Date: April 11, 1994

To: Dean Wilson (MD-14)
EPA OAQPS/TSD/SRAB

From: Brenda Johnson
EPA Region IV

Here are CPP's responses to EPA's comments on the Cape Industries fluid modeling demonstration for equivalent building heights. RADIAN has expressed an interest in having a conference call to determine what is needed to satisfy our concerns and whether or not a new report needs to be prepared documenting the modeling study. I would like to arrange a conference call with RADIAN, CPP, Jim Roller, Region IV and OAQPS at some times in the near future. However, I would like for you to look at this and let's talk about it prior to the conference call with the Cape people. Thank you for your cooperation.

CPP Wind Engineering Consultants

April 7, 1994

Mr. Jim Roller
North Carolina Department of
Environment, Health and Natural Resources
Division of Environmental Management
Air Quality Section
PO Box 29535
Raleigh, NC 27626-0535

Re: Cape Industries—Response to EPA Comments
CPP Project 93-0955

Dear Mr. Roller:

This letter is written in response to EPA's comments summarized in your February 23 letter to Mr. David Keen of Radian Corporation. This letter should provide the necessary details to assure DEHNR and EPA that the equivalent building dimensions that CPP has presented are appropriate. Each area of concern mentioned in the February 2 letter from Dean Wilson to Brenda Johnson is addressed by paragraph in Attachment I. CPP's response to comments in the December 8 letter from John Irwin to William Snyder and William Snyder's return comments in the letter dated January 14 are addressed by comment number in Attachments II and III, respectively.

While we agree that the study contained a few minor typographical errors, we believe that the study conclusively determined the equivalent building dimensions for ISC input. In conducting the study, CPP was diligent in following the procedures outlined in the test protocol dated August 9, 1993 which was reviewed by the State of North Carolina DEHNR and EPA Region IV prior to commencement of the study (see September 20, 1993 letter from Tom Anderson of DEHNR to Mr. David Keen). Since the results of this review did not question the basic equivalent building dimension methodology, CPP assumed that DEHNR and EPA Region IV had accepted the basic approach.

In summary, CPP believes that the study has provided well documented equivalent building dimensions that can be used for direct input into ISC. While the identified typographical errors or inconsistencies might have raised concerns about the technical merit of the approach, the errors are minor in nature and do not affect the conclusions of the report (i.e., the tabulated equivalent building dimensions). We therefore recommend that the equivalent building dimensions be approved on the basis of discussions herein and attached. If necessary, the report will be modified to reflect the changes discussed herein and resubmitted. Before proceeding with the report modifications, however, CPP and its client would like general agreement on the issues discussed in this transmittal. We therefore further recommend that a conference call or face-to-face meeting be scheduled as soon as possible to discuss these responses and to settle any unresolved issues.

Sincerely,

CERMAK PETERKA PETERSEN, INC.
Wind Engineering Consultants

Ronald L. Petersen, Ph.D., CCM
Vice President

RLP:lrn
Attachments

cc: Brenda Johnson, EPA Region IV
David Keen, Radian Corporation
Ron Walton, Cape Industries

ATTACHMENT I

RESPONSE TO CONCERNS MENTIONED IN THE FEBRUARY 1 LETTER FROM DEAN WILSON TO BRENDA JOHNSON

Paragraph 1—EPA agrees that the wind tunnel can be used to determine equivalent building dimensions but is not convinced that CPP has demonstrated and documented within an acceptable level of uncertainty that the equivalent building dimensions provided are appropriate.

As indicated in the cover letter, the purpose of this transmittal is to furnish DEHNR and EPA with the information necessary to provide assurance that the wind tunnel derived equivalent building dimensions CPP has presented are appropriate.

Paragraph 2—Dr. Snyder had a difficult time forming a conclusive opinion on the study and does not believe that the study should be designed around the requirement of GEP.

Direct responses to Dr. Snyder's comments are included in Attachment III. Most of the comments pertained to typographical errors, misinterpretations of the results or discussions that were not clear. With regard to designing the study around the requirement of GEP, CPP's response under Comment 1 of Attachment III specifically defends the simulation method and criteria used for determining the equivalent building dimensions.

Paragraph 3—Not enough data points were obtained in every case to define equivalent building dimensions within an acceptable level of uncertainty.

CPP measured ground-level concentrations at a minimum of 40 receptors for every simulation. Concentrations were measured at a minimum of 5 downwind distances that covered the range where the maximum ground-level concentration was expected to occur. At each downwind distance concentrations were measured at a minimum of 5 horizontal locations (typically 7 or 9 receptors were located at each downwind distance). The coordinates of the sampling points relative to the center of the turntable are provided in Appendix F of the report. If the maximum concentration was not bracketed in either the lateral or longitudinal direction, the test was repeated with a revised grid. Only the final runs are reported. Attachment IV includes an uncertainty analysis which indicates that the uncertainty associated with the finite grid is approximately 6 percent in the lateral direction and 13 percent in the longitudinal direction. The total uncertainty due to grid spacing is approximately 15 percent. CPP believes that this level of uncertainty is acceptable given that the results will be used in an air quality model which yields results with a much larger uncertainty.

Paragraph 4—A more complete analysis and write up might be convincing. The following specific items should be addressed in the report: a) write up should be educational enough for regulators/public and more technical reviewers; b) information should be supplied to define the criteria employed to ensure that the wind tunnel simulations are appropriate and meaningful; c) show that maximum concentrations at 5 downwind distances are sufficient to define the overall maximum (i.e., the uncertainties in the results need to be defined); d) show clearly how the equivalent buildings meet the criteria that was defined.

CPP and its client want to be sure, before undertaking additional work on the report, that all important issues are addressed and that agreement on these issues is reached. If DEHNR and

EPA agree with the responses, the report can be revised to reflect the changes. If DEHNR or EPA disagree with some of the responses, a mutually agreeable resolution to the issues should be developed prior to any report revisions. With regard to comments a, b and d above, the following additional discussion is provided for clarification. Comment c was addressed in the response to paragraph 3.

Equivalent Building Dimensions (EBD) are the dimensions (height and width) that should be input into the ISCST model to allow the model to produce realistic concentration estimates for sites where the building geometry is not consistent with the assumed geometry in ISCST (i.e., dispersion from a stack located directly downwind of a building with height to width to length ratio of 1:2:1—EPA, 1987). When a solid rectangular building that has height to width to length ratio of 1:2:1 and is directly upwind of a stack, the actual building dimensions are the appropriate ISCST inputs. When the structure is some distance removed from the stack, downwind of the stack, tiered, porous, circular or some other shape that is not consistent with the ISCST assumed geometry, the equivalent building dimensions will be different than the actual dimensions.

The building wake prediction problem is recognized by EPA. The ISCST Users Guide (EPA, 1987) contains the following statement concerning the building wake algorithm that is based on the work of Huber and Snyder (1976):

> "Their suggestions are principally based on the results of wind-tunnel experiments using a model building with a crosswind dimension double that of the building height. Thus, the data reported by Huber and Snyder reflect a specific stability, building shape and building orientation with respect to the mean wind direction. It follows that the ISC Model wake-effects evaluation procedure may not be strictly applicable to all situations."

Huber and Snyder (1982) further state that the stack was placed midway about the lee side of the building and that the building height to width to length ratio was 1:2:1. Based on this information it is clear that the ISCST model predicts concentrations due to a stack located directly downwind of the center of a rectangular building with a height to width to length ratio of 1:2:1. To make this prediction, the model uses the dimensions of the largest nearby structure which may be porous, tiered, irregular or some distance removed from the stack. Hence, the purpose of an equivalent building dimension study is to find the dimensions of a Huber/Snyder building that will produce similar (as defined below) maximum ground level concentration as produced by the actual site configuration.

Figure 1 (attached) illustrates this discrepancy for stack H–3 for a wind direction from 260 degrees. At this wind direction a 24 m (80 ft) tall by approximately 48 m (160 ft) wide lattice structure is located approximately 50 m (160 ft) upwind of the stack. Following the ISC procedures, the downwash due to this structure would be modeled as if a 24 m x 48 m solid structure was directly upwind of the H–3 stack. Figure 1 shows that the downwash resulting from this solid structure (solid triangles) overestimates the downwind concentrations when compared to the concentration profile from the actual site configuration (solid circles). The figure also indicates that the actual concentration profile can be modeled accurately using an equivalent solid structure with dimensions 15.2 m (50 ft) x 30.48 m (100 ft) (open triangle).

At present, the only method the Environmental Protection Agency (EPA) has concurred with for determining EBD is through the use of wind-tunnel modeling. A paper (Petersen *et al.*,

1992) describing the first such study CPP conducted for AMOCO, for which the protocol was reviewed and accepted by EPA (Region V and RTP), is included as Attachment IV.

To determine the equivalent building dimensions for Cape Industries, wind tunnel tests were first conducted for 18 wind directions (at 20 degree increments) with all plant structures in place for each source. Concentrations were measured in a sampling grid as described above and in Appendix F of the report. Next, the nearby buildings were removed (see discussion in Attachment III under Comment 3) and the tests were repeated for the same wind directions. If the maximum concentration with the structures present was not excessive for a particular wind direction, and thus building downwash is not considered a problem, the equivalent building dimensions were set equal to zero. For wind directions where excessive concentrations occurred, additional testing was conducted to determine the equivalent building dimensions. For this testing, the site model was removed from the wind tunnel and replaced with a uniform roughness that represented the site roughness. The roughness upwind and downwind of the model remained unchanged. A single rectangular building with height to length to width ratios of 1:2:1 was then placed upwind of the stack under evaluation and the maximum ground-level concentrations versus downwind distance were measured as described above. This setup was specifically designed to reproduce the wind tunnel configuration used by Huber and Snyder (1976). The process was repeated for various building dimensions until a dimension was found that gave a similar (as defined below) ground level concentration profile as with all buildings present. The dimensions of all equivalent buildings are provided in Table 4 of the report.

Figure 2 (attached) shows a typical result from the study for stacks H–3 and CA–B for the wind direction from 0 degrees. The figure shows the maximum ground level concentration profiles measured with plant structures in place, with the nearby structures removed (multiplied by 1.4), and for different equivalent buildings. The curves are generated using a cubic spline fit from SIGMAPLOT Scientific System (a commercially available software program from Jandel Corporation, Copyright 1990, Version 4.04). The method can be crudely described as a running interpolation of cubic polynomials. The resulting curves, which are forced to pass through each data point, are similar in shape to the downwind profile curves described by Turner (1970) for ground level concentrations. Data points were not included for these curves for ease in interpreting the figures. The actual concentrations are reported in Appendix F of the report.

The first step in the equivalent building dimension determination is to determine whether the maximum ground-level concentration with the structures present is excessive (i.e., less than 1.4 times the maximum ground-level concentration with the nearby structures removed). This is accomplished by inspecting the data in Appendix F and the curves in Appendix G of the report, of which Figure 2 is an example. For source H–3 (top graph in the figure), the maximum concentration with the structures present is less than 1.4 times the maximum concentration with nearby structures removed. Hence, for this wind direction the downwash is not considered to be a problem and thus the equivalent building height is zero. The figure also shows that if an equivalent building were specified it would be BH3. This equivalent building has a 15.2 m (50 ft) height and 30.48 m (100 ft) width. The stack height for H–3 is 43.6 m (143 ft). If the 15.2 m equivalent building height were input into ISCST, the downwash algorithm would not be used since the stack height is greater than 2.5 times the building height. Hence, using a zero equivalent building or actual equivalent building dimensions for this case would produce the same result in ISCST. This illustrates why a zero equivalent building height is used for those cases where non-excessive concentrations are found.

For source CA–B (shown in the bottom graph of Figure 2), excessive concentrations were observed and thus the nearby building removed curve was not included so that an additional equivalent building profile could be shown. For this source, and all others where an excessive concentration has been demonstrated to exist, the equivalent building was determined by first comparing the overall maximum concentration for the various equivalent building tests to the test with the actual site structures present. The equivalent building is then taken to be the building that produces an overall maximum concentration that is closest to and within 10 percent or greater than the overall maximum concentration with the actual site structures in place (i.e., the 90 percent criteria). The corresponding equivalent building is recorded in Table 5 of the report. The lower graph in Figure 2 indicates that the equivalent building for CA–B at a wind direction from 0 degrees would be BH7 following this selection criteria.

The 90 percent criteria was established because experience has shown that wind tunnel measurements are generally repeatable within 10 percent (i.e., two measured concentrations within ±10 percent are considered equivalent). This is consistent with the criteria used for Reynolds number independence tests to indicate that the measured concentrations are not influenced by Reynolds number affects. In addition, the statistical analysis presented in Attachment IV suggests that the uncertainty should range from ±9 to ±16 percent. Therefore, two measurement points that are within 18 to 32 percent are within the experimental uncertainty. Hence, allowing for a 10 percent lower concentration with the equivalent building is a reasonable and somewhat conservative assumption.

Paragraph 5—The report will need to contain not only the scientific details but also considerable explanatory material such that these scientific details can be translated into more commonly understood language.

So as to avoid going back and forth on report revisions (if needed), CPP recommends that the report format be finalized during the meeting or conference call mentioned in the cover letter.

References

EPA, "Industrial Source Complex (ISC) Dispersion Model User's Guide—Second Edition (Revised) Volume I," USEPA Office of Air Quality, Planning and Standards, Research Triangle Park, North Carolina, EPA–450/4–88–002a, 1987.

EPA, "Guideline for Use of Fluid Modeling to Determine Good Engineering Practice Stack Height," USEPA Office of Air Quality, Planning and Standards, Research Triangle Park, North Carolina, EPA–450/4–81–003, July 1981.

Huber, A.H., and W.H. Snyder, "Wind Tunnel Investigation of the Effects of a Rectangular-Shaped Building on Dispersion of Effluents from Short Adjacent Stacks," *Atmospheric Environment*, Vol. 16, No. 12, pp. 2837–2848, 1982.

Huber, A.H., and W.H. Snyder, "Building Wake Effects on Short Stack Effluents," preprint volume for the Third Symposium on Atmospheric Diffusion and Air Quality, American Meteorological Society, Boston, Massachusetts, 1976.

Petersen, R.L., D.N. Blewitt, and R. Panek, "Lattice Type Structure Building Height Determination for ISC Model Input," 85th Annual AWMA Conference, Kansas City, Missouri, June 21–26, 1992.

Turner, B.D., "Workbook of Atmospheric Dispersion Estimates," Air Research Field Research Office, Environmental Science Services Administration, Environmental Protection Agency, Office of Air Programs, Research Triangle Park, North Carolina, 1970.

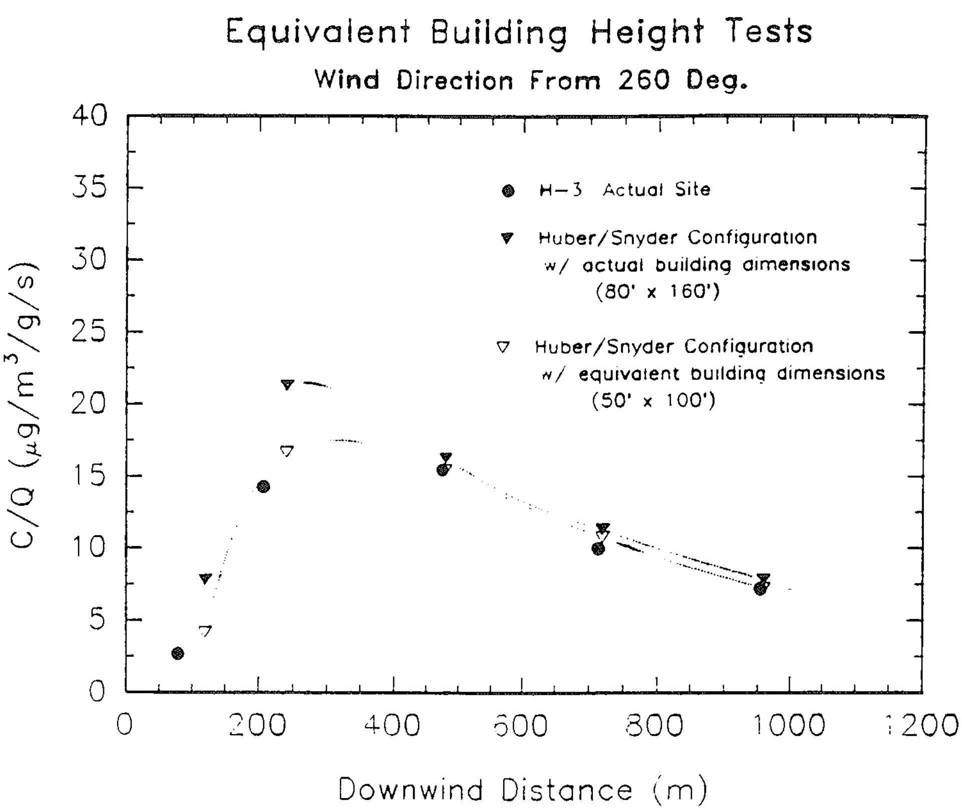
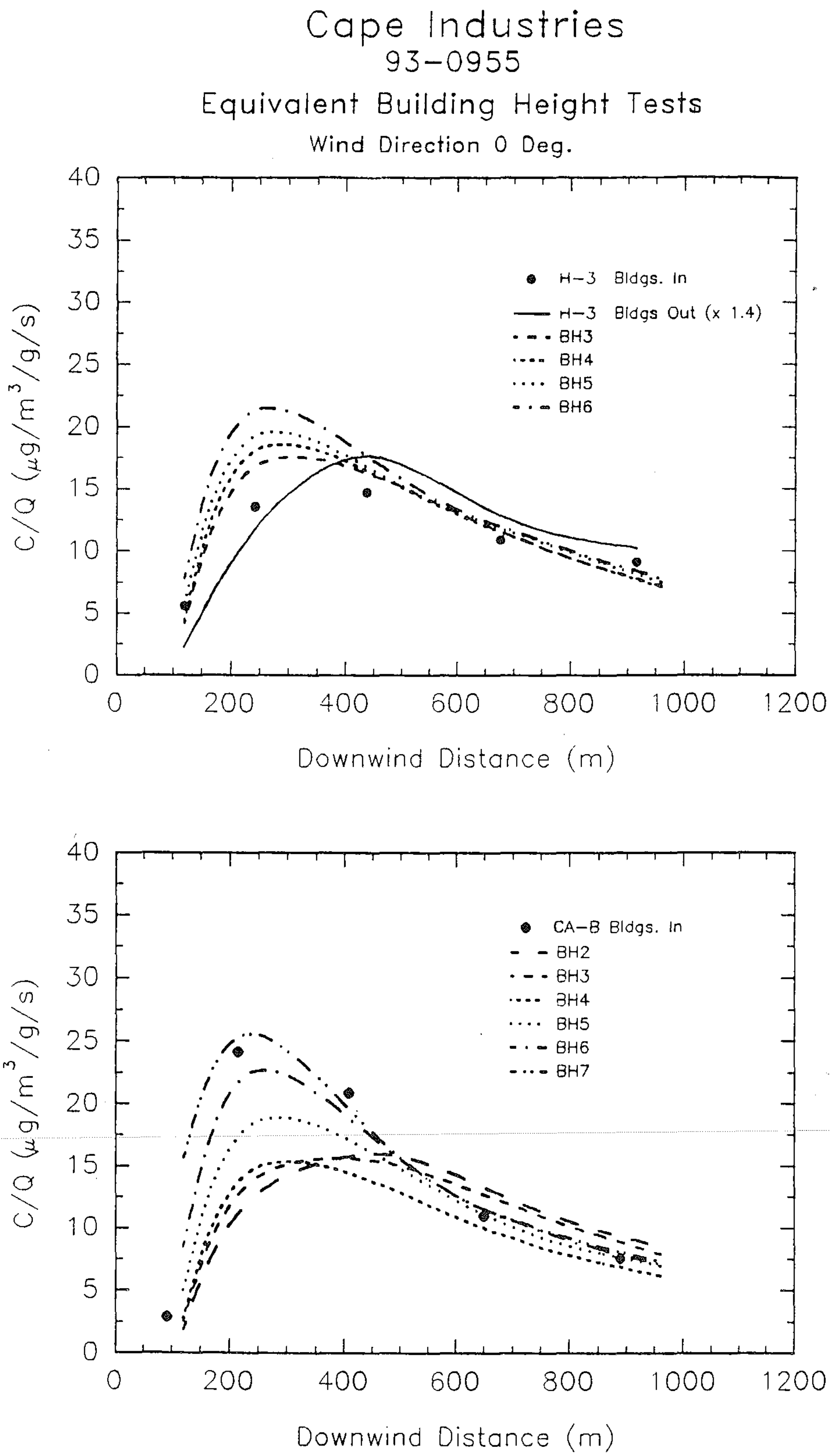

Equivalent Building Height Tests
Wind Direction From 260 Deg.
H-3 Actual Site
Huber/Snyder Configuration
w/ actual building dimensions
(80' x 160')
Huber/Snyder Configuration
w/ equivalent building dimensions
(50' x 100')
C/Q (μg/m3/g/s)
Downwind Distance (m)
0
5
10
15
20
25
30
35
40
0
200
400
600
800
1000
1200

Figure 1



Cape Industries
93-0955
Equivalent Building Height Tests
Wind Direction 0 Deg.
H-3 Bldgs. In
H-3 Bldgs Out (x 1.4)
BH3
BH4
BH5
BH6
C/Q (μg/m³/g/s)
Downwind Distance (m)
CA-B Bldgs. In
BH2
BH3
BH4
BH5
BH6
BH7
C/Q (μg/m³/g/s)
Downwind Distance (m)

Figure 2

ATTACHMENT II

RESPONSE TO COMMENTS IN LETTER DATED DECEMBER 8, 1993 FROM JOHN IRWIN TO WILLIAM SNYDER

1. *Change title to equivalent building dimension study.*

   CPP concurs that a more appropriate title would be an equivalent building dimension study. This change can be added to a revised report.

2. *What is the effect of stability?*

   While the effect of atmospheric stability was not addressed, the study was conducted in a manner consistent with the design of ISCST. ISCST assumes the same dispersion coefficients for all stabilities between 3 H_b and 10 H_b. These dispersion coefficients in turn are based on the wind tunnel work of Huber and Snyder which was conducted under neutral stratification. Its seems that if different stabilities were evaluated, that ISCST would also have to be modified to treat stable wakes in a different manner.

3. *Are conclusions compromised due to complexity of facility?*

   No. In fact, the complexity of the facility is the very reason why such a study is needed. As mentioned in the previous attachment, the downwash algorithms in ISCST were designed to predict the downwash for a specific building shape and location. For sites where the buildings are some distance removed from the stack, porous, tiered, or some other geometry not covered by ISCST, an equivalent building dimension study would be appropriate.

4. *Bothered by the scheme where the equivalent building height is assumed zero based on the 40 percent excess concentration test.*

   The basis for this technique is threefold. First, the same method was applied for AMOCO, for which the protocol was reviewed and approved by EPA Region V and RTP. Second, the technique is reasonable. An excessive concentration due to wake effects has been defined to be one that is 40 percent greater than that in the absence of wake effects. For a GEP stack, 40 percent excessive concentrations are allowed and even built into the ISC model (i.e., the downwash algorithms in ISC are turned off when the stack is GEP). Thus, the procedure used by CPP maintains regulatory consistency. As an aside, if a building height were determined for the directions that did not have an excessive concentration, it is likely that the equivalent building height would be such that the stack would be GEP for that direction (i.e., a building height that is lower than the stack height by at least a factor of 2.5); hence, wake effects would be turned off in ISC anyhow. A specific example of this is discussed in Attachment I under the response to paragraph 4. Third, this technique was specified in the protocol which was reviewed by both the State of North Carolina and EPA Region IV. Comments received from this review did not include any concerns pertaining to the 40 percent excess concentration criteria.

5. *The "90 percent criteria" described on page 16 of the report seems arbitrary and really not all that conservative.*

The use of the 90 percent criteria has a strong precedent. As discussed previously in Attachment II, a vast experience in wind tunnel testing has been relied upon to dictate the level of uncertainty. The 10 percent level is specified in EPA's Guideline for Use of Fluid Modeling to Determine Good Engineering Practice Stack Height (EPA, 1981) for demonstrating Reynolds number independence. This criteria has been used by CPP in previous studies, particularly GEP studies, which have been reviewed and approved by EPA (Petersen, 1985, 1987a, 1987b, 1987c, 1987d, 1987e, 1992; Halitsky, 1986). A detailed uncertainty analysis described in Attachment IV also indicates that the uncertainties in the maximum concentration at each downwind location (the data points shown on the concentration profile plots) are on the order of ±10 percent.

From a statistical standpoint, the use of the 90 percent criteria has not been established to bias the results in any particular direction, rather it is an acknowledgement of the level of precision inherent in wind tunnel testing. Recognizing this level of uncertainty leads to the conclusion that any two measured concentrations which are within approximately 20 percent of each other cannot be considered dissimilar.

6. *Typographical error on page iii, B-3 should be B-4.*

This is a typographical error and can be corrected in a revised report.

7. *Difficult to assess which buildings removed. Need drawings of equivalent buildings. Need location of equivalent building. Have no actual dimensions for plant structures.*

The original copy of the report showed the removed buildings in the color red. Additional color copies can be provided upon request. With regard to dimensions, CPP has either model construction drawings or site blueprints (provided by Cape Industries) that are available for review.

8. *Should not the ISCST2 runs using the original building dimensions be compared to the estimates with the new building dimensions?*

No, the whole impetus behind the study is that using the actual building dimensions as input when running ISCST2 will not accurately portray the true downwash.

References

EPA, "Guideline for Use of Fluid Modeling to Determine Good Engineering Practice Stack Height," United States Environmental Protection Agency, Office of Air, Noise, and Radiation, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, June 1981.

Petersen, R.L., "Wind Tunnel Tests for Kennecott GEP Stack Height Evaluation," prepared for Kennecott, Salt Lake City, Utah, by Cermak Peterka and Associates, Report No. C/PA 85–0279, December 1985.

Halitsky, J., R.L. Petersen, S.D. Taylor, and R.B. Lantz, "Nearby Terrain Effects in a Good Engineering Practice Stack Height Demonstration," 79th Annual APCA Meeting, Minneapolis, Minnesota, June 22–27, 1986.

Petersen, R.L., "Fluid Modeling for Good Engineering Practice Stack Height at Cincinnati Gas & Electric Company's Miami Fort Station," prepared for Cincinnati Gas & Electric Company, by Cermak Peterka and Associates, Report No. C/PA 86–0355, January 1987.

Petersen, R.L., "Fluid Modeling for Good Engineering Practice Stack Height at Bruce Mansfield Plant," prepared for Pennsylvania Power Company, New Castle, Pennsylvania, by Cermak Peterka and Associates, Report No. C/PA 86–0344, March 1987.

Petersen, R.L., "Fluid Modeling for Good Engineering Practice Stack Height at Homer City Generating Station," prepared for TRC Environmental Consultants, Inc., East Hartford, Connecticut, by Cermak Peterka Petersen, Inc., Report No. 860338, October 1987.

Petersen, R.L., "Fluid Modeling Study to Determine Excessive Concentrations at Indianapolis Power and Light Company's H.T. Pritchard Generating Station," prepared for Indianapolis Power and Light Company, Indianapolis, Indiana, by Cermak Peterka Petersen, Inc., Report No. 87–0435, November 1987.

Petersen, R.L., "Fluid Modeling for Good Engineering Practice Stack Height at Public Service Indiana's Gibson Station," prepared for Public Service Indiana, Plainfield, Indiana, by Cermak Peterka Petersen, Inc., Report No. 87–0433, November 1987.

Petersen, R.L., and D.K. Parce, "Fluid Modeling for Good Engineering Practice Stack Height at Titus Generating Station," report prepared for Metropolitan Edison Company, Reading, Pennsylvania, by Cermak Peterka Petersen, Inc., Report No. 92–0804, July 31, 1992.

ATTACHMENT III

RESPONSE TO COMMENTS IN JANUARY 14, 1994 LETTER FROM DR. WILLIAM SNYDER TO JOHN IRWIN

1. *Strict and proper similarity requirements include matching plume buoyancy so that a Froude number or Buoyancy length scale would need to be matched between model and full scale.*

While matching Froude number, velocity ratio and density ratio (or a buoyancy length and momentum length) may simulate plume trajectories more accurately, these requirements are overly restrictive for an equivalent building dimension evaluation for the following reasons. First, for an EBD evaluation, concentration estimates that match full scale values are not required since the concentrations from this study are not used directly to assess compliance with NAAQS. Rather, the purpose of this evaluation is to determine an idealized building that will provide the same dispersion characteristics as the actual site configuration.

Second, this study is similar, in a sense, to GEP stack height and excessive concentration demonstrations, in that building wake effects on plume dispersion are being evaluated. The guideline (EPA, 1981), however, recommends neglecting plume buoyancy and setting the velocity ratio and density ratio equal in model and full scale. This approach allows for an accurate simulation of the near field plume rise (i.e., where momentum effects dominate) and the most flexibility in setting wind tunnel operating conditions. This is the approach that was utilized in the Cape study.

Third, the equivalent building, in principal, should be independent of the plume trajectory, and hence the simulation method. Ideally, the equivalent building will have a similar wake structure, and similar plume dispersion, to that produced by the actual site configuration. This similar wake structure is indicated by similar distributions of maximum ground level concentration for the equivalent building and the actual site configuration. In practice, this *exact* similarity of the wake structure is probably not achieved and therefore a more practical approach to the problem is from a conservative basis (i.e., one that results in higher equivalent buildings). The general trend is for the equivalent building height to decrease with increasing stack height or plume rise. To see this consider the two extremes, a high wind with low plume rise and a calm condition. For the high wind case, the plume rise will be low and the building wakes due to the plant structures will have a maximum effect. For this case some equivalent building can be specified. For a calm wind, the plume rise will be great and the building wakes with the plant structures will not significantly affect the plume trajectory. For the latter case the equivalent building height would tend toward zero. Hence, the general trend of increased equivalent building dimension with decreased plume rise indicates that the simulation method will lead to conservative results. For the same reason, all equivalent building height tests were conducted at a relatively high wind speed to minimize the plume rise. The 6.6 m/s wind speed which was simulated for this study is exceed only 6 percent of the time at the airport anemometer.

Finally, the approach followed is similar to that used in the AMOCO study for which EPA reviewed and approved the protocol. Also, this approach was outlined in the protocol for this study which was reviewed by EPA.

In conclusion, CPP feels that the simulation method was appropriate and will yield valid, yet conservative, equivalent building dimensions.

2. *The reporting is quite sloppy, with myriad inconsistencies.*

The items addressed by Dr. Snyder are discussed below.

a. *Reynolds number of 1000 incorrect.*

This was not a typographical error in the text. Even though the guidance document states that a Reynolds number in excess of 11,000 is acceptable, it also states that Reynolds number independence has been observed over a range from 1000 to 94,000 (Snyder, 1981, p. 134). The intent of the discussion was to point out that lower Reynolds numbers than the recommended critical value may be feasible, pursuant to the results of Reynolds number independence tests.

b. *CPP claims to have varied the Reynolds number over a range from 5232 to 17,440, a factor of 3.3, whereas the wind speed only varied over a factor of 2.*

Building Reynolds number tests were conducted for all 5 groups of stacks (12 stacks total) as indicated in Table 3 on page 61 of the report. As noted by Dr. Snyder, the tests were conducted at two different wind tunnel reference wind speeds (2 and 4 m/s). However, the building Reynolds number was computed based on the height of the dominant upwind building and, as such, varied for each of the 5 groups of stacks. The range of building Reynolds numbers quoted in the report (5232 to 17,440) corresponds to both the variation in wind speed and the variation in upwind building height, hence the discussion in the report is correct.

c. *Inconsistency in the height used for the 2 percent wind speed.*

The correct measurement height for the airport anemometer is 6.1 m (20 ft). The values in the tables presented in Appendix A are incorrect. The tables should have a 6.1 m height for the anemometer. The effect of this error in the tables is that all wind speeds were 6.6 m/s at the anemometer height rather than 8 m/s. This error does not affect the reported concentrations or the equivalent building dimensions, only all tables where wind speed or measurement height needs to be corrected. These corrections can be added to a revised report.

d. *Equation 8 is wrong.*

The equation was typed incorrectly and, as Dr. Snyder pointed out, the correct equation was used in all calculations. This correction can be incorporated into a revised report.

e. *Log-law fit on Figure 8 is not correct.*

CPP has checked the calculations and can find no error. The log-law fit of the boundary layer velocity profiles, shown in Figures 8 and 9, were obtained using the following equation:

$$\frac{U}{U_R} = \frac{U^*}{U_R\, k} \ln \left[\frac{z}{z_o} \right]$$

where the values for z_R , U^*/U_R , z_0 are indicated in the legend of each plot. For Figure 8 the appropriate values are:

z_R = 240 m

U^*/U_R = 0.0549

z_0 = 0.20 m

Substituting these values into the above equation leads to the following table of values which appear to correspond directly to the values indicated in the log-law profile in Figure 8. A similar check of the log-law profiles shown in Figure 9 also indicates that the curve fits are properly indicated.

z/z_R	U^*/U_R
0.10	0.657
0.25	0.777
0.50	0.878
0.75	0.934

f. *Spire heights labeled inconsistently.*

The spire height is correctly labeled in both Figure 6 of the main report and in Figure B–1 of Appendix B as 152.4 cm (60 inches). A typographical error in the text of Appendix B incorrectly stated the spire height as 1.4 m instead of 1.5 m.

g. *Roughness length mislabeled. They flip-flop based on what fits the discussion.*

The evaluation of the mean velocity profiles was conducted using the results from three profiles taken with a split-film anemometer. The analysis included comparisons between measured and theoretical values for U^* and n. The analysis was designed to indicate that the simulated surface friction velocity was appropriate for the design values and that the profile adequately simulated an atmospheric boundary layer. It is unfortunate that the intended rationale of using both the target surface roughness (20 cm) and the measured surface roughness (3 to 12 cm) was not clearly defined. It was certainly not the intent of the author to use "whatever value best fits the discussion at hand" but rather the appropriate value. As it turns out, using either the measured or the target value for z_0 would not have differed the conclusions of either analysis. This discussion can be clarified in a revised report.

3. *Details woefully lacking.*

It appears that Dr. Snyder did not receive an original copy of the report. The original copy did identify the buildings-out configuration with a color code as he suggested. Presenting schematics of a facility as complex as Cape Industries, in a report format, with the dimensional details required to document the building configurations would be both cumbersome and confusing. The study included four separate turntables, each with hundreds of structures including buildings, tanks, towers, and pipe racks. The model drawings were developed from site blueprints, CAD drawings, aerial and ground level photographs provided by Cape Industries, and photographs taken by CPP personnel during a site visit. CPP would be willing to provide any of this information under separate cover upon request.

4. *Overall procedure difficult to follow.*

CPP is not exactly sure how to respond to this issue. Hopefully, some of the details provided in this transmittal will clarify the procedures.

5. *I really cannot find much in the report to reject it outright, but I am absolutely nonplussed by it. ... CPP appears to have followed the formal required procedures, but to me they have done so following the "letter of the law" and not the "spirit of the law."*

In his final comment, Dr. Snyder acknowledges that CPP has followed the formal required procedures.

References

EPA, "Guideline for Use of Fluid Modeling to Determine Good Engineering Practice Stack Height," United States Environmental Protection Agency, Office of Air, Noise, and Radiation, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, June 1981.

Snyder, W.H., "Guideline for Use of Fluid Modeling to Determine Good Engineering Practice Stack Height," EPA Office of Air Quality, Planning and Standards, Research Triangle Park, North Carolina, EPA–450/4–81–003, July 1981.

ATTACHMENT IV

UNCERTAINTY ANALYSIS

1.0 Introduction

This attachment describes an uncertainty analysis which was conducted to estimate the expected errors in determining the maximum ground-level concentrations during a wind tunnel simulation using a grid of laterally and longitudinally spaced receptors. The analysis was specifically designed to address equivalent building dimension tests in which the emphasis is placed on comparing downwind concentration profiles from various building configurations. It is not the intent of equivalent building dimension tests to establish actual full scale concentration values at receptor locations. Therefore, the uncertainty analysis does not address the uncertainty resulting from the wind tunnel simulation itself (i.e., how well it compares with the real world, mismatching of Reynolds number, Froude number, etc.). In addition, the uncertainty analysis does not address those parameters which may affect the concentration profiles but are invariant throughout the equivalent building dimension tests (for example: stack diameter, modeled building dimensions, and ambient turbulence levels).

Most wind tunnel testing falls under the category of single-sample experiments since a specific simulation is rarely duplicated to the extent that sample statistics can be derived. Therefore, the uncertainty analysis must be developed based on estimates of the uncertainties of the variables involved in the final single-sample measurement. The classical technique for defining the uncertainties in single-sample experiments has been defined by Kline and McClintock (1953) as:

$$\frac{\Delta R}{R} = \frac{\left[\left[\frac{\delta R}{\delta X_1}\Delta X_1\right]^2 + \left[\frac{\delta R}{\delta X_2}\Delta X_2\right]^2 + \ldots + \left[\frac{\delta R}{\delta X_n}\Delta X_n\right]^2\right]^{\frac{1}{2}}}{R} \qquad (1)$$

where

$$R = R\left(X_1, X_2, \ldots, X_n\right) \qquad (2)$$

R = Result of a given function of independent variables.

X_n = Independent variables of function R.

ΔR = Uncertainty in the result.

ΔX_n = Uncertainty in the independent variable X_n.

If it can be assumed that all variables are independent and linearly related, i.e., no weighted biasing, Equation (1) reduces to the form:

$$\frac{\Delta R}{R} = \left[\left[\frac{\Delta X_1}{X_1} \right]^2 + \left[\frac{\Delta X_2}{X_2} \right]^2 + \ldots + \left[\frac{\Delta X_n}{X_n} \right]^2 \right]^{\frac{1}{2}} \quad (3)$$

For equivalent building dimension tests, where the primary emphasis is placed on determining the maximum ground-level concentrations, the total uncertainty can be defined by the uncertainty associated with three independent variables: 1) the uncertainty in predicting the full scale concentration at a given receptor for an assumed test configuration, ΔC_f; 2) the uncertainty associated with measuring the maximum concentration along a lateral grid, ΔC_y ; and 3) the uncertainty associated with measuring the maximum concentration along the longitudinal profile, ΔC_x .

For a few of the independent variables identified within this uncertainty analysis, the exact form of the relationship ($\delta R/\delta X_n$) is not directly available from the wind tunnel results. To properly define the relationship would require multiple repetitions of the wind tunnel simulation under specific conditions. Since the results of these tests would be case specific, and thus would not necessarily apply to any other simulation, it is typically not feasible to define the exact relationship in this manner. Instead, EPA's SCREEN2 dispersion model was used to help define these relationships. It should be noted that the SCREEN2 results are used only to define the characteristics of these relationships rather than to define site specific concentrations.

The results presented in this attachment pertain to an uncertainty analysis performed using the stack parameters listed in Table 1. The two stacks shown in Table 1 (Stack A and Stack B) represent a typical range in stack operating conditions (specifically in terms of the flow volume) used during the Cape study. While the results of this uncertainty analysis are case specific, they are expected to provide an indication of the magnitude of the uncertainty for typical stack parameters.

2.0 Uncertainty in Predicting the Full Scale Concentrations

The uncertainty in predicting the full scale concentration at a given receptor for an assumed test configuration is attributed to the uncertainty due to setting the wind tunnel simulation parameters and the uncertainty in the actual tracer gas concentration measurement. The combined uncertainty can be determined by applying the techniques outlined by Kline and McClintock and assuming that the two variables are independent and linearly related, i.e., no weighted biasing. With this assumption, Equation (3) becomes:

$$\frac{\Delta C_f}{C_f} = \left[\left[\frac{\Delta C_r}{C_r} \right]^2 + \left[\frac{\Delta C_m}{C_m} \right]^2 \right]^{\frac{1}{2}} \quad (4)$$

where

C_f = Full scale concentration prediction ($\mu g/m^3$).

C_r = Tracer gas concentration at receptor (μg/m^3).

C_m = Measured concentration at receptor (μg/m^3).

ΔC_f = Uncertainty in the full scale concentration prediction, (μg/m^3).

ΔC_r = Uncertainty in the concentration at receptor due to wind tunnel settings (μg/m^3).

ΔC_m = Uncertainty in the measured concentration at receptor due to sensitivity of measurement apparatus (μg/m^3).

The sensitivity of the concentrations at a receptor, C_r, to the uncertainty in setting the wind tunnel parameters was analyzed using EPA's SCREEN2 dispersion model as described in the introduction to this attachment. The variables included in the SCREEN2 model, for which downwind concentration errors can be attributed to, consist of: 1) the stack height, H_s ; 2) the exit velocity, V_e ; 3) the exhaust temperature, T_s ; and 4) the 10 m wind speed, U_a . The uncertainty associated with setting each of these parameters during the wind tunnel simulation was evaluated for Stacks A and B. During this evaluation it was assumed that the stack height could be set within ±0.25 cm (±2.1 percent for Stack A and ±2.2 percent for Stack B), that the flow rate of each gas could be set within ±1 increment on the flow rate gauge (a total error of ±1.5 percent for Stack A and ±3.1 percent for Stack B), and that the wind tunnel speed could be set within ±0.05 m/s at the reference height (±1.67 percent for both Stack A and Stack B). During a wind tunnel simulation the full-scale exhaust temperature is modeled using a buoyant exhaust gas. Therefore, the uncertainty associated with the exhaust temperature is dependent upon the uncertainty in the exhaust gas density. For Stack A, where the exhaust gas was mixed during each test, the uncertainty was calculated using the possible extremes in density from the flow measurement uncertainties for the gas mixtures. Again, assuming uncertainty in setting the gas flow rates of ±1 increment on the flow rate gauge, the resulting uncertainty in the exhaust density, $(\Delta\rho_a/\rho_a)$, was ±0.007; this corresponds to an uncertainty in the full scale temperature of ±3.45 K or ±0.67 percent. For Stack B, a premixed gas was used and thus the density was constant throughout the study, so the resulting uncertainty in the exhaust temperature is negligible. The resulting model and full scale uncertainties are shown in Tables 2 and 3.

The combined uncertainty was determined by substituting the four variables discussed above into Equation (1), where:

$$C_r = C_r\left(H_s,\ V_e,\ T_s,\ U_a\right) \tag{5}$$

$$\frac{\Delta C_r}{C_r} = \frac{\left[\left(\frac{\delta C_r}{\delta H_s}\Delta H_s\right)^2 + \left(\frac{\delta C_r}{\delta V_e}\Delta V_e\right)^2 + \left(\frac{\delta C_r}{\delta T_s}\Delta T_s\right)^2 + \left(\frac{\delta C_r}{\delta U_a}\Delta U_a\right)^2\right]^{\frac{1}{2}}}{C_r\left(H_s,\ V_e,\ T_s,\ U_a\right)} \tag{6}$$

The rate change in the ground-level concentration as a function of each of the four variables (i.e., $\delta C_r / \delta X_n$) was evaluated using SCREEN2. The dispersion model was initially run with the baseline stack parameter values indicated in Table 1, and then again for each of the variables with their respective uncertainty (the Table 1 values plus the uncertainty indicated in Tables 2 and 3). The percent change in the maximum ground level concentration, as calculated by SCREEN2, as a result of the uncertainty in each of the variables was applied to Equation (6) to obtain the uncertainty in the concentration at the receptor. (Again, it should be noted that the SCREEN2 results are used only to define the uncertainty distribution for each of the four variables; the actual downwind concentration values calculated by SCREEN2 are not used within the analysis.) The results, shown in Tables 2 and 3, for Stacks A and B, indicate that the uncertainty in the modeled concentrations range from ±3.6 percent for Stack A to ±6.1 percent for Stack B.

The uncertainty in measuring the concentration, C_m, is primarily attributed to the repeatability and accuracy of the sample collection and analysis system. This system consists of a syringe collection system and a gas chromatograph (GC). During normal quality assurance procedures the sample collection and analysis system undergoes both a syringe system check and a GC linearity check to assure that the signal output is consistent and linearly related to the input gas concentration. For the syringe system check a single gas mixture is supplied to each of the 50 sampling syringes. The concentration of hydrocarbons in each syringe is measured with the GC; a ±3 percent or less deviation between syringes is allowable. For the GC linearity check a series of certified gases with variable levels of hydrocarbons are analyzed with the GC. Typical results indicate that the maximum error between the measured value and the predicted value, based on a least squares fit of the measured data, is less than or equal to ±4 percent. Therefore, the uncertainty in the measurement of the concentration at a given receptor, using the Kline and McClintock technique, is ±5.0 percent (i.e., $(3.0\%^2 + 4.0\%^2)^{1/2}$).

The results from the uncertainty analysis due to wind tunnel setting errors, $\Delta C_r / C_r$, and due to errors in the tracer gas measurement, $\Delta C_m / C_m$, were applied to Equation (4) to determine the total uncertainty, $\Delta C_f / C_f$, in the predicted concentration at a given receptor. Tables 2 and 3 indicate that the total uncertainty is 6.2 percent for Stack A and ±7.9 percent for Stack B.

3.0 Uncertainty in Maximum Concentration Due to Lateral Grid Spacing

During the wind tunnel testing, a series of receptors are installed in crosswind rows at selected distances downwind of the operating stacks. If an infinite number of receptors could be placed at each of the downwind distances, one could be certain that the maximum concentration in the lateral grid is measured. However, in reality a finite number of receptors must be used. The uncertainty associated with using a finite number of receptors is evaluated assuming that the lateral concentration profile follows a Gaussian distribution.

The first step in evaluating the uncertainty in the maximum concentration along the lateral grid is to determine the standard deviation, σ_y, of the measured concentrations. This procedure is conducted by applying a non-linear regression curve fit to the lateral concentration measurements using the iterative subroutine R2LIN of the IMSL Stat/Library (1987). During this routine the curve is forced to follow a gaussian distribution with the value of σ_y adjusted to minimize the errors ("best fit").

With a known σ_y, the maximum uncertainty in the maximum concentration can be determined using the Gaussian probability equation:

$$E = 1 - e^{\frac{-\eta^2}{2}} \tag{7}$$

$$\eta = \frac{\left[\frac{\Delta Y}{2}\right]}{\sigma_y} \tag{8}$$

where

ΔY	=	Lateral distance between receptors, *m*.
η	=	Maximum distance between receptor and maximum concentration in terms of standard deviation.
E	=	Maximum uncertainty between measured and maximum concentration.
σ_y	=	Standard deviation of the Gaussian distribution in the lateral direction.

The results of the uncertainty analysis for maximum concentration along the lateral grid, $\Delta C_y / C_y$, conducted for Stacks A and B are provided in Table 4. The table indicates that the maximum errors are between 1.5 percent and 6.3 percent for downwind distances with appreciable concentrations.

4.0 Uncertainty in Maximum Concentration Along the Longitudinal Profile

As with the lateral grid, the maximum concentration in the longitudinal direction cannot be obtained with 100 percent confidence unless an infinite number of receptor locations are sampled. Since a finite number of receptors must be used, an uncertainty analysis was conducted to determine the possible errors in associating the measured maximum concentration to the true maximum value.

The longitudinal concentration profile does not follow a Gaussian distribution like the lateral profile, rather it is described by a complex equation which combines both stack operating conditions, ambient wind speed and site dispersion characteristics. Therefore, rather than applying a curve fit to the concentration profile, SCREEN2 was once again utilized to provide an indication of the concentration distribution along the longitudinal profile. Using this distribution, an estimate of the uncertainty due to various longitudinal grid spacings can be determined.

To analyze the uncertainty in the maximum concentrations along the longitudinal profile, SCREEN2 was run with the stack parameters listed in Table 1, with a fine mesh of downwind distances. From these results, curves were derived which relate the reduction in concentration to the distance from the maximum concentration. The downwind concentration values are presented in terms of a percent of the maximum concentration, and the downwind distances are presented in terms of a percent distance from the maximum concentration. (These two parameters have been converted to a non-dimensional form, as shown in Figure 1, so that the SCREEN2 dispersion model's impact on the uncertainty analysis is limited to defining the shape of the concentration distribution in the longitudinal direction.) The measured concentration profile was analyzed to evaluate the uncertainty in the maximum concentration. For Stack A the maximum concentration from the wind tunnel results was predicted to occur at a downwind distance of 720 m. Therefore, the true maximum concentration fell somewhere between 480 m and 960 m (the first measurement locations on either side of 720 m). The maximum ratio of the downwind distance of the measured concentration to the downwind distance to the maximum concentration was thus −20 percent ((480−720)/(480+720)) or +14.3 percent ((960−720)/(960+720)) depending upon whether the maximum concentration occurred between 480 m and 720 m or between 720 m and 480 m. From Figure 1 the corresponding percentage of maximum concentrations are 96.2 percent and 98.2 percent. Therefore, a conservative estimate of the uncertainty in the maximum concentration along the longitudinal profile for Stack A would be 3.8 percent. A similar analysis for Stack B, shown in Table 5, indicates the maximum uncertainty would be 13.4 percent. This increased uncertainty is primarily due to the maximum concentration occurring closer-in to the stack where the concentration increases more rapidly with downwind distance for the region between the stack and the location of maximum impact. A tighter grid spacing would reduce this uncertainty; however, when modeling industrial facilities the close-in grid spacing is limited by the position of surrounding structures.

5.0 Total Uncertainty in the Presented Results

The total uncertainty associated with predicting the maximum ground-level concentrations during each of the equivalent building dimension tests can be determined by combining the results from the three uncertainty categories described above. First, the uncertainty in the maximum concentration at a given downwind distance, C_d, can be attributed to the uncertainty in the full scale concentration, C_f, and the uncertainty in obtaining the maximum concentration along the y-axis, C_y, using Equation (9) below. The results indicate that the uncertainty in C_d range from ±8.0 percent for Stack A to 10.0 percent for Stack B. Second, the uncertainty in the overall maximum concentration, C_t, can be attributed to the uncertainty in the full scale concentration, C_f, the uncertainty in obtaining the maximum concentration along the y-axis, C_y, and the uncertainty in obtaining the maximum concentration along the x-axis, C_x. Again, applying the technique of Kline and McClintock, using Equation (10) below, the total uncertainty, $\Delta C_t / C_t$, in measuring the overall maximum ground-level concentrations range from ±8.8 percent for Stack A to ±16.7 percent for Stack B.

$$\frac{\Delta C_d}{C_d} = \left[\left[\frac{\Delta C_f}{C_f} \right]^2 + \left[\frac{\Delta C_y}{C_y} \right]^2 \right]^{\frac{1}{2}} \qquad (9)$$

$$\frac{\Delta C_t}{C_t} = \left[\left[\frac{\Delta C_f}{C_f} \right]^2 + \left[\frac{\Delta C_y}{C_y} \right]^2 + \left[\frac{\Delta C_x}{C_x} \right]^2 \right]^{\frac{1}{2}} \qquad (10)$$

6.0 References

Kline, S.J., and F.A. McClintock, "Describing Uncertainties in Single-Sample Experiments," *Mechanical Engineering*, p. 3, January 1953.

IMSL, "Stat/Library FORTRAN Subroutines for Statistical Analysis," Version 1.0, IMSL Inc., Houston, Texas, 1987.

Table 1
Source Parameters

Parameter	Stack A		Stack B	
	English	Metric	English	Metric
Stack Height, H_b	120 ft	36.6 m	112 ft	34.1 m
Exit Temperature, T_s	427°F	493 K	95°F	308 K
Volume Flow, v	2785 ft^3/sec	78.9 m^3/sec	415 ft^3/sec	11.8 m^3/sec
Exit Diameter, D	5.5 ft	1.68 m	2.6 ft	0.79 m
Exit Velocity, V_e	117.2 ft/sec	35.7 m/sec	78.5	23.9 m/sec

Table 2
Simulation Uncertainty Analysis—Stack A

Uncertainty in Simulating Concentration

SCREEN2 Input Uncertainties

	Model Scale	Full Scale
ΔH_s	0.33 cm	0.80 m
ΔV_e	17.56 cm/sec	0.52 m/sec
ΔT_s	0.007*	3.45 K
ΔU_a	0.05 m/sec	0.10 m/sec

* – $\Delta(\rho_s/\rho_a)$

SCREEN2 Results

	Max Concentration ($\mu g/m^3$)	Estimated Uncertainty $\Delta C_r/C_r$
$S(H_s, V_e, T_s, U_a)$	0.7948	
$S(H_s + \Delta H_s, V_e, T_s, U_a)$	0.7738	−0.026
$S(H_s, V_e + \Delta V_e, T_s, U_a)$	0.7812	−0.017
$S(H_s, V_e, T_s + \Delta T_s, U_a)$	0.7847	−0.013
$S(H_s, V_e, T_s, U_a + \Delta U_a)$	0.8052	0.013
Total		0.036

Uncertainty in Measuring Concentration

Source of Uncertainty	Estimated Uncertainty $\Delta C_m/C_m$
Syringe System	0.03
GC Linearity	0.04
Total	0.05

Total uncertainty in predicting the full scale concentration at a given receptor for an assumed simulation, $\Delta C_f/C_f$ 0.062

Table 3
Simulation Uncertainty Analysis—Stack B

Uncertainty in Simulating Concentration

SCREEN2 Input Uncertainties

	Model Scale	Full Scale
ΔH_s	0.33 cm	0.80 m
ΔV_e	25.52 cm/sec	0.74 m/sec
ΔT_s	0.0 K	0.0 K
ΔU_a	0.05 m/sec	0.10 m/sec

SCREEN2 Results

	Max Concentration ($\mu g/m^3$)	Estimated Uncertainty $\Delta C_r / C_r$
$S(H_s, V_e, T_s, U_a)$	7.316	
$S(H_s + \Delta H_s, V_e, T_s, U_a)$	6.997	−0.044
$S(H_s, V_e + \Delta V_e, T_s, U_a)$	7.016	−0.041
$S(H_s, V_e, T_s + \Delta T_s, U_a)$	7.316	−0.000
$S(H_s, V_e, T_s, U_a + \Delta U_a)$	7.253	−0.009
Total		0.061

Uncertainty in Measuring Concentration

Source of Uncertainty	Estimated Uncertainty $\Delta C_m / C_m$
Syringe System	0.03
GC Linearity	0.04
Total	0.05

Total uncertainty in predicting the full scale concentration at a given receptor for an assumed simulation, $\Delta C_f / C_f$ 0.079

Table 4
Uncertainty in Peak Concentration Along the Lateral Grid

Stack A

Downwind Distance, x (m)	Δ_y (m)	σ_y (m)	$\Delta_y / (2 \sigma_y)$ (−)	Maximum Error $\Delta C_y / C_y$
132	17	0*	0	0
240	24	40.0	0.300	4.4
480	36	61.0	0.295	4.3
720	48	75.1	0.320	5.0
960	48	85.2	0.282	3.9

Stack B

Downwind Distance, x (m)	Δ_y (m)	σ_y (m)	$\Delta_y / (2 \sigma_y)$ (−)	Maximum Error $\Delta C_y / C_y$
156	17	27.6	0.308	4.6
270	24	33.3	0.360	6.3
480	36	62.7	0.287	4.0
720	48	69.0	0.348	5.9
960	48	84.4	0.284	4.0

Note: *—Flat profile (minimal concentrations)

Table 5
Uncertainty in Peak Concentration Along the Longitudinal Profile

Stack A

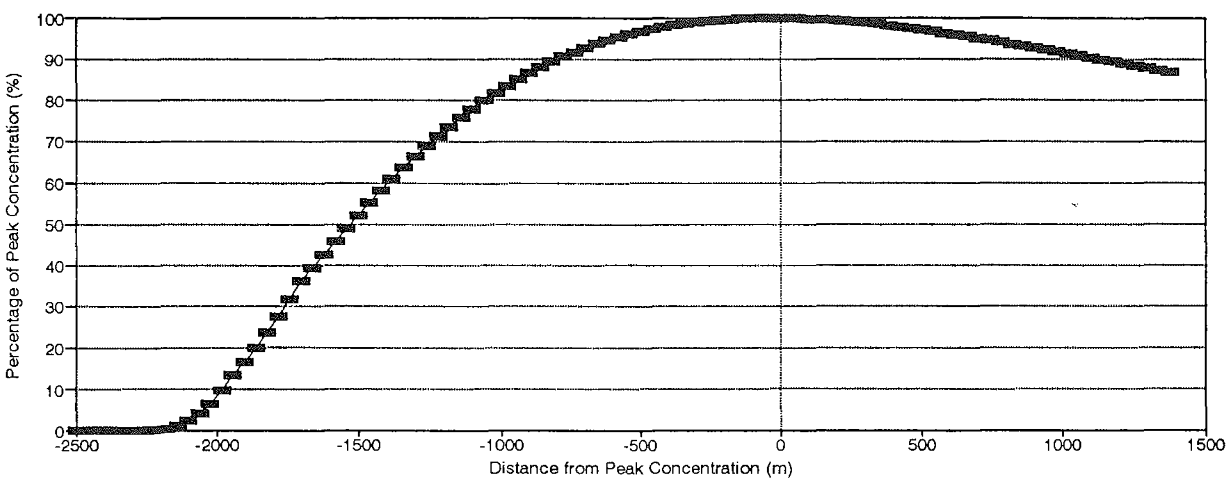
Downwind Distance, x (m)	Δx (m)	Maximum Distance From Peak (%)	Maximum Error $\Delta C_x / C_x$
480			
720	240	−20.00	3.79
960	240	14.29	1.77

Stack B

Downwind Distance, x (m)	Δx (m)	Maximum Distance From Peak (%)	Maximum Error $\Delta C_x / C_x$
160			
270	110	−25.58	13.4
480	210	28.00	7.44

Longitudinal Uncertainty Analysis
(Data obtained Using EPA's SCREEN2 Dispersion Model)

Stack A



Stack B

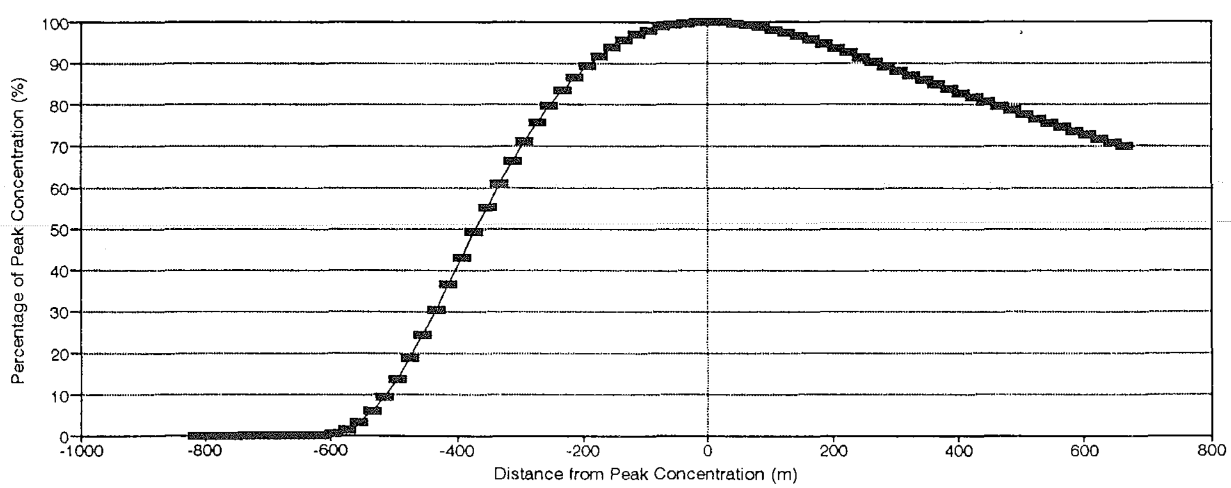


Figure 1

ATTACHMENT V

"LATTICE TYPE STRUCTURE BUILDING HEIGHT DETERMINATION FOR ISC MODEL INPUT"

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92-100.07

Lattice Type Structure Building Height Determination for ISC Model Input

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INTRODUCTION

When running the ISCST model (Wackter and Foster, 1986) in Urban Mode 3 with the Schulman–Scire downwash algorithm, it was found that maximum concentration estimates for a source (referred to as FCU 6) in an oil refinery were in excess of the 24-hour National Ambient Air Quality Standard for SO_2 (365 $\mu g/m^3$). Currently, the ISCST model incorporates the Schulman–Scire downwash algorithm when the stack height is less than 1.5 times the building height, which is the case for FCU 6, and the Huber–Snyder downwash algorithm (Huber and Snyder, 1976) when the stack height is greater than 1.5 times the building height but less than 2.5 times the building height. These ISCST modeled concentrations for FCU 6 are approximately a factor of 3.5 times higher than estimates obtained using the previous version of ISCST (Bowers *et al.*, 1979) run in Urban Mode 3. The previous version of ISCST utilized the Huber–Snyder downwash algorithm for all stack heights less than 2.5 times the building height. In addition, the ISCST downwash algorithms (both the Schulman–Scire and Huber–Snyder) assume that the stacks are adjacent to the structure and that the structure is solid. Upon review of the stack and structure configuration for FCU 6, it was found that the stack is not adjacent to the structure and the structure is an open lattice structure. Hence, both of the downwash algorithm assumptions are not representative of the physical configuration and would lead to inaccurate model predictions for this source.

To address the above problem, fluid modeling was conducted to determine building dimensions based on similar concentration fields for a solid and lattice structure for use as input into the ISCST model. A test protocol for the study was developed and was reviewed by USEPA and Indiana Department of Environmental Management (IDEM). Thereafter, a 1:240 scale model of FCU 6 and surrounding structures within a 0.4 km radius of FCU 6 was constructed from facility drawings and placed in CPP's environmental wind tunnel. Tests were then conducted for various wind directions with all structures in place, with all nearby[1] structures removed, and with solid structures of varying heights positioned at the stack location (all nearby structures still removed). To determine wind direction specific building dimensions, the ratio of maximum concentration with and without the nearby structures for each wind direction was first evaluated. If this ratio was less than 1.4 (part of the definition of an excessive concentration as found in EPA, 1985), the ISCST building height input for that wind direction was specified as 0 m. If the ratio was greater than 1.4, a wind direction specific building height was specified by finding a solid structure height that produced similar maximum concentration fields as those produced for the simulation with all plant structures present.

Initial testing was conducted to determine the site specific building dimensions for 6 wind directions. A preliminary report was reviewed by IDEM and EPA, and approval was given to the test procedure and the use of the wind tunnel determined building dimensions for ISCST input. This paper discusses various technical issues, the experimental methods and building dimension results for the complete set of 36 wind directions for input into ISCST.

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[1]Defined by EPA (1985) to be within five times the lesser of the building height or width.

TECHNICAL CONSIDERATIONS

Scaling Requirements

An accurate simulation of the boundary-layer winds and stack gas flow is an essential prerequisite to any wind-tunnel study of diffusion from an industrial stack. The similarity requirements can be obtained from dimensional arguments derived from the equations governing fluid motion. A detailed discussion on these requirements is given in the EPA fluid modeling guideline (Snyder, 1981) and will not be repeated here.

Model operating conditions were calculated for FCU 6 for a 9 m/s wind speed at a 10 m height using the appropriate scaling criteria. Table 1 provides the model and full scale parameters as well as similarity parameters. The table shows that all important similarity criteria are met. It should be noted that Reynolds number independence tests were conducted to determine the minimum acceptable operating speed in the wind tunnel.

Buoyancy effects were not modeled because their inclusion would have required a low wind tunnel operating speed with corresponding low building Reynolds numbers. To evaluate this effect, sensitivity tests including buoyancy were conducted and the resulting building heights were similar to those determined when buoyancy effects were not included.

Determination of Excessive Concentration Due to Building Wake Effects

The EPA stack height regulation (1984) defines an excessive concentration as:

> "a maximum ground-level concentration due to emissions from a stack due in part or whole to downwash, wakes, or eddy effects produced by nearby structures or terrain features which individually is at least 40 percent in excess of the maximum concentration experienced in the absence of such downwash, wakes, or eddy effects and which contributes to a total concentration due to emissions from all sources that is greater than an ambient air quality standard."

No comparison with NAAQS is required for complicated structures (see Table 3.1 on page 50 in EPA, 1985), such as lattice type structures, as long as the actual stack height is less than that obtained using the Equations 1 or 2 in the stack height regulation. Only the 40 percent test is required and was the only criteria used to define excessive concentrations.

Based on this definition, the maximum ground-level concentration from wind-tunnel testing with the structures present was compared to the maximum concentration without the structures present. If the ratio of these concentrations was 1.4 or less, downwash effects were considered insignificant and the ISCST model can be run with a building height equal to zero. If the ratio was greater than 1.4, the stack was less than GEP and downwash effects must be considered in ISCST modeling. For this case, additional tests were conducted to find the solid structure dimensions that produce similar concentrations as the lattice structure. The dimensions of the equivalent solid structure were then used for ISCST model input.

Emission Rate

An SO_2 emission rate of 110.25 g/s was used for the FCU 6 stack for the purpose of converting model concentrations to full scale concentrations.

Nearby Structures

To evaluate the effect of the nearby structures, tests were first conducted with all structures in place. It should be noted that the buildings in the vicinity of the FCU 6 stack are the FCU 5 and FCU 6 structures. Both of these structures are open lattice structures. These nearby structures were removed and the resulting concentrations compared to those measured with the structures in place. Structures are classified as nearby when the stack is closer than 5 times the lesser of the height or width of the structure. In order to find the equivalent solid building dimensions that produce similar concentrations as those produced by the lattice structures located on the site, tests were conducted with a solid structure located at the FCU 6 stack location and with the nearby structures removed.

Test Wind Speed

The EPA stack height guideline (EPA, 1981) requires that the design wind speed for GEP stack height evaluations be less than the 2 percent wind speed (speed that is exceeded less than 2 percent of the time) unless it can be demonstrated that higher speeds cause exceedances of NAAQS or PSD limits. ISCST modeling showed that the wind speeds ranged from 3 to 7 m/s when the highest 24-hour average SO_2 concentrations are predicted. The 2 percent wind speed as a function of wind direction was determined by analyzing meteorological data (10 m anemometer height) collected at the refinery. All wind-tunnel testing to determine site specific building heights was conducted at a wind speed of 9 m/s which was slightly lower than the 2 percent wind speed.

Evaluation of Simulated Boundary Layer

In order to document the wind characteristics approaching the model, profiles of mean velocity and longitudinal turbulence intensity were obtained upwind of the model test area. These profiles verified that the simulated surface roughness was 1.25 m and that the turbulence intensity profile was characteristic of an urban setting (turbulence intensity of 25 percent at a 30 m height).

EXPERIMENTAL METHODS

Scale Model and Wind Tunnel

A 1:240 scale model of FCU 6 and surrounding structures was designed and constructed. A plan view of the area modeled is depicted in Figure 1. The model included all significant structures within a 0.4 km radius of the FCU 6 stack. Upwind and downwind of the area modeled, roughness elements were installed to represent an urban area (z_0 = 1.25 m and a 0.25 power law exponent). The model was constructed so that nearby structures could be removed and so that a solid structure could be installed at the stack location. An isometric view of the solid structure is shown in Figure 2. Figure 3 shows a closeup view of the model of the FCU 6 lattice structure from one angle.

The solid structure (see Figure 2) was constructed with (full scale) plan dimensions of 18.3 by 39.6 m. These dimensions were estimated to be equivalent to the plan dimensions of the solid core of the tallest portion of the FCU 6 main lattice structure. The solid structure was fabricated so that the height could be varied from 12.2 to 48.8 m, in 3.1 m increments.

The stack parameters for all tests are provided in Table 1. Table 1 provides the model and full scale parameters for all tests modeled using momentum and density ratio scaling. The stacks were supplied with a gas mixture of the appropriate density. Gas flow meters were used to monitor and regulate the discharge velocity.

Concentration sampling taps were installed at numerous downwind locations, and sample locations were measured relative to a point centered on the FCU 6 stack. The measurement locations were selected so that the maximum concentration versus downwind distance could be defined. All testing was carried out in CPP's environmental wind tunnel.

Data Acquisition

Concentration measurements for each of the runs were obtained using a 50 port gas sampling system and flame ionization gas chromatograph. Volume flow and wind speed measurements were also obtained for documentation and to set wind tunnel operating conditions.

Quality Control

To ensure that accurate and reliable data were collected, certain quality control steps were taken. These included:

- multi-point calibration of hydrocarbon analyzer with certified standard gas;
- calibration of stack flow measuring device with soap bubble meter;
- calibration of velocity measuring device with mass flow meter;
- wind tunnel testing to show the Reynolds number independence of the concentration measurements; and
- comparison of wind tunnel diffusion and velocity characteristics with those observed in the atmosphere.

RESULTS

The maximum ground-level concentrations versus downwind distance were determined due to emissions from the FCU 6 stack for 18 wind directions with a 9 m/s wind speed at a 10 m height. For selected wind directions tests were also conducted at a 6 m/s wind speed to evaluate the sensitivity of the results to wind speed. The maximum concentrations were measured with and without the nearby structures present as described previously and with a solid structure of varying height present. Figure 4 shows plots of maximum SO_2 concentration versus downwind distance for one of the wind directions evaluated (135 degrees) for 6 and 9 m/s wind speeds. Similar plots were prepared for each of the wind directions evaluated. Included in each plot are the concentrations for cases with all structures in the model, cases with all nearby structures removed, and cases with solid structures of varying height located at the FCU 6 stack location. Inspection of Figure 4 shows a large difference in concentrations with and without the structure present and also shows the solid building case that agrees best with the lattice structure concentration predictions.

Table 2 provides the maximum concentration for each test summarized in Figure 4 and the ratio of observed concentrations (with and without the structures in place) to those observed with the lattice structure in place. By inspecting Figure 4 and Table 2, the appropriate building height for ISCST input was determined. The criteria for specifying the building height is to find a solid structure height that gives a maximum concentration that is within ±10 percent of the maximum concentration measured with the lattice structure present. For example, inspection of Table 2 shows that at 9 m/s with a 33.5 m solid structure height, the maximum concentration is 2 percent larger than the maximum concentration with the lattice structure present (concentration ratio of 0.98 in the table). Hence, for the 135 degree wind direction a 33.5 m building height and 42.3 m building width would be used for ISCST input. The width was computed by calculating the cross-wind width of the solid structure shown in Figure 2. The plan dimensions of the solid structure shown in Figure 2, 18.28 m × 39.62 m (60 ft × 130 ft), are the approximate plan dimensions of the tallest portion of the lattice structure which occupies most of the lattice structure volume.

The appropriate structure heights and widths for ISCST model input for all wind directions were determined in a similar manner and the results are summarized in Figure 5. The figure shows that the wind-tunnel determined heights are less than the actual lattice structure height for all wind directions. The figure also shows that for the wind direction sectors 160 through 200 degrees and 340 through 20 degrees, the building height input is zero. For these sectors, no significant structures are up or downwind of the FCU 6 stack and structure downwash effects are insignificant. This was evidenced by the concentration measurements that showed concentration ratios less than 1.4 for these wind sectors. Normally, a building height and width would be input into ISCST for some of these wind directions since the structures would be considered nearby (within the lesser of 5 times the height or width of the structure). This result shows that when the stack is offset from the structure by some distance and the wind direction is such that the building is not upwind, building downwash effects are insignificant.

Figure 5 shows that the largest heights for ISCST input (30 to 34 m) occur for the 135 and 225 degree wind directions. For these wind directions, the structures associated with FCU 5 or FCU 6 are upwind of the stack and the flow is oriented at an angle of 45 degrees from a building face. Wake effects on concentrations for solid structures have been shown to be greatest with a similar flow orientation (Robins and Castro, 1977).

Table 3 lists the recommended 36 wind-direction specific building heights and building widths for input into the ISCST dispersion model. The building heights were determined from interpolation of the wind-tunnel-determined values in Figure 5. Building widths were the computed cross-wind projected widths of the solid structure in Figure 2.

Figure 4 illustrates the effect of wind speed on the determination of the appropriate solid structure height for a 135 degree wind direction. Tests were first conducted at a 9 m/s wind speed to determine the appropriate solid structure height, and this height was found to be 33.5 m (110 ft). Tests were then conducted at a 6 m/s wind speed to determine if the concentrations with this height solid structure would agree with the concentrations observed with all structures in place. The figures show that good agreement was obtained. Table 2 shows the maximum concentration with the solid structure is 11 percent less than the concentration with the lattice structure present. Overall, this result suggests that the building height determination would be insensitive to the wind speed used for testing.

CONCLUSIONS

This evaluation has indicated that the previous ISCST approach of modeling FCU 6 as a solid structure at the stack with the dimensions of the lattice structure does not represent actual dispersion from the source. In addition, this study has demonstrated that the wind tunnel can be used to determine "equivalent solid structure" dimensions such that similar concentration fields occur from wind tunnel simulations with the FCU 6 lattice type structures in place or the "equivalent solid structure" in place of the lattice structure. This equivalent structure can then be used as a building input to the ISCST model. The study has also shown that this "equivalent solid structure" dimension determination is insensitive to the wind speed used for the evaluation.

"Equivalent solid structure" dimensions were determined for wind directions in approximately 20 degree increments. Since ISCST requires building dimension inputs for 36 wind directions, the remaining building dimension inputs were determined by interpolation. The building widths were calculated by computing the cross-wind dimension for the solid structure shown in Figure 2. Table 3 contains the "equivalent solid structure" dimensions for input into ISCST.

REFERENCES

Bowers, J.F., Bjorkland, J.R., and Cheney, C.S., "Industrial Source Complex (ISC) Dispersion Model User's Guide, Volume II," USEPA, Research Triangle Park, NC, EPA–450/4–79–030, 1979.

EPA, "Guideline for Determination of Good Engineering Practice Stack Height (Technical Support Document for the Stack Height Regulation)," USEPA Office of Air Quality, Planning and Standards, Research Triangle Park, NC, EPA–45014–80–023R, 1985.

EPA, "Guideline for Use of Fluid Modeling to Determine Good Engineering Practice Stack Height," USEPA Office of Air Quality, Planning and Standards, Research Triangle Park, NC, EPA–450/ 4–81–003, July 1981.

Huber, A.H., and Snyder, W.H., "Building Wake Effects on Short Stack Effluents," Preprint Volume for the Joint Conference on Applications of Air Pollution Meteorology, American Meteorological Society, Boston, MA, 1976.

Robins, A.G., and I.P. Castro, "A Wind Tunnel Investigation of Plume Dispersion in the Vicinity of a Surface Mounted Cube," *Atmospheric Environment*, v. 17, pp. 291–311, 1977.

Snyder, W.H., "Guideline for Fluid Modeling of Atmospheric Diffusion," USEPA, Environmental Sciences Research Laboratory, Office of Research and Development, Research Triangle Park, NC, 27711, Report No. EPA–600/881–009, 1981.

Wackter, D.J., and Foster, J.A., "Industrial Source Complex (ISC) Dispersion Model User's Guide—Second Edition—Volume I," TRC Environmental Consultants, Inc., prepared for Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC, June 1986.

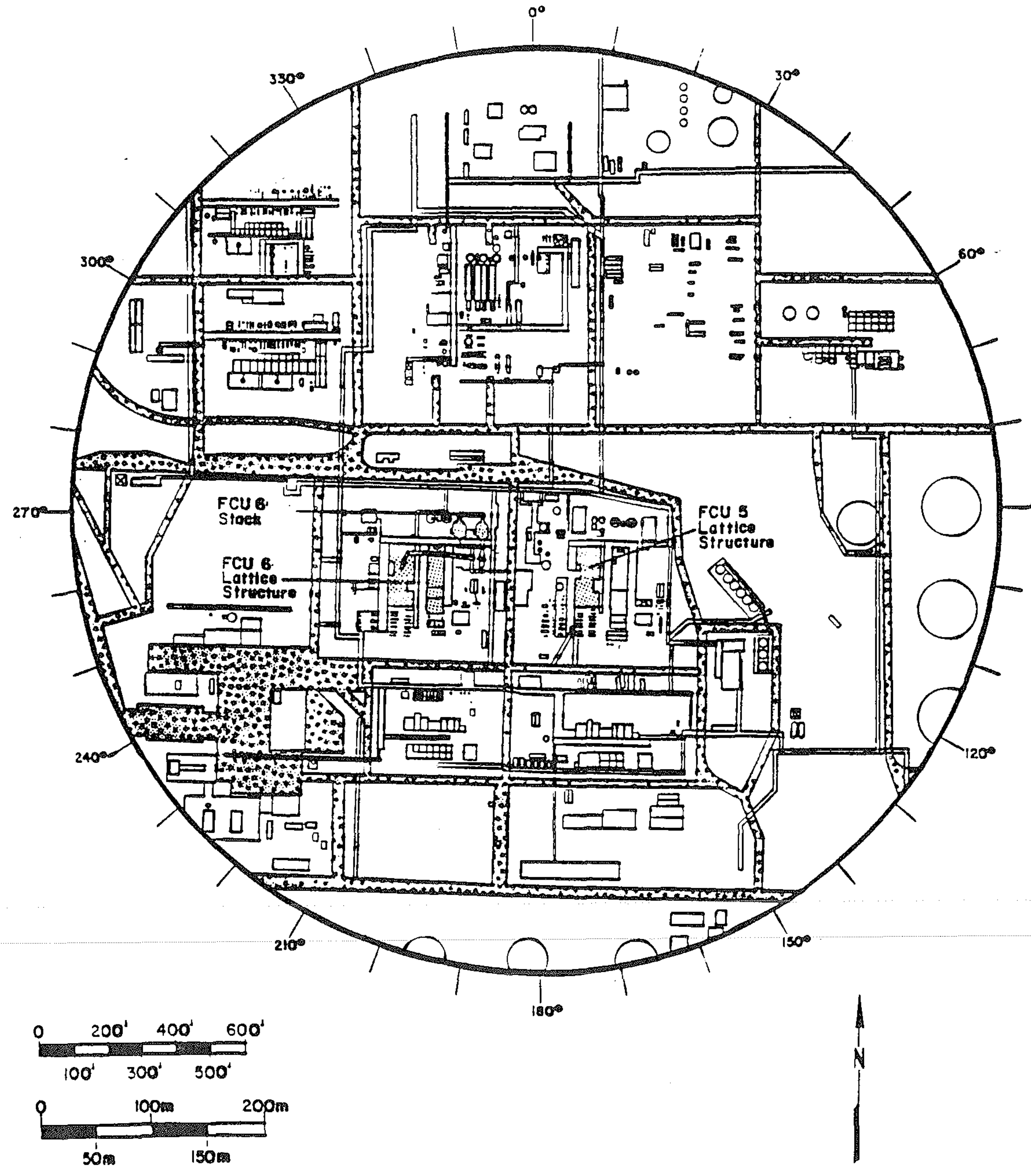


FIGURE 1. Plan view of Refinery model.

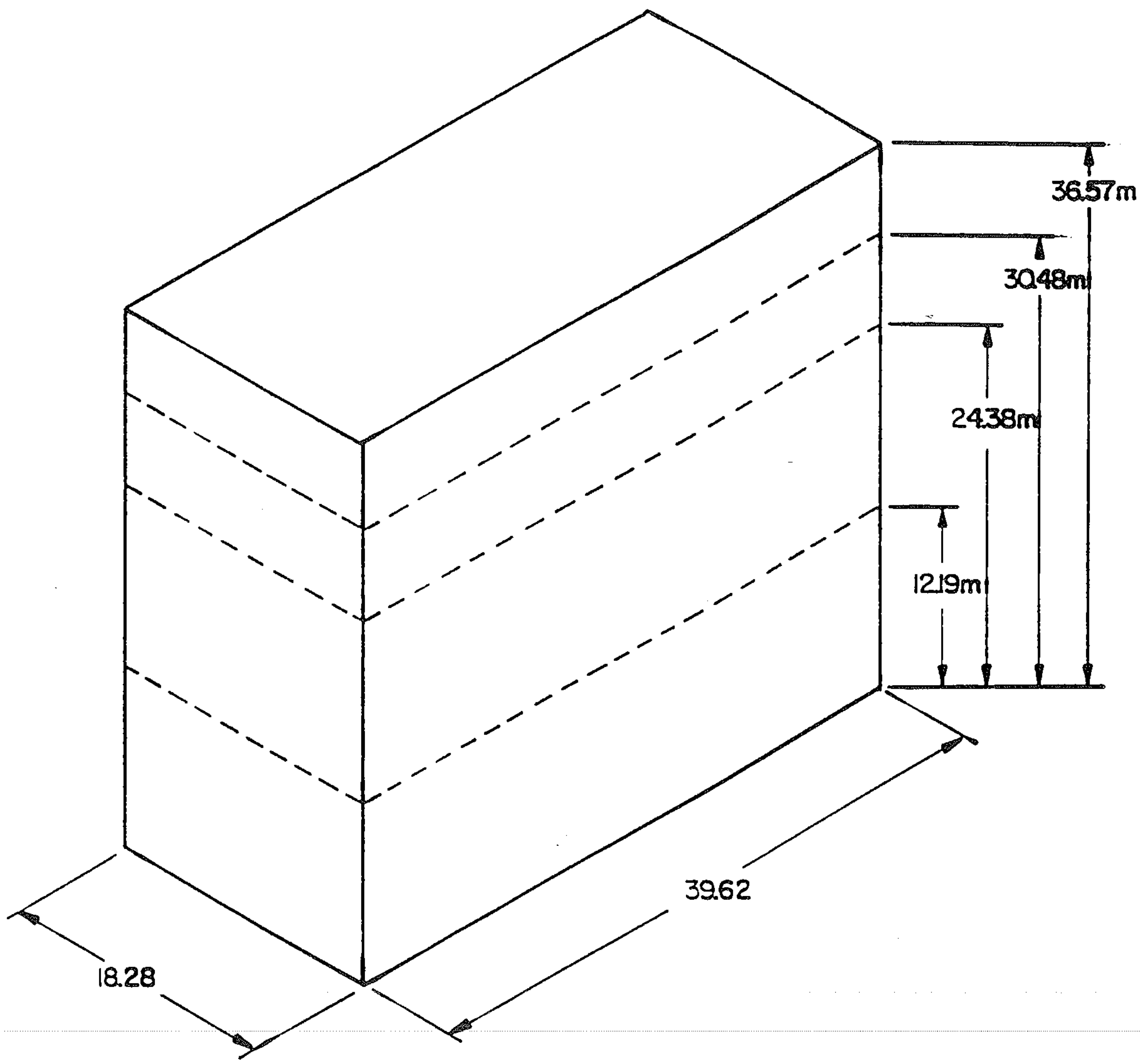


FIGURE 2. Isometric view of solid structure.

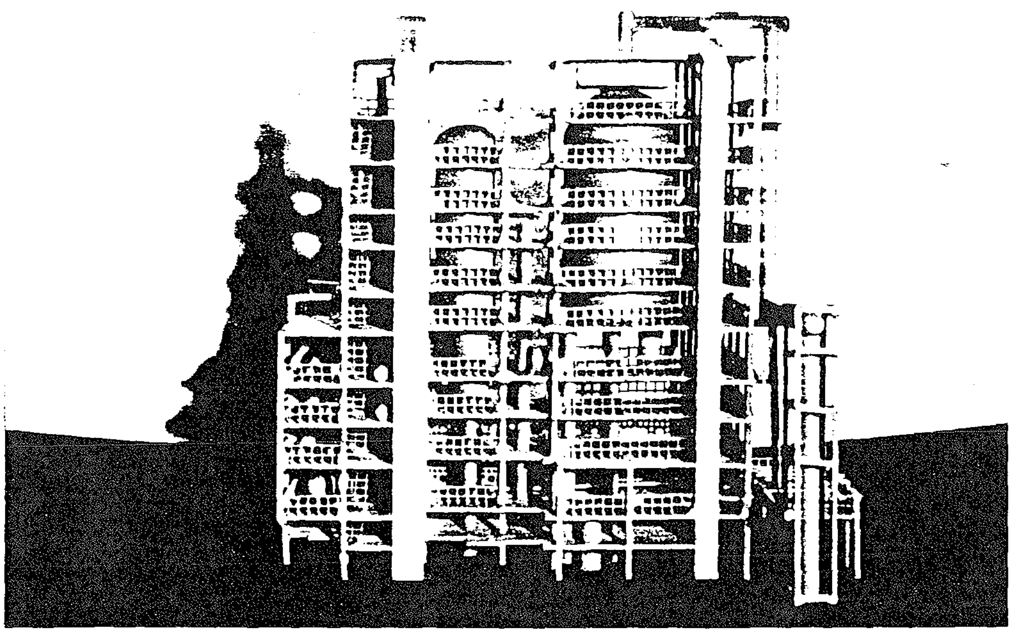
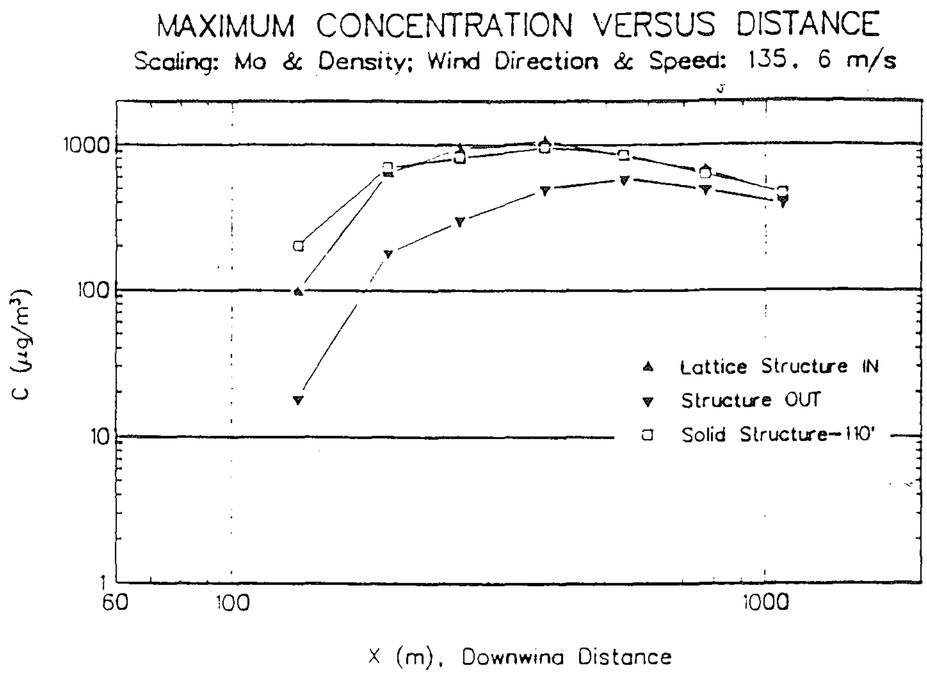


FIGURE 3. Photograph of FCU 6 model.



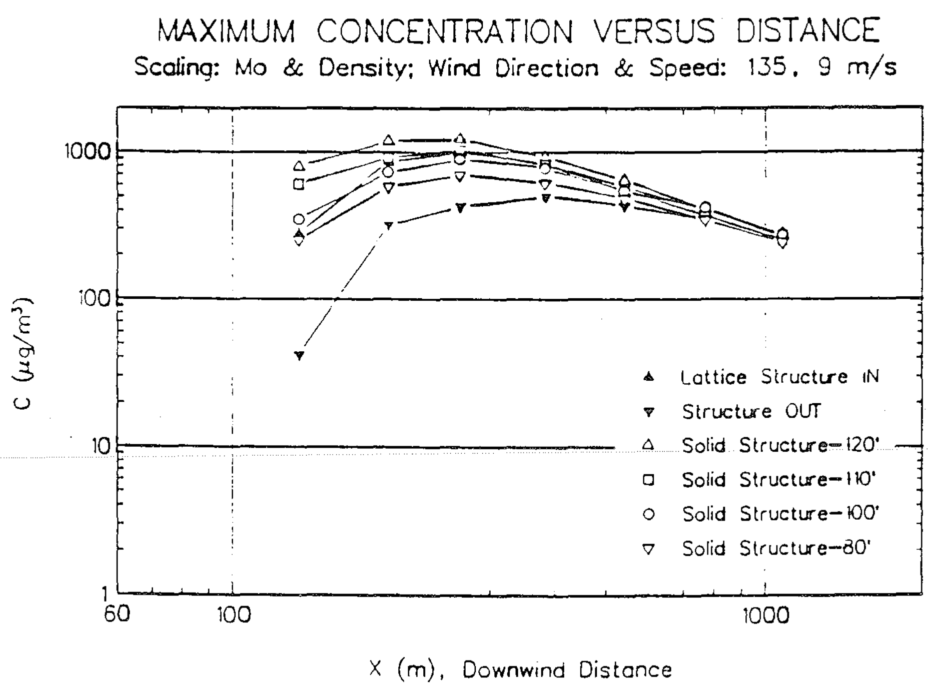


FIGURE 4. Maximum SO_2 concentration versus downwind distance with structures, without nearby structures and with various solid structures present for a 135 degree wind direction with 6 and 9 m/s wind speeds.

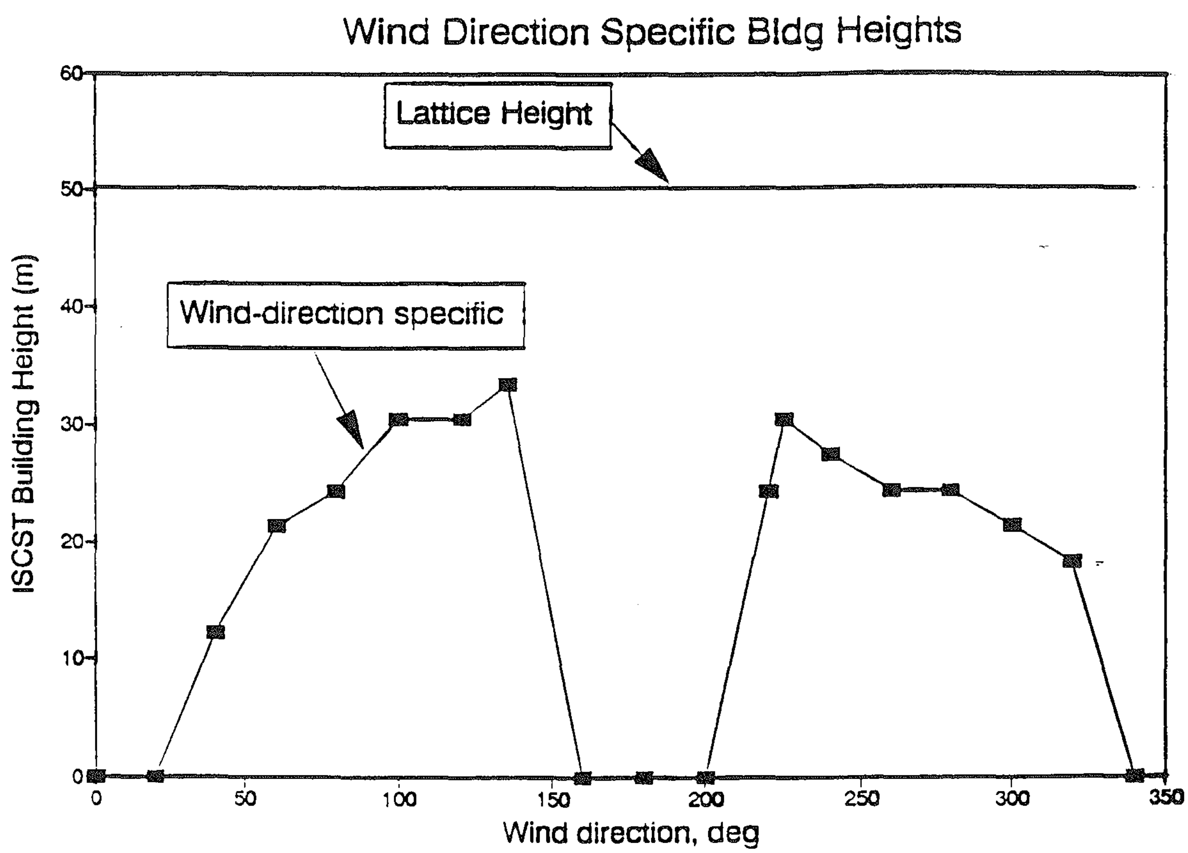


FIGURE 5. Wind direction specific building heights as determined by wind-tunnel testing.

**TABLE 1. Model and full scale parameters for FCU 6 stack.
9 m/s Cases; Scale Reduction = 240**

Description	Full Scale English	Full Scale Metric	Model Metric
Dimensional Parameters			
1 . Building Height, H_b (ft—m)	165.0	50.3	0.210
2 . Stack Height, h (ft—m)	160.0	48.8	0.203
3 . Stack Inside Diameter, d (ft—m)	8.00	2.440	1.02E–02
4 . Ambient Pressure, P_a (Atm)	1.000	0.988	0.85
5 . Ambient Temperature, T_a (F—K)	49.3	282.6	293
6 . Exit Temperature, T_s (F—K)	675.1	630.3	293
7 . Exit Velocity, V_e (ft/min—m/s)	3954	20.09	2.668
8 . Volume Flow Rate, V (ft^3/min—m^3/s)	198894	93.94	2.166E–04
9 . Reference Wind Speed, U_r (mph—m/s)	50.5	22.6	3.00
10 . Reference Height, z_r (ft—m)	1312	400.0	1.67
11 . Anemometer Wind Speed, U_a (mph—m/s)	20.13	9.00	1.20
12 . Anemometer Height, z_a (ft—m)	32.8	10.00	0.042
13 . SO_2 Emission Rate, Q (lb/hr—g/s)	875	110.35	n/a
14 . Site Surface Roughness Factor, z_0 (ft—m)	4.10	1.25	5.21E–03
15 . Site Power Law Exponent, n	0.25	0.25	0.25
Dimensionless Parameters			
16 . Velocity Ratio	0.89	0.89	0.89
17 . Momentum Ratio	1.33E–05	1.33E –05	1.33E–05
18 . Density Ratio	0.448	0.4484	0.4484
19 . Froude Number	3.70	3.70	7.61
20 . Stack Reynolds Number	8.71E+05	8.71E+05	1.13E+03
21 . Building Reynolds Number	4.75E+07	4.76E+07	2.12E+04
22 . Surface Reynolds Number	1.06E+05	1.06E+05	46.80

TABLE 2. Summary of maximum concentrations for 135 degree wind direction.

Run No.	Building Type	Building Height (m)	Wind Direction	Wind Speed (m/s)	C_{max} ($\mu g/m^3$)	$(C_{max})_{ref}$ [1] / $(C_{max})_i$
25	Lattice	50.3	135	6.00	1070.1	1.00
27	Solid	33.5	135	6.00	961.9	1.11
26	NA	0.0	135	6.00	585.8	1.83
12	Lattice	50.3	135	9.00	1010.6	1.00
20	Solid	36.6	135	9.00	1235.9	0.82
23	Solid	33.5	135	9.00	1033.3	0.98
22	Solid	30.5	135	9.00	897.5	1.13
21	Solid	24.4	135	9.00	703.5	1.44
15	NA	0.0	135	9.00	500.7	2.02

[1] The subscript $_{ref}$ refers to the lattice structure test. The subscript $_i$ refers to the indicated run.

TABLE 3. Site specific building dimensions for input into the ISCST model.

Wind Direction	Height (ft)	Height (m)	Width (ft)	Width (m)
0	0	0.0	60	18.3
10	0	0.0	82	24.9
20	0	0.0	101	30.7
30	20	6.1	117	35.6
40	40	12.2	130	39.5
50	55	16.8	138	42.1
60	70	21.3	143	43.5
70	75	22.9	143	43.5
80	80	24.4	138	42.2
90	90	27.4	130	39.6
100	100	30.5	138	42.2
110	100	30.5	143	43.5
120	100	30.5	143	43.5
130	107	32.5	138	42.1
140	88	26.8	130	39.5
150	44	13.4	117	35.6
160	0	0.0	101	30.7
170	0	0.0	82	24.9
180	0	0.0	60	18.3
190	0	0.0	82	24.9
200	0	0.0	101	30.7
210	40	12.2	117	35.6
220	80	24.4	130	39.5
230	97	29.5	138	42.1
240	90	27.4	143	43.5
250	85	25.9	143	43.5
260	80	24.4	138	42.2
270	80	24.4	130	39.6
280	80	24.4	138	42.2
290	75	22.9	143	43.5
300	70	21.3	143	43.5
310	65	19.8	138	42.1
320	60	18.3	130	39.5
330	30	9.1	11	35.6
340	0	0.0	101	30.7
350	0	0.0	82	24.9