WCAP-14084

Westinghouse Non-Proprietary Class 3

PHASE IVa WIND TUNNEL TESTING FOR THE WESTINGHOUSE AP600 REACTOR

Westinghouse Energy Systems

WCAP-14084

PHASE IVa WIND TUNNEL TESTING FOR THE WESTINGHOUSE AP600 REACTOR

G. R. Lythe
D. Surry

BLWT-SS4-1994

BOUNDARY LAYER WIND TUNNEL LABORATORY
THE UNIVERSITY OF WESTERN ONTARIO
FACULTY OF ENGINEERING SCIENCE
LONDON, ONTARIO, CANADA
N6A 5B9

TABLE OF CONTENTS

SUMMARY

This report details the first part of the fourth phase of the wind tunnel testing of the Westinghouse AP600 nuclear reactor (there was no phase III). The design for this reactor employs passive means for emergency cooling, including natural draft cooling and water film evaporative cooling. This cooling is dependent on natural convection through the building, which could be affected by wind conditions. Phase I testing examined the potential for wind-induced flows through the building and the sensitivity of the wind effects to various changes in the geometry of the containment building and its surroundings. Phase I testing is detailed in reference 8. Phase II testing included the modelling of the complete flow path within the building and was used primarily to provide information for the design of the baffle wall. This testing is detailed in reference 9.

The aims of this phase of the testing are to:

1. Check for any sensitivity of the measurements to Reynold's number;

2. Provide final design data for the baffle wall;

3. More accurately examine the effects of the hyperbolic cooling tower;

4. Examine the effects of a uniform velocity profile for determining potential tornado loads, and;

5. To provide some information for the modelling of the cooling tower in Phase IVb (these data will be presented in the report for Phase IVb).

To accomplish these aims, two models were used, and testing was done in two wind tunnels. The first model was the 1:96.67 scale model which was used in previous phases (in the "current design" configuration, with internal flow passages modelled). It was modified to include more pressure tapping locations and to allow the internal flow path to be sealed at the base of the chimney. The second model was a new model constructed at a scale of 1:30. This model did not include the internal flow paths, but did include an internal volume to correspond to the internal volume of the sealed 1:96.67 model. The testing was done in two wind tunnels: the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario (UWO), as in previous phases, and the 30' x 30' wind tunnel at the National Research Council of Canada (NRC) in Ottawa, Canada. In both wind tunnels and at both scales, the models were tested in turbulent boundary layer flow representative of the flow in an open country terrain (i.e. ANSI exposure C), except for the tornado loading case, where near uniform flow was used. The configurations tested are listed in table 1.

The highlights and main findings of the study are as follows:

1. The effects of Reynold's number (Re) can be seen in the plots of figure 18. At the higher Re's tested, the results become insensitive to increasing Re. To account for the changes in results between the Re used for the main UWO tests and the Re above which the results do not change, the main UWO results for the baffle loads were adjusted based on the data in figure 18. This amounted to an increase in the mean coefficients by a factor of 1.23 and no change in the rms coefficients. Peak loads were then formed from the mean and rms loads and an appropriate peak factor.

2. A summary of the baffle loads are presented in figure 19. These loads are in the form of coefficients which, for design, must be multiplied by a design dynamic pressure at roof height. Appendix D of reference 9 contains a discussion regarding the calculation of such design dynamic pressures.

3. The cooling tower substantially reduces mean baffle loads, but increases the rms loads, resulting in somewhat larger peak loads. Although the peak loads are somewhat larger, they remain within the upper bound of figure 19, thus the data do not warrant any "adjustment" due to the cooling tower.

4. The loading under a tornado flow simulation decreases from that under a "normal" flow simulation, due to the significant reduction in the unsteady loads. Since the design dynamic pressure for tornado winds is almost the same as for hurricane winds (see appendix D of reference 9), the baffle loads for the latter, based on figure 19, will be conservative for tornado loading.

ACKNOWLEDGEMENTS

This study was initiated by Westinghouse Electric Corporation. The co-operation and interest of the Sponsors, in particular Ms. S. V. Fanto, are gratefully acknowledged.

Acknowledgement is also made of the contributions by various members of the technical staff of the Laboratory: Mr. S. Norman carried out the experimental phase of the study at UWO and instrumented the models. Mr. D. Morrish was responsible for the data acquisition system and assisted with the testing at NRC, and Mr. A. Burggraaf assisted with the data acquisition system. The 1:96.67 test model was originally built and subsequently modified by members of the University of Western Ontario Coordinated Machine Shops. The 1:96.67 proximity model was built by Mr. G. Stevens. The 1:96.67 cooling tower model was built by Mr. J. Collishaw. The 1:30 test model was built by Mr. S. Horvath. Mr. J. Golab took the photographs of the UWO tests.

The considerable assistance and advice provided by members of the NRC staff are also gratefully acknowledged. In particular, Messrs. S. Zan and K. Cooper coordinated the NRC experiments and designed the devices that were necessary to produce appropriate boundary layers in the 30' x30' wind tunnel. The operation of the 30' x 30' wind tunnel was performed by Mike and Cameron of the NRC technical staff. Mr. J. McKellar took the photographs of the NRC experiments.

Finally, the authors would like to acknowledge the general direction, advice and encouragement received from Dr. A.G. Davenport, Director of the Boundary Layer Wind Tunnel Laboratory.

1· INTRODUCTION

The Westinghouse AP600 nuclear reactor is designed to use passive means for emergency cooling. These include natural draft and water film evaporative cooling which are made possible by an air flow path through the containment building. The air flows in inlets at the top of the building, downwards past a baffle wall, then around the bottom of the baffle, upwards between the baffle and the containment vessel and out the chimney at the top of the building.

A goal of the design is that the wind not resist the air flow through the building. Phase I testing, detailed in reference 7, examined the effects of various design changes on the potential for wind-induced flows through the building. In that testing , the flow through the building was not modelled, but the pressure difference between inlets and chimney (i.e. the pressure driving any flow) was measured. In the Phase II tests, reported in reference 9, the air flow path was modelled for two different building designs: the most wind neutral design found in Phase I testing, and the current design of the building. The purpose of the Phase II testing was primarily to provide information for the design of the baffle wall. The information sought was the loads on the wall and how uniform the flow was at various points along the flow path. Buoyancy was not considered since the driving pressure due to buoyancy amounts to only about 1 to 5% of the wind-induced driving pressure for the design wind cases.

At the end of Phase II, there remained several outstanding questions. First, the effect of Reynolds number on the results. This could only be addressed definitively by testing a larger model in a faster wind tunnel such that the Reynold's numbers were high enough that no further significant aerodynamic changes would be expected at full scale values. Secondly, the effect of a tornado wind profile (near uniform) on the results. This could be accomplished using the same test model as in previous phases, but with a different flow model. Thirdly, the effects of the hyperbolic cooling tower on the results. Some limited measurements were made in Phase II; however, the blockage of the cooling tower in the University of Western Ontario (UWO) wind tunnel was excessive. This question could be addressed by testing the 1:96.67 model in a larger wind tunnel where the blockage would be small. The current phase of testing, phase IVa (there was no phase III), is aimed at addressing these questions. A further question, the effect of severe terrain, will be the subject of Phase IVb.

Table 1 shows a summary of the tests that were performed as part of phase IVa. The tests can be subdivided into three series:

1. The UWO tests. These tests (cases 1 to 4a in table 1), were performed using the 1:96.67 scale model used for previous phases, with some added pressure measurement locations. Tests were performed at the UWO wind tunnel, as in previous phases. Since testing in this wind tunnel is relatively economical, data were taken for a full range of wind azimuths to form the basis of the design loads. Data were also taken that would be used for comparison with data taken at the National Research Council of Canada (NRC) (see below). Finally, data were taken at a few wind angles in uniform flow to represent tornado loading conditions.

2. The 1:30 NRC tests. For these tests, a new 1:30 scale model was built, without the internal flow passages and hence with fewer measurement locations. The tests were performed in the 30' x 30' wind tunnel at the NRC for a range of speeds. The speeds ranged from a speed corresponding to the Reynolds number (Re) of the UWO tests, up to the maximum speed of the wind tunnel. The speeds and Re's used for all tests are listed in table 2. These tests would be used to examine Re effects. Note that the data for the lowest speed (case 5) are not expected to be as reliable as those for higher speeds, but may be useful for observing trends.

3. The 1:96.67 NRC tests. These tests were performed using the same model and instrumentation as was used for the UWO tests, but were performed in the 30' x 30' NRC wind tunnel for speeds ranging from the UWO test speed up to the maximum speed of the wind tunnel. Since the blockage of the hyperbolic cooling tower is negligible at this scale in this tunnel, data were taken with the cooling

tower in place in order to quantify its effect. Two wind angles were chosen: one with the cooling tower directly upstream of the site and the second such that the site would be in the shear layer at the edge of the cooling tower wake.

All of the above tests were performed in turbulent boundary layer flow representative of the flow in an open country terrain (ANSI exposure C). In addition to the above measurements, measurements were made of the pressure distribution around the throat of the cooling tower and of the velocity distribution across the wake behind the cooling tower for use in Phase IVb. Those data will be reported with phase IVb.

2· EXPERIMENTAL PROCEDURE - UWO TESTS

2·1 Modelling of the Surrounding Site and the Wind

The basic tool for these tests was the Laboratory's Boundary Layer Wind Tunnel. The 1:96.67 scale model of the containment building was placed at the centre of a turntable and, for most of the tests, was surrounded by a "proximity" model consisting of the other plant buildings as shown in Figure 1 (some tests were done without the surroundings). This entire assemblage could be rotated to simulate different wind directions. The turbine building height was 125.33 feet. The model is shown in the wind tunnel in Figure 2.

The wind tunnel also allows extended fetches of coarsely modelled upstream terrain to be placed in front of the building under test. The wind tunnel flow then develops boundary layer characteristics representative of those found in full scale. This methodology has been highly developed and is detailed elsewhere (1,2,3). In this case, a 1:96.67 scale boundary layer representative of open country conditions (ANSI exposure C) was required. To achieve this, spires and a trip were used along with floor roughnesses with heights of 0.75 and 2.0 inches. The upstream terrain model is shown in Figure 3.

Vertical profiles of mean speed and the longitudinal component of the turbulence intensity, measured immediately upstream of the proximity model, are shown in Figure 4 compared with reference profiles for open country terrain. The latter have been developed by ESDU (4,5,6) through fitting theoretical models to available full scale data. The roughness length, z_o, (a characteristic parameter of the mean speed profile) calculated from the wind tunnel data, is approximately 0.02 metres. This is well within the acceptable range of a factor of 2 from the accepted median open country value of 0.03. The ratios of mean speeds at particular heights to those at roof height are shown in Table 3, along with similar reference values. Also shown are values of the local turbulence intensity, which is simply the root-mean-square (rms) speed divided by the mean speed at each height. The table includes heights up to 1.5 times the building height. The table shows that except for the few points closest to the ground, the mean ratios are within 0.05 of the reference values and the local intensities are within 2 percentage points of the ESDU values. Hence this is a very good representation of the wind structure for an open country terrain.

The simulation was further checked by measuring a spectrum of the wind speed at roof height. This spectrum is shown in Figure 5, along with the reference spectrum for open country terrain. The figure shows that the spectrum is well within the acceptable range of a factor of 2 over the entire range of wave numbers.

In addition to the main tests described above, a limited number of tests were done in a flow simulation used to determine tornado loads. Figure 6 shows vertical profiles of velocity and turbulence intensity for this simulation, which is within the goal of a boundary layer less than 1/3 the height of the building, with the flow over the upper 2/3 being uniform to within 5%.

2·2 Modelling of the Containment Building, Including the Flow Path

The model scale of 1:96.67 was chosen for Phase I to allow the model to be large enough to include small details and to be practical to work with. Also, the scale needed to be within the range of atmospheric model flows attainable in the wind tunnel and it was desirable to choose a scale that would accommodate standard material sizes to aid in the construction. The model built for Phase I and modified for use in Phase II, was further modified for the current tests by adding new circumferential rings of pressure taps at the following locations:

1. on the exterior of the main building at 2/3 the height of the inlets;
2. on the exterior of the main building just below the inlets;
3. just inside the inlet manifold;
4. on the exterior 1/2 way up the chimney, and;
5. at the top of the containment annulus.

These locations, along with all other pressure measurement locations, are shown as arrows in Figure 7. Photographs of the model in the wind tunnel are shown in Figure 2.

In previous phases and for the UWO tests in the current phase, the exterior of the chimney was roughened. The reason for roughening was that since the full scale Reynold's number (Re) could not be matched in the tests, it was desireable to alter the flow around the chimney to more closely approximate the flow expected at higher Re and to provide results that were insensitive to Re. Experiments in phase I, based on the limited information available from the pressure taps inside the chimney (none had been installed on the exterior), and on tests done over a limited range of Re, indicated that roughening on the chimney produced the most appropriate results; without roughening on the chimney, results changed with speed. It was recognized that roughening the chimney would increase its drag a little and hence make the chimney base pressure somewhat more negative; however, it was expected that roughening the chimney would likely cause only second order effects on the results of interest, namely the pressures inside the chimney. These pressures would likely be dominated by effects of the separation of the flow from the top of the chimney.

In modelling the flow path, the most important aspect to model is not strictly the geometry, but the flow losses in the various parts of the flow path. The loss values to model were derived from experiments conducted by Westinghouse Electric Corporation (WEC), which are detailed in reference 7. In phase II, the model was designed to have lower losses than these values and calibration experiments and model modifications were performed to adjust the losses to the WEC values. Details of this modelling of the flow losses and the Phase II calibration experiments are given in appendix A of reference 9. For the current phase IVa tests, the calibration experiments were repeated to ensure that the model modifications, which required partially dismantling the model, had not appreciably changed the losses throughout the flow path. Results of this recalibration are presented in appendix A of this report.

2·3 Pressure measurements

All pressure data were measured using a solid state pressure scanner system which sampled pressures at a rate approximating 5 samples per second in full scale for a period approximating 22 minutes in full scale. All of these samples are kept for later analysis (e.g. to determine the maximum, minimum, mean and rms values in each case). During the tests, the speed, denoted Vref, was monitored by a pitot-static tube mounted just upstream of the proximity model, at a height near the roof of the wind tunnel. All of the pressure data are presented in this report in the form of non-dimensional pressure coefficients as defined in reference 1. They are referenced to the mean dynamic pressure at roof height, 1/2 ρV^2roof, where Vroof is calculated from the Vref measured during the test using the Vroof/Vref ratio from the measured velocity profile.

Pressures were measured at the locations shown in Figure 7. As well, several combinations of the pressure measurements were made at each sampling instant to form data records for new "combination" taps. The combination taps are all numbered in the 600's and are defined in Table 4. Many of these combinations are the same as those used in Phase II, while others are new combinations made possible by the new pressure tap locations. Combination taps 601 to 624, and 643 to 650 represent loads on the baffle at particular locations, since they are the difference between the pressure in the shield building annulus (SBA) and the pressure in the containment annulus (CA). Combination taps 625 to 632 represent the difference between the pressure at the inlet taps and the pressure at the upper level SBA taps. Combination taps 633 to 640 represent somewhat approximate baffle loads at the top, since they are the difference between SBA and CA taps that are not directly opposite one another (taps 643 to 650, which were unavailable for Phase II, are better taps to use here). Three of the most important combination taps are the average of the inlet taps (tap 651), the average of the chimney taps (tap 652) and the difference between the average of the inlet taps and the average of the chimney taps (for this test, tap 642; in phase II tap 641 was used).

3 EXPERIMENTAL PROCEDURE - NRC 1:30 SCALE TESTS

3.1 Modelling of the Surrounding Site and the Wind

The basic tool for these tests was the 30' x 30' wind tunnel at the NRC. The 1:30 scale model of the containment building was bolted to the floor of the wind tunnel in a position such that the surrounding buildings could be added if necessary. For this reason, it was not centrally located. Provision was made for including surrounding buildings if significant Re number effects were found without the surroundings, based on the rationale that Re sensitivity is likely to reduce as interference effects from the surroundings increase. The model is shown in the wind tunnel in figure 8.

In the 30' x 30' wind tunnel the boundary layer is generated by the use of spires and trips. In this case, a 1:30 scale boundary layer representative of open country conditions (ANSI exposure C) was required. The spires and trip used to achieve this are shown in figure 9.

Vertical profiles of mean speed and the longitudinal component of the turbulence intensity, measured on the centreline of the wind tunnel without the model present, are shown in Figure 10 compared with reference profiles for open country terrain. The latter have been developed by ESDU (4,5,6) through fitting theoretical models to available full scale data. The roughness length, z_0, (a characteristic parameter of the mean speed profile) calculated from the wind tunnel data, is approximately 0.03 metres. This is well within the acceptable range of a factor of 2 from the accepted median open country value of 0.03. The ratios of mean speeds at particular heights to those at roof height are shown in Table 5, along with similar reference values. Also shown are values of the local turbulence intensity, which is simply the root-mean-square (rms) speed divided by the mean speed at each height. The table includes heights up to 1.5 times the building height. The table shows that except for a few points close to the ground and the two highest points, the mean ratios are within 0.05 of the reference values (where they differ, the actual values tend to be higher than the reference values and hence are conservative). The local intensities are all within 2 percentage points of the ESDU values. Hence this is a very good representation of the wind structure for an open country terrain.

The simulation was further checked by measuring a spectrum of the wind speed at roof height. This spectrum is shown in Figure 11, along with the reference spectrum for open country terrain. The figure shows that the spectrum is well within the acceptable range of a factor of 2 over the upper range of wave numbers; however, it is missing some of the low frequency fluctuations. This was considered acceptable since the overall energy in the flow as measured by the turbulence intensity is comparable to the reference values.

3-2 Modelling of the Containment Building

The model scale of 1:30 was chosen with the aim of achieving the highest Re possible. This scale was the largest scale for which a reliable boundary layer could be generated in the NRC wind tunnel. In order to examine the effects of the chimney roughening, tests were performed with and without chimney roughening. The size of the roughness used was the same relative size as for the 1:96.67 scale test. Photographs of the model in the wind tunnel are shown in Figure 8.

3-3 Pressure measurements

All pressure data were measured using a solid state pressure scanner system which sampled pressures for a period approximating 20 minutes in full scale. The pressures were sampled at a rate approximating 9 samples per second in full scale at the highest wind speed tested and about 70 samples per second at the lowest wind speed tested (in the analysis, only frequencies up to 2 hz in full scale are used). All of these samples are kept for later analysis (e.g. to determine the maximum, minimum, mean and rms values in each case). During the tests, the speed, denoted Vref, was monitored by a pitot-static tube mounted just downstream of the test model, at a height well above the test model. All of the pressure data are presented in this report in the form of non-dimensional pressure coefficients as defined in reference 1. They are referenced to the mean dynamic pressure at roof height, $1/2\ \rho V^2$roof, where Vroof is calculated from the Vref measured during the test using a Vroof/Vref ratio measured as part of the velocity profile.

Pressures were measured at the same, but fewer locations than on the 1:96.67 model. Five circumferential rings of tapping locations were used (see Figure 7):

1. Ring 1 is at level 2a, on the exterior of the main building at 2/3 height (taps 85 to 100);

2. Ring 2 is at level 4a, on the exterior of the main building, just below the inlets (taps 109 to 124);

3. Ring 3 is at level 4a, just inside the inlets (taps 125 to 140);

4. Ring 4 is at level 6, on the exterior of the chimney (taps 141 to 148);

5. Ring 5 is at level 6, in the interior of the chimney (taps 149 to 156).

As well, several of the combination taps, as described in section 2.3, were formed; namely, the average of the inlet taps (tap 651), the average of the chimney taps (tap 652) and the difference between the average of the inlet taps and the average of the chimney taps (tap 642).

4 EXPERIMENTAL PROCEDURE - NRC 1:96 SCALE TESTS

4-1 Modelling of the Surrounding Site and the Wind

The basic tool for these tests was the 30' X 30' wind tunnel at the NRC. The 1:96.67 scale model of the containment building that was used in the UWO tests was used here with the same instrumentation and the same surroundings model. The test model and the surroundings model (when used) were mounted on a 1" thick base that extended 6" beyond the outer edge of the surroundings model. The protruding 6" were sloped down to floor level at the outer edge. The base was used to allow more efficient model changeovers (e.g. turning the model to simulate another wind angle) since the models could be screwed to the base instead of having to be bolted to the wind tunnel floor. The presence of the base is not expected to significantly affect the results, since it does not raise the model significantly and since it is relatively close downstream from the flow trip (see below). The model is shown in the wind tunnel in Figure 12.

In the 30' x 30' wind tunnel the boundary layer is generated by the use of spires and trips. In this case, a 1:96.67 scale boundary layer representative of open country conditions (ANSI exposure C) was required. The spires and trip used to achieve this are shown in figure 13.

Vertical profiles of mean speed and the longitudinal component of the turbulence intensity, measured on the centreline of the wind tunnel without the model or base present, are shown in Figure 14 compared with reference profiles for open country terrain. The latter have been developed by ESDU (4,5,6) through fitting theoretical models to available full scale data. The roughness length, z_0, (a characteristic parameter of the mean speed profile) calculated from the wind tunnel data is approximately 0.03 metres. This is well within the acceptable range of a factor of 2 from the accepted median open country value of 0.03. The ratios of mean speeds at particular heights to those at roof height are shown in Table 6, along with similar reference values. Also shown are values of the local turbulence intensity, which is simply the root-mean-square (rms) speed divided by the mean speed at each height. The table includes heights up to 1.5 times the building height. The table shows that for all heights the mean ratios are within 0.05 of the reference values and the local intensities are all within 2 percentage points of the ESDU values. Hence this is a very good representation of the wind structure for an open country terrain.

The simulation was further checked by measuring a spectrum of the wind speed at roof height. This spectrum is shown in Figure 15, along with the reference spectrum for open country terrain. The figure shows that the spectrum is within the acceptable range of a factor of 2 over the upper range of wave numbers; however, it is missing some of the low frequency fluctuations. This was considered acceptable since the overall energy in the flow as measured by the turbulence intensity is comparable to the reference values.

4.2 Modelling of the Containment Building

The same 1:96.67 scale model that was used for the UWO tests was used here (see section 2.2). Chimney roughening was used for the initial tests and then removed to provide comparison data. Since the model had not been altered since the UWO tests, the flow losses through the flow path did not need to be recalibrated; they will remain the same as those detailed in appendix A. Photographs of the model in the NRC wind tunnel are shown in Figure 12.

4.3 Pressure measurements

All pressure data were measured using a solid state pressure scanner system which sampled pressures for a period approximating 20 minutes in full scale at the lowest wind speed tested and about 35 minutes at the highest wind speed tested. The pressures were sampled at a rate approximating 3 samples per second in full scale at the highest wind speed tested and about 6 samples per second at the lowest wind speed tested (in the analysis, only frequencies up to 2 hz in full scale are used). All of these samples are kept for later analysis (e.g. to determine the maximum, minimum, mean and rms values in each case). During the tests, the speed, denoted *Vref*, was monitored by a pitot-static tube mounted just downstream of the test model, at a height well above the test model. All of the pressure data are presented in this report in the form of non-dimensional pressure coefficients as defined in reference 1. They are referenced to the mean dynamic pressure at roof height, $1/2\ \rho V^2$roof, where Vroof is calculated from the Vref measured during the test using a Vroof/Vref ratio measured in a separate experiment after the testing (with the model base in place, but without the test model or surroundings).

Pressures were measured at the same locations as for the UWO tests (see Figure 7) and the same combination taps were formed (see table 4).

5 EXPERIMENTAL RESULTS AND DISCUSSION

5-1 General

For all tests, statistics of the pressure coefficient records (maximum, minimum, mean and rms) have been determined for all taps and are tabulated in Appendix B. Taps are numbered in accordance with the numbering system shown in Figure 7 and Table 4. These data are examined more closely in the following sections.

Some of the current data from the UWO tests (case 4) are comparable to data taken in Phase II. Figure 16 shows some comparisons; the repeatability is quite good, lending confidence to both studies.

The main purpose of these tests was to determine the best estimates of the loads on the baffle wall inside the containment building under normal conditions, and then to determine the effect of a tornado wind profile and the cooling tower on these loads. The most complete set of data is the UWO test data. The NRC data was obtained to assess concerns with the UWO data regarding Re scaling and blockage and can be used to determine if any adjustments are necessary.

Since the baffle loads are of primary interest and because the 1:30 scale model did not include the internal flow path, the data that are most important for observing trends are the data from the following three "combination" taps: the spatial average of the inlet taps (tap 651), the spatial average of the inside chimney taps (tap 652) and the spatial average inlet minus spatial average chimney tap (tap 642). The last of these is the most important of all. If further information on trends seen in the data from these taps is needed, then the data from the rings of taps on the outside of the building and chimney can be used.

5-2 Main Results

Figure 17 shows the data from the three primary taps for all cases, referenced to the case numbering in tables 1 and 2. This figure gives a good indication of the overall variability of the results over all Re's, with and without chimney roughness, with and without surroundings, with the chimney open and closed and in three different simulations. The last two sets of data show the effect of adding the cooling tower. The main observation from this plot is that even with all of the differences between configurations, there is not a great deal of variability in the data. Trends with Re can be seen, as can open/closed chimney trends and smooth/rough chimney trends, but differences tend to be small.

In analysing the data for the NRC 1:96 scale tests, it was observed that the rms data increased with wind speed, while the mean data remained constant. It was determined that this was primarily due to acoustic noise in the wind tunnel itself and not a real trend in the data. Details of this investigation are given in appendix D.

In order to determine if the UWO data needs to be corrected for Re effects and/or other effects, mean and rms data for matched closed chimney, no surroundings cases have been plotted in figure 18 vers s the main building Re for the three primary taps. The following observations can be made from figure 18:

1. For the inlet tap, the chimney roughening has very little effect.

2. At the inlets, there is some variation of the mean pressure with Re up to about 1.2×10^6, but very little above this. The rms pressure shows little variation with Re.

3. At the inlets, the difference between the mean UWO data and the high Re mean data is small; a Cp difference of -0.03 or a ratio of 1.17. For rms data, the difference is negligible.

4. At the chimney, the effect of roughening is significant for the lower Re, but less so at the higher Re. Roughening tends to make the variations at low Re's less severe and more predictable.

5. At the chimney, there is significant variation of the mean pressure with Re up to about 2×10^6 and some residual variation above this. Note that the Re used is based on the containment building diameter. Relative to the local chimney diameter, the Re would be reduced by a factor of about 1.8. The equivalent Re to the onset of stable results at the inlets as observed above in point 2 would be about 2.2×10^6, consistent with the results of figure 18b for the chimney. For the roughened chimney, the pressures appear to have stopped changing at the highest Re tested. It can also be seen (from data for tap 147) that the magnitude of the wake pressure is smaller for the rough chimney than for the smooth chimney. At very high Re, where the wake pressure is independent of further changes in Re, roughness is known to increase the wake pressure. Hence, it is expected that the smooth chimney results would eventually approach the roughened chimney value, or something slightly less negative, at higher Re's. The rms pressure shows smaller variation with Re.

6. At the chimney, the difference between the mean UWO data and the rough chimney mean data at the highest Re is a Cp difference of 0.16 or a ratio of 1.23. For rms data, the difference is negligible.

7. For the inlet minus chimney tap, the effect of roughening is significant, since it reflects the effects seen at the chimney. Roughening tends to make the variations at low Re's less severe and more predictable.

8. For the inlets minus chimney tap, there is significant variation of the mean pressure with Re up to about 1.2×10^6 and some residual variation above this. For the roughened chimney, the pressures appear to have stopped changing at the highest Re tested and it is expected that the smooth chimney results would eventually approach this value at higher Re's. The rms pressure shows smaller variation with Re.

9. For the inlet minus chimney tap, the difference between the mean UWO data and the rough chimney mean data at the highest Re is a Cp difference of 0.12 or a ratio of 1.23. For rms data, the difference is negligible.

The conclusion from the above observations is that the UWO data requires a correction to the mean inlet minus chimney difference of a factor of 1.23. The rms requires no correction. This factor has been derived from closed chimney cases, but it is assumed, reasonably, that it can be applied to the relevant open chimney case. For conservatism, the total inlet minus chimney correction can be applied to all pressure differences across the baffle wall. Since the mean data are to be adjusted, the peak data (maximums and minimums) will have to be formed as follows:

$$Cp(\text{maximum}) = \text{adjusted } Cp(\text{mean}) + g * Cp(\text{rms})$$
$$Cp(\text{minimum}) = \text{adjusted } Cp(\text{mean}) - g * Cp(\text{rms})$$

where g is an appropriate peak factor. This peak factor was calculated as the average peak factor from all positive and negative peaks from all relevant combination taps on the bafflw (i.e. taps 601 to 624 and 643 to 650) for all wind angles. It was calculated to be 4.58. This process also tends to smooth out some of the variability associated with the single-point peak results.

The final pressure coefficients relevant to the baffle design, adjusted as [illegible] described, are tabulated in appendix C. A summary of the worst values is given in table 7. Figure 19 shows a summary of this data: for each wind angle, the largest positive (inward-acting) and negative (outward-acting) peak coefficient was found from all taps at each level and is plotted at that level (the positive and negative peaks have been slightly offset vertically for clarity). The figure includes an upper bound line to the data showing linear behaviour for the lower portion of the baffle, extending to the centreline of the inlets where pressure differences would be expected to be maximum. Above this, the upper bound pressure difference is shown as constant. This upper bound line has shifted to the right somewhat from the corresponding line from Phase II, largely as a result of the adjustment to the current data as described above.

5-3 Effects of the Tornado Profile

Figure 20 shows the data from the tornado profile tests superimposed on comparable data from a "normal" profile test (neither set of data includes the adjustments discussed above), for the combination taps on the baffle. The figure shows that in all cases the peak pressure coefficients are lower for the tornado case, primarily resulting from the reduction in unsteady components. This means that the design values of figure 18 would be conservative under tornado conditions.

5-4 Effects of the Cooling Tower

In the NRC 1:96.67 scale tests, tests were done at 310° both with and without the cooling tower. This angle represents the condition where the containment building is on the edge of the wake from the cooling tower. A test was also done with the cooling tower in place for an angle (280°) representing the condition where the containment building is directly downstream of the cooling tower.

Figure 21 shows a comparison of the with and without cooling tower data at 310°. Figure 21a includes data from all 3 speeds, while Figure 21b includes data from only the lowest speed. Each point on these plots represents data from one tap under two configurations: the x coordinate of the point is the Cp for the tap without the cooling tower in place and the y coordinate of the point is the Cp for the tap with the cooling tower in place. Thus points that fall on the solid 45° line indicate taps where the data is the same for the two configurations; points above the 45° line indicate taps where the Cp with the cooling tower is greater than the Cp without it. Data for baffle difference taps (taps 601 to 624 and 643 to 650) are shown. A least squares fit to the data, forced through zero, is shown as a dashed line and its parameters are shown in the lower right corner of each plot. The slope indicates the ratio of with to without cooling tower data (i.e. a slope greater than 1 would indicate that Cp's are greater with the cooling tower than without) and the correlation indicates how well the line fits the data (a correlation of 1.0 would indicate all data points fall on the line). The actual numerical values for the data from the higher two speeds are not as reliable as the data for the lowest speed, since the higher speeds were subject to the acoustic noise discussed above and in appendix D; however, the comparison between two cases for the two higher speeds should still be valid, since both cases were subject to the same noise, which only constituted 5 to 10% of the rms signal level (hence less of the peak values).

Figure 21a indicates that the cooling tower actually reduces the peak loads somewhat, with a large reduction in the mean load and little change in the rms. Figure 21b, which is based on the most reliable data indicates that with the addition of the cooling tower, positive peak loads are reduced, negative peak loads are increased, mean loads are substantially reduced and rms loads are increased. Although some peak loads are increased, they remain within the upper bound line of figure 19.

Similar comparisons for 280° are somewhat more difficult to make, since data were not taken at NRC without the cooling tower at this wind angle. Therefore, UWO data without the cooling tower for this angle must be used for the comparison; however, the configuration is slightly different (UWO includes chimney roughening).

To take into account differences in configuration, data at azimuth 310° from both wind tunnels, without the cooling tower, were compared in a similar manner to that shown in figure 21. The slopes from the least squares fits were used to "convert" the UWO data for 280° to equivalent NRC data for 280°. These adjusted data are compared with the NRC data that include the cooling tower in figure 22. This figure again shows a substantial reduction in the mean load and a slight increase in the rms. The positive peak loads are decreased and the negative peak loads are increased slightly. Although some peak loads are increased, they remain within the upper bound line of figure 19.

The conclusion from the above is that the cooling tower reduces mean loads but increases the rms loads, resulting in somewhat larger negative peak loads and somewhat smaller positive peak loads. It is important to note that it is the positive peak loads that define the upper bound in figure 19, and that in all cases examined the cooling tower reduces these loads, although sometimes at the expense of a small increase in the negative peaks. Thus the largest peak loads observed with the cooling tower remain within the upper bound of figure 19, and no adjustments to the data for the presence of the cooling tower are warranted. Note that this trend of reduced mean loads and increased rms loads is similar to that seen in Phase II; however, the Phase II cooling tower peak loads were exagerated due to blockage effects.

5-5 Residual Uncertainties

The Phase II and Phase IVa testing have investigated the wind-induced pressures on the AP600 reactor in a very comprehensive manner, consistent with the current state-of-the-art in wind engineering. The extrapolation of these test results to full scale appears to be very reasonable in the light of the arguments presented in the preceding sections and the significant degree of repeatability that has been obtained over a range of test conditions. In this context, it is worth bearing in mind a number of factors that contribute to the differences observed, and also that contribute to the confidence that the primary variations in results have been explored.

Residual differences in the test results can be associated with a number of factors.

1. The three wind simulations used all differ slightly, both in their primary characteristics of mean speed distribution away from the reference speed at the top of the buildings and their local turbulence intensity distributions, as well as in their secondary characteristics associated with the spectral distribution of the turbulence. There are also other characteristics associated with cross-flow components, spatial non-uniformities etc. that were not monitored, but undoubtedly differ a little from case to case and contribute to small differences in the resulting aerodynamic responses.

2. Model locations within the wind tunnels differed, and blockage effects (discounting the unacceptable blockage associated with the cooling tower in the UWO tunnel) were always present to differing degrees. No corrections were attempted for these, but it is known that they tend to lead to conservative results due to the increased acceleration of the flow past the model and its wake.

3. Over the variety of length scales and speeds that were used in the tests, record lengths were maintained at approximately the same full scale value (about 20 minutes). The sampling rate was also varied according to the time scaling where feasible to approximate a constant full scale value. Nevertheless, differences did occur. Moreover, many of the experimental frequency response characteristics inevitably remained constant, effectively changing their associated full scale characteristics between tests. These differences will have added variability to the natural variability associated with the random processes examined.

It is difficult to quantify precisely these various factors. Perhaps their best measure is the degree of consistency in the overall results as presented in the text. In extrapolating these results to full scale, which is an additional factor of about 200 in Reynolds number, a number of positive factors should be borne in mind.

1. The tests carried out here extend to Reynolds numbers in the so-called transcritical range for smooth flow around two-dimensional circular cylinders. It is also well-established that the presence of shear, turbulence and three-dimensionality all act to reduce the effects of Reynolds number. All these factors are strongly in evidence for the AP600 system.

2. Full scale wind characteristics vary considerably, depending on terrain and other elements of surface roughness. The tests carried out here simulate an open country exposure, which is generally conservative for loads. Mean and peak wind speeds are reduced as terrain roughness increases. Special terrain cases are considered further in Phase IVb.

A SUMMARY OF THIS REPORT APPEARS AT THE BEGINNING

REFERENCES

1. Davenport, A.G. and Isyumov, N., "The Application of the Boundary Layer Wind Tunnel to the Prediction of Wind Loading", International Research Seminar on Wind Effects on Buildings and Structures, Ottawa, Canada, September 1967, University of Toronto Press, 1968.

2. Whitbread, R.E., "Model Simulation of Wind Effects on Structures", NPL International Conference on Wind Effects on Buildings and Structures, Teddington, England, 1963.

3. Surry, D. and Isyumov, N., "Model Studies of Wind Effects - A Perspective on the Problems of Experimental Technique and Instrumentation", ICIASF-75, Ottawa, Sept. 1975.

4. ESDU, "Characteristics of atmospheric turbulence near the ground. Part I: definitions and general information", Item number 74030, ESDU International Ltd, London, England, 1974.

5. ESDU, "Characteristics of atmospheric turbulence near the ground. Part II: single point data for strong winds (neutral atmosphere)", Item no. 85020, ESDU International Ltd, London, 1985.

6. ESDU, "Strong winds in the atmospheric boundary layer. Part I: mean hourly wind speeds", Item no. 82026, ESDU International Ltd, London, England, 1982.

7. Stewart, W.A. and Pieczynski, A.T., "Tests of Air Flow Path for Cooling the AP-600 Reactor Containment", Westinghouse Electric Corporation, Report 88-8E9-ADLWR-R2, March 28, 1988.

8. Lythe, G.R. and Surry, D., "Phase I Wind Tunnel Testing for the Westinghouse AP600 Reactor", The University of Western Ontario, BLWT-SS36-1991

9. Lythe, G.R. and Surry, D., "Phase II Wind Tunnel Testing for the Westinghouse AP600 Reactor", The University of Western Ontario, BLWT-SS15-1992

The information contained in the following Tables, Figures, and Appendices is classified Westinghouse Proprietary Class 2, and thus, has been excluded from this non-proprietary version of this report:

TABLE:

2 Reynold's Numbers for Phase 4A
3 Comparison of Velocity and Turbulence Intensity Profiles for the UWO Tests
4 Definition of Tap Combinations
5 Comparison of Velocity and Turbulence Intensity Profiles for the 1:30 Scale NRC Tests
6 Comparison of Velocity and Turbulence Intensity Profiles for the 1:100 Scale NRC Tests
7 Phase 4A (UWO 1:96) - With Surroundings, Chimney Open & Rough, Extreme Values of Pressure Coefficients Over All Azimuths

FIGURE:

4 Vertical Profiles of Mean Wind Speed and Turbulence Intensity Compared with Theoretical Profiles for Open Country Terrain - UWO 1:96.67 Tests
5 Spectrum of Velocity at Roof Height Compared with Theoretical Spectrum for Open Country Terrain - UWO 1:96.67 Tests
6 Vertical Profiles of Mean Wind Speed and Turbulence Intensity for the Tornado Wind Simulation - UWO 1:96.67 Tests
10 Vertical Profiles of Mean Wind Speed and Turbulence Intensity Compared with Theoretical Profiles for Open Country Terrain - NRC 1:30 Tests
11 Spectrum of Velocity at Roof Height Compared with Theoretical Spectrum for Open Country Terrain - NRC 1:30 Tests
14 Vertical Profiles of Mean Wind Speed and Turbulence Intensity Compared with Theoretical Profiles for Open Country Terrain - NRC 1:96.67 Tests
15 Spectrum of Velocity at Roof Height Compared with Theoretical Spectrum for Open Country Terrain - NRC 1:96.67 Tests
16 Comparison of Pressure Coefficients From Between Phase II and Phase IVa Testing
17 Pressure Coefficients for Average Inlet Tap (651), Average Chimney Tap (652), and Inlet Minus Chimney Tap (642) Versus Case Number
18 Pressure Coefficients From Closed Chimney Cases
19 Distribution of Worst Pressure Differences Across the Baffle
20 Comparison of Pressure Coefficients From the Tornado Case With Those From the Comparable Non-Tornado Case
21 Comparison of Pressure Coefficients With and Without the Cooling Tower (Azimuth 310)
22 Comparison of Pressure Coefficients With and Without the Cooling Tower (Asimuth 280)

APPENDIX:

A Calibration of Flow Losses
B Computer Listings of Pressure Coefficients
C Computer Listings of Adjusted Pressure Coefficients
D Investigation of Speed Dependency in the NRC 1:96 RMS Data

TABLE 1 - PHASE 4A CONFIGURATIONS

CASE*	TUNNEL	SCALE	SURROUND-INGS?	COOLING TOWER?	CHIMNEY	ANGLES	NO. SPEEDS	TORNADO?
1	UWO	1:96	NO	NO	OPEN, ROUGH	315°	1	NO
2					CLOSED, ROUGH			
3			YES		CLOSED, ROUGH	FULL 360° + 315°		
4					OPEN, ROUGH			
4a					OPEN, ROUGH	315°, 225°, 135°		YES
5 - 10	NRC	1:30	NO	NO	CLOSED, SMOOTH	315°	6	NO
11-15					CLOSED, ROUGH		5	
16-18	NRC	1:96	NO	NO	CLOSED, ROUGH	315°	3	NO
19-21					CLOSED, SMOOTH			
22-24					OPEN, SMOOTH			
25-27			YES		OPEN, SMOOTH			
28-30					OPEN, SMOOTH	310°		
31-33				YES	OPEN, SMOOTH			
34-36					OPEN, SMOOTH	280°		
37	NRC	1:96	COOLING TOWER PRESSURE DISTRIBUTION AND WAKE					

* For cases with multiple speeds, cases are numbered from lowest to highest speed.

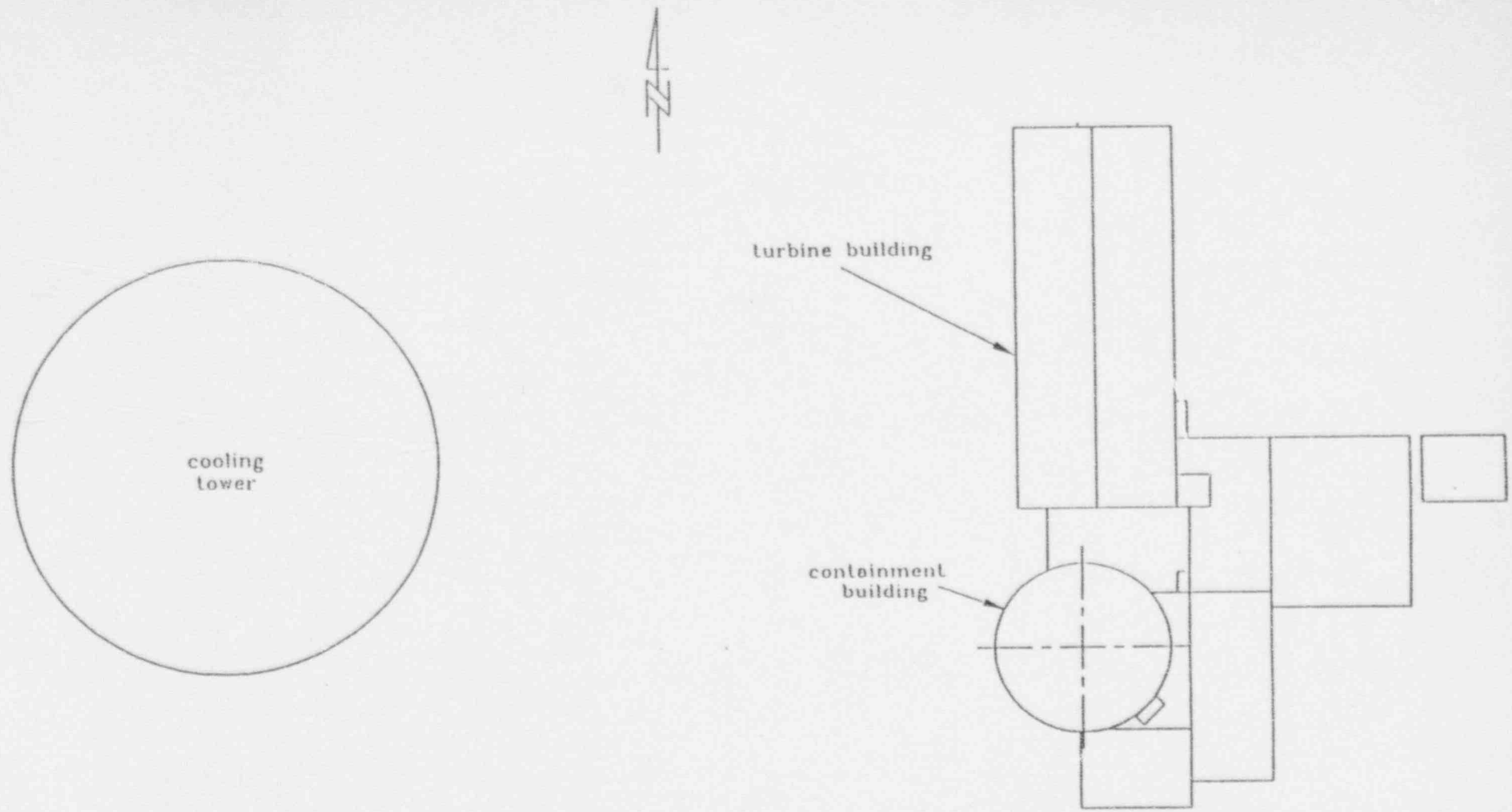

FIGURE 1 LAYOUT DRAWING FOR AN AP600 PLANT

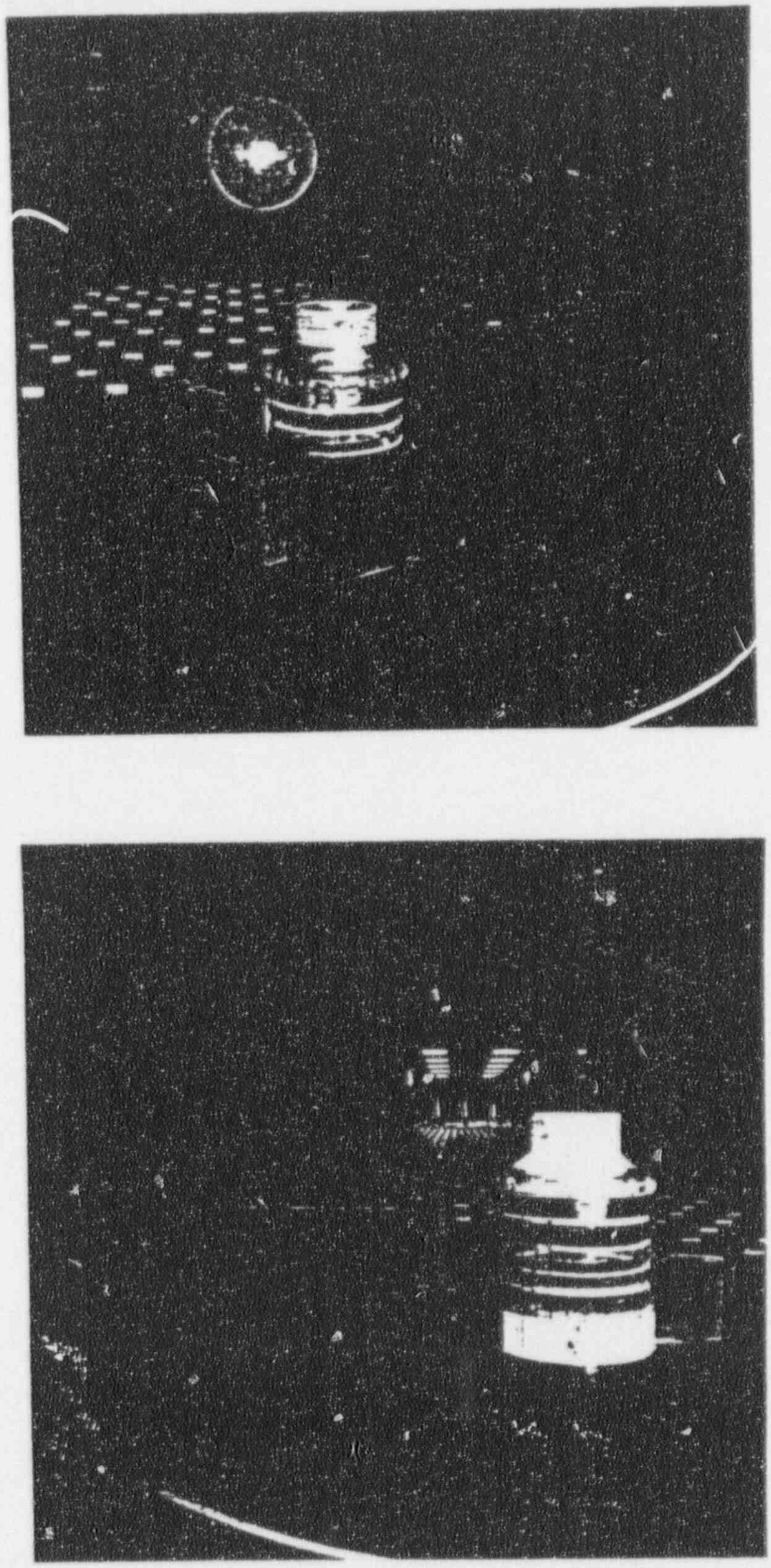

FIGURE 2 PHOTOGRAPHS OF THE MODEL IN THE WIND TUNNEL
UWO 1:96.67 TESTS

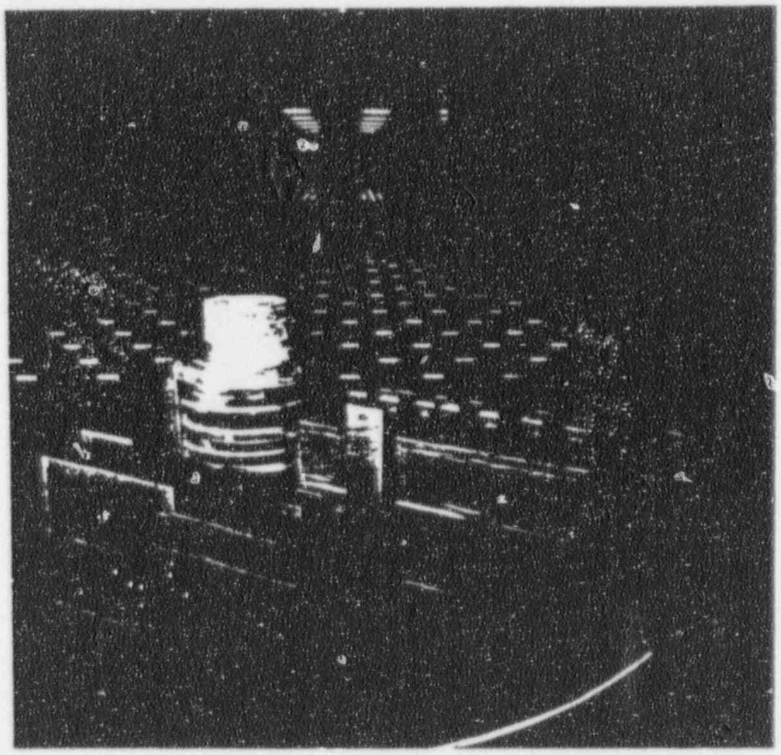

FIGURE 3 VIEW OF THE MODEL IN THE WIND TUNNEL SHOWING THE UPSTREAM TERRAIN MODEL USED
UWO 1:96.67 TESTS

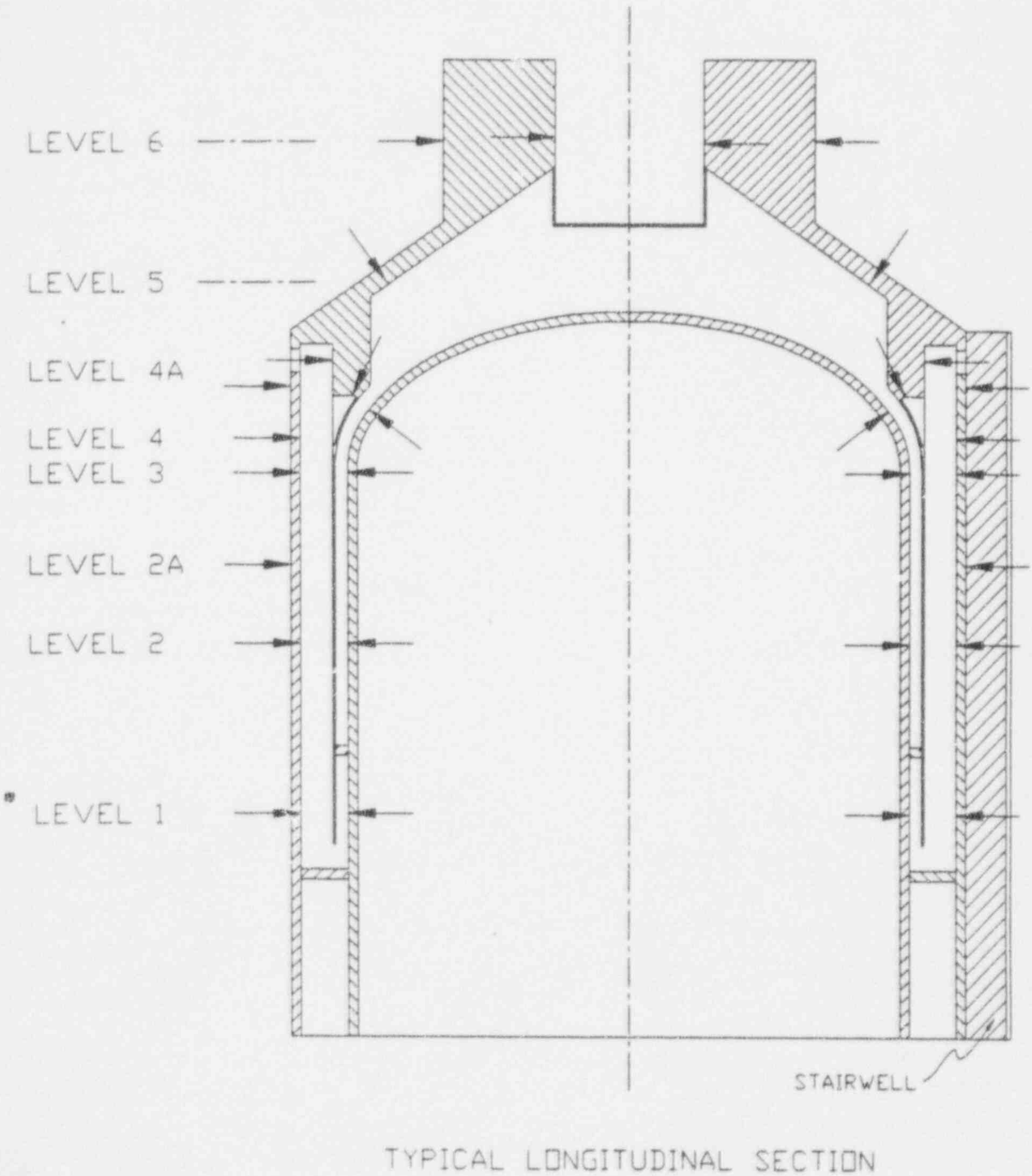

FIGURE 7a VERTICAL SECTION OF THE MODEL SHOWING PRESSURE TAP LEVELS

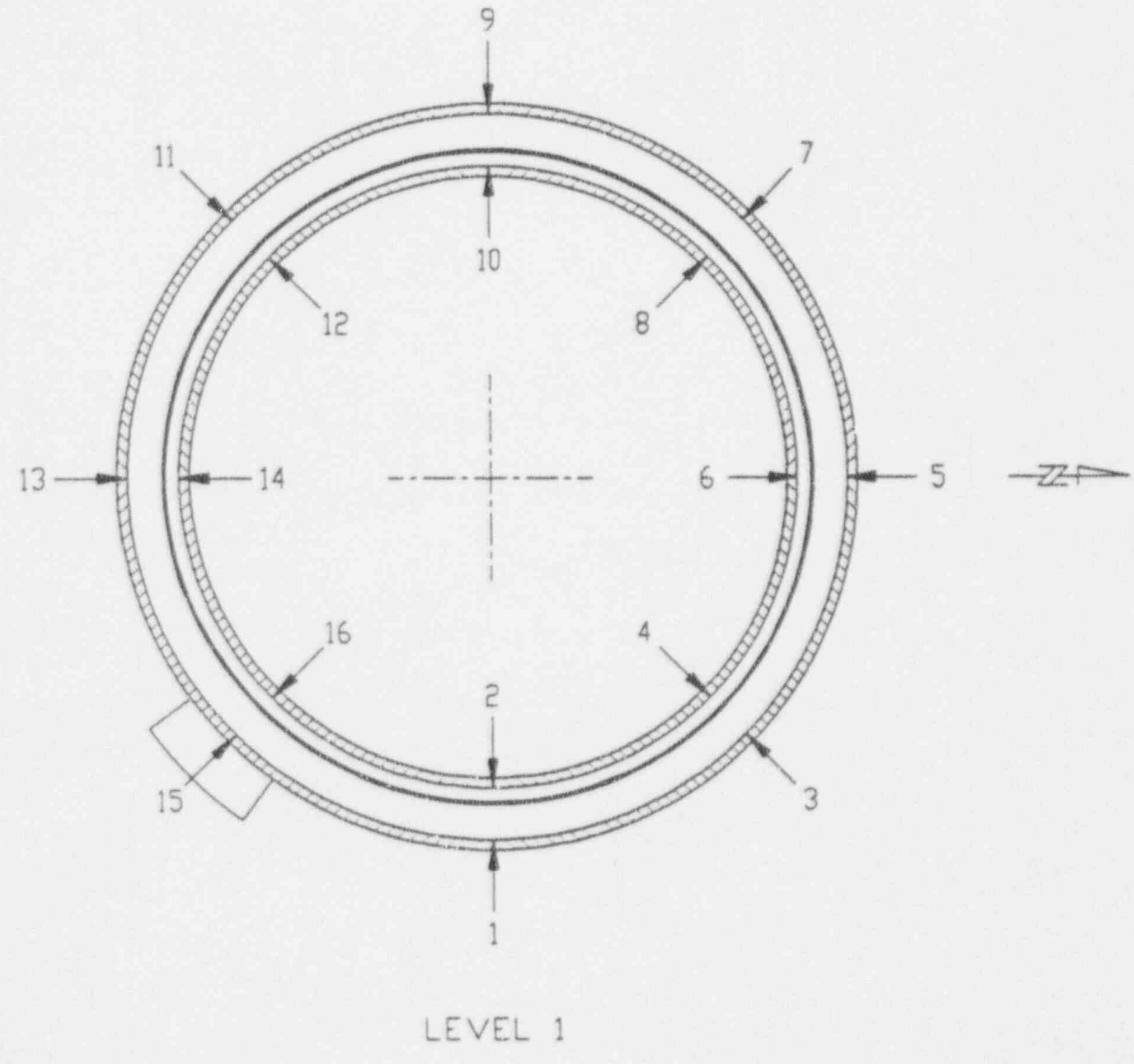

FIGURE 7b HORIZONTAL SECTION OF THE MODEL SHOWING PRESSURE TAP NUMBERING - **LEVEL 1**

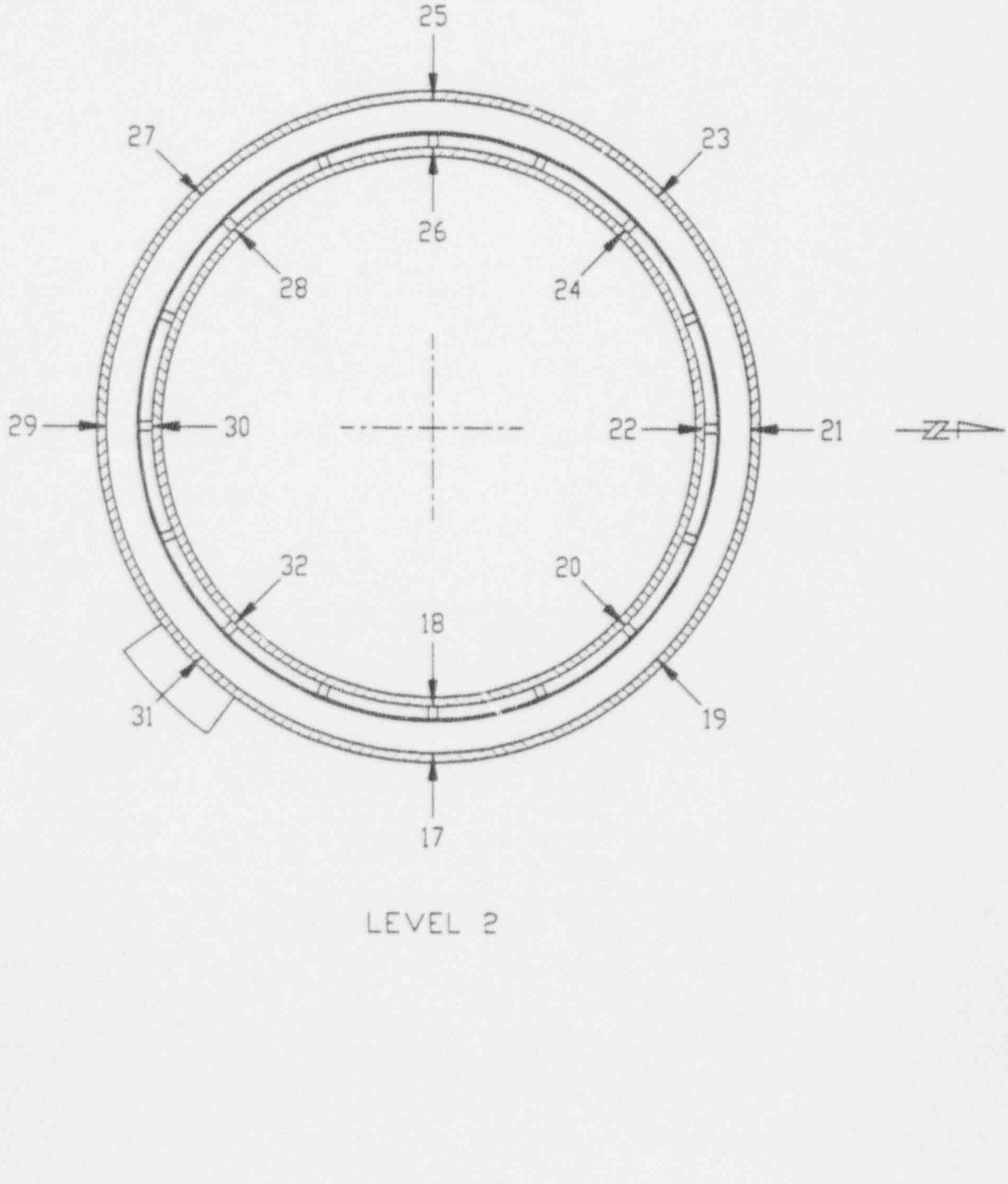

FIGURE 7c HORIZONTAL SECTION OF THE MODEL SHOWING PRESSURE TAP NUMBERING - **LEVEL 2**

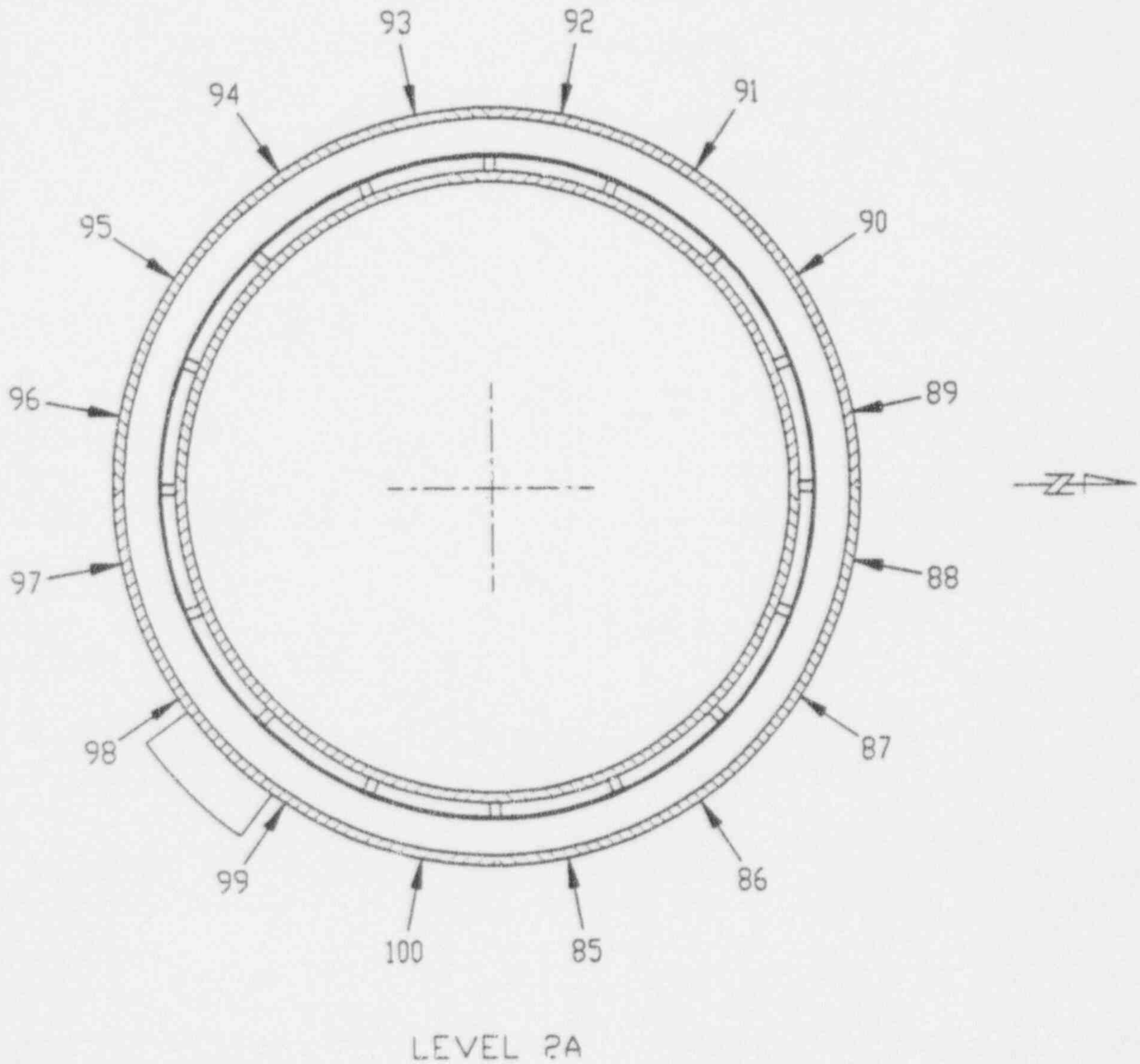

FIGURE 7d HORIZONTAL SECTION OF THE MODEL SHOWING PRESSURE TAP NUMBERING - **LEVEL 2A**

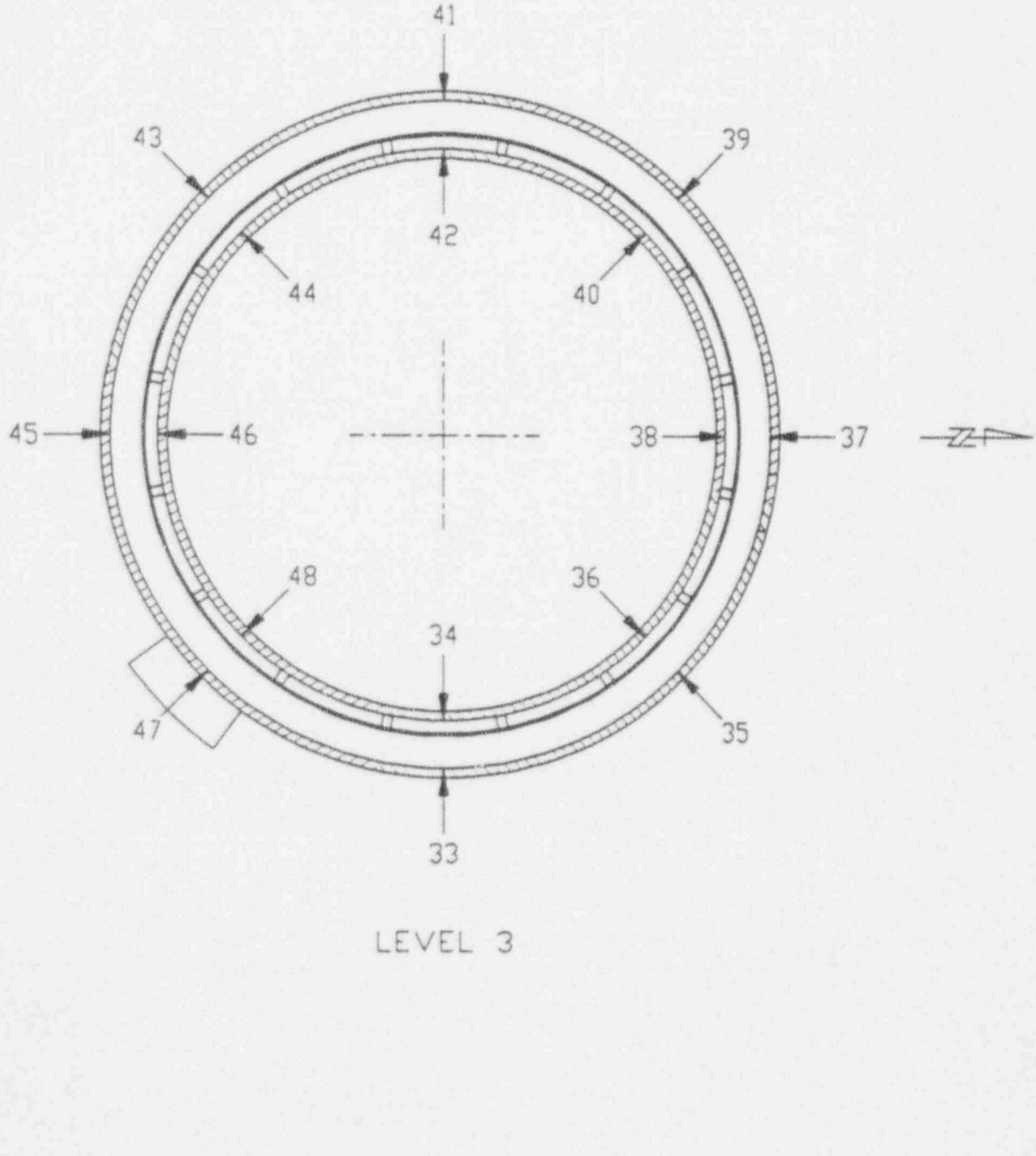

FIGURE 7e HORIZONTAL SECTION OF THE MODEL SHOWING PRESSURE TAP NUMBERING - **LEVEL 3**

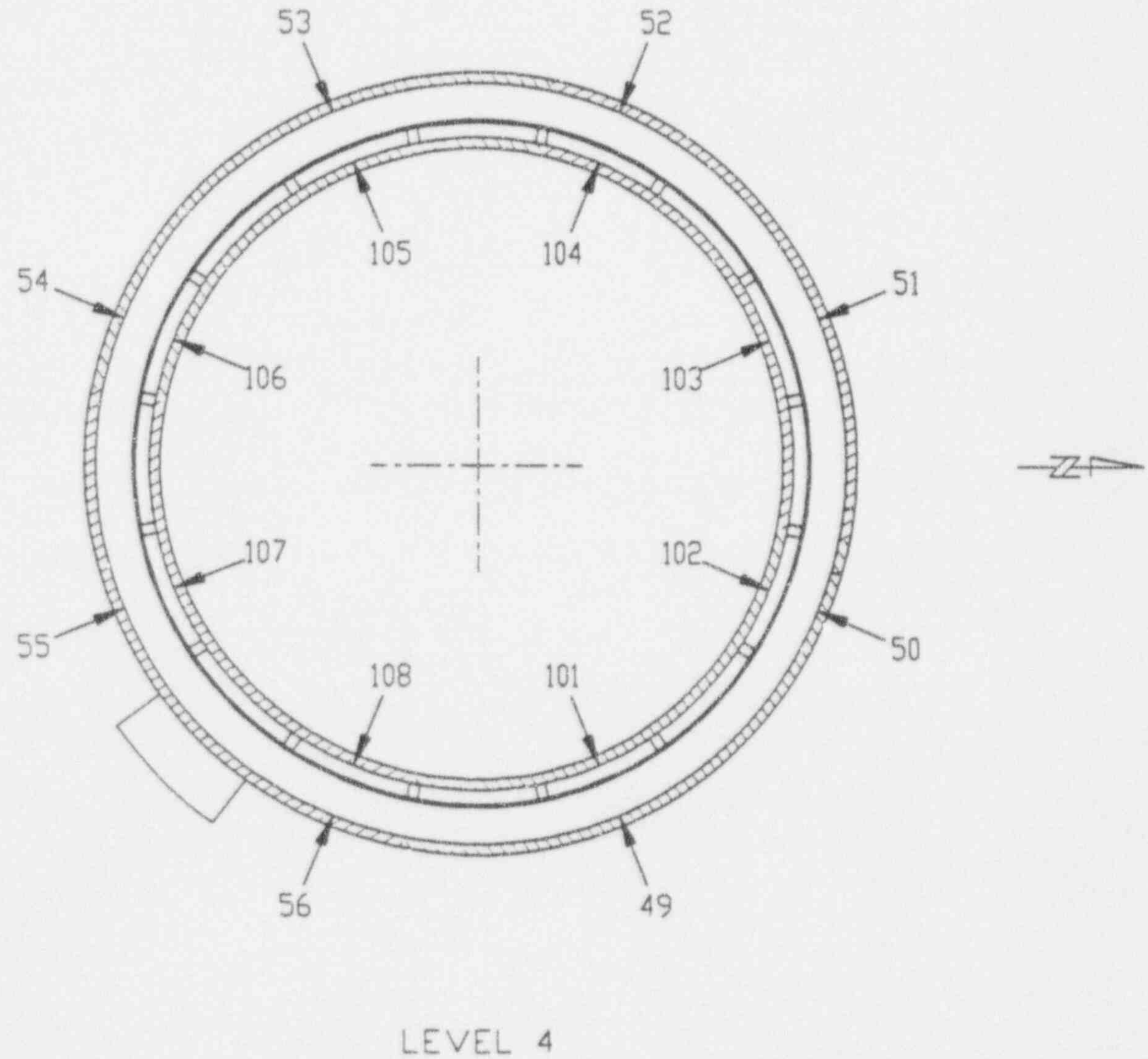

FIGURE 7f HORIZONTAL SECTION OF THE MODEL SHOWING PRESSURE TAP NUMBERING - **LEVEL 4**

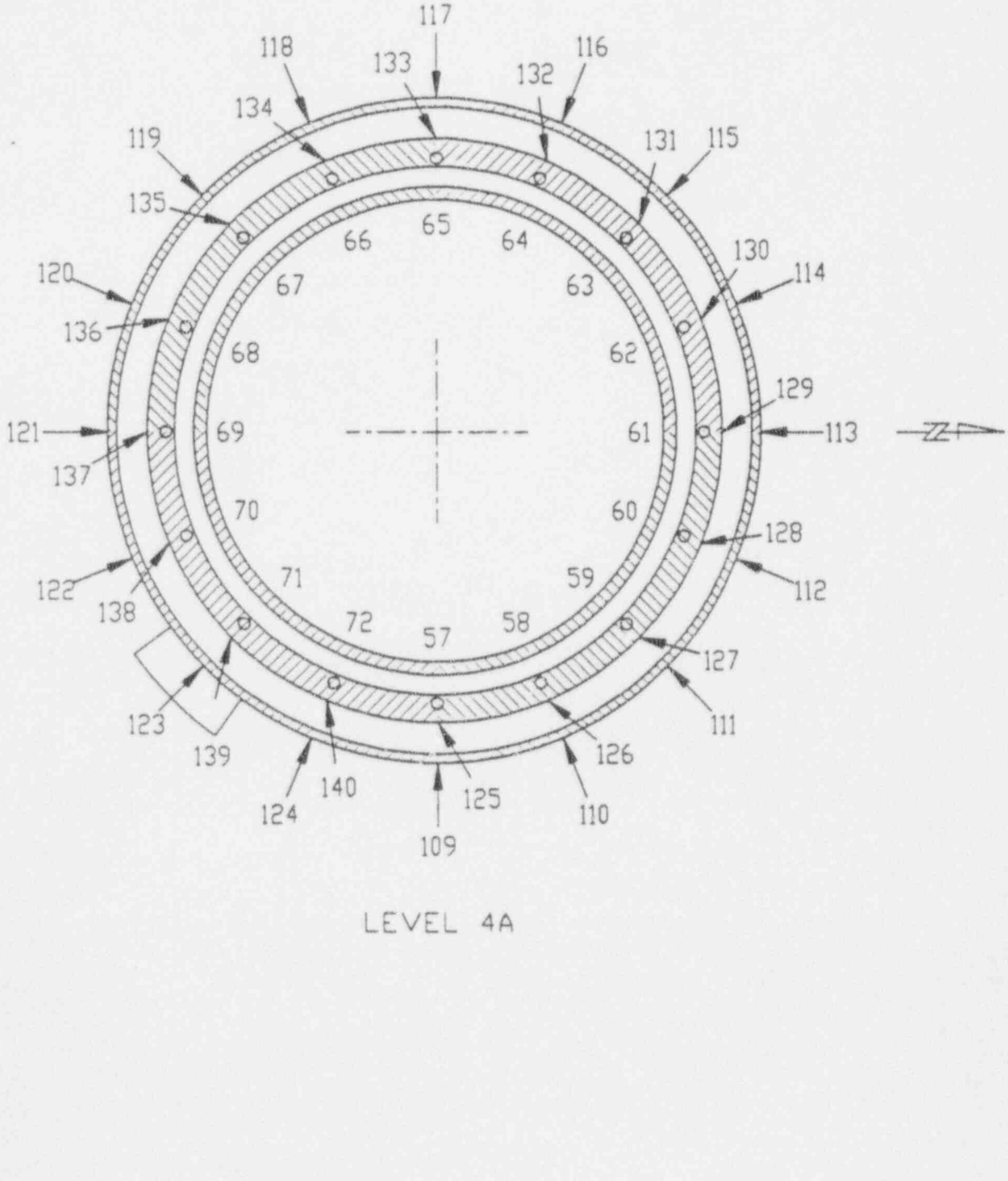

FIGURE 7g HORIZONTAL SECTION OF THE MODEL SHOWING PRESSURE TAP NUMBERING - **LEVEL 4A**

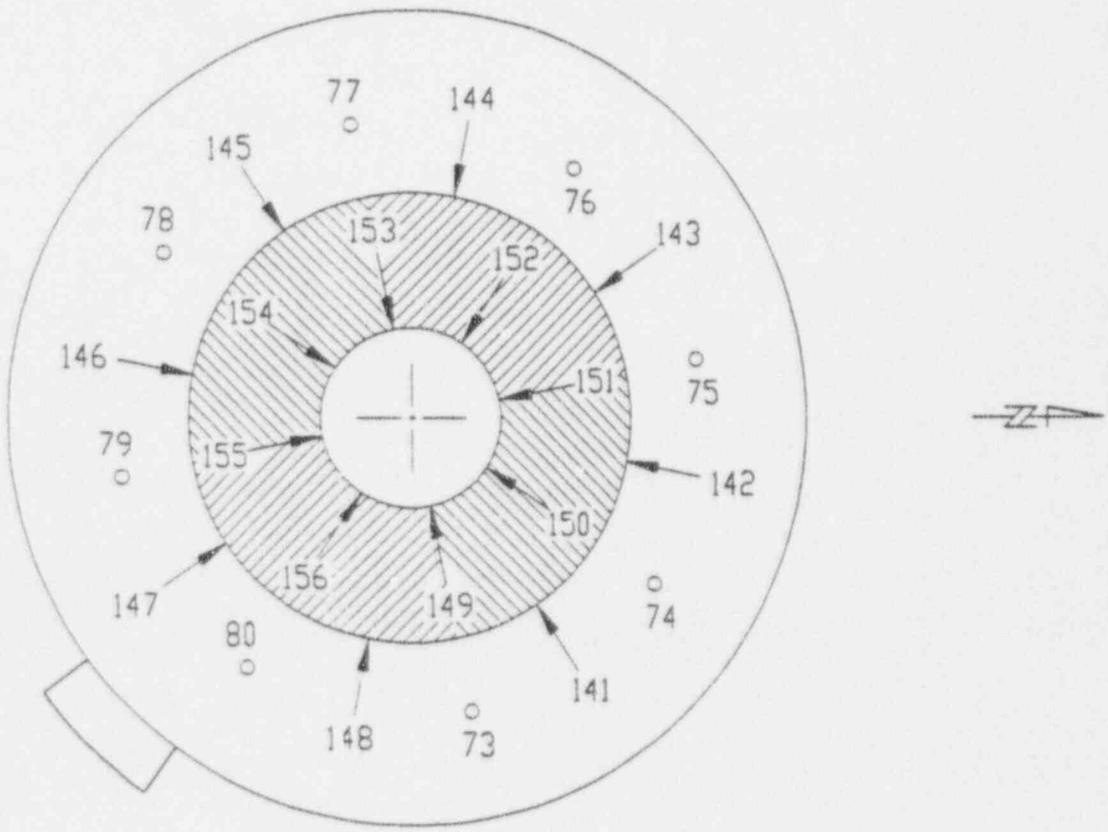

FIGURE 7h HORIZONTAL SECTION OF THE MODEL SHOWING PRESSURE TAP NUMBERING - **LEVELS 5 AND 6**

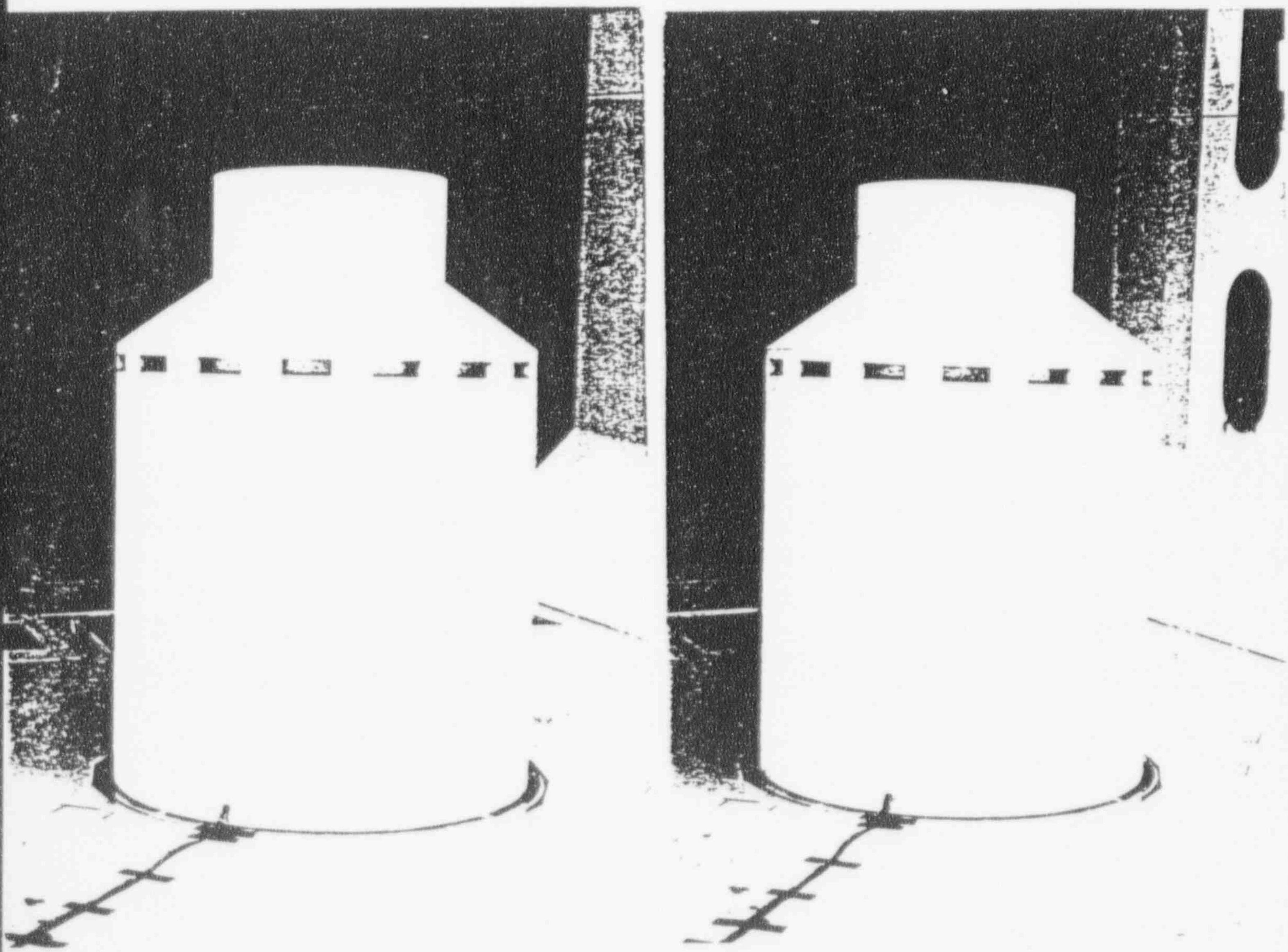

FIGURE 8 PHOTOGRAPHS OF THE MODEL IN THE WIND TUNNEL
NRC 1:30 TESTS

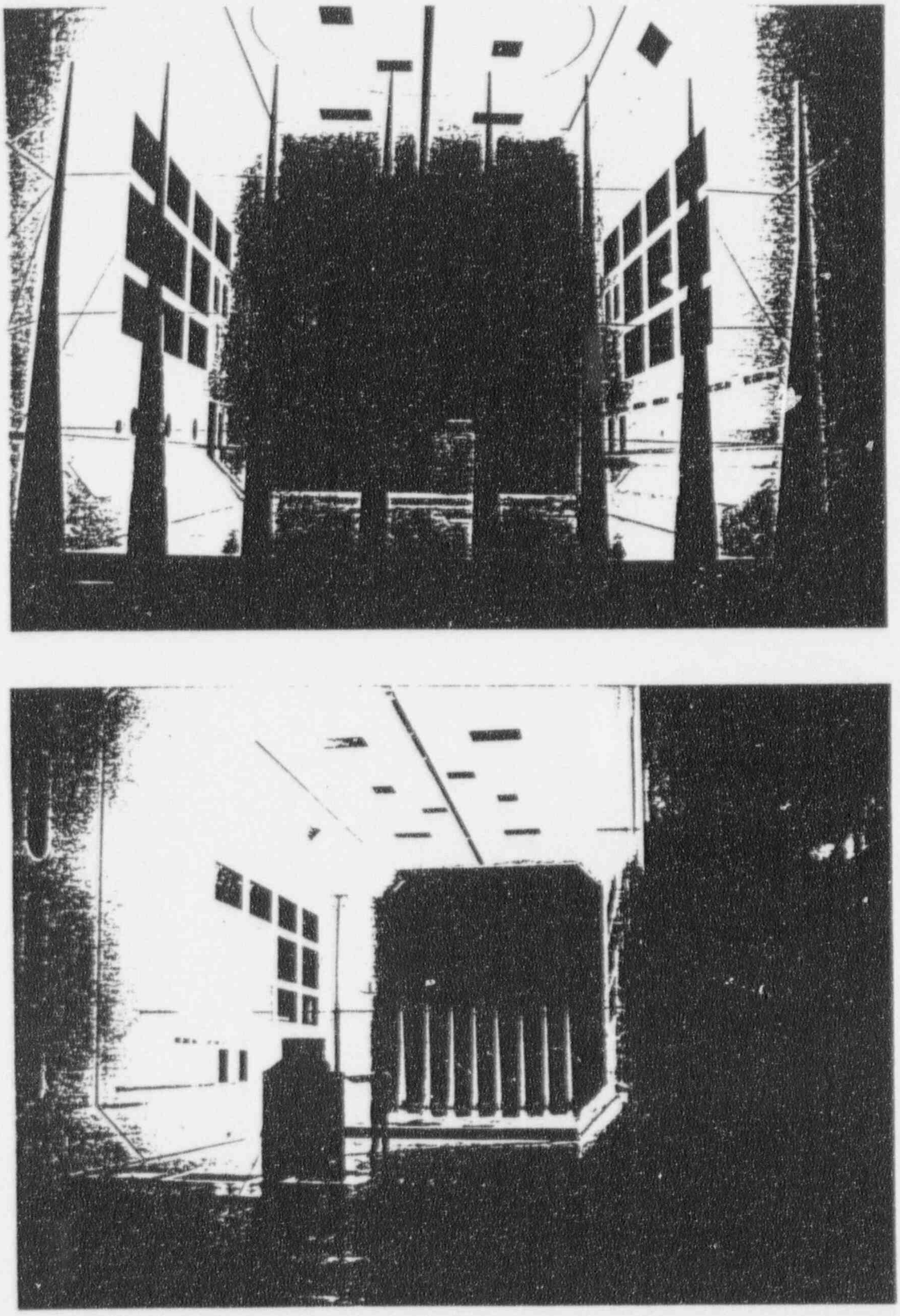

FIGURE 9 VIEW OF THE MODEL IN THE WIND TUNNEL SHOWING THE UPSTREAM TERRAIN MODEL USED
NRC 1:30 TESTS

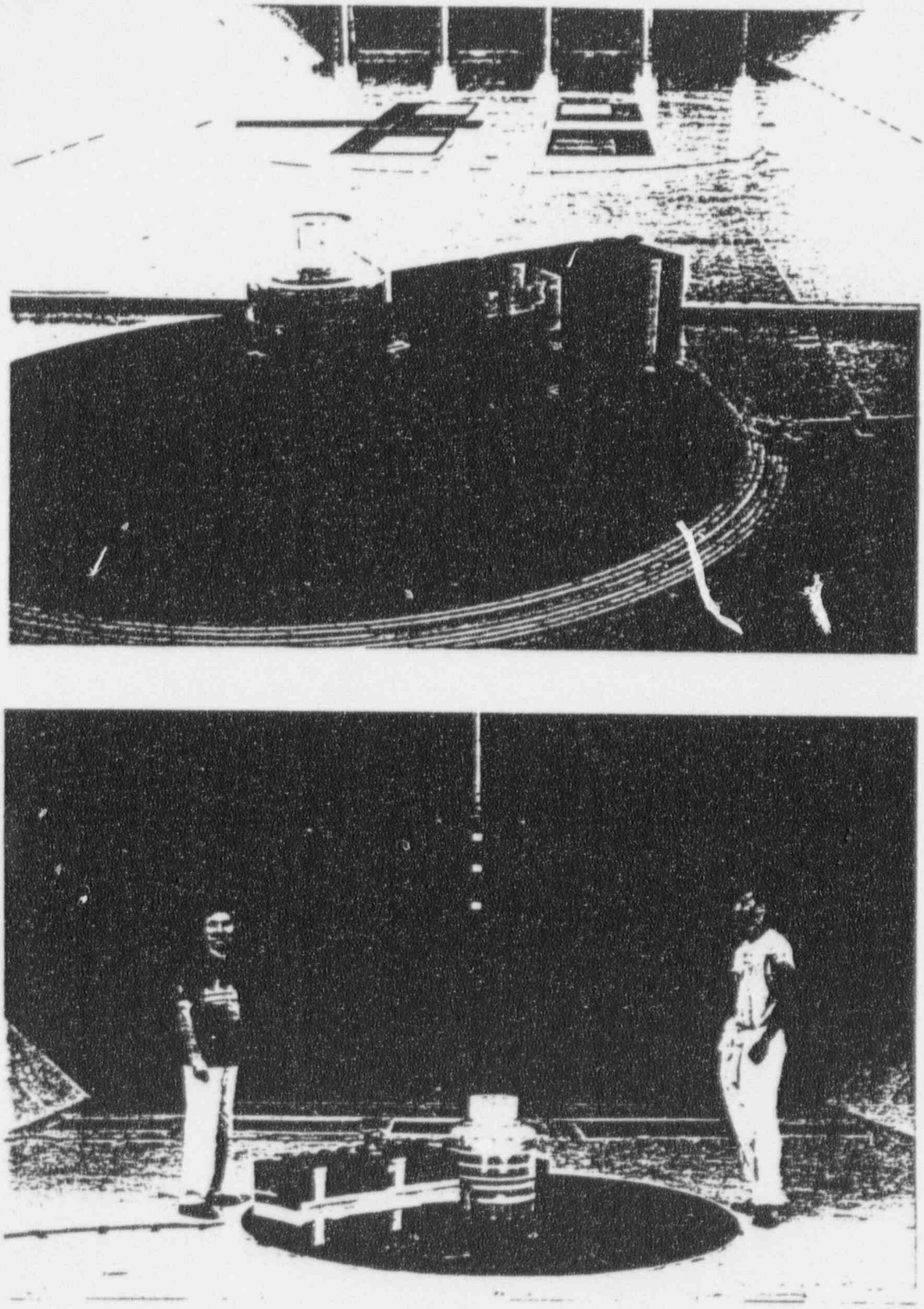

FIGURE 12 PHOTOGRAPHS OF THE MODEL IN THE WIND TUNNEL
NRC 1:96.67 TESTS

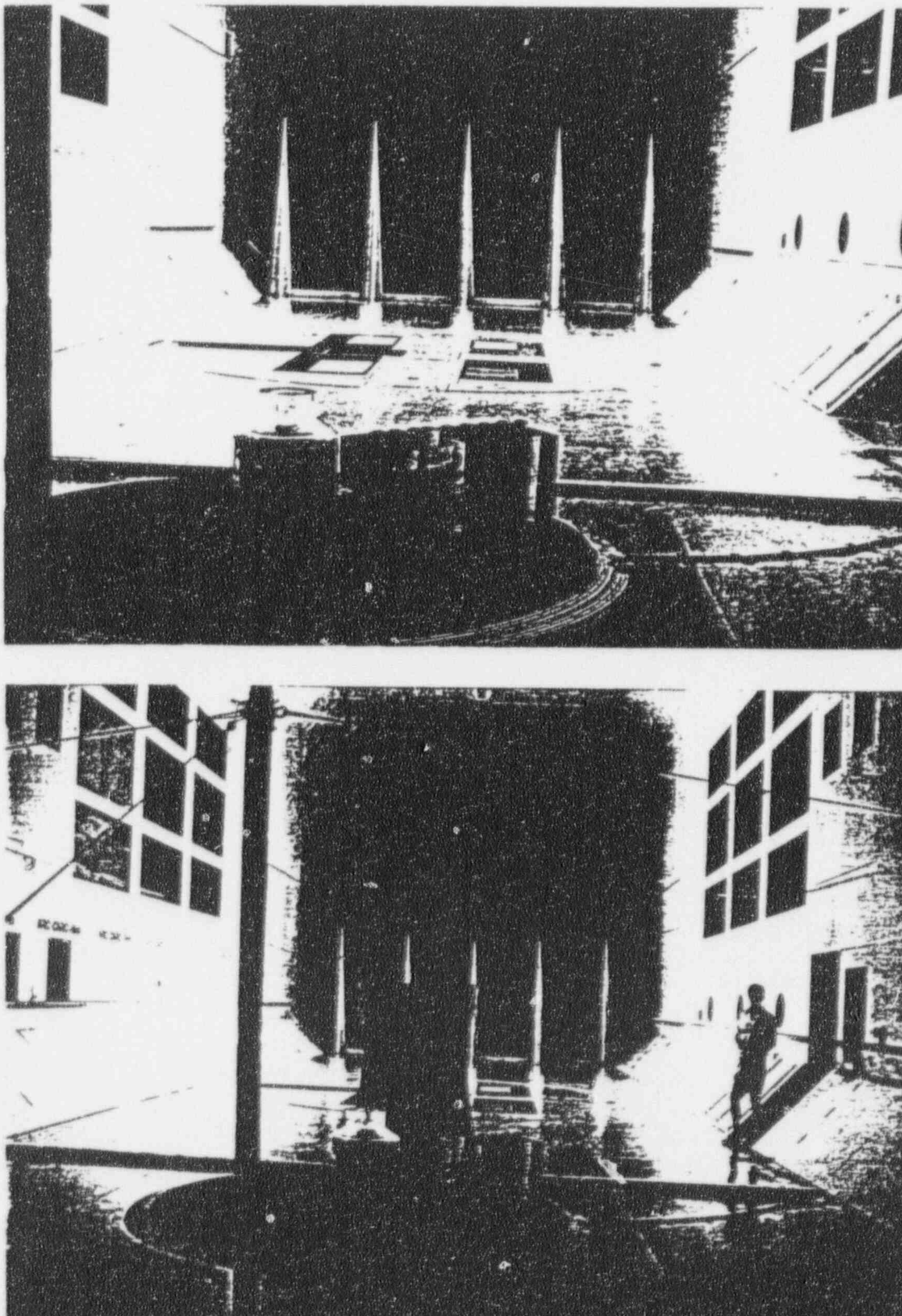

FIGURE 13 VIEW OF THE MODEL IN THE WIND TUNNEL SHOWING THE UPSTREAM TERRAIN MODEL USED
NRC 1:96.67 TESTS