and traverse a path of up to 15 mi with a typical path width of 1/4 mile. The most violent tornadoes are much longer-lived. On May 26, 1917, a tornado traveled 293 mi across Illinois and Indiana, lasting 7 hr and 20 min (ESSA, 1969). Table 1 lists typical tornado characteristics. A more complete review of tornado characteristics and the attendant meteorology is given by Davies-Jones and Kessler (1974).

Windspeeds and Classification of Tornadoes

From 1953 to 1972, tornadoes were responsible for approximately 113 deaths and over \$75 million in property damage annually (Davies-Jones and Kessler, 1974). To rationally apply tornado statistics, we

need a means of specifying the intensity and affected area of a tornado strike as well as the attendant probabilities. The probability, P , of a tornado strike in a year's time may be defined as

$$P = \frac{(\text{area of average damage path}) \times (\text{frequency})}{(\text{geographical area})} .$$

For a given location in the most tornado-prone area of the country, $P = 0.0363$ (ESSA, 1969). Further discussions of tornado strike and damage probabilities are given by Abbey and Fujita (1975), Wen and Chu (1973), Doan (1970),

McDonald et al. (1974, 1975), Abbey (1976), and Markee et al. (1974). Hart (1976) discusses structural damage and dollar loss probabilities.

A knowledge of the maximum tangential windspeed is essential for

Table 1. Tornado characteristics.

Location	Almost exclusively in the eastern half of the U.S. but tornadoes have been reported in all 50 states.
Time of Year	Peak occurrence in April, May, and June
Time of Day	Typically, 3:00 to 7:00 p.m. local time
Frequency	600 to 1000/yr
Lifetime	15 to 60 min ^a
Funnel Shape	Various: inverted cone, long ropelike, cylindrical, multifunnel, or no funnel at all
Path Length	4.7 mi ^b
Path Width	165 yd ^b
Direction of Rotation	Almost always cyclonic (counterclockwise)
Peak Tangential Windspeeds	Estimated at ~300 mph for most severe tornadoes
Direction of Travel	Southwest to northeast
Translational Velocity	0 to 70 mph, 30 mph average
Temperature	73.6°F ^c
Dew Point	62.2°F ^c
Atmospheric Pressure Change	0.05 to 0.1 atm ^a
Sea Level Pressure	1007.1 mbar ^c

^aYing and Chang (1970).

^bHowe (1974).

^cSurface conditions at the time of tornado strike (Pearson, 1976).

describing tornado intensity. As noted earlier, a gap remains in our knowledge of the physics of tornadoes. Field data is scarce and hence, even the value of windspeeds is of considerable doubt. Meteorological instruments, even if properly located, cannot be expected to survive a severe tornado. Highest estimates for maximum tangential windspeeds range around 350 mph. Most estimates are 50 to 100 mph lower. Golden (1976) has reviewed many of these estimates and suggests 240 to 250 mph as the peak windspeed. Current methods for estimating windspeeds include photogrammetric analysis of motion pictures and still pictures of tornadoes, damage surveys, analysis of ground marks, doppler radar and lidar, and aircraft probes of water spouts.

A general characterization of tornado intensity has been developed by Fujita and Pearson (1973). Their FPP scale (Tables 2 and 3) reflects maximum windspeeds, path length, and path width as obtained from damage surveys. An F-scale rating from 0 to 6 can be assigned to a tornado, reflecting windspeeds and expected damage.

Table 2. Fujita F scale (after Fujita, 1971).

F Scale	Windspeeds (mph)	Damage
F0	40-72	light
F1	73-112	moderate
F2	113-157	considerable
F3	158-206	severe
F4	207-260	devastating
F5	261-318	incredible
F6	319-sonic speed	inconceivable

Table 3. Pearson path length and width scale (after Fujita and Pearson, 1973).

Scale	Path Length (mi)	Path Width (yd)
Negative	<0.3	<6
0	0.3-0.9	6-17
1	1.0-3.1	18-55
2	3.2-9.9	56-175
3	10-31	176-556
4	32-99	560-1584 (0.3-0.9 mi)
5	100-315	1760-5456 (1.0-3.1 mi)
6	315-999	5632-17,424 (3.2-9.9 mi)

Tornado Structure Interaction

Tornado-resistant design is now required for all nuclear facilities. A recent USNRC publication, "Design Basis Tornado for Nuclear Power

Plants" (Regulatory Guide 1.76, AEC, 1974), lists the requirements for tornado-safe designs and the physical parameters of a Design Basis Tornado

(DBT). In part, the report states that "Nuclear power plants must be designed so that the plants remain in a safe condition in the event of the most severe tornado that can reasonably be predicted to occur at a site as a result of severe meteorological conditions." Hence, absolute protection is required. Supplemental information to Regulatory Guide 1.76 may be found in AEC Standard Review Plans 3.3.1 (1974), 3.3.2 (1974), and in Markee et al. (1974).

Structural damage resulting from tornadoes is usually divided into two categories, wind effects and missile-impact effects. Wind effects are further broken down into pressures induced by the wind flowing over and around the building and pressures induced by the low-pressure core region of the tornado. (Missile-related forces and damages are not considered in this report.)

The DBT characteristics currently in use are given in Table 4 and the geographic-intensity regions are shown in Fig. 1. This list is far from complete but it does provide a starting point for tornado-resistant design. A complete listing and discussion of USNRC and industry criteria has been given by Stevenson (1976).

Additionally, a suitable vortex model is needed to define the flow field. Regulatory Guide 1.76 does

not provide such a model. The most frequently used model is the Rankine Combined Vortex in which the tangential-velocity field is given by an inner region of solid-body rotation and an outer potential-flow region. Here,

$$v = \frac{rv_m}{r_m}, \quad 0 \leq r \leq r_m;$$

$$v = \frac{r_m v_m}{r}, \quad r_m \leq r < \infty; \quad (1)$$

where v_m is the maximum tangential velocity and r_m is the radius where v_m occurs. Definitions of other terms are presented in the Nomenclature section. The use of this model is based on the work of Hoecker (1960, 1961) who photogrammetrically analyzed the Dallas tornado of April 2, 1957. Further qualitative justification for this model has been provided by more recent photogrammetric studies (Golden, 1976), field studies on dust devils (Sinclair, 1973), and velocity-field measurements made on laboratory vortex flows (Chang, 1969, 1971). From Hoecker's work, approximate expressions for radial and vertical velocity are

$$u = \frac{v}{2}, \quad (2)$$

$$w = \frac{2v}{3}. \quad (3)$$

The rotational component of the wind is usually defined as the vector

Table 4. Design Basis Tornado characteristics (USNRC Regulatory Guide 1.76, 1974).

Region	Maximum wind speed ^a (mph)	Rotational speed (mph)	Translational Speed (mph)		Maximum rotational speed (feet /sec)	Pressure Drop (psf)	Rate of Pressure Drop (psi/sec)
			Maximum ^b	Minimum ^b			
I	360	200	100	0	170	120	2.0
II	300	200	0	0	140	110	1.2
III	240	190	0	0	110	110	0.6

^aThe maximum wind speed is the sum of the rotational speed component and the maximum translational speed component.

^bThe minimum translational speed, which allows maximum transit time of the tornado across exposed plant features, is to be used whenever low travel speeds (maximum transit time) are a limiting factor in design of the ultimate heat sink. The ultimate heat sink is that complex of water sources, including associated retaining structures, and any lands or facilities connecting the sources with, but not including, the intake structures of nuclear reactor units. Regulatory Guide 1.27 (Safety Guide 27), "Ultimate Heat Sink," describes a basis that may be used to implement General Design Criterion 4 of Appendix A to 10 CFR Part 50 with regard to the ultimate heat sink.

Fig. 1. Tornado intensity regions of the continental United States.

sum of the radial and tangential components:

$$V_{\text{rot}} = \sqrt{u^2 + v^2} \quad (4)$$

The maximum windspeed V_{max} is obtained with the addition of the translation speed of the tornado:

$$V_{\text{max}} = V_{\text{rot}} + V_{\text{trans}} \quad (5)$$

Equations (1) and (5) form the basis for most engineering wind-velocity pressure calculations.

To account for atmospheric pressure change (APC) effects, one additional equation is needed. If the tornado flow field is assumed to be axisymmetric and tangential, the radial momentum equation reduces to the cyclostrophic wind equation:

$$\frac{\partial P}{\partial r} = \frac{\rho v^2}{r} \quad (6)$$

This relationship may be thought of as a balance between inward pressure forces and outward centrifugal forces. Substituting Eq. (1) into Eq. (6) and integrating yields, the pressure field is obtained:

$$P = P_0 - \frac{\rho v_m^2}{2} \left(2 - \frac{r^2}{r_m^2} \right),$$

$$0 \leq r \leq r_m;$$

$$P = P_0 - \frac{\rho v_m^2}{2} \left(\frac{r_m^2}{r^2} \right),$$

$$r_m \leq r < \infty; \quad (7)$$

where P_0 is the ambient atmospheric pressure. Hence, the second term on the right side of each expression may be thought of as a pressure deviation (APC) from ambient conditions.

With the DBT and tornado vortex model thus defined, all that remains is to convert the wind field parameters into external structural pressures. Design forces obtained with an ANSI Standardlike approach are outlined below.

CALCULATING VELOCITY PRESSURES

The velocity (stagnation) pressure is related to velocity by

$$P = \frac{1}{2} \rho v^2 \quad (8)$$

Upon substitution of the rotational and tangential components of the vortex flow into Eq. (8), we obtain an expression for velocity pressure as a function of radial distance from the center of the tornado:

$$P(r) = \frac{1}{2} \rho \left[V_{\text{rot}}(r) + V_{\text{trans}} \right]^2, \quad (9)$$

or

$$P(r) = \frac{1}{2} \rho \left(\sqrt{u^2 + v^2} + V_{\text{trans}} \right)^2. \quad (10)$$

From the Rankine vortex model,

$$P(r) = \frac{1}{2} \rho \left[\frac{r}{r_m} V_{\text{rot(max)}} \right]^2, \quad 0 \leq r \leq r_m;$$

$$P(r) = \frac{1}{2} \rho \left[\frac{r_m}{r} V_{\text{rot(max)}} \right]^2, \quad r_m \leq r \leq \infty. \quad (11)$$

Hence,

$$P_{\text{max}} = \frac{1}{2} \rho V_{\text{rot(max)}}^2 \quad (12)$$

or

$$P_{\text{max}} = 0.00256 V_{\text{rot(max)}}^2,$$

where P_{max} is the maximum velocity pressure (psf) and $V_{\text{rot(max)}}$ is the maximum wind speed (mph). The constant term 0.00256 incorporates the

standard sea-level density of air (0.07651 pcf at 760 mm of mercury and at 15°C). A plot of velocity pressure and APC vs radius is given in Fig. 2.

CALCULATING BUILDING SIZE COEFFICIENT

From Eq. (12), we see that velocity pressure is not uniform. For design purposes, it is convenient to define a size coefficient, C_s , as

$$C_s = \frac{P_{\text{avg}}}{P_{\text{max}}}. \quad (13)$$

We obtain C_s by integrating $P(r)$ over the contributing width, L , of the building:

$$P_{\text{avg}} = \frac{1}{L} \int_a^b P(r) dr, \quad (14)$$

Fig. 2. Velocity pressure and APC for a Rankine vortex.

$$P_{avg} = \frac{\rho V_{rot(max)}^2}{2L} \times \left(\frac{4r_m^3}{3} - \frac{a^3}{3r_m^2} - \frac{r_m^2}{b} \right) \quad (15)$$

This integration is maximized when $ab = r_m^2$ and the design-size coefficient becomes

$$C_s = \frac{4r_m^3 - a^3 - 3ar_m^2}{3Lr_m^2} \quad (16)$$

where

$$a = -\frac{L}{2} + \sqrt{\frac{L^2}{4} + r_m^2}$$

DETERMINING DESIGN VELOCITY PRESSURES

External pressure coefficients, C_p , are used to obtain design forces on exterior walls and corners. Values for C_p are given in Section 6.5 of the ANSI Standard and are listed here in Appendix B. Pressure coefficients are experimentally obtained for straight wind flows around rectangular structures. The design pressure for rigid frames is

$$P = C_s C_p P_{max} \quad (17)$$

while the design pressure for individual wall panels is

$$P = C_p P_{max} \quad (18)$$

From Eq. (7), the maximum change in atmospheric pressure is found to be

$$\Delta P_{max} = \frac{1}{2} \rho v_m^2 \quad (19)$$

COMBINING WIND LOADING EFFECTS

Tornado wind-loading effects are accounted for by applying the following definitions:

$$W_t = W_q \quad (20)$$

$$W_t = W_a \quad (21)$$

$$W_t = W_q + \frac{1}{2} W_a \quad (22)$$

where W_t = design load, W_q = load due to wind velocity, and W_a = load due to APC. Equation (22) arises when summing W_q and W_a at $r = r_m$. Here, the APC is exactly half of its maximum value.

The foregoing discussion assumes a design vortex model that has no vertical variation in u or v . Most current design models are based on Hoecker's analysis and some include vertical variations in v near the ground. Shanahan (1976) has developed several design-purpose models that include velocity components and gradients; a basic Rankine profile is used as a basis.

Tornado Simulation

THEORETICAL MODELS

The tornado flow field can be visualized in four regions (Lewellen, 1976) which are shown in Fig. 3. In brief, these regions may be described as follows:

- Region I: The core-flow region; it extends radially from the tornado centerline out to perhaps a few thousand meters. Vertically, it extends from about a hundred meters above ground to the cloud ceiling.
- Region II: The boundary-layer region; flow is strongly influenced by the ground.

● Region III: The corner-flow region; approximate r and z dimensions are 200 and 100 m. Boundary effects are dominant here also. All components of velocity and velocity gradient are important.

- Region IV: The top layer; flow extends from the top of Region I into the thunderstorm cell.

The continuity and momentum equations for axisymmetric, incompressible flow are given in the following cylindrical coordinate form:

$$\frac{1}{r} \frac{\partial(ru)}{\partial r} + \frac{\partial w}{\partial z} = 0 ; \quad (23)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + w \frac{\partial u}{\partial z} - \frac{v^2}{r} = -\frac{1}{\rho} \frac{\partial p}{\partial r} + \nu \left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} - \frac{u}{r^2} + \frac{\partial^2 u}{\partial z^2} \right) , \quad (24)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial r} + w \frac{\partial v}{\partial z} + \frac{uv}{r} = \nu \left(\frac{\partial^2 v}{\partial r^2} + \frac{1}{r} \frac{\partial v}{\partial r} - \frac{v}{r^2} + \frac{\partial^2 v}{\partial z^2} \right) , \quad (25)$$

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial r} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + \nu \left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r} \frac{\partial w}{\partial r} + \frac{\partial^2 w}{\partial z^2} \right) - g . \quad (26)$$

Fig. 3. Tornado flow regions (after Lewellen, 1976).

Neglected in this formulation is background rotation of the earth, thermodynamic effects, and spatial variation of the diffusion (viscosity) coefficient.

If u and w are neglected, the simplest solution to Eqs. (23-26) that is applicable to Region I is given by the Rankine vortex model, Eq. (1). Angular momentum is satisfied everywhere except in the transition region where $r = r_m$. The pressure distribution follows from Eq. (24) as given in Eq. (7). The Rankine formulation is usually completed by assuming a hydrostatic pressure balance in the vertical direction where

$$v = \frac{r_m}{r} v_m, \quad 0 \leq r < r_m;$$

$$v = \frac{r}{r_m} v_m, \quad r_m \leq r < \infty; \quad (27)$$

$$\frac{\partial p}{\partial r} = -\frac{v^2}{r}; \quad (28)$$

$$\frac{\partial p}{\partial z} = -\rho g. \quad (29)$$

In the Rankine vortex model, the following assumptions are made: axisymmetric flow, incompressible flow, steady flow, $u = w = 0$, and all u and w gradients are zero.

Another simple solution to Eqs. (23-26) that includes all velocity components is the Burgers-Rott vortex model. This model was obtained independently by Burgers in 1948 and by Rott in 1958. Here,

$$u = -ar, \quad (30)$$

$$v = \frac{\Gamma_\infty}{2\pi r} \left[1 - \exp\left(-\frac{ar^2}{2v}\right) \right], \quad (31)$$

$$w = 2az, \quad (32)$$

$$P(r, z) = P(0, 0) + \rho \int_0^r \frac{v^2}{r} \times dr - \frac{\rho a^2}{2} (r^2 + 4z^2), \quad (33)$$

where $\Gamma_\infty = rv|_{r=\infty}$, a constant called the circulation, and $2a$ = horizontal convergence, a constant. The Burgers-Rott model gives maximum velocity and pressure drops of

$$v_m = \frac{0.72}{2\pi r_m} \left(r_m = 1.12 \sqrt{2\nu/a} \right),$$

$$\Delta P_{\max} = 1.68 \rho v_m^2.$$

A third, more general series of solutions is given by Donaldson and Sullivan (1960) and Sullivan (1959) gives a two-celled solution with the following velocity components:

$$u = -ar + \frac{6\nu}{r} \times \left[1 - \exp \left(-\frac{ar^2}{2\nu} \right) \right], \quad (34)$$

$$v = \frac{\Gamma_\infty}{r} \left[\frac{H(ar^2/2\nu)}{H(\infty)} \right], \quad (35)$$

$$w = 2az \left[1 - 3 \exp \left(-\frac{ar^2}{2\nu} \right) \right], \quad (36)$$

where,

$$H(x) = \int_0^x \exp \left[-t + 3 \times \int_0^t \frac{(1-e^{-s})}{s} ds \right] dt.$$

It should be noted that in this solution, v is essentially decoupled from u and w .

A comparison of the tangential velocity profiles for these three models is given in Fig. 4 where the Burgers-Rott and Sullivan models have

been normalized to have the same Γ_∞ and a/ν ratio.

Other vortex models are given by Gutman (1957), Long (1961), and Lewellen (1962). Two-celled models are developed by Sullivan (1959), Kuo (1966), and Bellamy-Knights (1970). Models dealing with the flow in Regions II and III are given by Smith and Smith (1965), Chi et al. (1969), Burggraf et al. (1971), Carrier (1971), Kuo (1971), and Serrin (1972).

Advances in computing capability have enabled the development of several numerical models of the tornado vortex. The vortex is modeled as an axisymmetric flow in the r, z plane. Incompressibility is usually assumed. The type of numerical scheme, the treatment of boundary conditions, and the treatment of viscous effects vary from model to model.

Fig. 4. Comparison of tangential velocity profiles (after Lewellen, 1976).

Computer programming of the continuity, momentum, and energy equations is accomplished by various finite-difference techniques. The equations are usually cast in a vorticity-stream function form or in the so-called primitive-variable form where u , v , w , and P are computed directly. Results are strongly influenced by the choice of boundary conditions. Usually, one or more assumptions must be made concerning the velocity profiles at the r and z computational boundaries. The treatment of v , which must be regarded as an eddy viscosity, also strongly influences the results. Lewellen (1976) discusses the need for a better model of atmospheric turbulence in this regard.

Recent calculations of vortex flow in and above the boundary layer, include Bode et al. (1975); Hsu and Tesfamariam (1976); Jischke and Parang (1975); Chi and Jih (1974); Harlow and Stein (1974); Mal'Bakhov (1972); Davies-Jones and Vickers (1971); and Wipperman et al. (1969).

LABORATORY MODELS

Laboratory vortex flows have provided valuable insight into the fluid dynamics of tornadoes. Numerous experiments have been undertaken, most in the last fifteen years. Historically, these efforts fall into two general categories, rotating tank

experiments and vortex chamber experiments. Many of the flows generated strongly resemble tornadoes, at least outwardly. However, as discussed by Davies-Jones (1976), physical appearance alone does not guarantee that the model is similar to a tornado.

Similarity requirements between full-scale and laboratory simulations apply equally to the more common "straight wind" situation. Cermak (1973) outlines the following similarity requirements imposed by the conservation of mass, momentum, and energy:

- Undistorted scaling of geometry.
- Equal Rossby number,
 $Ro = U/\omega L$.
- Equal Richardson number,
 $Ri = (U/T)(L/v^2)g$.
- Equal Reynolds number,
 $Re = UL/\nu$.
- Equal Prandtl number,
 $Pr = \nu C_p/k$.
- Equal Eckert number,
 $Ec = U^2/C_p \Delta T$.

Additionally, a similarity is required for the model surface and approach flow conditions (see Chang, 1971, for a discussion of similarity requirements for tornado flows).

In all probability, no laboratory vortex model will ever be able to satisfy every similarity requirement but, fortunately for the engineer, this may not be necessary. The Richardson, Prandtl, and Eckert number requirements may be discarded for the present in attempting to understand tornado-structure interaction. Ultimately, however, these parameters cannot be ignored if all physical effects are to be considered. Tornadoes are typically high-Rossby-number flows based on the background rotation of the earth and typically are of $O(10^3-10^4)$ (Morton, 1966). Defining tangential and radial Reynolds numbers, we have

$$Re_t = \tau_0 / \nu,$$

$$Re_r = Q / r_m \nu,$$

where Q = mass flow rate. We see also that Re_t and Re_r typically are of $O(10^9)$, based on the laminar value of kinematic viscosity. While Rossby-number similarity can be obtained in the laboratory, to date, all models are several orders of magnitude low for Re_t and Re_r similarity. When considering the aerodynamics of buildings, Reynolds number will be important.

For laboratory models, only four independent nondimensional numbers

exist (Davies-Jones, 1976). Referring to Figs. 5 and 6, we define r_o/r_s as the ratio of convergent and confluent zone radii, h/r_o as a , the aspect ratio, $\tau_o/2Q$ as S , the swirl ratio, and $Q/2\pi rh$ as N , the radial Reynolds number for a laboratory vortex.

Long (1956, 1958, 1961), Granger (1966, 1972), Turner and Lilly (1963), Turner (1966), among others, have conducted rotating tank experiments. In such experiments, water is extracted from the bottom or top of a cylindrical tank and vorticity is provided by rotating the tank. Turner and Lilly (1963) simulated buoyant effects by injecting suitable nuclei into carbonated water near the axis of rotation.

More recent experimental programs have consisted mostly of vortex chambers. In these, air is used as the working fluid and, typically, a fan provides an undraft. Vorticity is introduced mechanically by a rotating wire screen or disk and flow visualization is accomplished with smoke, dry ice, or helium bubbles. Figure 5 illustrates the vortex model used by Chang (1969), Ying and Chang (1970), and Wan and Chang (1972) at Catholic University. Velocity and pressure measurements were made, respectively, with a hot-film anemometer and a static-sphere probe. The observations of Ying and Chang (1970) include:

- A core diameter above the ground boundary layer $r_c \approx 5$ cm.
- Turbulent flow in the boundary layer.
- A tangential velocity field that closely resembled a Rankine vortex in the three reported tests.
- Small u , except in the lowest 10 cm.
- A sharp, maximum radial-inflow velocity occurring close to the ground (at $z = 0.6$ cm) and varying in proportion to the circulation strength.
- Small w outside of the core region with maximum vertical velocity occurring at the vortex centerline, increasing slowly with height.
- A pressure minimum at the core.

Perhaps the most frequently referenced vortex chamber is Ward's device at the National Severe Storms Laboratory (NOAA-NSSL) in Norman, Oklahoma. Experiments performed there are reported by Ward (1972), Davies-Jones (1973), and Jischke and Parang (1974, 1975). Ward's device (see Fig. 6) attempts to model the radial

Fig. 5. The vortex chamber at Catholic University (after Wan and Chang, 1972).

Fig. 6. Ward's vortex chamber (after Davies-Jones, 1973).

convergence and vertical updraft geometry of a thunderstorm in an attempt to induce a more realistic tornadolike vortex. Ward (1972) notes three characteristics of tornado vortex flow:

- A characteristic surface-pressure profile that includes a high-pressure ring outside the low-pressure core. This profile arises when the pressure effects of purely tangential flow

(cyclotrophic balance) are combined with purely radial flow.

- The tendency of the vortex core to bulge.
- Flow transition to multiple vortices. Ward concludes that this transition is sensitive to the inflow angle θ defined by the ratio $\theta = \tan^{-1} (v/u)$ as measured at the rotating screen.

From these experiments, Ward also concludes that for a given test geometry, the vortex-core size can also be found from the inflow angle. However, Davies-Jones (1973) shows that the volume flow rate, Q , must also be included. Defining the swirl ratio, S , as

$$S = \frac{r_o \tan \theta}{2h},$$

or

$$S = \frac{r_o \Gamma_{\text{screen}}}{2Q},$$

Davies-Jones concludes, after a careful analysis of Ward's data, that the core radius is a function of the swirl ratio, alone, rather than of the inflow angle. This fact has important implications for vortex-building, geometric similarity in laboratory modeling of tornado-structure interaction.

The most extensive tests with Ward's device have been made by Jischke and Parang (1975). Their findings include:

- A pressure minimum at the core.
- u and v vary as $1/r$ and w is negligible in the confluent zone (i.e., where r is large).

- u varies as r , v varies as $1/r$, and w varies as z in the convergent area (i.e., at intermediate values of r outside the core).

The vortex chamber of Hsu and Fattahi at Iowa State University is shown in Fig. 7. In this model, a jet of air is forced downward by a fan. Vorticity is introduced by rotating a honeycomb disk at 1700 rpm. Tests with and without the ground plate conducted by Hsu and Fattahi (1975) show:

- A variable sized core with $r_c \approx 0.5$ in. near the ground.
- u is very small except in the core region at distances greater than 13 in. above the ground.
- The v profile is generally Rankine in nature near the ground; for z greater than 13 in., v increases with r and a jump transition is seen at $r = 6$ in.
- w is a function of z only and increases with height; a jump transition is also seen at $r = 6$ in.

These three vortex chambers appear to be potentially the most applicable to the problems concerning tornado-structure interaction. Chang (1971) conducted a preliminary laboratory study to determine the feasibility of

Fig. 7. Hsu's vortex chamber (after Hsu and Fattahi, 1976).

a vortex simulator to study tornado-wind loadings on a building. A 2-in. cube was instrumented with 80 pressure taps and was allowed to interact with a quasi-stationary vortex. The experimentally obtained pressure contours for both a high- and low-swirl ratio case yield pressure coefficient, C_p , contours ranging from 0 to -0.7.

Net values of C_p for each face of the cube are therefore within this range. It is most interesting to note that no positive pressures were recorded, indicating that the APC dominates the dynamic forces everywhere. (See Davies-Jones, 1976, for a more complete discussion of laboratory vortex models.)

Numerical Modeling of Tornado Structure

Numerical values for building surface pressures are obtained by modeling the tornado-structure interaction phenomena in two dimensions on the ground plane. Hence, for purposes of this study, all vertical components of velocity, velocity gradient, and pressure gradient are ignored. A rectangular building is placed in the flow field of the model tornado. In the series of numerical tests that follow, the tornado is given an initial horizontal velocity profile of a Rankine vortex with characteristics corresponding to the USNRC Design Basis Tornado.

The tornado is allowed to interact with the building for 5 to 10 sec, long enough for dynamic effects to develop. To calculate the flow field, we use a two-dimensional, multifluid, Eulerian hydrodynamics code, BBC. The physical characteris-

tics of the problem are specified by rectangular zoning and an initially specified flow field. The problem is advanced in time by four Lagrangian subcycles with a zone remap at the end of each time cycle (Sutcliffe, 1974).

A plan view of a typical two-dimensional building is shown in Fig. 8 together with the notation that describes the problem. Referring to Fig. 8, we define building-force coefficients C_{Fx} and C_{Fy} as

$$C_{Fx} = \frac{F_x}{(1/2)\rho U_{WH}^2}$$

$$C_{Fy} = \frac{F_y}{(1/2)\rho U_{LH}^2}$$

We made seven TSI runs using three different building sizes. In four cases, the tornado translates into

Fig. 8. Labeling conventions for tornado-structure interaction studies.

the building while, in the three other cases, a stationary vortex is considered. Following is a geometric description of each run plus time-history plots of the building surface pressures. We then draw a comparison with the ANSI Standard approach in three areas: design pressures for rigid frame, design pressures for

individual wall panels, and design pressures for wall corners. In general, we made the most conservative comparison with ANSI design pressures. Other comparisons are possible and would be necessary if an actual structure were being designed. A tabular listing of pressures and force coefficients is given in Appendix C.

Building dimensions:

200 ft (x),

200 ft (y).

Initial vortex characteristics:

$v_m = 290$ mph,

$v_{rot} = 290$ mph,

$v_{trans} = 0$ mph,

$r_m = 150$ ft.

Initial displacement of vortex center
 from building center:

300 ft to the west.

Computational zone width:

20 ft on all building surfaces.

See Figs. 9 and 10 for pressure-time
 histories and air flow patterns for
 this run.

Fig. 9. Surface pressures for run No. 1.

Fig. 10. Velocity vector plots for
run No. 1.

TORNADO STRUCTURE INTERACTION:
RUN NO. 2

Start-up geometry, translating vortex:

Building dimensions:

200 ft (x),

200 ft (y).

Initial vortex characteristics:

$v_m \approx 290$ mph,

$v_{rot} \approx 290$ mph.

$v_{trans} \approx 70$ mph (west to east),

$r_m \approx 150$ ft.

Initial displacement of vortex center
from building center:

300 ft to the west.

Computational zone width:

20 ft on all building surfaces.

See Figs. 11 and 12 for pressure-time
histories and air flow patterns for
this run.

Fig. 11. Surface pressures for run No. 2.

$t = 0 \text{ sec}$

$t = 0.5 \text{ sec}$

$t = 2 \text{ sec}$

$t = 5 \text{ sec}$

2

Fig. 12. Velocity vector plots for run No. 2.

TORNADO STRUCTURE INTERACTION:
RUN NO. 3

Building dimensions:

200 ft (x),

200 ft (y).

Initial vortex characteristics:

v_m = 290 mph,

v_{rot} = 290 mph,

v_{trans} = 0 mph,

r_m = 150 ft.

Initial displacement of vortex center
from building center:

100 ft to the west,

100 ft to the south,

Vortex is positioned over the
southwest corner of the building.

Computational zone width:

20 ft on all building surfaces.

Start-up geometry, stationary vortex:

See Figs. 13 and 14 for pressure-time histories and air flow patterns for this run.

Fig. 13. Surface pressures for run No. 3.

Fig. 14. Velocity vector plots for
run No. 3.

TORNADO STRUCTURE INTERACTION:
RUN NO. 4

Building dimensions:

200 ft (x),

200 ft (y).

Initial vortex characteristics:

$v_m = 290$ mph,

$v_{rot} = 290$ mph,

$v_{trans} = 0$ mph,

$r_m = 150$ ft.

Initial displacement of vortex center
from building center:

None, vortex is centered over the
building center.

Computational zone width:

20 ft on all building surfaces.

Start-up geometry, stationary vortex:

See Figs. 15 and 16 for pressure-
time histories and air flow patterns
for this run.

Fig. 15. Surface pressures for run No. 4.

$t = 0 \text{ sec}$

$t = 0.5 \text{ sec}$

$t = 2 \text{ sec}$

$t = 5 \text{ sec}$

Fig. 16. Velocity vector plots for
run No. 4.

Building dimensions:

200 ft (x),

200 ft (y).

Initial vortex characteristics:

$v_m = 290$ mph,

$v_{rot} = 290$ mph,

$v_{trans} = 70$ mph (southwest to
northeast),

$r_m = 150$ ft.

Initial displacement of vortex center
from building center:

282.8 ft to the west,

282.8 ft to the south.

Computational zone width:

20 ft on all building surfaces.

See Figs. 17 and 18 for pressure-
time histories and air flow patterns
for this run.

Fig. 17. Surface pressures for run No. 5.

2

Fig. 18. Velocity vector plots for run No. 5.

TORNADO STRUCTURE INTERACTION:
RUN NO. 6

Building dimensions:

300 ft (x),
100 ft (y).

Initial vortex characteristics:

v_m = 290 mph,
 v_{rot} = 290 mph,
 v_{trans} = 70 mph (west to east),
 r_m = 150 ft.

Initial displacement of vortex center
from building center:

300 ft to the west.

Computational zone width:

10 ft on west and east walls,
20 ft on south and north walls.

Start-up geometry, translating vortex:

See Figs. 19 and 20 for pressure-time histories and air flow patterns for this run.

Fig. 19. Surface pressures for run No. 6.

$t = 0 \text{ sec}$

$t = 0.5 \text{ sec}$

$t = 2 \text{ sec}$

$t = 5 \text{ sec}$

Fig. 20. Velocity vector plots for run No. 6.

TORNADO STRUCTURE INTERACTION:
RUN NO. 7

Building dimensions:

300 ft (x),

200 ft (y).

Initial vortex characteristics:

v_m = 290 mph,

v_{rot} = 290 mph,

v_{trans} = 70 mph (west to east),

r_m = 150 ft.

Initial displacement of vortex center
from building center:

300 ft to the west.

Computational zone width:

20 ft on all building surfaces.

Start-up geometry, translating vortex:

See Figs. 21 and 22 for pressure-time histories and air flow patterns for this run.

Fig. 21. Surface pressures for run No. 7.

Fig. 22. Velocity vector plots for run No. 7.

Discussion of Results

Using the ANSI Standard approach as a basis, we compared appropriate design pressures for the seven TSI test runs (see Tables 5-11). Numbers listed in parentheses represent the percentages of the governing ANSI design value. All pressures are given in pounds per square foot (psf). When making a comparison, we must note that the terms "windward wall," "leeward wall," and "side wall" have meaning only for a straight wind situation. Additionally, when pressures are quoted for the more common wind-engineering problems, a steady-state flow is usually implied. Neither of these two conventions is directly applicable to the TSI case and hence, the sides of the building are simply denoted as west, east, south and north. Similarly, a time is quoted with reference to an initial flow-field condition.

The high and low calculated pressures, expressed as a percentage of the ANSI value, are summarized:

- Rigid Frames: 34% (run No. 1)
117% (run No. 1)
- Individual
Wall Panels: 51% (run No. 2)
126% (run No. 3)
- Wall Corners: 44% (run No. 2)
79% (run No. 3)

We see that for each run, pressures have a large initial magnitude. Most likely, these values are extremes and are regarded as "high." The initial velocity field "set-up" gives an impulse loading to the walls that results in an early time-pressure spike immediately after $t = 0$. A period of time is needed to allow the flow field to assume a realistic profile; this time is taken to be 0.3 sec. The early time pressures ($t < 0.3$ sec) should not be totally discarded until a detailed analysis can be made of the numerical fluid dynamics of that time period. For the present, the early time values are regarded as upper bounds of BBC-computed pressures for a given problem formulation. A qualitative check on the behavior of the code can be found by examining the results of run No. 4 where a "stationary" vortex is positioned directly over a square building. Figure 15 shows a nearly identical pressure-time history for all four walls. All pressures listed in Tables 5-11 were calculated at $t > 0.3$ sec.

The structural loadings obtained from the two-dimensional BBC calculations are limited in several respects:

- The vortex dissipates. Initially, a tornadolike flow field is

Table 5. Comparison of design pressures (psf) for run No. 1 of the tornado-structure interaction study.

Rigid Frame									
ANSI Standard Approach				BBC Calculation					
				Maximum Average Pressure					
Wall	W_q	W_a	$W_q + (1/2)W_a$	Wall	Positive	Negative			
Windward	97	-413	-119	West	--	-147, 0.3 sec			
Leeward	-60	-431	-276	East	--	-108, 0.75 sec			
				South	114, 1.25 sec	-85, 0.75 sec			
				North	52, 1.75 sec	-105, 1.25 sec			
Positive Design Pressure:			97	Positive Design Pressure: 114 (117%) ^a					
Negative Design Pressure:			-431	Negative Design Pressure: -147 (34%) ^a					
Individual Wall Panels									
ANSI Standard Approach				BBC Calculation					
				Maximum Pressure					
Wall	Pressure			Wall	Positive	Negative			
Windward	172			West	61, 1.0 sec	-187, 0.3 sec			
Side	-151			East	60, 1.0 sec	-212, 0.75 sec			
Leeward	-108			South	134, 1.25 sec	-138, 0.75 sec			
				North	98, 1.75 sec	-170, 0.75 sec			
Positive Design Pressure: 172				Positive Design Pressure: 134 (78%) ^a					
Negative Design Pressure: -151				Negative Design Pressure: -212 (140%) ^a					
Wall Corners									
ANSI Standard Approach				BBC Calculation					
				Maximum Pressure					
Wall	Pressure			Wall	Positive	Negative			
All Corners	-431			East	--	-212, 0.75 sec			
Negative Design Pressure:			-431	Negative Design Pressure: -212 (49%) ^a					

^a Percentage of ANSI Standard approach value.

Table 6. Comparison of design pressures (psf) for run No. 2 of the tornado-structure interaction study.

Rigid Frame						
ANSI Standard Approach				BBC Calculation		
Wall	W _q	W _a	W _q + (1/2)W _a	Maximum Average Pressure		
				Wall	Positive	Negative
Windward	149	-431	-67	West	--	-135, 0.3 sec
Leeward	-93	-431	-308	East	64, 1.75 sec	-216, 2.5 sec
				South	96, 1.25 sec	-87, 2.5 sec
				North	88, 1.75 sec	-136, 2.5 sec
Positive Design Pressure:			149	Positive Design Pressure: 96 (64%) ^a		
Negative Design Pressure:			-431	Negative Design Pressure: -216 (50%) ^a		
Individual Wall Panels						
ANSI Standard Approach				BBC Calculation		
Wall	Pressure			Maximum Pressure		
				Wall	Positive	Negative
Windward	-265			West	82, 1.75 sec	-211, 0.3 sec
Side	-232			East	90, 1.75 sec	-291, 0.4 sec
Leeward	-166			South	134, 0.3 sec	-148, 0.75 sec
				North	127, 1.75 sec	-180, 2.5 sec
Positive Design Pressure:			265	Positive Design Pressure: 134 (51%) ^a		
Negative Design Pressure:			-232	Negative Design Pressure: -291 (125%) ^a		
Wall Corners						
ANSI Standard Approach				BBC Calculation		
Wall	Pressure			Maximum Pressure		
				Wall	Positive	Negative
All Corners	-664			East	--	-291, 0.4 sec
Negative Design Pressure:			-664	Negative Design Pressure: -291 (44%) ^a		

^aPercentage of ANSI Standard approach value.

Table 7. Comparison of design pressures (psf) for run No. 3 of the tornado-structure interaction study.

Rigid Frame						
ANSI Standard Approach				BBC Calculation		
				Maximum Average Pressure		
Wall	W _q	W _a	W _q + (1/2)W _a	Wall	Positive	Negative
Windward	97	-413	-119	West	43, 2.0 sec	-211, 1.25 sec
Leeward	-60	-431	-276	East	58, 1.25 sec	-175, 1.75 sec
				South	17, 5.0 sec	-220, 0.75 sec
				North	--	-210, 0.3 sec
Positive Design Pressure:			97	Positive Design Pressure: 58 (60%) ^a		
Negative Design Pressure:			-431	Negative Design Pressure: -220 (51%) ^a		
Individual Wall Panels						
ANSI Standard Approach				BBC Calculation		
				Maximum Pressure		
Wall	Pressure			Wall	Positive	Negative
Windward	172			West	130, 0.75 sec	-236, 1.25 sec
Side	-151			East	88, 1.25 sec	-213, 0.75 sec
Leeward	-108			South	59, 2.0 sec	-323, 0.75 sec
				North	10, 1.75 sec	-341, 0.40 sec
Positive Design Pressure:			172	Positive Design Pressure: 130 (76%) ^a		
Negative Design Pressure:			-151	Negative Design Pressure: -341 (226%) ^a		
Wall Corners						
ANSI Standard Approach				BBC Calculation		
				Maximum Pressure		
Wall	Pressure			Wall	Positive	Negative
All Corners	-431			North	--	-341, 0.75 sec
Negative Design Pressure:			-431	Negative Design Pressure: -341 (79%) ^a		

^aPercentage of ANSI Standard approach value.

Table 8. Comparison of design pressures (psf) for run No. 4 of the tornado-structure interaction study.

Rigid Frame						
ANSI Standard Approach				BBC Calculation		
				Maximum Average Pressure		
Wall	W_q	W_a	$W_q + (1/2)W_a$	Wall	Positive	Negative
Windward	97	-431	-119	West	--	-171, 0.3 sec
Leeward	-60	-431	-276	East	--	-161, 0.3 sec
				South	--	-171, 0.3 sec
				North	--	-162, 0.3 sec
Positive Design Pressure: 97						
Negative Design Pressure: -431				Negative Design Pressure: -171 (40%) ^a		
Individual Wall Panels						
ANSI Standard Approach				BBC Calculation		
				Maximum Pressure		
Wall	Pressure			Wall	Positive	Negative
Windward	172			West	--	-297, 0.3 sec
Side	-151			East	--	-288, 0.3 sec
Leeward	-108			South	--	-295, 0.3 sec
				North	--	-281, 0.3 sec
Positive Design Pressure: 172						
Negative Design Pressure: -151				Negative Design Pressure: -297 (197%) ^a		
Wall Corners						
ANSI Standard Approach				BBC Calculation		
				Maximum Pressure		
Wall	Pressure			Wall	Positive	Negative
All Corners	-431			West	--	-297, 0.3 sec
Negative Design Pressure: -431				Negative Design Pressure: -297 (69%) ^a		

^aPercentage of ANSI Standard approach value.

Table 9. Comparison of design pressures (psf) for run No. 5 of the tornado-structure interaction study.

Rigid Frame									
ANSI Standard Approach				BBC Calculation					
				Maximum Average Pressure					
Wall	W_q	W_a	$W_q + (1/2)W_a$	Wall	Positive	Negative			
Windward	149	-431	-67	West	3, 1.75 sec	-162, 0.3 sec			
Leeward	-93	-431	-308	East	64, 1.25 sec	-103, 2.5 sec			
				South	133, 1.25 sec	-76, 4.0 sec			
				North	131, 1.75 sec	-111, 2.5 sec			
Positive Design Pressure:			149	Positive Design Pressure: 133 (89%) ^a					
Negative Design Pressure:			-431	Negative Design Pressure: -162 (38%) ^a					
Individual Wall Panels									
ANSI Standard Approach				BBC Calculation					
				Maximum Pressure					
Wall	Pressure			Wall	Positive	Negative			
Windward	265			West	42, 2.0 sec	-393, 0.3 sec			
Side	-232			East	119, 1.75 sec	-175, 0.5 sec			
Leeward	-166			South	159, 1.25 sec	-85, 4.0 sec			
				North	150, 1.75 sec	-121, 2.5 sec			
Positive Design Pressure: 265				Positive Design Pressure: 159 (60%) ^a					
Negative Design Pressure: -232				Negative Design Pressure: -393 (169%) ^a					
Wall Corners									
ANSI Standard Approach				BBC Calculation					
				Maximum Pressure					
Wall	Pressure			Wall	Positive	Negative			
All Corners	-664			West	--	-393, 0.3 sec			
Negative Design Pressure:			-664	Negative Design Pressure: -393 (59%) ^a					

^aPercentage of ANSI Standard approach value.

Table 10. Comparison of design pressures (psf) for run No. 6 of the tornado-structure interaction study.

Rigid Frame										
ANSI Standard Approach				BBC Calculation						
				Maximum Average Pressure						
Wall	W _q	W _q	W _q + (1/2)W _a	Wall	Positive	Negative				
Windward	194	-431	-21	West	45, 0.75 sec	-168, 1.5 sec				
Leeward	-121	-431	-337	East	44, 1.75 sec	-281, 0.4 sec				
				South	126, 1.25 sec	-157, 2.0 sec				
				North	140, 1.75 sec	-186, 0.3 sec				
Positive Design Pressure:			194	Positive Design Pressure:			140 (72%) ^a			
Negative Design Pressure:			-431	Negative Design Pressure:			-281 (65%) ^a			
Individual Wall Panels										
ANSI Standard Approach				BBC Calculation						
				Maximum Pressure						
Wall	Pressure			Wall	Positive	Negative				
Windward	265			West	121, 1.0 sec	-190, 1.5 sec				
Side	0-232			East	54, 1.25 sec	-420, 0.4 sec				
Leeward	-166			South	196, 1.25 sec	-249, 0.75 sec				
				North	165, 1.75 sec	-388, 0.3 sec				
Positive Design Pressure:				196 (74%) ^a						
Negative Design Pressure:				-420 (181%) ^a						
Wall Corners										
ANSI Standard Approach				BBC Calculation						
				Maximum Pressure						
Wall	Pressure			Wall	Positive	Negative				
All Corners	-664			East	--	-420, 0.4 sec				
Negative Design Pressure:			-664	Negative Design Pressure:			-420 (63%) ^a			

^aPercentage of ANSI Standard approach value.

Table 11. Comparison of design pressures (psf) for run No. 7 of the tornado-structure interaction study.

Rigid Frame						
ANSI Standard Approach				BBC Calculation		
Wall	W _q	W _a	W _q + (1/2)W _a	Maximum Average Pressure		
				Wall	Positive	Negative
Windward	149	-431	-67	West	--	-153, 0.3 sec
Leeward	-93	-431	-308	East	94, 1.75 sec	-208, 0.4 sec
				South	108, 1.25 sec	-167, 3.0 sec
				North	95, 1.75 sec	-183, 1.25 sec
Positive Design Pressure:			149	Positive Design Pressure: 108 (72%) ^a		
Negative Design Pressure:			-431	Negative Design Pressure: -208 (48%) ^a		
Individual Wall Panels						
ANSI Standard Approach				BBC Calculation		
Wall	Pressure			Maximum Pressure		
				Wall	Positive	Negative
Windward	265			West	90, 0.75 sec	-233, 0.3 sec
Side	-232			East	107, 1.75 sec	-351, 0.5 sec
Leeward	-166			South	190, 0.3 sec	-245, 0.75 sec
				North	132, 1.0 sec	-235, 1.25 sec
Positive Design Pressure:			265	Positive Design Pressure: 190 (72%) ^a		
Negative Design Pressure:			-232	Negative Design Pressure: -351 (151%) ^a		
Wall Corners						
ANSI Standard Approach				BBC Calculation		
Wall	Pressure			Maximum Pressure		
				Wall	Positive	Negative
All Corners	-664			East	--	-351, 0.75 sec
Negative Design Pressure:			-664	Negative Design Pressure: -351 (53%) ^a		

^aPercentage of ANSI Standard approach value.

specified for the horizontal plane. As the problem proceeds in time, the flow field relaxes because the entire computational mesh attempts to come to equilibrium and because numerical viscosity is introduced by the finite-difference equations.

- The vortex is not driven. The effect described above might not be so apparent if a means to power the vortex could be found. Clearly, a real tornado flow is almost entirely dependent on its energy source.
- The vortex does not really exist inside the building. While neglect of the three-dimensional effects of TSI is implied in the two-dimensional formulation of the problem, an obvious incompatibility exists when the core passes "over" the building. In two dimensions, there is no way (at present) to account for the core flow when this occurs. For a straight wind situation, this paradox does not exist because the governing influence on the flow may be taken properly as being far removed from the building.
- The initial pressure profile of the vortex is specified from an equation of state for an ideal gas. Because thermal effects are

ignored, we are left with a barotropic flow, i.e., pressure and density are related everywhere by a constant.

- The BBC code is inviscid, although some viscosity is introduced numerically. Although viscous effects are not of primary interest here, important phenomena such as separation, reattachment, and vortex shedding all depend on viscosity.
- No turbulence is considered. This follows from the point above but its importance to TSI may not be apparent. Suitable theoretical models of the tornado vortex often assume an eddy viscosity value for ν in the range 1 to 100 ft²/sec which is four to six orders of magnitude greater than the laminar value of ν for air.

At late times (6 to 10 sec), the dissipative effects become apparent and practically all pressure deviations from ambient conditions become small. This is seen clearly in a pressure-vs-time history of a vortex with no building present. The pressure in the core rises toward ambient pressure and hence, some of the APC effects are diminished.

Positive (compressive) pressures used to calculate positive design pressures for wall panels are about

75% of the ANSI value in all cases. The negative design pressures are, for the most part, 50% greater than the ANSI value. This results from the fact that extreme pressures are used in the negative pressure comparison. In each case considered here, the extreme negative pressures are always realized at a corner. These negative pressures are also used to compare design values at wall corners and hence, do "double duty" in this analysis. If corner points were excluded from consideration, the negative design pressures would be closer to the ANSI values.

The positive and negative pressures used to compare the design of a rigid frame are approximately 75% and 50% of ANSI, respectively. Since pressures over an entire wall must be considered, any comparison with ANSI is not subject to one or two extreme data points.

Wall corners designed by the ANSI approach must use a C_p value of -2.0. When coupled with the high maximum velocity in a tornado, a design value of -664 psf results. While this value may be defensible, the BBC calculations were generally about half this amount.

Overall, the computer-generated results give no indication of heretofore neglected pressure loadings in the event of a tornado strike. The results do support the belief held by many that APC effects are dominant. In view of the limitations and the approximations employed when using the ANSI Standard approach, a definitive statement is not yet possible on how conservative or nonconservative the current design values may be. However, based on these calculations, we conclude that the use of present design loadings is justifiable and that some margin of safety does exist.

Suggestions for Future Effort

At this point, we should recall the assumptions and approximations that are made with an ANSI Standard approach for calculating tornado-wind loadings.

- Steady flow. Although gust loadings which are defined in the ANSI Standards can be taken

into account, they are usually ignored because the DBT characteristics themselves are probably conservative.

- One-dimensional flow. The very nature of straight wind flows conveniently permits definition of a set of pressure coefficients

based on the same free-stream velocity. The ANSI Standard pressure coefficients also make the assumption that flow is normal to the windward wall; again, there is no direct correlation to vortex flow.

- Quasi-static pressures. The real fluid-dynamic effects near and around a building are assumed to be accounted for by the application of pressure and building-size coefficients.
- Cyclostrophic balance. This assumption follows from a vortex model such as the Rankine profile. If the region of interest were sufficiently removed from the ground, the cyclostrophic assumption would be justifiable, probably for all engineering applications. However, as noted earlier, the flow in Region III is strongly influenced by the ground and thus, cyclostrophic balance cannot be expected to hold. Furthermore, there is considerable evidence (Lewellen, 1976; Golden and Purcell, 1975) that the maximum tangential-wind velocities are realized near the ground.
- Separate treatment of velocity pressure and APC effects. The validity of the ANSI pressure coefficients is also assumed in

most TSI calculations. Again, the ANSI Standard does not represent itself as being applicable to tornado loadings

Even for straight-wind situations, there is a sizeable range of pressure coefficient values in use. Cermak and Akins (1976) list values of C_{Fx} obtained by five workers for a fixed cubic building. Values range from 0.81 to 1.6; the C_{Fx} obtained from ANSI A58.1-1972 is 1.3. Variations in pressure coefficients as a function of building geometry and wind vector angle-of-attack are also discussed.

The effects of turbulence intensity and angle of attack are reported by Crowe et al. (1974). Their experiments yield an average value of $C_p = -1.3$ for the side wall, almost twice the ANSI prescribed value of $C_p = -0.7$. In view of such uncertainty, we can reasonably argue that the ANSI Standard approach introduces no more uncertainty to tornado loadings than it does in the straight-wind case.

There are at least three major areas where significant effort is needed to obtain better tornado design loads: improved analytical techniques, numerical simulation of TSI, and laboratory experiments.

To date, analytical efforts have centered around the application of simple vortex models. Improved models that allow for nonzero u and w have

been proposed, but, in general, they do not conserve angular momentum. Wen (1975) has attempted to account for the time and spatial features of the wind field with a drag coefficient, an inertia coefficient, and Kuo's (1971) vortex model. Details of this approach are discussed in a critical review by Hunt (1975). In general, the calculation of bluff-body flow is complex and unamenable to closed-form solutions. Another source of investigation lies along the lines discussed by Bearman and Fackrell (1975) who model incompressible potential flow with a wake-source model. In this method, the wetted perimeter of a two-dimensional body is represented with a series of discrete point vortices. The effect of the wake is modeled with sources placed on the rear of the wetted surface. Numerical calculations yield a C_p that is in good agreement with experimental results; however, pressures in the separated region must still be obtained experimentally.

Future analytic improvement may depend strongly on better understanding of the nature of turbulence in tornado flow. Lewellen (1976) notes that determining maximum velocities in tornadoes may be closely linked to the role of turbulence. In this regard, USNRC has contracted the Aeronautical Research Associates of Princeton to develop a

tornado-turbulence model based on second-order closure.

Numerically, additional effort is needed to develop a computer tool designed specifically for TSI. Immediate improvements in the modeling of boundary conditions and irregular geometry would be seen for the two-dimensional case. The current problem of feeding the flow could be handled, in part, by suitable inflow and outflow boundary conditions. Several two-dimensional, finite-difference schemes (r, z coordinates) have successfully defined many features of axisymmetric tornado flow. These encouraging results tend to support the belief that vorticity and vertical momentum are needed to maintain a concentrated vortex. For TSI applications, a three-dimensional model will probably be required to capture all the important fluid dynamics. As noted earlier, the flow in Region III (Fig. 3) is strongly influenced by the ground; strong gradients exist in all velocity components. The problem is further complicated by the effects exerted by a building on the local flow field. Although it was once unfeasible to tackle such a problem computationally, computer speed and numerical fluid-dynamics techniques are now sufficiently improved to permit the development of a three-dimensional tornado model.

Suitable experimental data is needed to serve as a basis of comparison and to corroborate numerical and other approximate methods. To date, laboratory tests have been conducted primarily to study the phenomena of vortex flow. Chang's (1971) exploratory study with a fixed cubic model is the only known exception. Improved results can be obtained by building a vortex simulator designed especially for studying TSI. Such a chamber would allow for a wide range of flow rates and would have a larger capacity than existing apparatus.

A recent experiment by Cermak and Akins (1976) is also of interest. A fixed building model, instrumented with pressure taps, was placed in a wind tunnel. A deflector plate was located just upstream of the building to introduce a horizontal (y) velocity gradient. A comparison of results obtained with and without the deflector plate shows a significant decrease in pressure and force coefficients in the presence of the horizontal velocity gradient. Hence, further laboratory modeling of the more complex tornado phenomenon may produce even more surprising results.

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Appendix A: Nomenclature

C_{F_x}	Force coefficient for the x direction.
C_{F_y}	Force coefficient for the y direction.
C_p	Pressure coefficient, specific heat at constant pressure.
C_s	Building size coefficient.
F_x	Net force in the x direction.
F_y	Net force in the y direction.
g	Gravity.
H	Building height.
h	Height of laboratory vortex chamber.
k	Thermal conductivity.
L	Characteristic dimension.
M	Product of radius and tangential velocity.
N	Radial Reynolds number for laboratory vortex.
P	Pressure.
P_{avg}	Average pressure.
P_o	Ambient pressure.
Q	Volume flow rate.
r	Radial coordinate.
r_c	Core radius of laboratory vortex.
r_m	Radius of maximum tangential velocity.
r_o	Exhaust radius of laboratory vortex.
r_s	Inflow radius in a laboratory vortex chamber.
S	Swirl ratio.
T	Temperature.

t	Time, tangential.
U	Free stream velocity.
u	Radial velocity.
V	Velocity.
$V_{\max}$	Maximum velocity.
V_{rot}	Rotational velocity.
V_{trans}	Translational velocity.
v	Tangential velocity.
v_m	Maximum tangential velocity.
W	Building width.
W_a	Building load due to atmospheric pressure change.
W_t	Design load.
W_q	Building load due to velocity pressure.
w	Vertical velocity.
x	West to east coordinate.
y	South to north coordinate.
z	Vertical coordinate.
Γ	Circulation.
Ω	Angular velocity.
ρ	Density.
θ	Angular displacement.
ν	Coefficient of kinematic viscosity.

Appendix B: Procedure for Calculating Wind Loads for Straight Winds

For most wind loading calculations, the design loads are obtained by the procedure outlined in ANSI A58.1-1972. A brief summary is given below.

Wind loads on buildings and other structures are determined with the following procedure:

- A mean recurrence interval shall be selected which depends on the intended operational usage, anticipated life of the structure, degree of sensitivity to wind, and risk to human life and property in case of failure.
- A basic wind speed is selected based on a recurrence interval of 25, 50, or 100 yr.
- The basic wind speed is converted to effective velocity pressures q_F or q_P by the following formulas:

$$q_F = K_z G_F q_{30} ,$$

$$q_P = K_z G_P q_{30} ,$$

where q_F = effective velocity pressure for ordinary buildings and structures (psf), q_P = effective velocity pressure for parts and portions of buildings and structures (psf), $q_{30} = 0.00256 V_{30}^2$, basic wind pressure (psf), V_{30} = basic wind speed (mph), G_G = gust factor for ordinary buildings and structures, G_P = gust factor for parts and portions of buildings and structures, and K_z = velocity pressure coefficient of height z which depends upon type of exposure.

- The design pressures or design loads are obtained by multiplying the effective velocity pressures by appropriate pressure coefficients.

Appendix C: External Pressure Coefficients for Walls for Straight Winds^a

Wall Location	Pressure Coefficient
Windward wall	0.8
Leeward wall (both height/width and height/length ratios of building ≥ 2.5)	-0.6
Other buildings	-0.5
Side walls	-0.7
Wall corners (applies over a width 0.1 w, where w is the least width of the building)	-2.0

^aANSI A58.1-1972.

Appendix D: Time-History Tabulation of Building Surface Pressures and Force Coefficients

TORNADO STRUCTURE INTERACTION RUN NO. 1

WEST WALL											
TIME (SEC)	SURFACE PRESSURES (SOUTH TO NORTH) (PSF)										AVERAGE PRESSURE
0	-102	-114	-124	-132	-136	-136	-131	-123	-112	-100	-120
.05	150	58	5	-65	-131	-199	-260	-303	-314	-334	-138
.10	61	-4	-69	-129	-182	-220	-238	-246	-246	-254	-150
.15	-9	-52	-100	-146	-181	-204	-214	-216	-214	-213	-151
.20	-75	-92	-119	-146	-167	-180	-186	-183	-173	-150	-143
.30	-130	-139	-155	-173	-184	-186	-176	-155	-128	-80	-147
.40	-146	-146	-152	-158	-160	-156	-143	-122	-91	-53	-129
.50	-123	-118	-121	-126	-126	-125	-116	-96	-71	-38	-103
.75	-100	-82	-74	-76	-67	-107	-131	-154	-159	-126	-106
1.00	25	58	61	40	8	-20	-39	-45	-43	-29	2
1.25	-33	-53	-72	-88	-102	-113	-122	-129	-133	-130	-95
1.50	-122	-120	-122	-120	-110	-89	-63	-39	-22	-9	-79
1.75	-93	-105	-114	-116	-115	-105	-91	-69	-35	10	-81
2.00	-25	-30	-38	-46	-51	-52	-48	-39	-24	-4	-35
2.50	-34	-28	-27	-28	-31	-36	-40	-43	-43	-41	-34
3.00	-76	-78	-78	-75	-69	-61	-52	-41	-28	-11	-56
3.50	-38	-53	-66	-75	-81	-82	-78	-70	-56	-45	-63
4.00	-48	-50	-52	-51	-49	-45	-39	-32	-22	-10	-39
4.50	-30	-37	-45	-51	-54	-55	-52	-46	-41	-31	-43
5.00	-48	-44	-42	-39	-34	-28	-20	-10	0	10	-25
6.00	-54	-50	-50	-51	-50	-47	-42	-36	-27	-15	-41
7.00	-43	-39	-39	-40	-40	-39	-37	-34	-30	-24	-35
8.00	-47	-43	-44	-43	-42	-39	-34	-28	-22	-14	-34
9.00	-48	-41	-39	-38	-37	-36	-34	-30	-27	-22	-34
10.00	-18	-14	-15	-15	-16	-17	-17	-16	-14	-13	-15

EAST WALL											
TIME (SEC)	SURFACE PRESSURES (SOUTH TO NORTH) (PSF)										AVERAGE PRESSURE
0	-60	-89	-96	-101	-103	-103	-100	-95	-88	-79	-90
.05	29	17	-6	-10	4	23	44	58	36	-53	15
.10	21	48	58	69	61	29	-16	-54	-74	-110	4
.15	21	63	67	50	23	0	-18	-46	-83	-131	-5
.20	38	-3	8	10	4	-11	-29	-53	-82	-121	-31
.30	-117	-85	-70	-62	-60	-60	-60	-61	-70	-69	-69
.40	-153	-117	-98	-79	-66	-56	-50	-46	-43	-45	-74
.50	-148	-110	-91	-72	-56	-44	-36	-32	-30	-33	-64
.75	-212	-186	-129	-92	-60	-49	-60	-85	-110	-130	-108
1.00	-83	-68	-68	-61	-46	-26	0	23	6	40	-25
1.25	23	-22	-36	-47	-52	-53	-53	-54	-58	-65	-45
1.50	-109	-79	-69	-63	-55	-45	-32	-21	-18	-28	-51
1.75	-98	-70	-59	-50	-36	-19	-6	-3	-2	-4	-34
2.00	-94	-85	-87	-84	-78	-71	-66	-62	-61	-58	-74
2.50	-87	-82	-92	-96	-94	-86	-75	-62	-50	-41	-75
3.00	-63	-51	-44	-36	-26	-16	-5	6	19	31	-18
3.50	2	6	-2	-2	-3	-4	-4	-2	-1	-1	-6
4.00	-71	-60	-55	-46	-34	-22	-9	4	17	29	-24
4.50	-5	-6	-7	-7	-6	-4	-1	4	8	10	-1
5.00	-70	-52	-47	-43	-38	-33	-27	-19	-11	-3	-34
6.00	-61	-57	-60	-61	-61	-59	-54	-46	-35	-22	-51
7.00	-18	-9	-10	-9	-8	-6	-4	-2	-1	-2	-6
8.00	-2	-1	-2	-1	-1	-1	0	0	0	0	-6
9.00	-10	-3	-4	-5	-5	-5	-4	-4	-3	-3	-4
10.00	4	6	2	0	0	-1	-1	-1	-2	-3	1

TORNADO STRUCTURE INTERACTION RUN NO. 1

NORTH WALL

TIME (SEC)	SURFACE PRESSURES (WEST TO EAST) (PSF)										AVERAGE PRESSURE
.0	-70	-56	-45	-36	-28	-22	-16	-11	-7	-4	-30
.05	-373	-470	-552	-532	-526	-498	-456	-411	-311	-235	-436
.10	-306	-334	-346	-367	-403	-388	-348	-321	-299	-290	-336
.15	-228	-201	-174	-175	-191	-202	-239	-265	-313	-336	-231
.20	-66	-65	-69	-96	-109	-126	-160	-172	-215	-290	-140
.30	-28	-17	-12	-16	-21	-32	-49	-76	-110	-161	-52
.40	-0	0	0	-1	-2	-8	-20	-42	-64	-98	-23
.50	6	2	0	-0	-4	-13	-27	-47	-82	-179	-43
.75	17	31	28	13	-5	-27	-62	-107	-138	-170	-43
1.00	4	2	-2	-8	-12	-16	-16	-6	8	17	-3
1.25	-118	-112	-106	-102	-104	-107	-107	-102	-96	-98	-105
1.50	-2	-11	-20	-26	-33	-42	-52	-60	-64	-71	-37
1.75	88	98	98	86	67	46	27	13	4	-1	52
2.00	23	15	-2	-14	-30	-45	-55	-61	-63	-61	-29
2.50	-53	-65	-72	-77	-78	-75	-70	-61	-51	-44	-64
3.00	19	27	36	42	48	52	56	56	58	54	44
3.50	-32	-34	-38	-38	-39	-36	-30	-24	-16	-9	-29
4.00	17	23	31	33	36	40	42	44	44	44	35
4.50	-15	-11	-9	-9	-9	-8	-5	-1	4	6	-6
5.00	23	23	23	21	17	15	13	13	13	10	17
6.00	8	17	28	27	29	27	23	17	8	7	21
7.00	-14	-11	-9	-8	-6	-7	-6	-5	-4	-2	-7
8.00	-0	4	6	6	4	2	2	0	0	2	3
9.00	-12	-6	-5	-4	-3	-3	-4	-3	-3	-3	-5
10.00	-9	-8	-7	-7	-8	-9	-9	-8	-7	-5	-8

SOUTH WALL

TIME (SEC)	SURFACE PRESSURES (WEST TO EAST) (PSF)										AVERAGE PRESSURE
.0	-71	-57	-46	-36	-28	-22	-16	-11	-8	-4	-30
.05	328	424	545	531	585	560	528	466	336	221	454
.10	278	315	349	355	376	380	357	330	284	223	320
.15	226	232	215	166	166	162	169	171	180	175	169
.20	115	121	127	121	119	113	104	102	96	81	108
.30	58	67	69	69	67	63	58	50	40	22	54
.40	29	40	40	40	36	29	23	15	4	-16	21
.50	19	21	19	13	6	2	-4	-9	-17	-32	-0
.75	-25	-36	-46	-56	-75	-94	-112	-124	-132	-138	-85
1.00	31	25	21	10	-5	-23	-39	-50	-56	-56	-14
1.25	111	125	134	134	132	125	117	109	98	64	114
1.50	-17	-17	-18	-20	-23	-25	-28	-31	-37	-47	-28
1.75	-6	10	19	25	27	25	21	15	6	-9	12
2.00	17	27	38	46	52	50	44	29	10	-16	28
2.50	17	13	8	6	4	4	4	4	0	-10	4
3.00	-45	-47	-51	-55	-58	-60	-59	-57	-55	-52	-54
3.50	29	40	46	48	48	46	46	44	40	36	41
4.00	-6	-2	-0	-0	-1	-3	-7	-12	-19	-30	-9
4.50	23	27	29	27	27	23	21	19	17	13	22
5.00	-16	-18	-19	-22	-24	-26	-28	-31	-34	-39	-26
6.00	-8	-5	-6	-7	-8	-11	-14	-18	-20	-26	-13
7.00	23	29	31	33	33	33	31	27	23	15	27
8.00	13	19	23	25	27	29	29	27	25	21	23
9.00	8	13	17	17	19	19	19	19	19	17	16
10.00	29	36	38	40	40	40	38	36	31	27	35

TORNADO STRUCTURE INTERACTION RUN NO. 1

BUILDING FORCE COEFFICIENTS

TIME (SEC)	WEST-EAST CFX	SOUTH-NORTH CFY
.0	-.14	-.00
.05	-.71	4.14
.10	-.71	3.05
.15	-.68	1.95
.20	-.52	1.15
.30	-.36	.49
.40	-.26	.21
.50	-.18	.10
.75	.01	-.19
1.00	.13	-.05
1.25	-.23	1.02
1.50	-.13	.04
1.75	-.22	-.19
2.00	.18	.27
2.50	.19	.32
3.00	-.18	-.46
3.50	-.29	.33
4.00	-.07	-.20
4.50	-.20	.13
5.00	.04	-.20
6.00	.04	-.16
7.00	-.14	.16
8.00	-.16	.09
9.00	-.14	.10
10.00	-.07	.20

TORNADO STRUCTURE INTERACTION RUN NO. 2

WEST WALL											
TIME (SEC)	SURFACE PRESSURES (SOUTH TO NORTH) (PSF)										
0	-102	-114	-124	-132	-136	-136	-131	-123	-112	-100	-120
0.05	-395	-276	-249	-209	-144	-71	0	-61	-123	-217	-87
0.10	-284	-207	-138	-69	-8	-40	-79	-117	-151	-192	-12
0.15	-234	-159	-86	-17	-49	-104	-147	-178	-200	-219	-40
0.20	-169	-100	31	-34	-90	-134	-166	-186	-198	-204	-70
0.30	-44	-22	-61	-132	-172	-199	-211	-209	-199	-180	-135
0.40	-9	-61	-107	-143	-168	-182	-185	-178	-162	-137	-132
0.50	5	-37	-76	-109	-133	-148	-152	-146	-129	-102	-101
0.75	71	50	21	-14	-55	-99	-144	-183	-204	-181	-72
1.00	77	42	-7	-57	-97	-120	-127	-122	-108	-60	-60
1.25	-3	-41	-72	-98	-123	-145	-163	-175	-178	-160	-114
1.50	-56	-78	-93	-99	-91	-72	-44	-17	8	38	-49
1.75	-38	-51	-58	-59	-54	-42	-20	10	48	81	-17
2.00	-95	-11	-129	-140	-144	-137	-119	-93	-60	-28	-105
2.50	-72	-59	-99	-112	-120	-122	-119	-110	-98	-88	-102
3.00	-44	-5	-71	-62	-89	-90	-85	-75	-60	-40	-69
3.50	-31	-46	-60	-70	-77	-79	-77	-70	-60	-48	-61
4.00	-108	-111	-110	-105	-98	-89	-79	-69	-58	-47	-87
4.50	-78	-85	-92	-88	-81	-70	-59	-48	-39	-33	-67
5.00	-77	-78	-74	-70	-64	-57	-48	-38	-29	-23	-55
6.00	-72	-58	-52	-47	-43	-40	-38	-35	-31	-29	-44
7.00	-46	-39	-35	-30	-25	-21	-18	-16	-14	-13	-26
8.00	-24	-27	-28	-28	-28	-27	-26	-24	-20	-16	-25
9.00	-12	-9	-7	-6	-6	-6	-5	-5	-5	-5	-7
10.00	-34	-32	-31	-30	-29	-27	-26	-24	-22	-19	-27

EAST WALL											
TIME (SEC)	SURFACE PRESSURES (SOUTH TO NORTH) (PSF)										
0	-80	-89	-96	-101	-103	-103	-100	-95	-88	-79	-90
0.05	-163	-183	-246	-276	-272	-266	-233	-201	-165	-191	-215
0.10	-215	-182	-141	-129	-137	-165	-197	-220	-219	-230	-176
0.15	-246	-156	-109	-67	-91	-101	-107	-129	-169	-217	-137
0.20	-263	-178	-131	-100	-87	-87	-94	-109	-129	-148	-129
0.30	-263	-220	-167	-131	-127	-108	-92	-79	-71	-63	-134
0.40	-291	-228	-154	-156	-119	-92	-74	-60	-49	-39	-127
0.50	-273	-227	-179	-178	-147	-120	-101	-88	-79	-69	-146
0.75	-235	-233	-233	-164	-118	-84	-69	-72	-75	-58	-127
1.00	-119	-132	-130	-126	-111	-73	-52	17	40	58	-50
1.25	-36	-60	-61	-67	-82	-69	-54	-39	-28	-22	-55
1.50	25	36	42	46	52	58	67	73	73	69	54
1.75	52	58	56	54	52	54	63	75	86	90	64
2.00	-43	-50	-59	-66	-78	-61	-33	-62	-78	-73	-69
2.50	-176	-181	-197	-214	-229	-240	-248	-242	-232	-217	-218
3.00	-125	-119	-117	-112	-107	-99	-86	-75	-58	-42	-93
3.50	-18	-19	-23	-28	-36	-44	-52	-59	-66	-75	-41
4.00	-61	-59	-56	-52	-47	-43	-41	-41	-43	-52	-49
4.50	-31	-33	-39	-44	-48	-50	-51	-52	-52	-58	-45
5.00	-19	-9	-4	-1	2	6	8	10	13	8	2
6.00	-55	-52	-52	-52	-52	-51	-48	-44	-38	-28	-48
7.00	-58	-45	-38	-34	-29	-24	-22	-21	-22	-22	-31
8.00	-232	-18	-18	-19	-18	-16	-14	-12	-10	-9	-31
9.00	-60	-49	-45	-43	-41	-37	-34	-31	-27	-24	-39
10.00	-18	-15	-15	-15	-15	-13	-13	-12	-11	-12	-14

TORNADO STRUCTURE INTERACTION RUN NO. 2

NORTH WALL

TIME (SEC)	SURFACE PRESSURES (WEST TO EAST) (PSF)										AVERAGE PRESSURE
.0	-70	-56	-45	-36	-28	-22	-16	-11	-7	-4	-30
.05	-373	-440	-550	-558	-532	-504	-475	-431	-337	-259	-442
.10	-348	-341	-348	-344	-334	-313	-275	-248	-217	-193	-368
.15	-327	-273	-227	-189	-203	-199	-205	-285	-308	-317	-248
.20	-233	-175	-154	-136	-134	-129	-143	-155	-141	-171	-157
.30	-186	-131	-92	-67	-51	-41	-47	-43	-54	-69	-76
.40	-96	-82	-60	-44	-34	-28	-22	-19	-26	-33	-45
.50	-66	-65	-52	-39	-28	-23	-20	-24	-33	-48	-40
.75	-2	-48	-75	-94	-86	-90	-94	-84	-58	-21	-61
1.00	-31	-36	-38	-28	-11	10	38	58	79	84	12
1.25	-107	-99	-95	-94	-96	-96	-94	-85	-70	-55	-69
1.50	65	56	50	50	50	46	44	42	42	42	49
1.75	127	127	121	109	90	73	63	56	56	61	68
2.00	-14	-23	-33	-44	-53	-61	-66	-70	-72	-73	-51
2.50	-98	-107	-115	-122	-129	-137	-146	-156	-167	-180	-138
3.00	-0	13	25	38	48	54	56	54	46	31	35
3.50	-34	-35	-35	-35	-36	-37	-38	-40	-43	-47	-38
4.00	-30	-27	-24	-22	-20	-19	-18	-16	-19	-21	-22
4.50	-22	-18	-16	-13	-11	-9	-8	-6	-10	-15	-13
5.00	-21	33	44	50	54	58	58	58	54	48	47
6.00	-3	4	6	10	10	8	4	-2	-9	-18	1
7.00	-17	-21	-24	-28	-30	-32	-34	-32	-29	-28	-28
8.00	-11	-10	-10	-11	-12	-13	-14	-13	-12	-10	-12
9.00	-16	-17	-19	-22	-23	-24	-24	-23	-21	-20	-21
10.00	-17	-18	-19	-21	-23	-23	-23	-22	-20	-18	-20

SOUTH WALL

TIME (SEC)	SURFACE PRESSURES (WEST TO EAST) (PSF)										AVERAGE PRESSURE
.0	-71	-57	-46	-36	-28	-22	-16	-11	-6	-4	-30
.05	430	459	539	585	587	566	537	476	345	184	435
.10	382	386	421	405	403	388	388	301	238	150	339
.15	340	328	303	261	223	194	167	138	109	65	209
.20	242	216	190	167	142	119	96	89	38	-6	124
.30	134	121	102	86	71	54	40	21	-3	-42	55
.40	73	63	52	40	29	19	6	-11	-34	-72	13
.50	63	46	29	13	-1	-14	-28	-42	-61	-92	-12
.75	42	-1	-34	-56	-73	-89	-105	-122	-136	-148	-73
1.00	52	27	6	-11	-28	-42	-53	-59	-61	-64	-24
1.25	67	77	90	102	115	123	123	117	100	71	96
1.50	-3	4	10	17	25	31	38	38	36	35	22
1.75	10	27	45	63	79	92	96	98	92	79	67
2.00	-53	-35	-21	-13	-6	-7	-11	-16	-22	-28	-22
2.50	-63	-70	-77	-83	-87	-90	-92	-94	-98	-107	-87
3.00	-41	-46	-53	-60	-66	-73	-78	-84	-89	-95	-69
3.50	-12	-7	-2	2	6	8	10	8	6	2	2
4.00	-65	-65	-62	-79	-77	-74	-72	-70	-67	-65	-76
4.50	-39	-29	-20	-13	-8	-4	-3	-4	-6	-11	-14
5.00	-30	-21	-14	-10	-8	-7	7	-8	-9	-10	-13
6.00	-40	-37	-35	-34	-34	-33	-33	-33	-34	-37	-36
7.00	-35	-31	-27	-25	-23	-21	-20	-21	-23	-26	-26
8.00	-16	-11	-6	-1	4	6	10	13	8	8	2
9.00	-22	-25	-28	-30	-30	-30	-30	-29	-30	-33	-29
10.00	-45	-43	-43	-42	-42	-41	-38	-35	-30	-25	-38

TORNADO STRUCTURE INTERACTION RUN NO. 2

BUILDING FORCE COEFFICIENTS

TIME (SEC)	WEST-EAST CFX	SOUTH-NORTH CFY
.0	-.09	-.00
.05	.91	2.74
.10	.57	2.07
.15	.29	1.38
.20	.18	.85
.30	.00	.39
.40	-.01	.17
.50	.13	.09
.75	.17	-.40
1.00	-.00	-.11
1.25	-.18	-.36
1.50	-.31	-.06
1.75	-.25	-.06
2.00	-.11	.09
2.50	.34	.15
3.00	.07	-.31
3.50	-.05	.12
4.00	-.11	-.16
4.50	-.07	-.00
5.00	-.17	-.16
6.00	.02	-.11
7.00	.02	.01
8.00	.02	.04
9.00	.10	-.03
10.00	-.04	-.05

TORNADO STRUCTURE INTERACTION RUN NO. 3

WEST WALL

TIME (SEC)	SURFACE PRESSURES (SOUTH TO NORTH) (PSF)										AVERAGE PRESSURE
.0	-391	-383	-368	-345	-314	-276	-231	-178	-133	-102	-271
.05	-466	-549	-635	-729	-818	-888	-910	-855	-738	-656	-716
.10	-426	-512	-584	-626	-603	-524	-523	-573	-626	-693	-560
.15	-444	-401	-323	-268	-313	-346	-377	-429	-507	-614	-394
.20	-248	-180	-192	-188	-199	-222	-256	-305	-369	-463	-259
.30	-202	-153	-122	-108	-100	-101	-110	-133	-168	-221	-140
.40	-147	-118	-86	-67	-66	-80	-85	-103	-109	-110	-103
.50	-120	-102	-85	-77	-80	-85	-92	-98	-94	-86	-91
.75	-38	98	129	115	85	-2	-61	-98	-115	-143	0
1.00	-88	-105	-124	-137	-140	-136	-131	-122	-107	-94	-117
1.25	-175	-197	-211	-225	-234	-236	-231	-220	-205	-192	-211
1.50	-37	-38	-46	-56	-63	-66	-67	-64	-60	-63	-56
1.75	-29	-22	-16	-10	-10	4	13	21	29	31	1
2.00	56	73	79	75	67	56	44	25	4	-30	43
2.50	80	90	98	103	105	105	102	99	96	96	97
3.00	64	89	75	81	84	84	80	73	63	51	72
3.50	82	90	98	104	107	109	108	106	102	98	100
4.00	-22	-4	6	15	19	21	21	19	17	17	10
4.50	-30	-26	-23	-21	-20	-20	-22	-25	-30	-38	-26
5.00	-4	-6	-15	-23	-28	-31	-33	-35	-37	-39	-24
6.00	-8	-4	-3	-4	-6	-8	-12	-16	-21	-27	-11
7.00	-42	-41	-40	-39	-37	-34	-32	-28	-25	-22	-34
7.60	-38	-34	-32	-30	-29	-29	-28	-27	-27	-26	-30
8.00	-23	-22	-22	-22	-22	-21	-20	-19	-18	-18	-21
9.00	-31	-35	-38	-41	-43	-45	-46	-46	-45	-45	-41
10.00	-47	-48	-49	-49	-48	-47	-44	-39	-35	-29	-43

EAST WALL

TIME (SEC)	SURFACE PRESSURES (SOUTH TO NORTH) (PSF)										AVERAGE PRESSURE
.0	-398	-391	-375	-353	-322	-284	-238	-185	-138	-105	-270
.05	109	173	221	253	290	332	363	357	263	111	248
.10	84	186	231	290	301	265	192	129	81	19	180
.15	88	165	186	175	152	127	104	77	40	-14	109
.20	19	48	56	63	61	54	44	31	8	-28	35
.30	-100	-67	-51	-36	-27	-23	-24	-31	-48	-82	-50
.40	-133	-109	-100	-91	-83	-79	-79	-85	-99	-128	-99
.50	-146	-118	-108	-103	-98	-95	-95	-100	-109	-131	-110
.75	-213	-204	-187	-163	-139	-121	-116	-122	-135	-149	-154
1.00	-171	-110	-74	-51	-42	-41	-45	-51	-56	-69	-69
1.25	10	29	40	50	61	71	81	88	86	73	58
1.50	-35	-21	-22	-31	-43	-55	-68	-85	-107	-137	-61
1.75	-189	-179	-181	-188	-194	-197	-190	-175	-152	-127	-175
2.00	-60	-77	-93	-102	-109	-113	-116	-119	-125	-134	-104
2.50	15	8	2	-3	-9	-13	-19	-25	-34	-46	-13
3.00	-96	-82	-72	-63	-55	-47	-41	-34	-29	-24	-54
3.50	-28	-14	-3	4	10	17	19	21	19	13	8
4.00	-104	-98	-94	-90	-87	-83	-78	-73	-66	-59	-63
4.50	-27	-26	-26	-27	-28	-30	-32	-35	-39	-46	-32
5.00	-43	-48	-52	-53	-54	-54	-54	-55	-58	-63	-54
6.00	-38	-38	-34	-33	-33	-33	-33	-36	-39	-44	-37
7.00	-44	-43	-42	-41	-40	-38	-37	-36	-35	-35	-36
7.60	-34	-26	-22	-19	-17	-15	-14	-13	-13	-14	-19
8.00	-40	-39	-38	-37	-36	-35	-34	-32	-30	-30	-35
9.00	-16	-16	-16	-16	-15	-14	-13	-13	-13	-15	-15
10.00	-28	-21	-16	-11	-8	-4	-1	2	4	4	-8

TORNADO STRUCTURE INTERACTION RUN NO. 3

NORTH WALL

TIME (SEC)	SURFACE PRESSURES (WEST TO EAST) (PSF)										AVERAGE PRESSURE
0	-81	-81	-79	-75	-70	-64	-57	-51	-44	-38	-64
.05	-309	-245	-261	-306	-348	-378	-389	-361	-289	-242	-311
.10	-405	-359	-324	-280	-235	-203	-198	-217	-248	-296	-274
.15	-374	-311	-259	-222	-198	-174	-191	-177	-224	-285	-226
.20	-278	-249	-230	-215	-204	-193	-193	-203	-229	-266	-226
.30	-167	-166	-168	-172	-179	-192	-215	-249	-283	-340	-210
.40	-71	-75	-87	-103	-129	-162	-203	-245	-280	-341	-167
.50	-50	-51	-60	-74	-96	-129	-170	-205	-231	-287	-134
.75	-116	-90	-85	-50	-51	-77	-118	-158	-188	-240	-115
1.00	-48	-34	-27	-25	-30	-34	-35	-34	-34	-40	-35
1.25	-147	-146	-150	-151	-149	-141	-124	-96	-60	-27	-118
1.50	-63	-67	-119	-154	-184	-203	-214	-221	-225	-252	-171
1.75	10	-6	-23	-36	-45	-54	-66	-79	-90	-114	-50
2.00	-118	-152	-179	-198	-210	-215	-212	-203	-188	-178	-184
2.50	-96	-102	-111	-119	-123	-122	-118	-112	-105	-108	-111
3.00	-37	-38	-41	-43	-43	-40	-36	-32	-28	-29	-37
3.50	-68	-67	-68	-66	-62	-74	-53	-49	-34	-20	-67
4.00	10	8	4	-1	-7	-14	-22	-30	-39	-53	-14
4.50	-69	-84	-97	-106	-109	-108	-104	-98	-90	-90	-94
5.00	-60	-73	-83	-90	-94	-96	-95	-94	-91	-97	-87
6.00	-48	-58	-68	-72	-75	-76	-75	-74	-71	-77	-69
7.00	-22	-24	-26	-32	-35	-37	-40	-42	-44	-55	-36
7.50	-27	-29	-29	-30	-31	-31	-30	-28	-26	-25	-28
8.00	-17	-19	-21	-23	-25	-27	-29	-31	-32	-40	-26
9.00	-47	-49	-51	-50	-48	-46	-43	-40	-37	-42	-45
10.00	-17	-15	-14	-12	-10	-9	-7	-5	-3	-5	-10

SOUTH WALL

TIME (SEC)	SURFACE PRESSURES (WEST TO EAST) (PSF)										AVERAGE PRESSURE
0	-398	-398	-391	-375	-353	-322	-284	-238	-185	-138	-307
.05	-238	-123	17	190	382	560	675	687	553	451	308
.10	-78	46	142	205	234	242	255	307	315	292	190
.15	-115	-56	-19	15	58	102	129	167	192	198	63
.20	-202	-176	-140	-96	-46	8	36	98	129	140	-24
.30	-119	-102	-89	-80	-70	-52	-31	-11	2	6	-56
.40	-115	-107	-94	-77	-54	-29	-6	8	13	-3	-48
.50	-111	-106	-95	-81	-65	-48	-33	-24	-20	-28	-62
.75	-187	-242	-322	-323	-299	-255	-198	-141	-107	-106	-220
1.00	-99	-113	-111	-105	-101	-94	-81	-71	-67	-60	-93
1.25	-134	-122	-105	-85	-65	-47	-29	-14	-1	13	-59
1.50	-49	-47	-33	-14	-1	0	-7	-16	-19	-13	-20
1.75	-53	-63	-72	-79	-83	-82	-80	-82	-88	-97	-78
2.00	-7	-24	-27	-17	-2	25	48	58	56	38	15
2.50	-66	-63	-58	-47	-31	-11	8	25	36	38	-17
3.00	-65	-70	-76	-81	-85	-88	-85	-82	-78	-75	-78
3.50	-66	-64	-64	-64	-62	-58	-53	-46	-39	-58	-66
4.00	-80	-106	-126	-139	-148	-150	-148	-141	-130	-119	-128
4.50	-44	-50	-53	-56	-56	-54	-50	-44	-38	-32	-47
5.00	25	29	31	29	27	23	17	10	0	15	17
6.00	-23	-32	-40	-47	-52	-55	-56	-55	-51	-47	-45
7.00	-44	-46	-47	-48	-48	-48	-46	-44	-42	-41	-46
7.50	-53	-58	-63	-65	-66	-65	-62	-57	-51	-43	-58
8.00	-26	-32	-36	-39	-41	-42	-42	-41	-39	-37	-38
9.00	-26	-20	-19	-17	-16	-15	-14	-13	-13	-13	-16
10.00	-46	-47	-48	-48	-48	-47	-44	-41	-38	-33	-44

TORNADO STRUCTURE INTERACTION RUN NO. 3

BUILDING FORCE COEFFICIENTS

TIME (SEC)	WEST-EAST CFX	SOUTH-NORTH CFY
.0	-.01	-1.13
.05	-4.48	2.87
.10	-3.44	2.16
.15	-2.33	1.40
.20	-1.36	.94
.30	-.42	.71
.40	-.02	.65
.50	.09	.39
.75	.72	-.49
1.00	-.23	-.27
1.25	-1.25	.27
1.50	.03	.70
1.75	.82	-.13
2.00	.68	.82
2.50	-.39	.44
3.00	-.08	-.19
3.50	-.49	-.04
4.00	.43	-.53
4.50	.03	.22
5.00	.14	.48
6.00	.12	.11
7.00	.02	-.05
7.50	-.05	-.14
8.00	-.07	-.05
9.00	-.12	-.13
10.00	-.16	-.16

TORNADO STRUCTURE INTERACTION RUN NO. 4

WEST WALL

TIME (SEC)	SURFACE PRESSURES (SOUTH TO NORTH) (PSF)										AVERAGE PRESSURE
.0	-165	-193	-216	-231	-238	-238	-231	-216	-193	-165	-207
.05	17	121	125	15	-137	-274	-376	-422	-442	-497	-184
.10	-208	-179	-165	-127	-162	-38	-106	-220	-353	-521	-196
.15	-200	-180	-141	-138	-134	-130	-129	-168	-230	-350	-180
.20	-138	-142	-150	-157	-167	-176	-188	-209	-224	-274	-181
.30	-128	-109	-107	-115	-132	-159	-193	-225	-248	-297	-171
.40	-126	-112	-111	-118	-132	-155	-182	-200	-213	-52	-145
.50	-106	-95	-97	-108	-127	-152	-176	-188	-194	-231	-147
.75	-124	-128	-133	-138	-142	-143	-143	-140	-136	-167	-139
1.00	-82	-82	-93	-112	-131	-148	-156	-154	-147	-155	-127
1.25	-102	-110	-122	-132	-141	-146	-143	-134	-124	-136	-129
1.50	-78	-81	-90	-101	-110	-116	-114	-107	-103	-121	-102
1.75	-88	-91	-99	-106	-111	-114	-114	-111	-112	-128	-107
2.00	-73	-75	-81	-87	-91	-93	-91	-89	-90	-105	-88
2.50	-72	-75	-80	-85	-89	-90	-90	-88	-90	-102	-86
3.00	-69	-69	-73	-77	-80	-82	-82	-81	-82	-92	-79
3.50	-61	-64	-69	-73	-77	-78	-78	-77	-79	-89	-74
4.00	-60	-61	-64	-68	-70	-71	-70	-68	-68	-76	-67
4.50	-59	-62	-66	-69	-72	-72	-72	-71	-72	-80	-69
5.00	-55	-56	-58	-61	-63	-64	-63	-62	-62	-67	-61
6.00	-53	-53	-56	-58	-60	-61	-61	-60	-60	-65	-59
7.00	-47	-48	-51	-53	-55	-56	-56	-55	-55	-59	-54
8.00	-43	-44	-46	-48	-50	-51	-50	-49	-49	-52	-48
9.00	-37	-38	-39	-41	-42	-43	-42	-42	-42	-45	-41
10.00	-28	-28	-29	-30	-31	-32	-31	-31	-31	-35	-31

EAST WALL

TIME (SEC)	SURFACE PRESSURES (SOUTH TO NORTH) (PSF)										AVERAGE PRESSURE
.0	-208	-238	-261	-276	-284	-284	-276	-261	-238	-208	-254
.05	-534	-493	-485	-445	-356	-225	-79	38	44	-44	-254
.10	-546	-375	-235	-114	-41	-62	-128	-167	-183	-211	-204
.15	-372	-233	-165	-130	-116	-117	-119	-119	-136	-174	-168
.20	-276	-221	-201	-176	-159	-150	-136	-125	-116	-111	-166
.30	-288	-239	-217	-184	-148	-121	-104	-97	-99	-118	-161
.40	-255	-210	-199	-182	-155	-132	-117	-110	-111	-123	-159
.50	-235	-200	-197	-186	-162	-138	-118	-107	-104	-114	-156
.75	-152	-123	-126	-129	-126	-126	-120	-112	-103	-96	-121
1.00	-160	-143	-152	-155	-148	-131	-111	-93	-82	-84	-126
1.25	-134	-125	-137	-147	-150	-145	-135	-123	-109	-99	-130
1.50	-121	-105	-109	-116	-117	-112	-103	-93	-84	-80	-104
1.75	-117	-103	-103	-107	-107	-105	-100	-93	-84	-81	-100
2.00	-110	-99	-98	-102	-104	-103	-98	-91	-83	-79	-96
2.50	-107	-95	-93	-93	-93	-92	-89	-85	-81	-79	-90
3.00	-93	-74	-72	-74	-75	-74	-71	-68	-65	-65	-72
3.50	-93	-85	-85	-85	-87	-86	-83	-79	-74	-71	-83
4.00	-68	-60	-59	-60	-61	-61	-60	-57	-55	-55	-60
4.50	-78	-70	-69	-69	-70	-68	-65	-62	-58	-56	-66
5.00	-70	-62	-61	-61	-61	-60	-58	-55	-53	-51	-59
6.00	-56	-50	-48	-49	-49	-48	-47	-45	-43	-43	-48
7.00	-50	-44	-43	-42	-42	-41	-40	-38	-37	-36	-41
8.00	-45	-40	-39	-38	-38	-37	-36	-34	-32	-31	-37
9.00	-45	-40	-39	-38	-39	-39	-37	-35	-33	-32	-38
10.00	-45	-40	-39	-40	-39	-39	-37	-35	-33	-32	-38

TORNADO STRUCTURE INTERACTION RUN NO. 4

NORTH WALL

TIME (SEC)	SURFACE PRESSURES (WEST TO EAST) (PSF)										AVERAGE PRESSURE
.0	-171	-208	-238	-261	-276	-284	-276	-261	-238		-248
.05	8	100	100	-19	-171	-309	-410	-453	-474	-527	-212
.10	-211	-184	-167	-127	-59	-35	-102	-215	-350	-512	-195
.15	-186	-149	-131	-129	-123	-118	-128	-156	-215	-337	-167
.20	-123	-126	-134	-143	-154	-163	-176	-195	-210	-254	-162
.30	-123	-104	-101	-108	-124	-148	-183	-214	-236	-281	-155
.40	-121	-107	-105	-112	-127	-150	-177	-194	-207	-250	-150
.50	-109	-99	-102	-114	-132	-156	-180	-190	-195	-227	-119
.75	-111	-112	-114	-117	-120	-122	-121	-118	-113	-141	-129
1.00	-84	-84	-96	-115	-134	-151	-158	-156	-149	-164	-130
1.25	-104	-114	-126	-137	-145	-149	-145	-134	-123	-132	-102
1.50	-78	-81	-90	-100	-110	-115	-114	-107	-104	-120	-107
1.75	-92	-95	-102	-108	-113	-114	-112	-107	-106	-119	-87
2.00	-72	-75	-81	-87	-91	-93	-91	-88	-90	-103	-93
2.50	-77	-80	-86	-92	-96	-98	-98	-97	-98	-112	-83
3.00	-69	-71	-76	-81	-85	-87	-88	-88	-90	-100	-79
3.50	-68	-70	-74	-78	-81	-82	-82	-81	-82	-92	-68
4.00	-59	-63	-68	-73	-77	-77	-76	-77	-78	-85	-58
4.50	-53	-64	-66	-69	-70	-71	-69	-67	-69	-77	-53
5.00	-53	-55	-59	-62	-65	-66	-66	-65	-65	-69	-48
6.00	-52	-53	-56	-58	-60	-60	-60	-59	-59	-63	-43
7.00	-49	-50	-52	-54	-55	-55	-55	-53	-52	-56	-37
8.00	-42	-43	-44	-46	-47	-47	-46	-45	-44	-48	-34
9.00	-34	-35	-36	-37	-38	-39	-38	-38	-37	-41	-27
10.00	-27	-28	-30	-33	-34	-35	-36	-36	-37	-42	-34

SOUTH WALL

TIME (SEC)	SURFACE PRESSURES (WEST TO EAST) (PSF)										AVERAGE PRESSURE
.0	-171	-208	-238	-261	-276	-284	-276	-261	-238		-248
.05	-504	-499	-442	-400	-304	-173	-128	-88	-92	-5	-210
.10	-531	-372	-235	-119	-46	-62	-123	-160	-178	-208	-180
.15	-375	-244	-175	-139	-126	-125	-133	-136	-154	-192	-167
.20	-72	-231	-213	-190	-174	-164	-153	-143	-133	-129	-167
.30	-295	-251	-230	-197	-161	-133	-115	-106	-108	-124	-171
.40	-257	-214	-201	-182	-153	-129	-113	-106	-108	-121	-158
.50	-226	-193	-190	-180	-155	-131	-113	-103	-101	-113	-150
.75	-172	-143	-146	-149	-148	-143	-135	-126	-116	-108	-138
1.00	-158	-142	-150	-153	-146	-128	-108	-89	-78	-79	-123
1.25	-137	-126	-136	-146	-148	-142	-132	-120	-106	-95	-129
1.50	-119	-104	-108	-115	-116	-111	-102	-93	-83	-81	-103
1.75	-122	-107	-106	-108	-107	-104	-97	-90	-81	-79	-100
2.00	-109	-98	-98	-102	-103	-102	-97	-90	-82	-79	-96
2.50	-98	-88	-89	-92	-94	-95	-93	-89	-84	-82	-90
3.00	-95	-86	-84	-86	-87	-87	-85	-82	-79	-79	-85
3.50	-79	-71	-69	-70	-71	-70	-67	-63	-60	-59	-68
4.00	-82	-73	-75	-78	-80	-80	-78	-75	-72	-71	-77
4.50	-70	-63	-62	-63	-63	-63	-60	-57	-54	-52	-61
5.00	-75	-67	-66	-67	-67	-67	-65	-62	-59	-58	-65
6.00	-70	-63	-62	-62	-62	-61	-59	-56	-53	-52	-60
7.00	-58	-52	-50	-50	-50	-49	-47	-44	-42	-41	-48
8.00	-54	-49	-47	-47	-46	-45	-43	-41	-39	-38	-45
9.00	-48	-43	-42	-42	-42	-41	-39	-37	-35	-34	-40
10.00	-37	-35	-35	-36	-36	-36	-35	-34	-33	-33	-35

TORNADO STRUCTURE INTERACTION RUN NO. 4

BUILDING FORCE COEFFICIENTS

TIME (SEC)	WEST-EAST CFX	SOUTH-NORTH CFY
.0	.22	.0
.05	.33	.01
.10	.03	-.03
.15	-.05	-.06
.20	-.07	.01
.30	-.04	-.04
.40	.07	-.01
.50	.04	.00
.75	-.08	-.09
1.00	-.01	.03
1.25	.01	.01
1.50	.01	-.01
1.75	-.04	-.03
2.00	.04	-.04
2.50	.05	.01
3.00	.05	-.01
3.50	-.01	.25
4.00	.07	-.01
4.50	-.04	.04
5.00	.02	-.01
6.00	.00	-.01
7.00	-.03	.02
8.00	-.03	.00
9.00	-.02	-.01
10.00	.03	-.01

TORNADO STRUCTURE INTERACTION RUN NO. 5

WEST WALL

TIME (SEC)	SURFACE PRESSURES (SOUTH TO NORTH) (PSF)										AVERAGE PRESSURE
.0	-51	-41	-33	-26	-20	-15	-11	-7	-4	-1	-21
.05	-179	-198	-248	-272	-286	-253	-236	-212	-181	-165	-217
.10	-203	-230	-192	-165	-164	-183	-204	-216	-209	-211	-201
.15	-363	-261	-197	-160	-144	-138	-130	-136	-157	-189	-181
.20	-393	-281	-215	-169	-142	-128	-121	-122	-124	-121	-175
.30	-393	-282	-240	-185	-153	-120	-94	-76	-63	-53	-162
.40	-389	-268	-227	-199	-149	-112	-85	-63	-46	-31	-150
.50	-311	-227	-211	-188	-150	-117	-90	-68	-49	-32	-140
.75	-214	-130	-122	-102	-80	-62	-47	-36	-20	-4	-78
1.00	-126	-105	-117	-125	-126	-118	-105	-92	-78	-68	-104
1.25	-81	-100	-132	-146	-145	-137	-128	-115	-105	-102	-114
1.50	-57	-43	-35	-26	-14	-1	13	23	28	21	-7
1.75	31	21	10	4	2	2	-1	-6	-15	-39	3
2.00	42	33	23	10	-4	-22	-41	-62	-85	-123	-22
2.50	-67	-81	-93	-110	-114	-123	-128	-131	-134	-143	-111
3.00	15	19	19	19	17	15	15	17	19	19	17
3.50	-42	-41	-42	-45	-49	-54	-58	-61	-62	-62	-52
4.00	-53	-43	-35	-28	-22	-15	-10	-4	2	8	-20
4.50	-33	-32	-31	-28	-24	-20	-16	-11	-8	-7	-21
5.00	-74	-72	-68	-66	-62	-58	-53	-47	-41	-36	-58
6.00	-23	-17	-13	-10	-7	-5	-3	-2	-1	-2	-8
7.00	-18	-16	-13	-10	-7	-5	-3	-2	-1	-1	-7
8.00	-27	-23	-22	-21	-20	-20	-20	-19	-19	-19	-21
9.00	-8	-6	-5	-6	-8	-10	-12	-14	-17	-21	-11
10.00	2	2	0	0	-1	-2	-3	-4	-5	-7	-2

EAST WALL

TIME (SEC)	SURFACE PRESSURES (SOUTH TO NORTH) (PSF)										AVERAGE PRESSURE
.0	-43	-35	-28	-23	-17	-13	-9	-5	-2	0	-16
.05	88	63	38	25	27	31	36	33	8	-63	30
.10	44	68	77	79	67	38	-4	-39	-50	-92	20
.15	6	54	65	56	36	18	-1	-24	-55	-93	8
.20	-59	-10	3	15	13	2	-10	-26	-46	-70	-16
.30	-136	-93	-72	-58	-49	-42	-35	-30	-30	-38	-56
.40	-187	-119	-95	-76	-61	-52	-47	-44	-44	-46	-72
.50	-175	-126	-104	-87	-69	-55	-44	-38	-35	-36	-74
.75	-138	-87	-64	-47	-34	-26	-29	-40	-54	-60	-55
1.00	-132	-72	-44	-25	-9	6	21	29	33	36	-14
1.25	40	58	50	42	42	54	73	88	96	92	64
1.50	-14	13	17	19	29	46	67	81	82	84	45
1.75	17	29	27	23	29	44	63	81	102	119	55
2.00	-73	-71	-79	-68	-60	-66	-76	-62	-46	-28	-69
2.50	-108	-101	-101	-103	-106	-107	-105	-103	-100	-101	-103
3.00	-82	-47	-28	-15	-6	-2	-1	0	0	-2	-17
3.50	-119	-82	-62	-48	-36	-27	-21	-17	-18	-21	-44
4.00	-98	-75	-62	-53	-43	-31	-18	-4	8	21	-35
4.50	-78	-71	-63	-57	-49	-37	-22	-6	-59	-52	-50
5.00	-93	-82	-76	-73	-68	-61	-52	-43	-34	-26	-60
6.00	4	10	13	13	13	10	13	15	15	13	11
7.00	-19	-10	-6	-3	-1	0	2	4	6	6	-2
8.00	-28	-16	-11	-7	-3	0	4	6	6	6	-4
9.00	-30	-28	-28	-29	-29	-30	-30	-30	-30	-31	-29
10.00	-1	4	8	10	13	15	17	17	15	13	11

TORNADO STRUCTURE INTERACTION RUN NO. 5

NORTH WALL

TIME (SEC)	SURFACE PRESSURES (WEST TO EAST) (PSF)										AVERAGE PRESSURE
.0	2	4	4	6	6	8	8	10	10	10	7
.05	-216	-277	-355	-382	-390	-394	-391	-360	-288	-208	-32
.10	-201	-247	-257	-263	-266	-272	-238	-222	-224	-244	-24
.15	-227	-207	-183	-128	-130	-123	-138	-164	-187	-229	-167
.20	-93	-89	-100	-94	-93	-86	-95	-100	-110	-158	-101
.30	-46	-36	-33	-33	-30	-35	-45	-60	-84	-114	-51
.40	-8	-4	-1	-3	-7	-14	-23	-41	-62	-88	-25
.50	-7	-3	-1	-3	-6	-12	-21	-34	-48	-64	-20
.75	58	52	38	23	13	8	0	-14	-32	-56	9
1.00	-33	-36	-35	-30	-23	-19	-15	-8	4	23	-17
1.25	-46	-43	-46	-47	-57	-60	-56	-43	-16	23	-38
1.50	111	113	111	102	94	86	77	73	73	69	90
1.75	88	109	123	134	140	148	148	150	148	140	131
2.00	-44	-37	-34	-32	-28	-22	-18	-9	-6	-10	-25
2.50	-108	-105	-106	-107	-110	-112	-114	-115	-116	-121	-111
3.00	6	0	-4	-8	-11	-13	-15	-15	-16	-18	-8
3.50	-69	-73	-77	-79	-80	-78	-74	-67	-56	-43	-69
4.00	19	23	27	29	31	33	36	38	38	38	31
4.50	-16	-23	-29	-35	-39	-41	-42	-42	-41	-44	-35
5.00	-36	-40	-43	-45	-45	-43	-39	-27	-29	-24	-37
6.00	-4	-6	-8	-8	-7	-5	-4	-2	-1	-6	-5
7.00	13	17	17	19	19	17	15	13	8	-1	14
8.00	-24	-21	-20	-19	-16	-14	-11	-9	-9	-9	-16
9.00	-47	-40	-37	-36	-37	-37	-37	-36	-36	-38	-38
10.00	-20	-16	-14	-10	-8	-6	-4	-1	2	6	-7

SOUTH WALL

TIME (SEC)	SURFACE PRESSURES (WEST TO EAST) (PSF)										AVERAGE PRESSURE
.0	-32	-43	-35	-29	-23	-17	-13	-9	-5	-2	-23
.05	299	480	643	704	710	704	683	616	462	338	555
.10	195	305	378	430	476	478	453	428	378	311	375
.15	123	188	203	207	221	230	234	259	272	253	212
.20	33	102	136	150	157	159	157	152	138	119	124
.30	8	75	109	127	134	134	132	123	107	75	96
.40	-19	42	71	84	88	88	88	81	69	40	57
.50	-19	31	54	65	65	61	58	54	44	19	38
.75	-3	38	52	56	61	61	61	58	50	31	42
1.00	-7	21	31	36	36	35	36	31	23	2	21
1.25	75	107	123	136	142	150	157	159	157	148	133
1.50	-23	-3	13	23	31	38	46	54	61	58	28
1.75	38	48	61	73	86	94	100	104	104	96	79
2.00	23	15	8	2	-3	-8	-14	-18	-22	-28	-5
2.50	-31	-17	-9	6	15	19	17	10	-9	-23	-2
3.00	13	15	17	21	23	27	29	29	25	13	20
3.50	-53	-57	-59	-60	-61	-61	-61	-61	-63	-67	-61
4.00	-78	-84	-85	-84	-81	-77	-72	-67	-64	-64	-76
4.50	-31	-29	-25	-22	-18	-17	-16	-18	-22	-30	-23
5.00	-80	-80	-79	-75	-73	-70	-67	-65	-64	-66	-72
6.00	-36	-39	-41	-39	-36	-30	-23	-18	-8	0	-26
7.00	-13	-10	-7	-3	0	4	8	10	13	13	1
8.00	-26	-30	-31	-31	-30	-28	-25	-21	-18	-14	-26
9.00	-6	-7	-8	-9	-9	-9	-9	-8	-8	-9	-8
10.00	0	-1	-3	-4	-5	-7	-7	-8	-7	-5	-5

TORNADO STRUCTURE INTERACTION RUN NO. 5

BUILDING FORCE COEFFICIENTS

TIME (SEC)	WEST-EAST CFX	SOUTH-NORTH CFY
.0	-.01	-.09
.05	-.74	2.64
.10	-.67	1.67
.15	-.57	1.14
.20	-.48	.66
.30	-.32	.44
.40	-.23	.25
.50	-.20	.17
.75	-.07	.10
1.00	-.27	.11
1.25	-.54	.52
1.50	-.16	.19
1.75	-.16	-.16
2.00	-.14	.06
2.50	-.02	.33
3.00	-.10	.09
3.50	-.02	.02
4.00	.04	-.32
4.50	.15	.04
5.00	.01	-.11
5.50	-.06	-.07
7.00	-.02	-.04
8.00	-.05	-.03
9.00	-.06	.03
10.00	-.04	.01

TORNADO STRUCTURE INTERACTION RUN NO. 6

WEST WALL

TIME (SEC)	SURFACE PRESSURES (SOUTH TO NORTH) (PSF)										AVERAGE PRESSURE
0	-180	-198	-211	-225	-236	-245	-252	-258	-261	-263	-232
.05	424	378	317	257	211	178	132	56	-48	-180	-167
.10	305	240	169	90	10	-65	-135	-199	-261	-331	-19
.15	184	117	52	-10	-67	-120	-169	-218	-269	-330	-84
.20	119	65	13	-35	-81	-126	-169	-212	-260	-314	-100
.30	42	6	-29	-83	-98	-131	-165	-198	-233	-273	-113
.40	17	-9	-33	-57	-81	-103	-124	-144	-162	-181	-87
.50	33	15	-5	-25	-43	-61	-77	-92	-105	-118	-67
.75	84	81	77	69	58	46	33	19	6	-8	45
1.00	-54	-47	-39	-26	-7	17	44	71	98	121	17
1.25	-20	-27	-38	-51	-62	-72	-78	-79	-75	-66	-57
1.50	-138	-161	-185	-177	-186	-190	-189	-181	-168	-148	-168
1.75	-47	-43	-38	-33	-27	-17	-4	13	33	55	-10
2.00	-89	-78	-71	-66	-66	-65	-64	-61	-55	-42	-70
2.50	-17	-21	-24	-27	-30	-28	-27	-26	-24	-24	-25
3.00	-54	-49	-44	-37	-30	-21	-12	-3	4	10	-23
3.50	-92	-108	-118	-128	-136	-142	-148	-153	-160	-171	-134
4.00	-163	-186	-190	-145	-139	-133	-125	-120	-117	-119	-136
4.50	-80	-63	-67	-70	-72	-74	-76	-81	-88	-103	-74
5.00	-58	-60	-61	-61	-60	-59	-57	-58	-60	-68	-59
6.00	-26	-16	-13	-11	-8	-5	-3	1	2	-9	-9
7.00	10	6	4	0	-3	-6	-11	-16	-23	-31	-7
7.48	-21	-20	-18	-16	-14	-12	-10	-9	-7	-7	-13
8.00	40	38	38	33	31	27	23	19	13	4	26
9.00	-6	-5	-5	-6	-6	-7	-8	-9	-10	-11	-7
10.00	-22	-19	-17	-15	-15	-15	-16	-17	-19	-22	-18

EAST WALL

TIME (SEC)	SURFACE PRESSURES (SOUTH TO NORTH) (PSF)										AVERAGE PRESSURE
0	-142	-153	-164	-175	-186	-195	-203	-208	-212	-213	-176
.05	-161	-153	-148	-146	-151	-145	-126	-153	-199	-210	-155
.10	-147	-100	-83	-86	-80	-77	-78	-83	-96	-118	-93
.15	-175	-136	-107	-93	-89	-94	-102	-109	-118	-136	-112
.20	-9	-181	-193	-195	-124	-120	-124	-134	-148	-168	-131
.30	-343	-304	-281	-269	-255	-240	-228	-221	-219	-221	-253
.40	-420	-369	-337	-317	-300	-276	-249	-223	-195	-177	-281
.50	-341	-284	-257	-242	-225	-199	-170	-144	-122	-105	-205
.75	-341	-308	-299	-290	-273	-243	-207	-171	-135	-98	-234
1.00	-282	-253	-241	-223	-197	-173	-154	-143	-141	-142	-190
1.25	54	23	-7	-31	-49	-62	-73	-82	-91	-102	-40
1.50	-100	-85	-78	-73	-70	-67	-66	-67	-70	-77	-74
1.75	19	33	38	44	48	50	50	50	50	46	44
2.00	-100	-100	-99	-100	-101	-103	-107	-118	-120	-133	-107
2.50	-174	-168	-169	-171	-174	-177	-181	-184	-186	-187	-176
3.00	-149	-133	-128	-122	-111	-97	-85	-73	-62	-53	-100
3.50	10	10	8	10	10	13	13	13	10	10	11
4.00	6	30	-11	-3	-6	-3	-3	-31	-28	-24	-44
4.50	-16	-13	-11	-9	-6	-3	-3	-3	-2	4	-4
5.00	-52	-51	-47	-43	-39	-35	-30	-25	-21	-16	-36
6.00	-40	-37	-36	-37	-36	-41	-42	-44	-47	-50	-41
7.00	-15	-12	-12	-13	-15	-17	-19	-22	-24	-27	-17
7.48	-8	0	6	8	13	15	17	19	21	23	12
8.00	0	4	6	6	6	4	2	1	3	5	2
9.00	-45	-44	-44	-46	-46	-50	-53	-55	-58	-60	-50
10.00	-1	-1	-1	-2	-3	-4	-5	-6	-9	-14	-5

TORNADO STRUCTURE INTERACTION RUN NO. 6

NORTH WALL																AVERAGE PRESSURE
TIME (SEC)	SURFACE PRESSURES (WEST TO EAST) (PSF)															AVERAGE PRESSURE
.0	-212	-159	-120	-92	-71	-55	-43	-34	-25	-19	-14	-9	-5	-2	0	-59
.05	-617	-692	-824	-821	-764	-707	-656	-611	-572	-537	-506	-476	-436	-385	-291	-587
.10	-829	-848	-914	-881	-847	-800	-755	-711	-671	-631	-591	-551	-511	-471	-431	-501
.15	-991	-904	-954	-922	-886	-845	-805	-765	-725	-685	-645	-605	-565	-525	-485	-427
.20	-944	-866	-910	-873	-835	-797	-759	-721	-683	-645	-607	-569	-531	-493	-455	-353
.30	-388	-340	-291	-236	-192	-160	-143	-126	-114	-102	-92	-82	-72	-62	-52	-186
.40	-219	-211	-179	-140	-112	-92	-81	-72	-64	-56	-48	-40	-32	-24	-16	-110
.50	-125	-132	-119	-96	-78	-70	-63	-59	-51	-47	-40	-32	-24	-16	-8	-65
.75	-98	-91	-113	-122	-122	-125	-129	-130	-128	-128	-128	-121	-105	-77	-47	-108
1.00	134	125	121	119	119	123	132	138	138	125	113	104	95	83	25	110
1.25	-35	-37	-63	-75	-82	-113	-134	-153	-166	-175	-170	-153	-133	-112	-95	-117
1.50	-93	-76	-60	-48	-39	-30	-20	-8	4	13	19	17	10	-1	-19	-23
1.75	123	146	161	165	161	152	146	142	140	140	140	138	129	121	107	140
2.00	-80	-88	-89	-84	-74	-61	-50	-42	-37	-36	-38	-41	-45	-52	-65	-59
2.50	-35	-43	-52	-61	-70	-80	-89	-96	-107	-116	-126	-137	-151	-165	-179	-101
3.00	58	79	98	111	121	129	134	134	127	117	102	84	61	38	10	13
3.50	-100	-80	-63	-47	-31	-16	-3	10	21	27	31	31	31	27	23	-10
4.00	-36	-15	-3	4	8	8	2	4	8	8	-14	-18	-21	-22	-21	-10
4.50	-40	-32	-26	-21	-16	-10	-3	4	8	15	19	21	23	21	18	-2
5.00	-5	10	23	31	40	48	52	52	50	44	38	27	17	8	0	28
6.00	7	-1	-7	-14	-22	-30	-38	-48	-57	-64	-70	-72	-72	-69	-63	-42
7.00	-50	-83	-75	-85	-93	-99	-103	-102	-98	-91	-83	-73	-62	-48	-61	-61
7.46	21	23	23	21	19	15	13	10	10	10	13	17	19	23	25	17
8.00	-3	-13	-22	-31	-38	-45	-50	-53	-55	-54	-52	-47	-41	-35	-24	-37
9.00	-21	-28	-38	-47	-55	-63	-71	-77	-82	-85	-87	-87	-85	-81	-75	-85
10.00	-13	-16	-20	-25	-29	-32	-34	-36	-37	-38	-35	-32	-29	-25	-20	-28

SOUTH WALL																
TIME (SEC)	SURFACE PRESSURES (WEST TO EAST) (PSF)															AVERAGE PRESSURE
.0	-125	-101	-81	-65	-52	-41	-33	-25	-19	-14	-10	-6	-3	0	2	-39
.05	491	508	585	643	654	637	608	581	553	526	503	476	420	292	148	506
.10	437	443	455	466	478	510	545	566	550	518	445	355	260	211	125	423
.15	368	388	401	409	418	422	416	395	370	349	330	303	265	215	148	342
.20	301	326	336	336	328	308	284	261	244	226	209	196	184	161	115	251
.30	178	175	159	146	134	123	117	109	102	92	81	67	48	21	-29	89
.40	113	107	90	77	65	54	44	33	21	10	-3	-18	-38	-67	-118	22
.50	80	70	58	42	27	15	2	-11	-24	-37	-51	-67	-85	-108	-142	-18
.75	46	10	-13	-31	-41	-51	-63	-80	-102	-129	-160	-191	-216	-239	-249	-101
1.00	-61	-85	-83	-78	-72	-64	-58	-58	-76	-88	-99	-112	-126	-145	-173	-95
1.25	-1	21	44	65	90	113	134	155	171	184	192	196	194	186	163	126
1.50	-80	-74	-61	-51	-42	-33	-25	-16	-7	2	6	5	0	-14	-34	-50
1.75	-54	-46	-32	-18	-1	15	28	44	61	75	88	94	98	96	84	35
2.00	-136	-183	-182	-183	-195	-192	-184	-173	-160	-147	-137	-131	-128	-123	-115	-157
2.50	-4	3	-3	-1	2	14	6	6	6	2	-5	-16	-34	-62	-8	-8
3.00	-72	-83	-91	-96	-99	-100	-100	-99	-100	-101	-104	-107	-108	-114	-120	-86
3.50	-26	-0	19	31	42	48	48	48	42	36	29	23	19	19	17	25
4.00	-170	-188	-185	-157	-147	-138	-122	-108	-95	-82	-71	-62	-57	-54	-55	-110
4.50	-48	-41	-32	-24	-15	-8	-3	0	2	4	4	2	2	-1	-4	-11
5.00	-58	-58	-57	-53	-49	-45	-41	-39	-36	-35	-35	-35	-36	-38	-41	-44
6.00	-37	-23	-49	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48
7.00	21	25	31	36	40	44	48	52	54	56	54	52	48	40	27	41
7.46	-25	-29	-32	-34	-34	-33	-31	-28	-24	-20	-16	-12	-8	-5	-2	-22
8.00	-3	31	27	23	21	21	21	21	21	21	21	21	21	21	21	-27
9.00	-12	-10	-11	-13	-16	-18	-21	-23	-24	-24	-23	-23	-23	-23	-23	-19
10.00	-44	-39	-36	-34	-33	-31	-30	-29	-27	-25	-23	-20	-16	-12	-7	-27

TORNADO STRUCTURE INTERACTION RUN NO. 6

BUILDING FORCE COEFFICIENTS

TIME (SEC)	WEST-EAST CFX	SOUTH-NORTH CFY
.0	-.17	.06
.05	.97	3.29
.10	.22	2.79
.15	.09	2.32
.20	.09	1.82
.30	.42	.85
.40	.59	.40
.50	.48	.21
.75	.84	.02
1.00	.53	-.52
1.25	-.05	-.73
1.50	-.28	-.02
1.75	-.16	-.32
2.00	.11	-.29
2.50	.45	-.28
3.00	.23	-.57
3.50	-.44	-.11
4.00	-.28	-.30
4.50	-.21	-.03
5.00	-.07	-.22
5.00	.10	.04
7.00	.03	-.37
7.45	-.07	-.12
8.00	.07	.19
9.00	.13	.14
10.00	-.04	.00

TORNADO STRUCTURE INTERACTION RUN NO. 7

WEST WALL

TIME (SEC)	SURFACE PRESSURES (SOUTH TO NORTH) (PSF)										AVERAGE PRESSURE
.0	-168	-218	-240	-255	-262	-261	-253	-238	-214	-183	-230
.05	385	297	236	161	61	-49	-153	-236	-289	-350	5
.10	297	182	75	-20	-98	-151	-183	-204	-219	-242	-56
.15	207	98	4	-74	-137	-182	-212	-229	-238	-246	-99
.20	136	42	-40	-106	-156	-192	-216	-229	-244	-258	-131
.30	40	-24	-89	-141	-182	-211	-230	-240	-243	-253	-153
.40	-4	-54	-100	-138	-166	-183	-189	-185	-175	-160	-133
.50	-5	-46	-85	-116	-139	-154	-160	-156	-141	-114	-110
.75	90	77	54	17	-30	-83	-138	-189	-227	-237	-66
1.00	79	58	8	-46	-87	-111	-119	-112	-88	-43	-45
1.25	-36	-60	-68	-116	-139	-156	-164	-168	-169	-170	-127
1.50	-127	-152	-169	-175	-185	-194	-198	-198	-194	-17	-107
1.75	-130	-129	-127	-122	-112	-96	-72	-39	2	46	-77
2.00	-134	-128	-123	-114	-101	-82	-59	-37	-18	-7	-60
2.50	-32	-50	-73	-93	-108	-117	-123	-126	-125	-123	-97
3.00	-66	-57	-56	-60	-66	-70	-68	-57	-38	-12	-88
3.50	-74	-87	-99	-108	-113	-114	-111	-104	-95	-91	-99
4.00	-150	-152	-144	-126	-104	-80	-59	-41	-27	-25	-90
4.50	-61	-66	-66	-61	-55	-48	-42	-36	-37	-45	-51
5.00	-94	-85	-78	-71	-63	-55	-47	-39	-30	-29	-58
6.00	-85	-76	-72	-72	-73	-74	-73	-70	-64	-36	-71
7.00	-37	-40	-42	-43	-44	-43	-41	-38	-33	-30	-39
8.00	6	-3	-13	-22	-29	-36	-42	-47	-51	-59	-27
9.00	-7	-12	-18	-25	-30	-34	-37	-39	-42	-42	-27
10.00	-23	-24	-25	-26	-28	-29	-30	-32	-35	-42	-29

EAST WALL

TIME (SEC)	SURFACE PRESSURES (SOUTH TO NORTH) (PSF)										AVERAGE PRESSURE
.0	-147	-170	-191	-205	-213	-212	-204	-188	-167	-144	-177
.05	-153	-157	-212	-245	-244	-231	-213	-181	-140	-176	-191
.10	-199	-148	-130	-117	-118	-137	-169	-197	-195	-208	-157
.15	-213	-134	-91	-71	-76	-86	-89	-110	-146	-190	-117
.20	-211	-129	-92	-71	-68	-70	-77	-94	-116	-146	-104
.30	-259	-189	-152	-117	-98	-94	-99	-112	-129	-151	-137
.40	-326	-276	-263	-236	-210	-190	-175	-161	-149	-132	-208
.50	-331	-266	-223	-165	-106	-57	-17	13	33	33	-108
.75	-331	-266	-223	-165	-106	-57	-17	13	33	33	-108
1.00	-90	-102	-100	-99	-95	-78	-46	-15	2	10	-60
1.25	-3	-102	-74	-96	-102	-97	-89	-79	-66	-57	-68
1.50	-32	-24	-20	-16	-10	4	25	36	36	21	2
1.75	107	102	94	90	90	88	90	94	98	98	94
2.00	-48	-43	-42	-42	-42	-38	-29	-13	6	31	-26
2.50	-150	-149	-156	-170	-183	-192	-196	-194	-186	-172	-174
3.00	-179	-157	-137	-118	-101	-89	-79	-70	57	-42	-102
3.50	-10	-13	-15	-18	-20	-24	-29	-33	-38	-45	-24
4.00	-98	-73	-57	-39	-20	-3	13	23	31	31	-16
4.50	31	31	25	21	19	17	17	15	13	2	20
5.00	-41	-27	-19	-13	-7	1	4	13	21	29	-4
6.00	-83	-60	-60	-61	-63	-64	-64	-63	-61	-57	-61
7.00	-19	-9	-7	-5	-6	-9	-13	-17	-21	-21	-11
8.00	0	0	-5	-8	-10	-11	-12	-14	-17	-21	-9
9.00	-28	-26	-31	-36	-40	-44	-48	-52	-56	-60	-42
10.00	36	29	23	19	13	8	2	-4	-13	-23	9