INVESTIGATING COMPUTER MODELING OF CLEANROOM AIRFLOW PATTERNS

Tony Lemaire and Peter Luscuere

Today's powerful computing capabilities make it possible to simulate and investigate two- and three-dimensional, nonisothermal turbulent airflows with high resolution. In this way potential airflow-related contamination problems in a cleanroom environment can be identified and investigated for a variety of alternative design concepts prior to the start of construction. In addition, the use of smoke generators and other flow visualization aids, which are often sources of unacceptable contamination, can be minimized during the postconstruction certification period.

The case studies described in this article were selected by researchers from the international architectural and engineering firm Philips Building Design and Engineering AIB (Eindhoven, the Netherlands) and the Netherlands Organization for Applied Scientific Research, TNO (Delft) to investigate this engineering tool. Several typical cleanroom airflow situations were investigated using a computer program capable of modeling three-dimensional nonisothermal turbulent airflow patterns. The resulting patterns and turbulence-intensity mappings were both found useful as a means of identifying potential problems. Additional investigations were then conducted into the diffusion of an assumed contaminant by means of the calculated flow patterns. In the future this type of computer analysis could be extended to include gravity and drag forces in order to arrive at a complete particle behavior model.

THE COMPUTER PROGRAM

Capabilities and Applications. The flow modeling performed in our studies was done with the computer program WISH3D, which was developed at TNO. The program is based on the commonly used finite volume method and is optimized for minisupercomputers to minimize computing time. At present the program is able to compute three-dimensional laminar and turbulent airflows in rectangular enclosures that are filled with obstacles. A separate preprocessor is used for flexible definition of geometry and boundary conditions. Convection and diffusion of heat and mass species are taken into account.

The most frequently used applications of the flow-modeling technique are the prediction of thermal comfort and indoor air quality in rooms or large spaces with heating, cooling, ventilation, and contaminant sources; and the prediction of the spread of smoke and fire, including thermal radiation. The flow modeling of a cleanroom environment, which was the focus of the investigation presented in this article, is among the new applications for the modeling technique that have been developed recently.

The Modeling Method. The computer program solves the time-averaged equations of conservation of mass, momentum, and chemical species by the finite volume method, using nonlinearly spaced grids to account for high gradients near room walls. Air is considered an ideal gas and an incompressible fluid. Turbulence is modeled with the well-known k-ϵ model, resulting in extra transport equations for k, the kinetic energy of turbulent fluctuations, and ϵ, the energy dissipation of turbulent fluctuations. The dynamic viscosity of the air is replaced by an effective viscosity, which is determined by k and ϵ. The flow near walls is modeled with standard logarithmic wall functions.

Several types of parameter presentations are achievable, including the following:

- Flow patterns by means of colored velocity vectors (where each color represents a velocity range).
- Iso-velocity contours—lines of constant absolute velocity.
- Iso-turbulence-intensity contours—lines of constant turbulence intensity.
- Iso-mass-fraction contours—lines of constant mass fraction of contaminant.

EXPERIMENTAL CONDITIONS

The theoretical cleanroom posited in our investigation of airflow pattern modeling was a full-laminar or unidirectional downflow room with a height of 3.2 m, including a raised floor. The cleanroom walls or assumed symmetry planes were used as vertical boundaries, and all surfaces were assumed to be smooth. In some experiments a two-dimensional approach was used to allow an increase in resolution of the grid. The principal boundary conditions are listed in Table I. The turbulence intensity given there was based on experiences with free flows into spaces, and turbulent kinetic energy and its dissipation rate were calculated from that intensity value. Additional boundary data for another, two-dimensional study are presented in Table II.

Only the transport of contaminants caused by convection and diffusion was investigated, using a transport equation based on the conservation of chemical species. The molecular diffusion coefficient in the equation was replaced by an effective diffusion coefficient to account for turbulent mixing. An effective Schmidt number of 1 was assumed.

Parameter	Value
Downflow supply velocity (m/sec)	0.45
Return velocity through floor (m/sec)	0.45
Turbulence intensity at supply (%)	5
Turbulent kinetic energy at supply (J/kg)	7.6×10^{-4}
Turbulent energy dissipation (J/kg. sec)	1.9×10^{-4}
Turbulent kinetic energy at walls (J/kg)	0.0
Turbulent energy dissipation at walls (J/kg. sec)	0.0

Table I: Main cleanroom boundary conditions.

Parameter	Value
Downflow rate (m^3/sec.m)	1.012
Return flow rate through floor (m^3/sec.m)	0.612
Exhaust flow rate through bench top (m^3/sec.m)	0.280
Exhaust flow rate through rear side (m^3/sec.m)	0.120
Contaminant mass flow at bath surface (g/sec.m)	0.305
Contaminant velocity at bath surface (m/sec)	0.001

Table II: Boundary conditions for two-dimensional wet-bench study.

CASE STUDY RESULTS

Airflow around a Wet Bench. Two-dimensional modeling was used to generate airflow patterns and turbulence contours for the area around a wet bench located against the wall of the above-described cleanroom. In cross section, the bench consisted of an actively exhausting top and rear side and a process station for wet-chemical baths. The study focused on the effects of placing a spoiler along the top of the bench to guide the airflow so as to decrease turbulence and velocity near the process station.

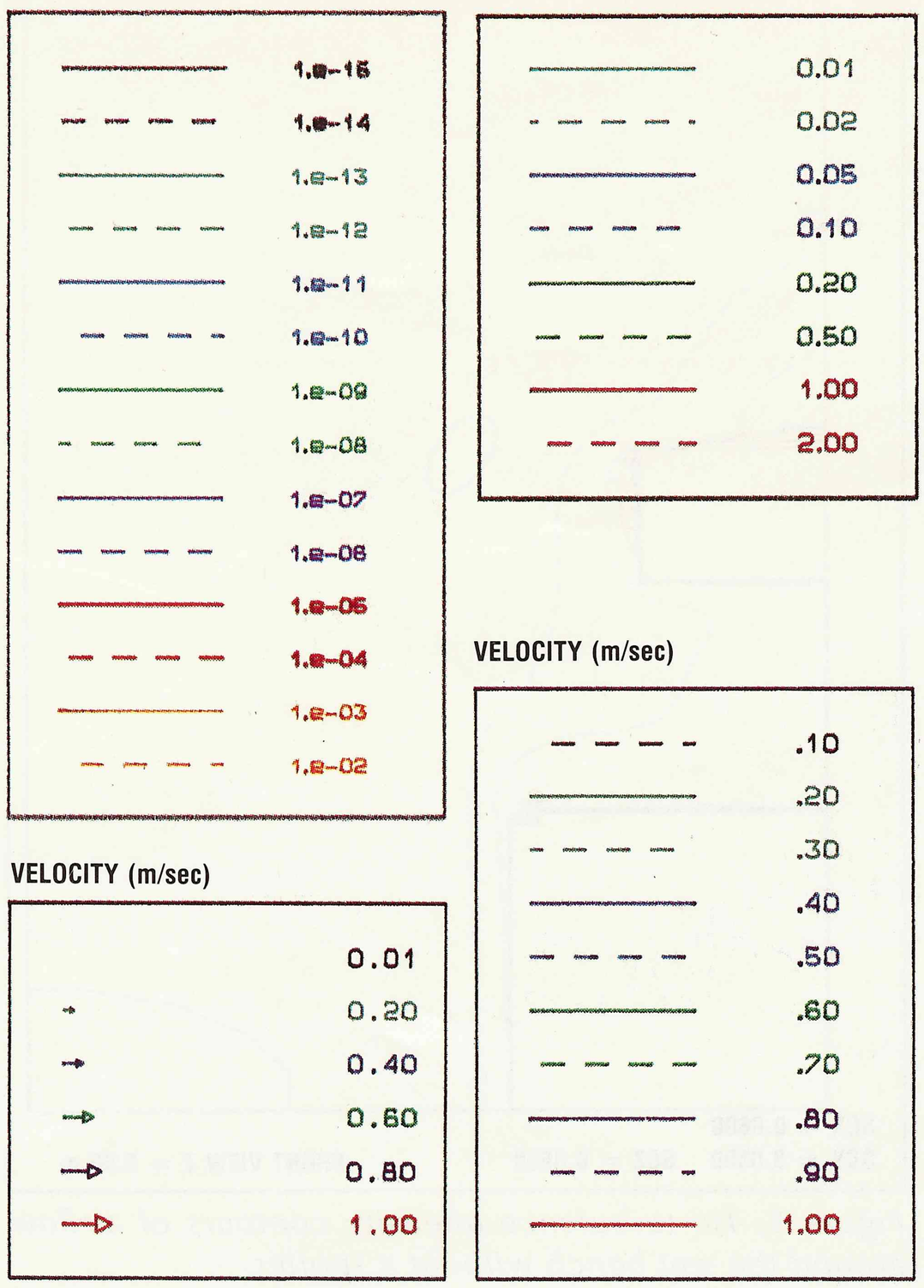
Figure 1 depicts these conditions using a computational grid of 68 × 72 cells. The spoiler is modeled by a stepped curve, and the figure's right vertical axis represents a vertical symmetry plane at a distance of 2.25 m from the rear wall. It was assumed that air would be exhausted uniformly through the underside of the top of the bench and through its rear side between the process station and the top. A contaminant source (from a process bath) would exist at a height of 0.82 m above the floor and a distance of 0.50–0.754 m from the rear side (see also Table II).

Results of the computer modeling, shown in Figures 2–6, indicate that the spoiler would act as a resistance to airflow along the top of the bench, causing a decrease in velocity and turbulence only in that area; the contaminant spread near the process station would not be affected by the spoiler.

Airflow near Ceiling Grid Support Bars. Airflow disturbances near the filter-support bars in a typical cleanroom ceiling were also investigated, using three-dimensional flow modeling. The filter-support system was assumed to consist of smooth 5 × 10-cm rectangular support bars in a 60 × 120-cm grid. Figure 7 illustrates one support bar in this structure with a high-resolution numerical grid of 32 × 26 × 19 cells. One symmetry plane is assumed; a second is left out for ease of interpretation. There is an imaginary horizontal boundary at a distance of 1.0 m from the ceiling, where the influence of the filter-support grid on the airflow has disappeared.

Airflow disturbances and recombinations near the support grid were modeled, and investigations into particle transport below the ceiling by convection and diffusion were conducted using iso-mass-fraction mappings of an assumed contaminant. Results of these simulations are presented as Figures 8 through 15. The turbulence mappings (Figures 12 and 13) clearly show that the isolated areas just beneath the support bars contain the higher turbulences, and Figures 14 and 15 indicate that such turbulence is the driving force behind contaminant transport. The simulations also support the theory of ceiling-grid-tracing contaminants; i.e., the iso-mass-fraction contours follow the grid, even around corners, rather than propagating into the flow field.

Airflow at Ceiling/Wall Interfaces. The interfaces of the ceiling filter-support system and the walls of a cleanroom are also possible sites of airflow disturbance. The flow characteristics of two commonly used interface sealing systems (wet and dry) were compared in our study. The two-dimensional modeling was done in grids of 37 × 72 and 32 × 62 cells, respectively. Because of the boundary conditions, it was necessary to simulate the complete cleanroom height, which was done by using a nonlinearly spaced grid. The left vertical axis in



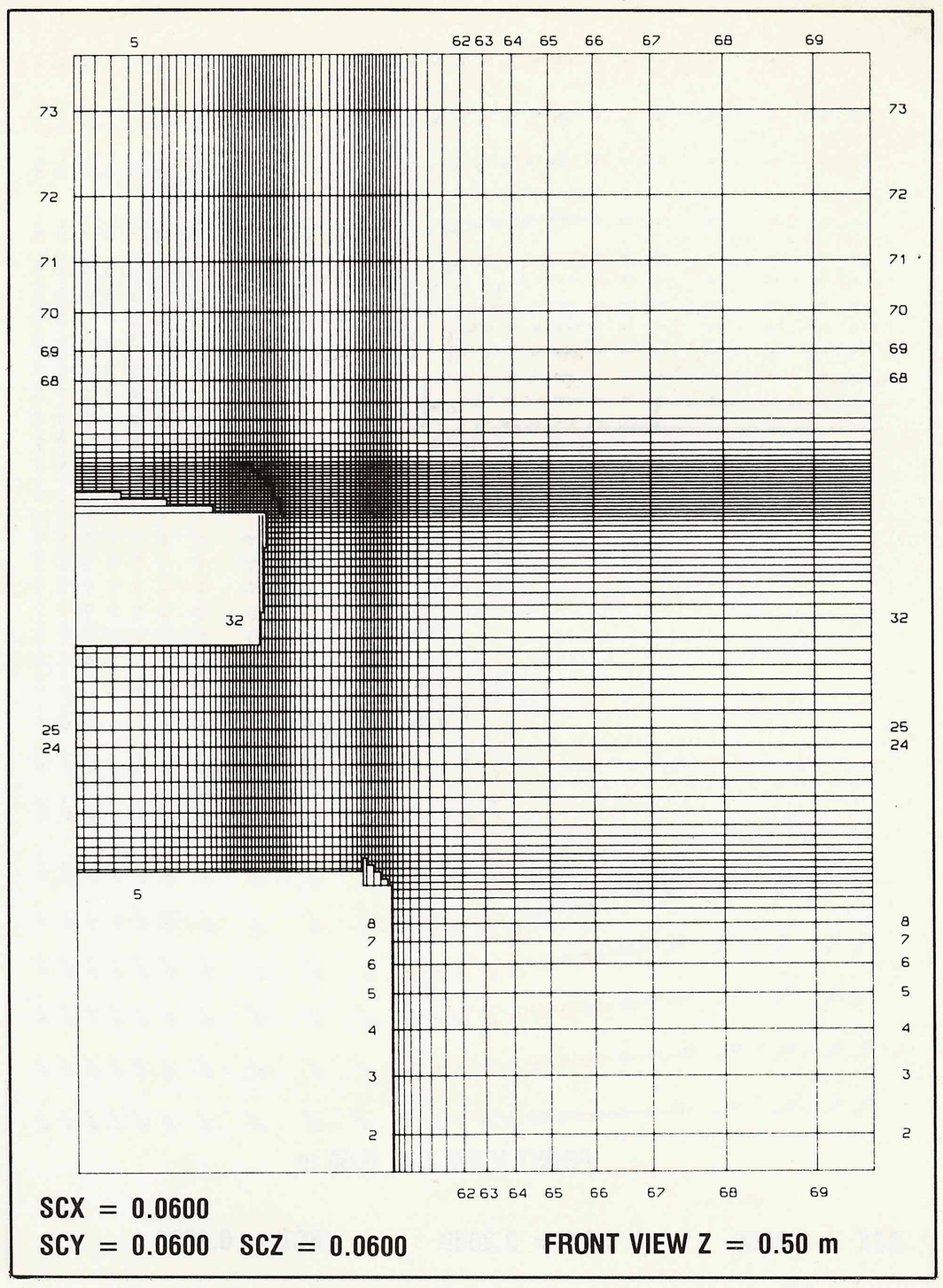


Figure 1: A two-dimensional numerical grid showing the hypothetical cleanroom with wet bench. The local grid refinement was done to allow detailed flow analysis at critical locations.

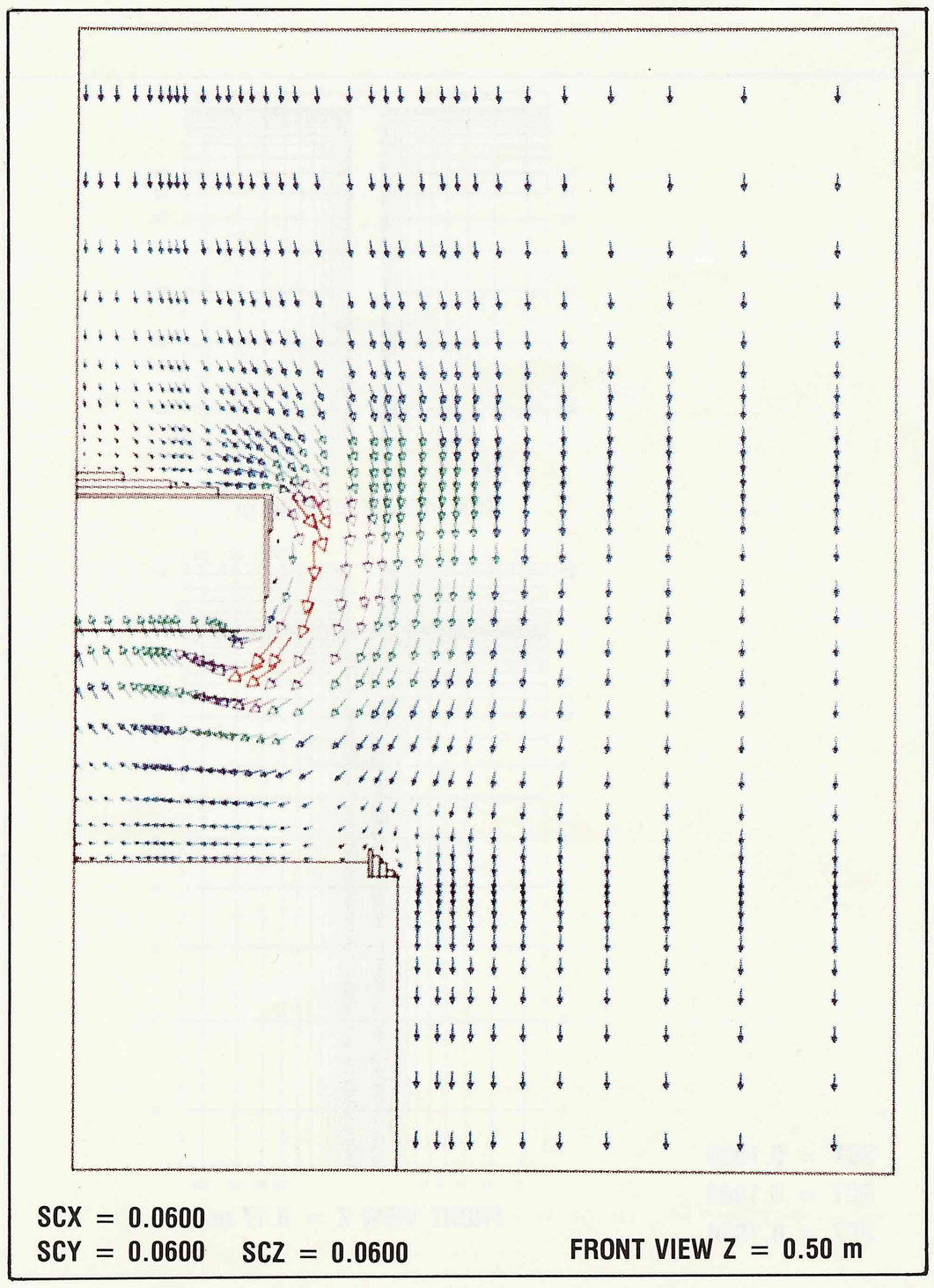


Figure 2: Airflow velocity pattern around the wet bench, showing a stagnant area in front of the bench top and airflow in the direction of actively exhausting parts.

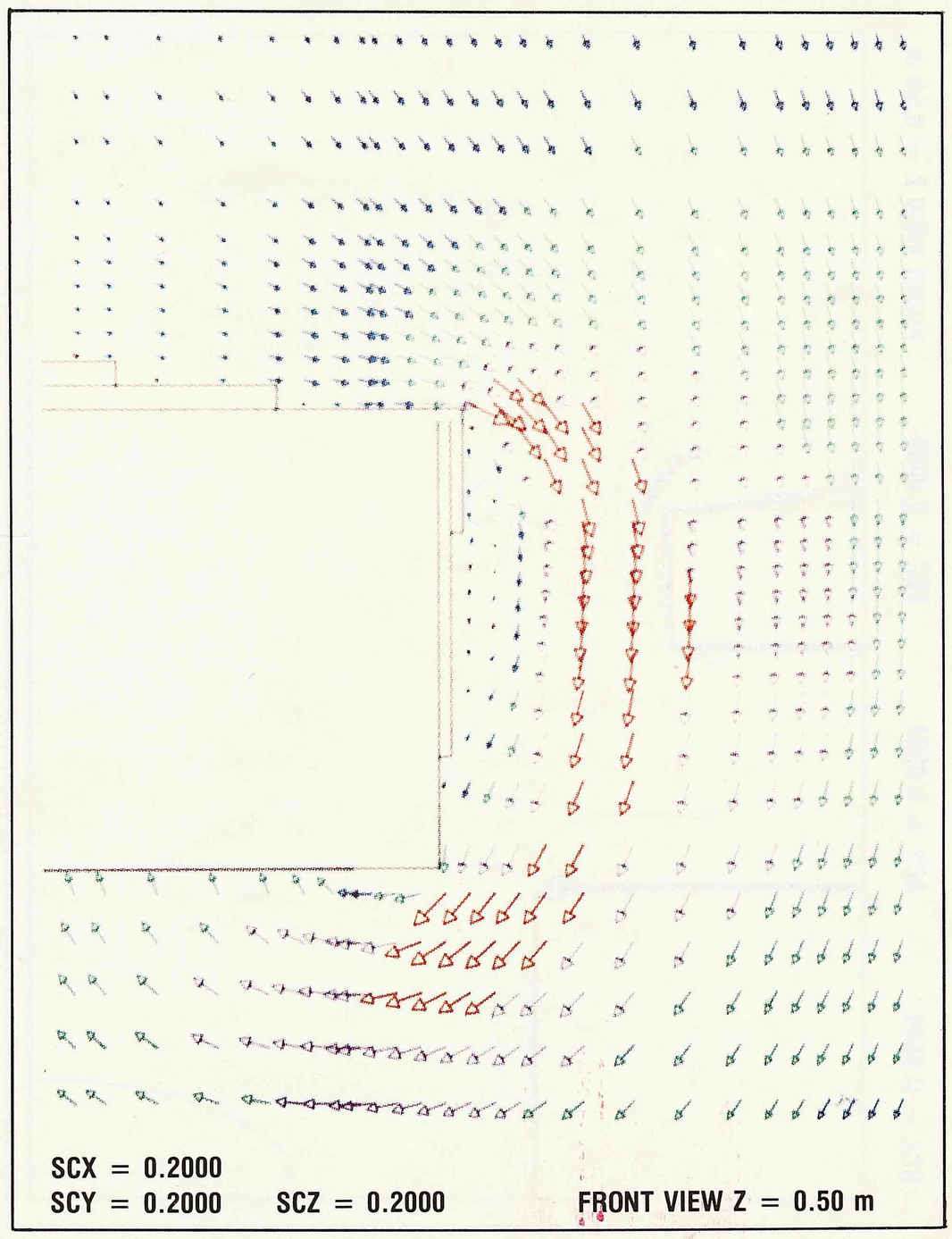


Figure 3: Detailed view of the velocity pattern near the top of the wet bench without a spoiler, showing a recirculation zone in front of the top.

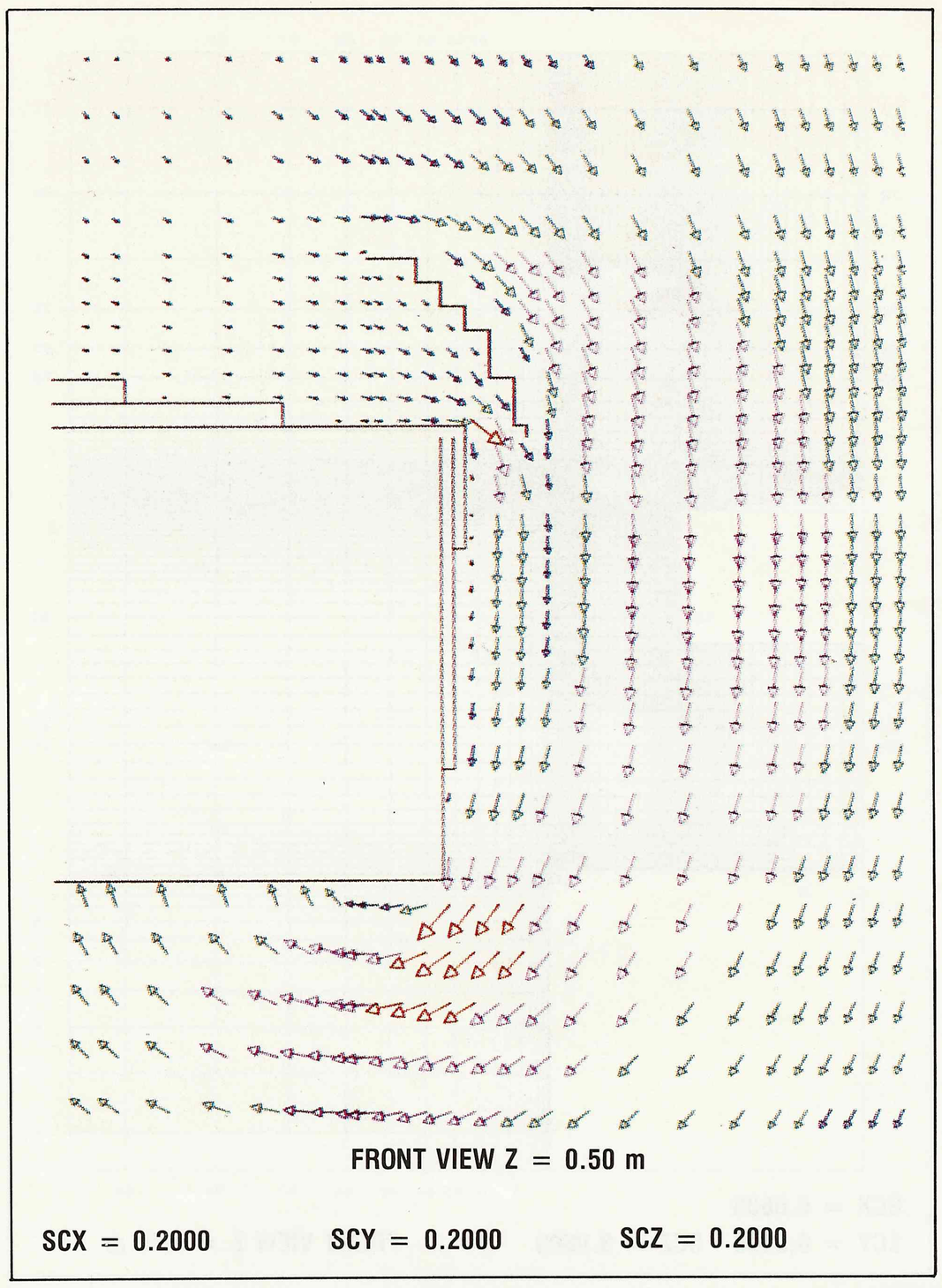


Figure 4: Detailed view of the velocity pattern near the top of the wet bench with a spoiler, showing that the spoiler eliminates the recirculation zone shown in Figure 3.

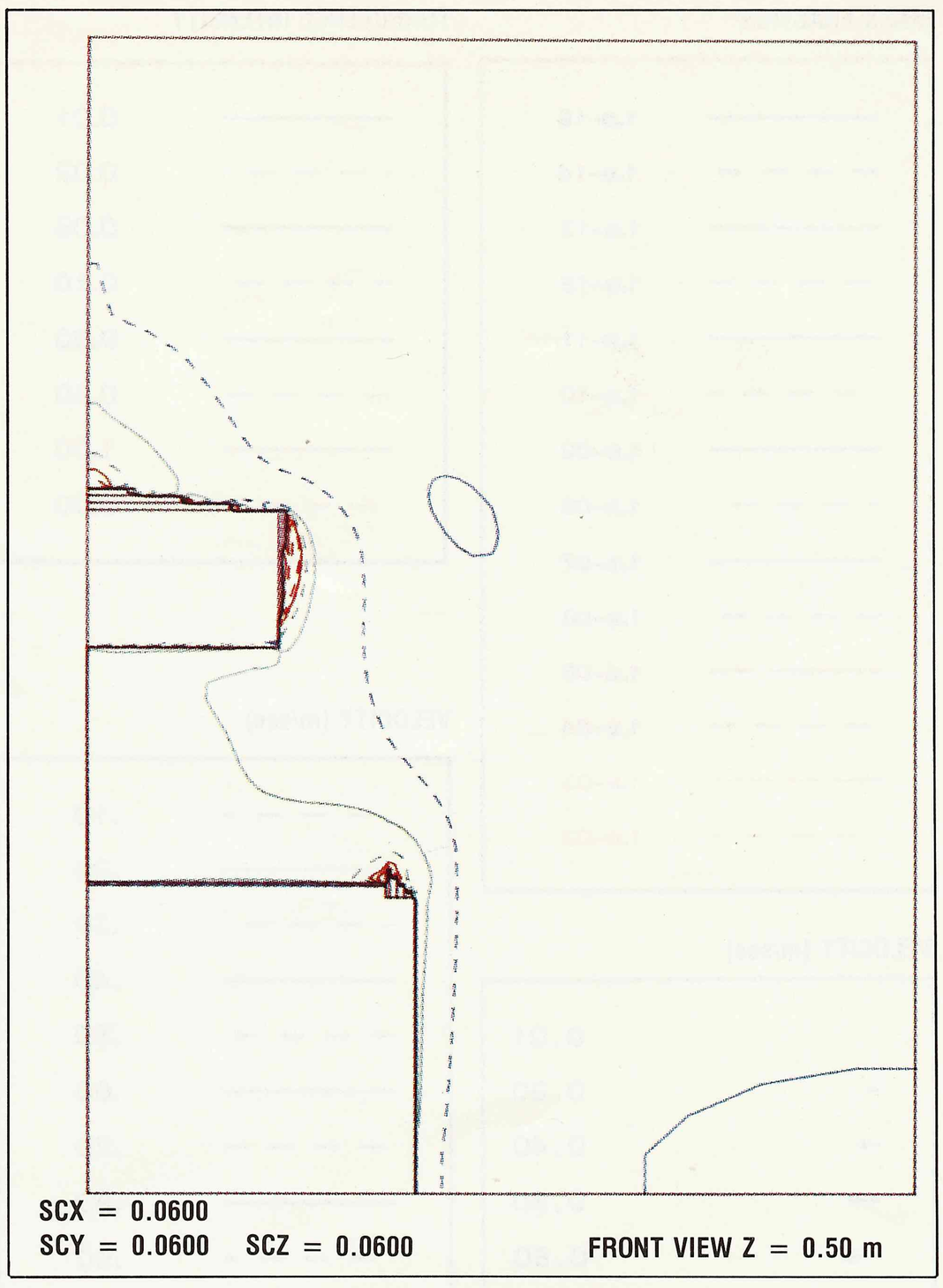


Figure 5: Iso-turbulence-intensity contours of airflow around the wet bench without a spoiler.

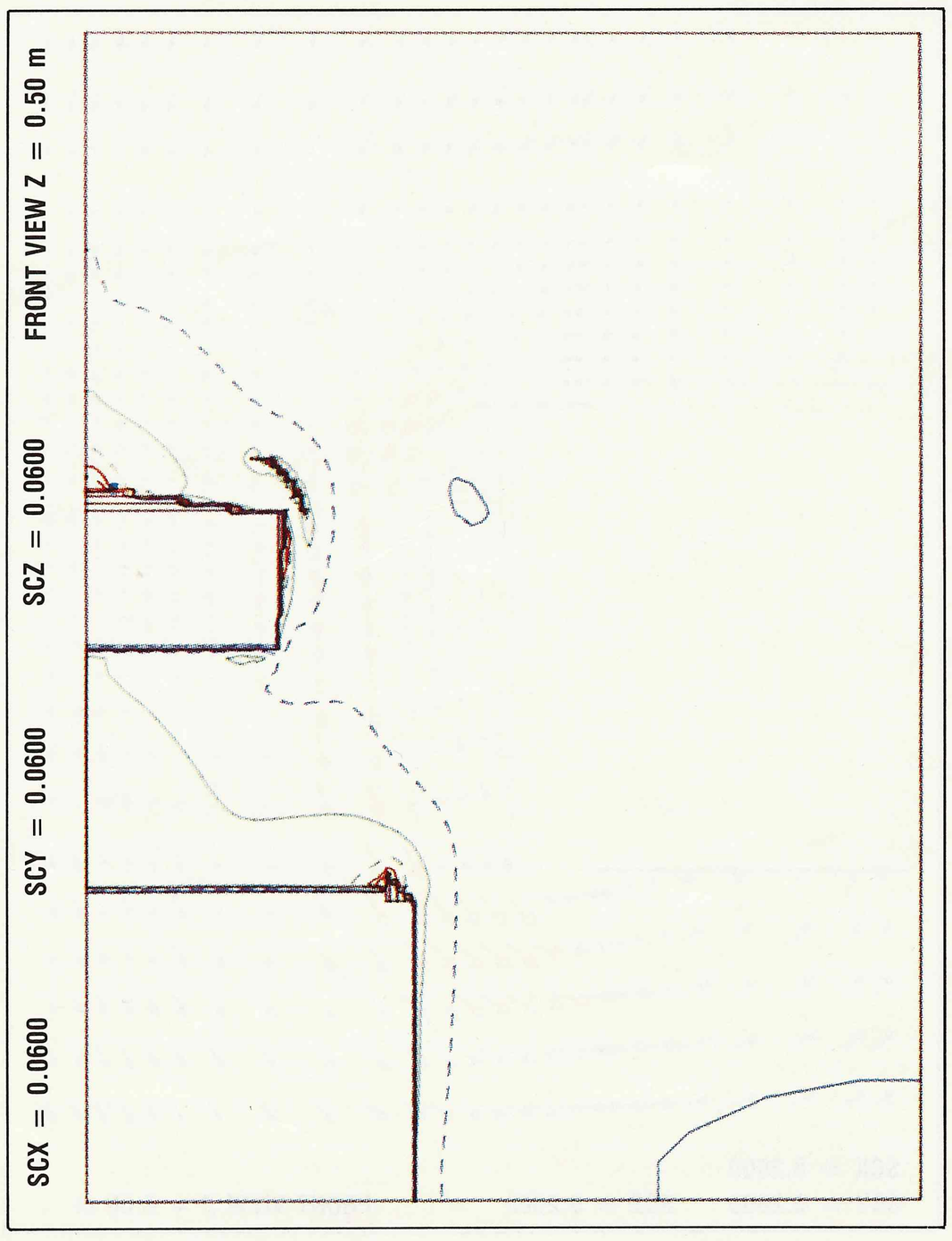


Figure 6: Iso-turbulence-intensity contours of airflow around the wet bench with a spoiler, showing a decrease in turbulence intensity relative to that in Figure 5.

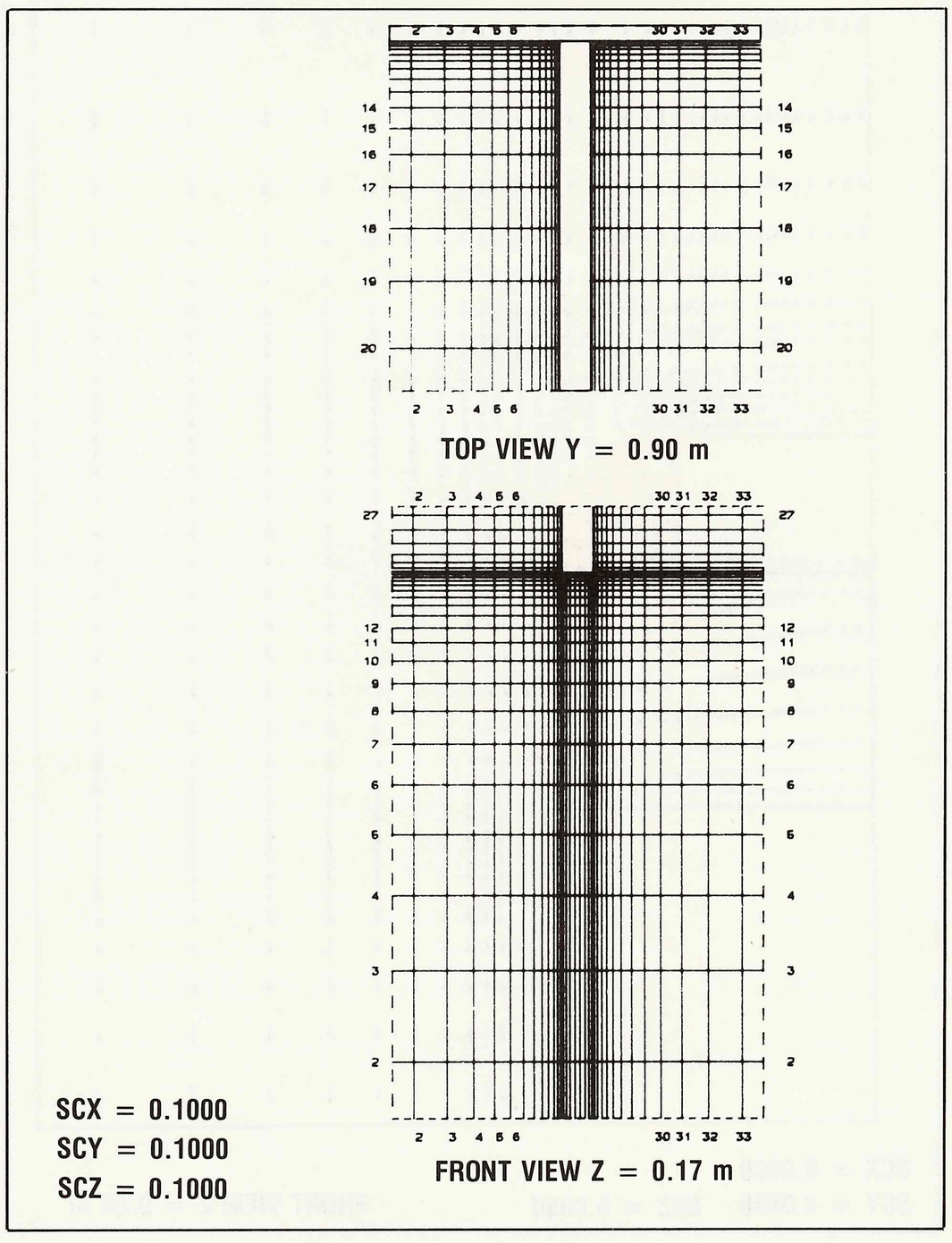


Figure 7: Three-dimensional numerical grids showing the hypothetical ceiling filter-support system.

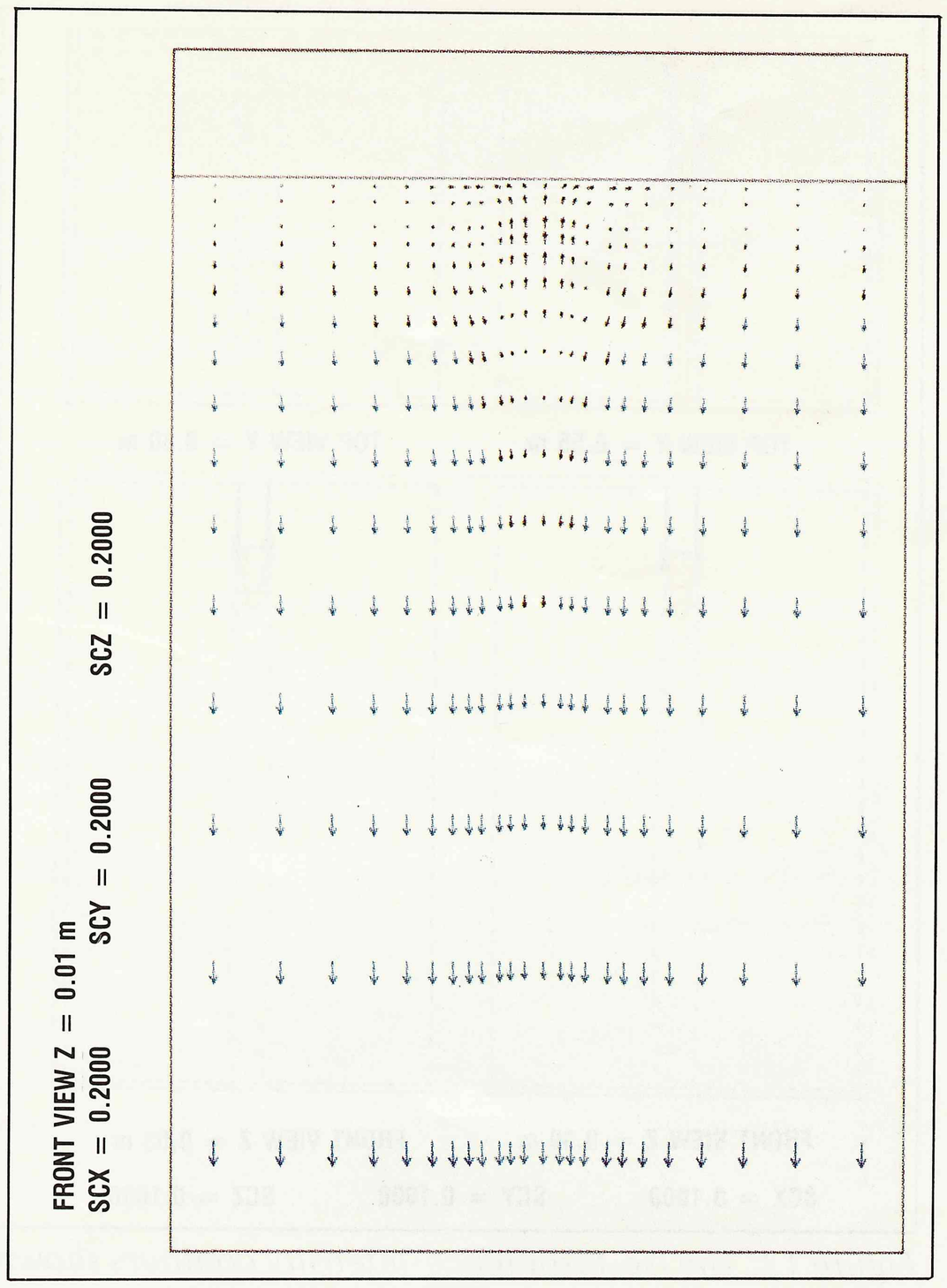


Figure 8: Airflow velocity pattern near a filter-support bar in the ceiling grid. The recirculation zone under the support bar is extended because of similar flow disturbances under the perpendicular support bars.

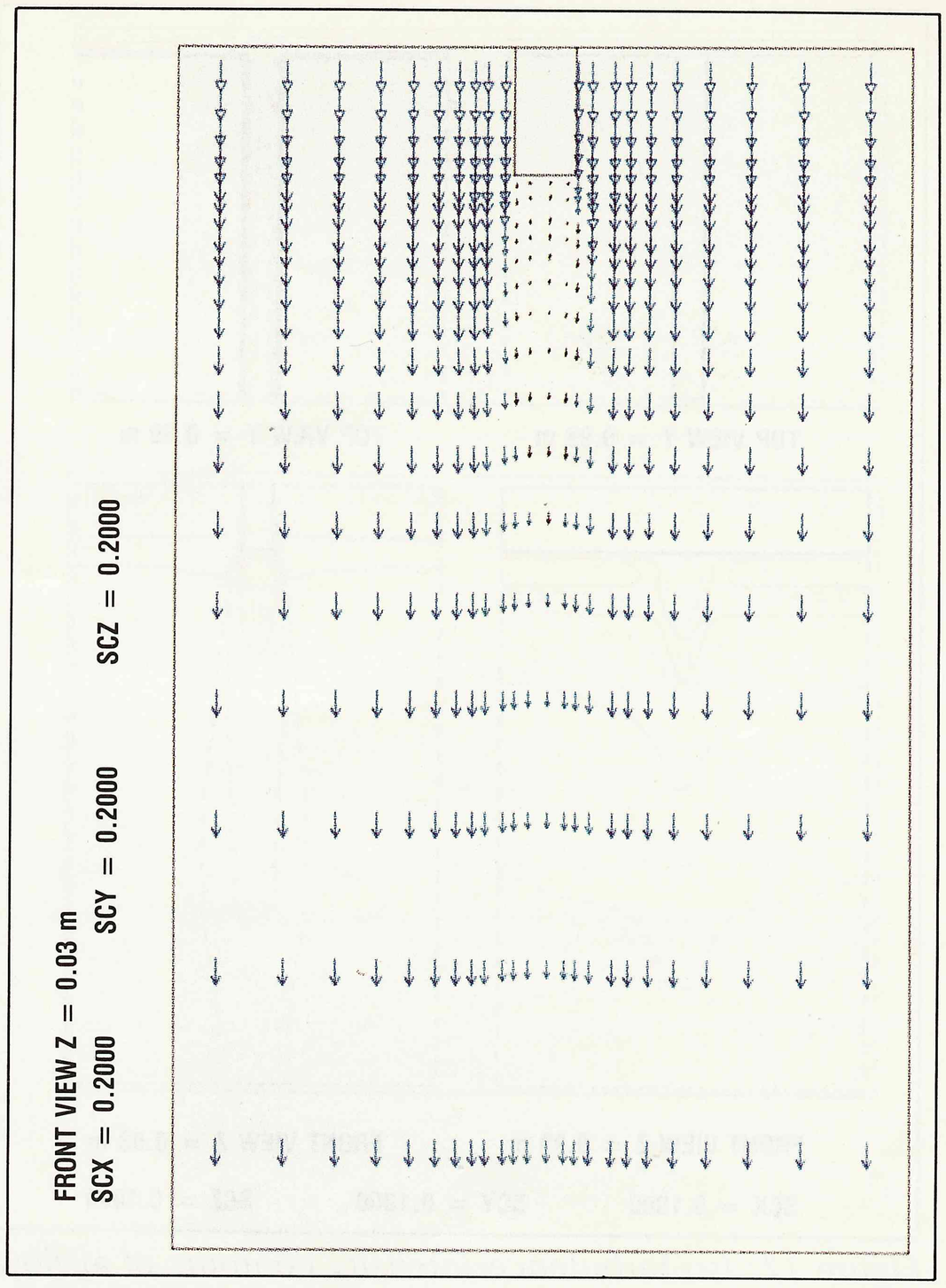


Figure 9: The airflow velocity pattern shown in Figure 8 on a different plane.

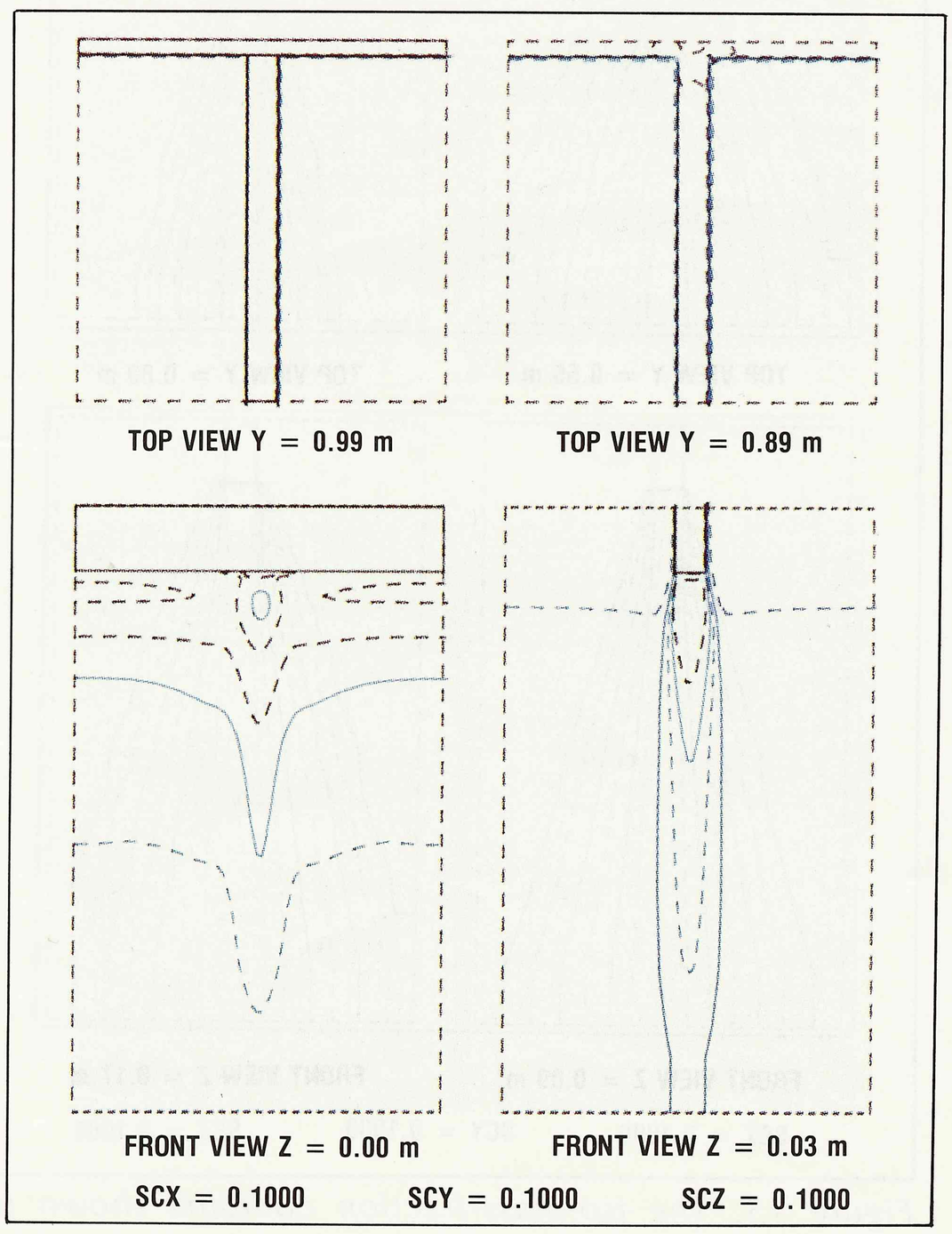


Figure 10: Iso-velocity contours of airflow near filter-support bars, showing the propagation of velocity disturbances downward.

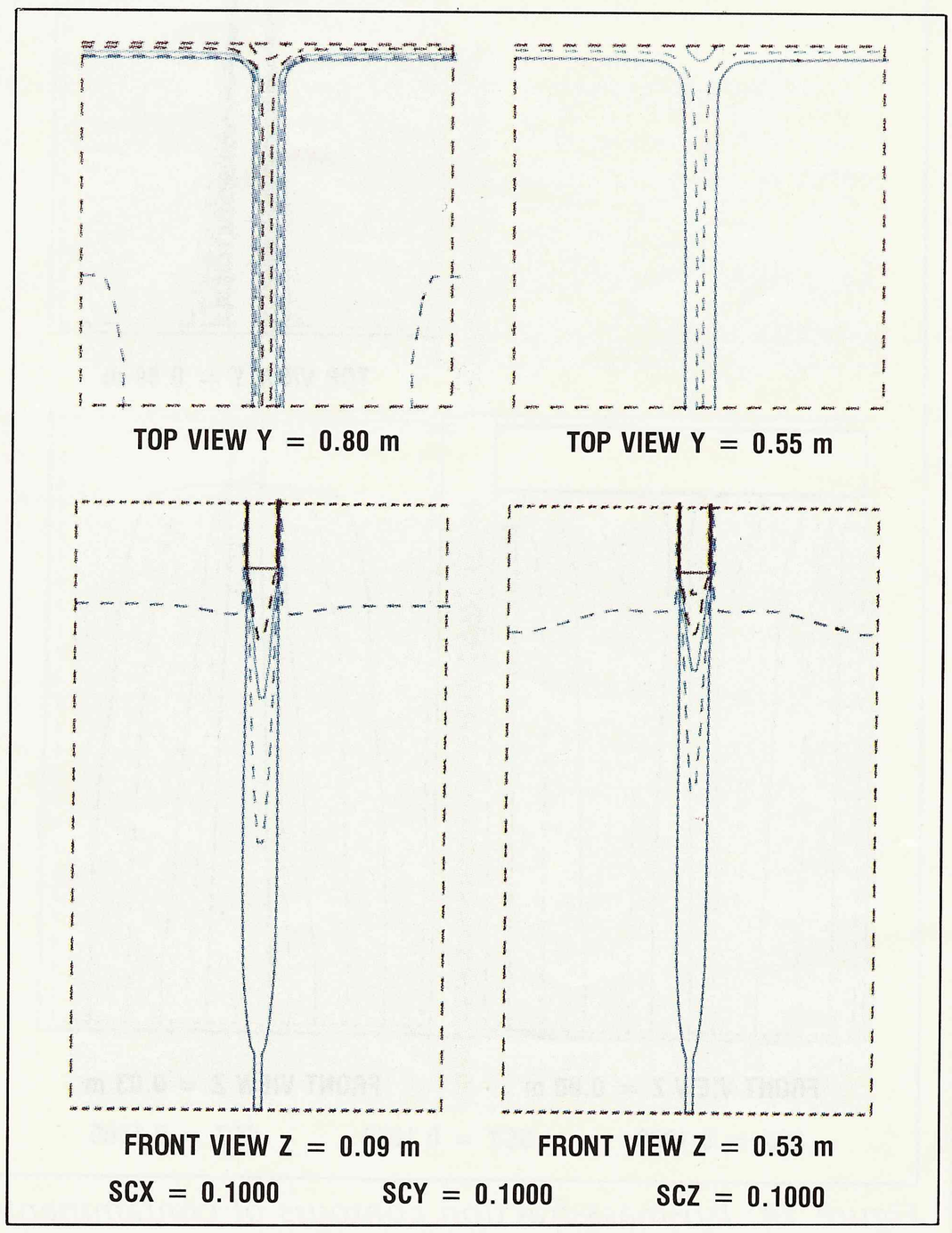


Figure 11: The iso-velocity contours shown in Figure 10 on a different plane.

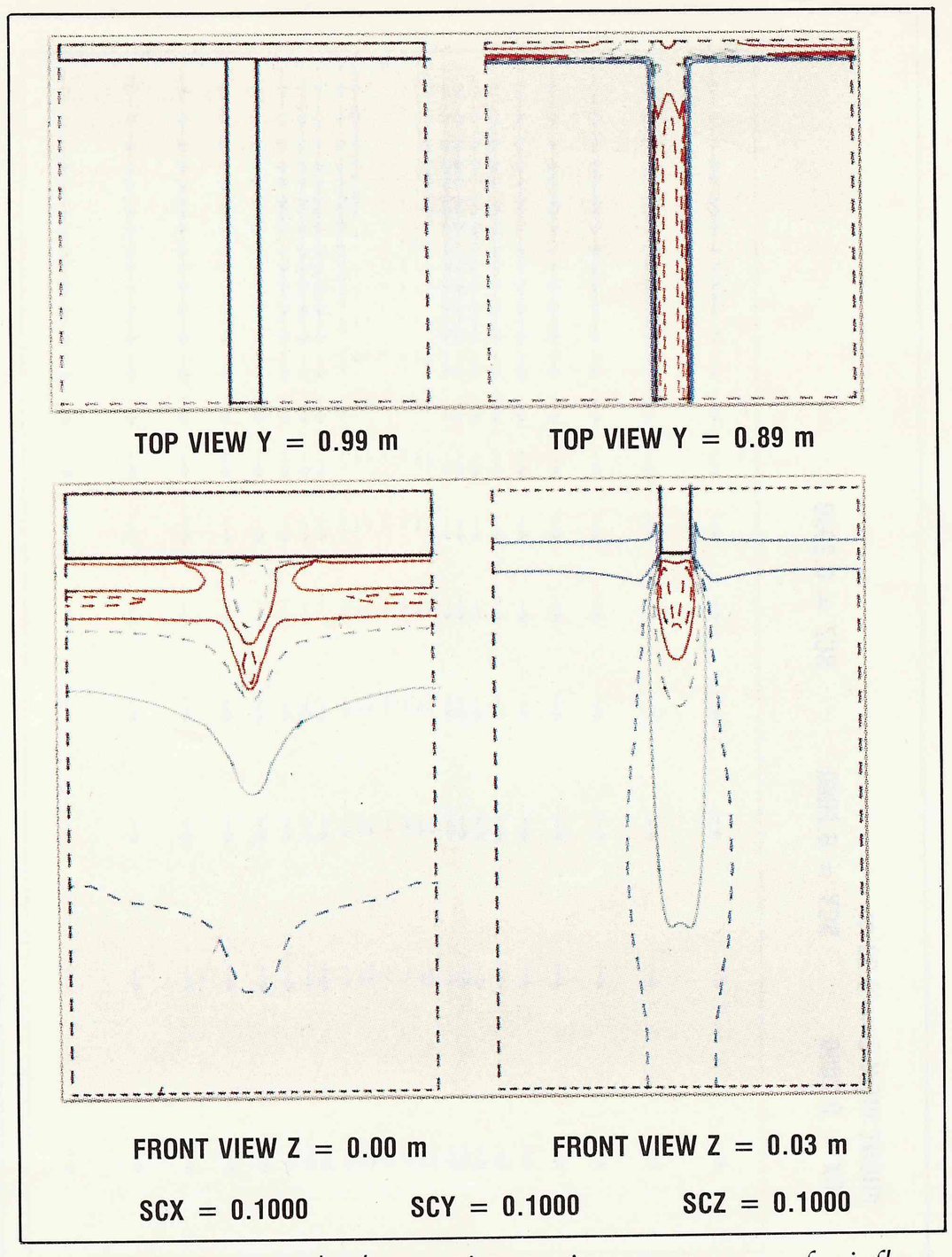


Figure 12: Iso-turbulence-intensity contours of airflow near filter-support bars, showing higher turbulence under the bars.

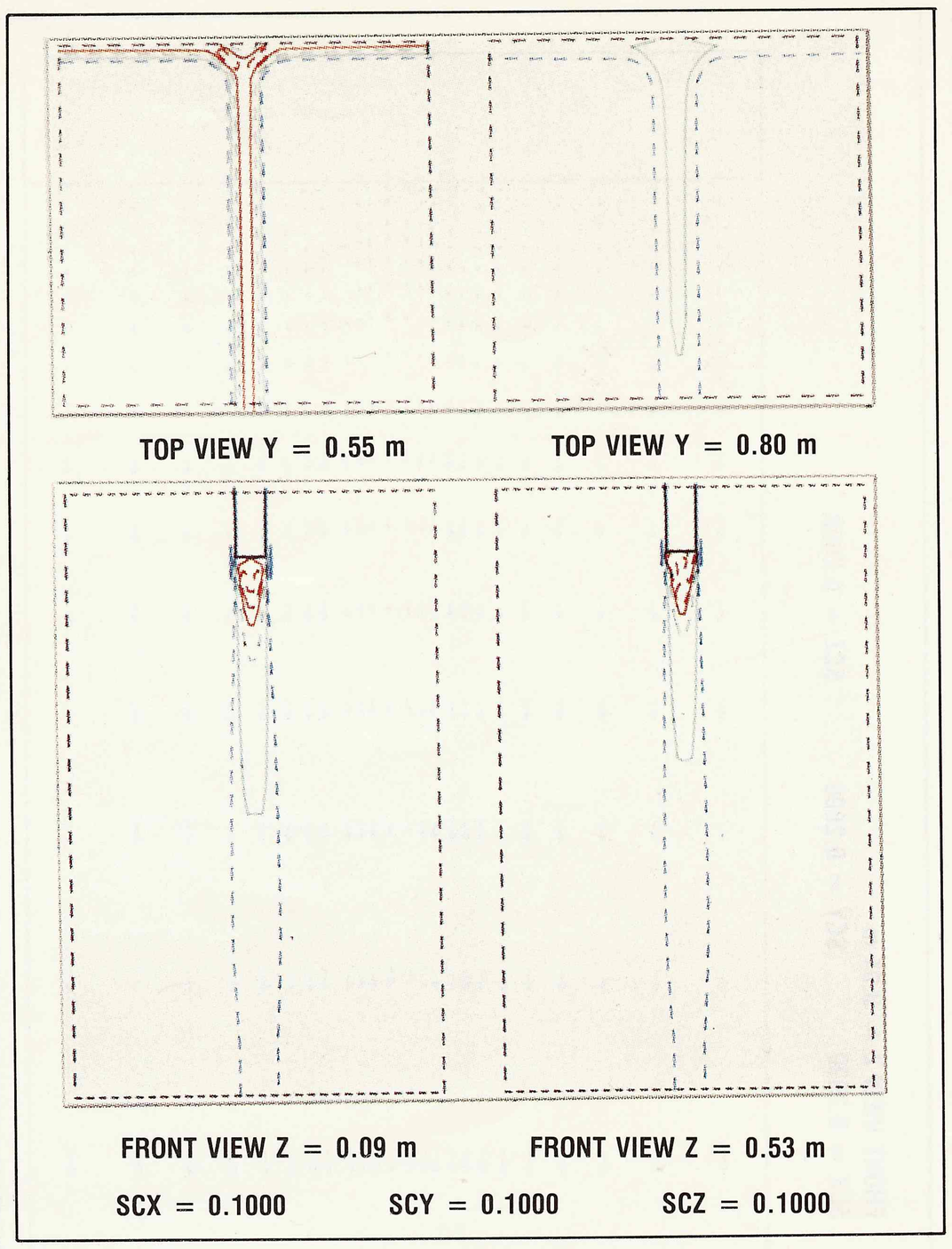


Figure 13: The iso-turbulence-intensity contours shown in Figure 12 on a different plane.

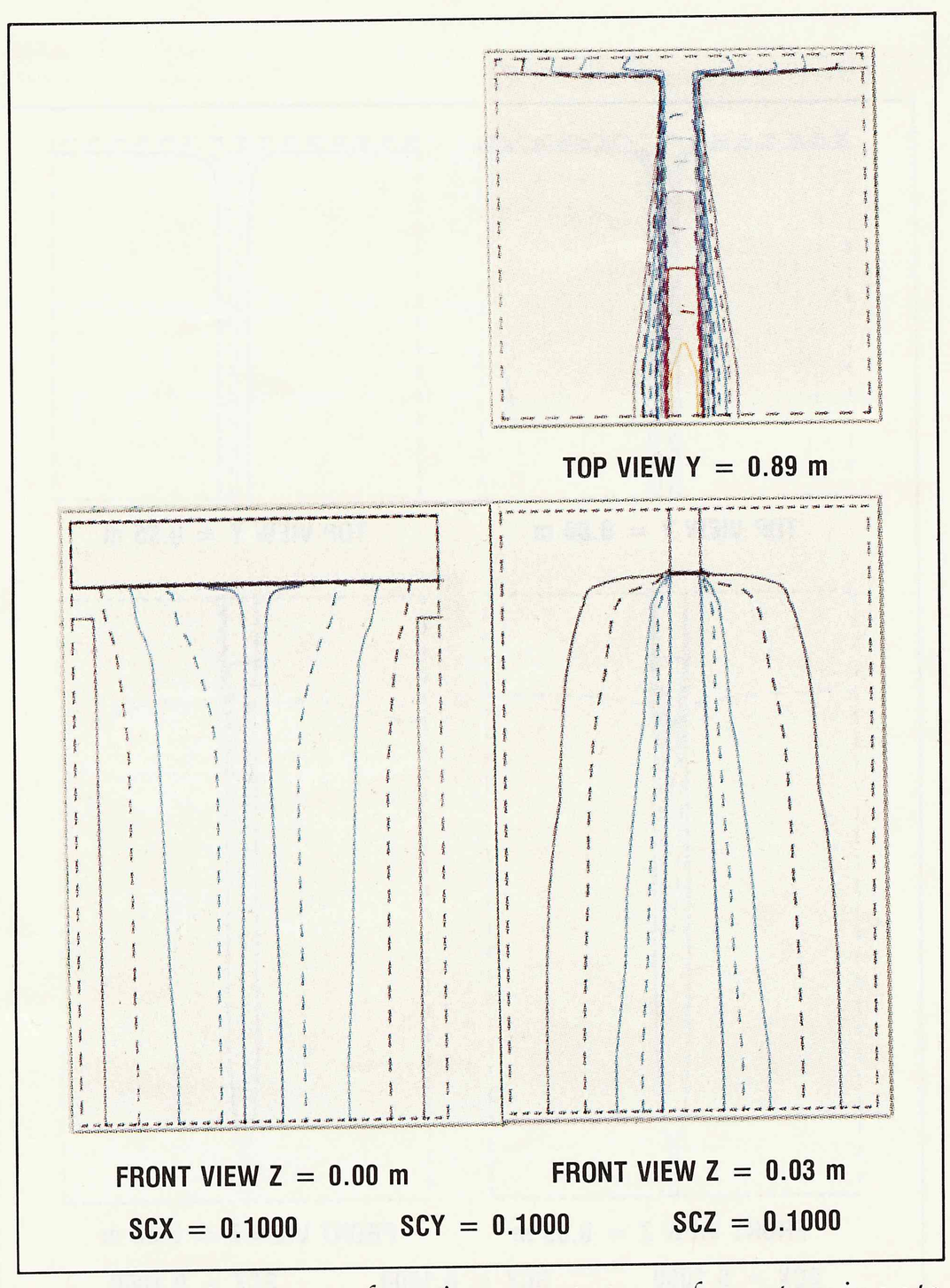


Figure 14: Iso-mass-fraction contours of contaminants spread by convection and diffusion, showing relatively low levels of contaminant spread into the flow field as well as "ceiling-grid-tracing contaminants."

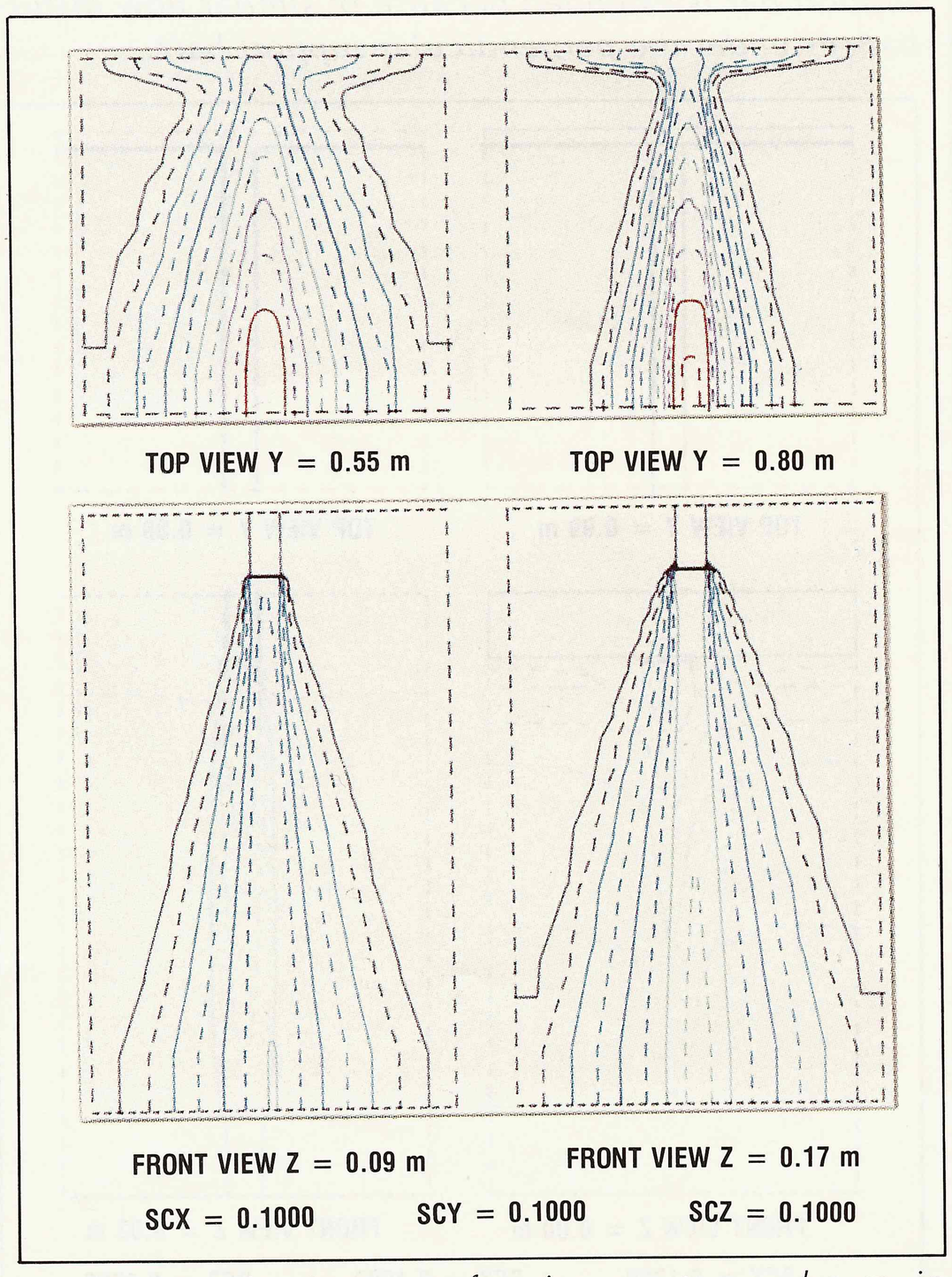


Figure 15: The iso-mass-fraction contours shown in Figure 14 on a different plane.

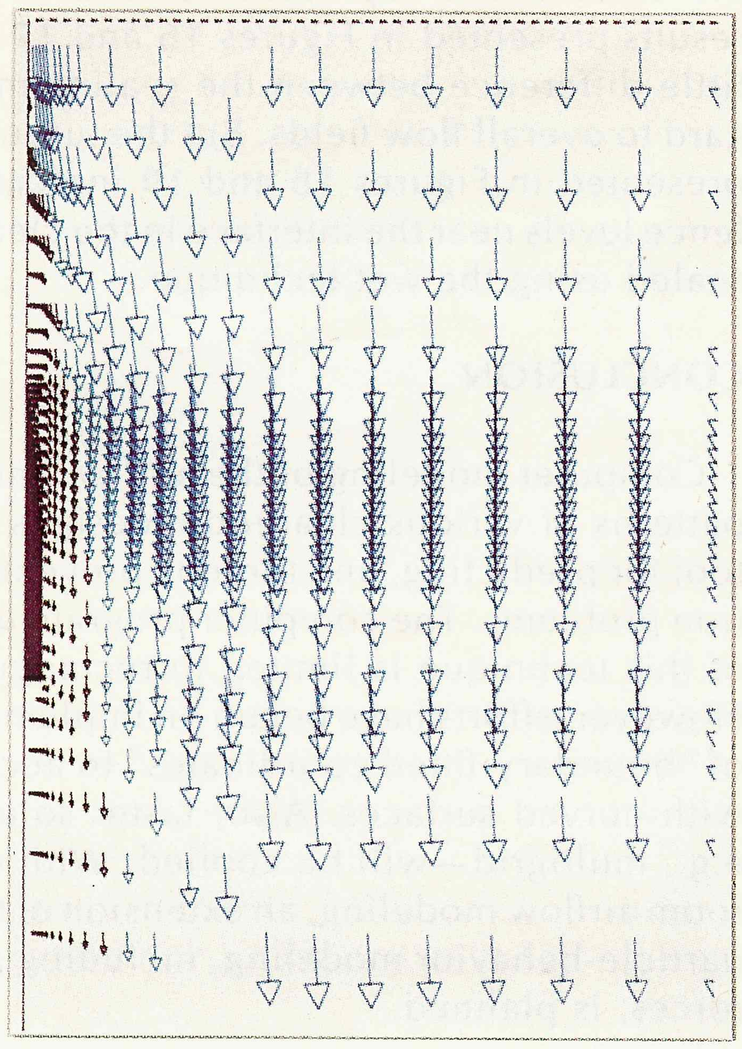


Figure 16: Airflow velocity pattern near a ceiling/wall interface in a dry-sealed cleanroom, showing a clearly visible boundary layer. (This type of seal is modeled as a localized thickening of the wall.)

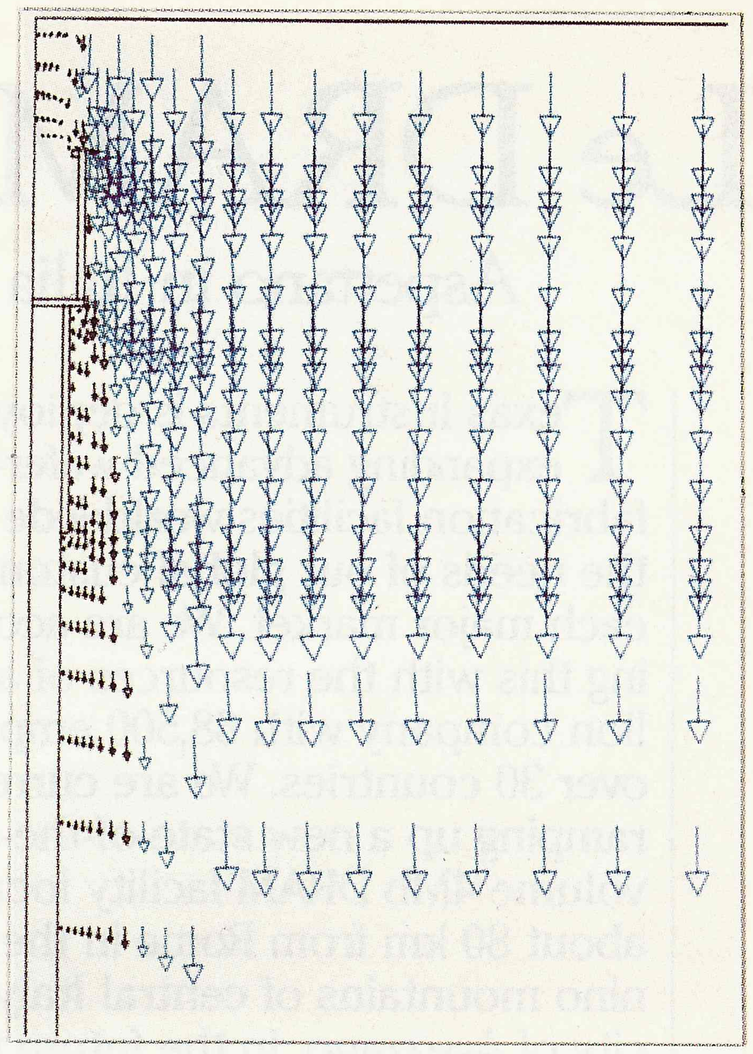


Figure 17: Airflow velocity pattern near a ceiling/wall interface in a wet-sealed cleanroom, showing an adjacent area of stagnant flow. (This type of seal is modeled as a U-shaped gutter with a knifelike separation in the middle.)

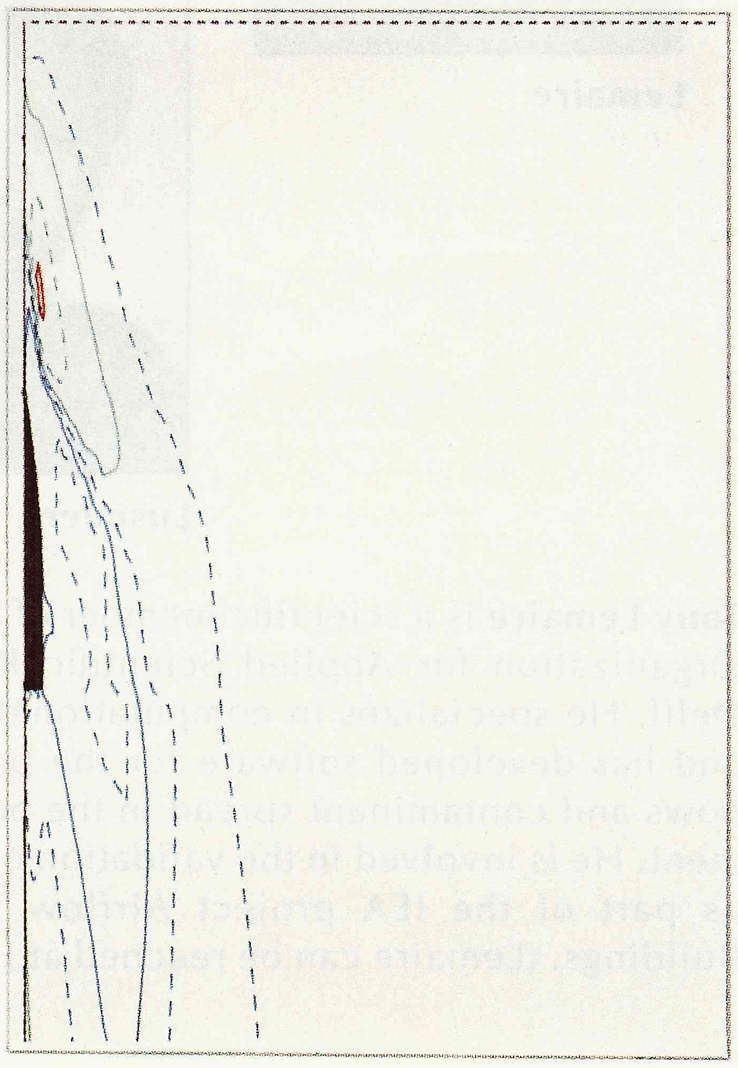


Figure 18: Iso-turbulence-intensity contours near a ceiling/wall interface in a dry-sealed cleanroom.

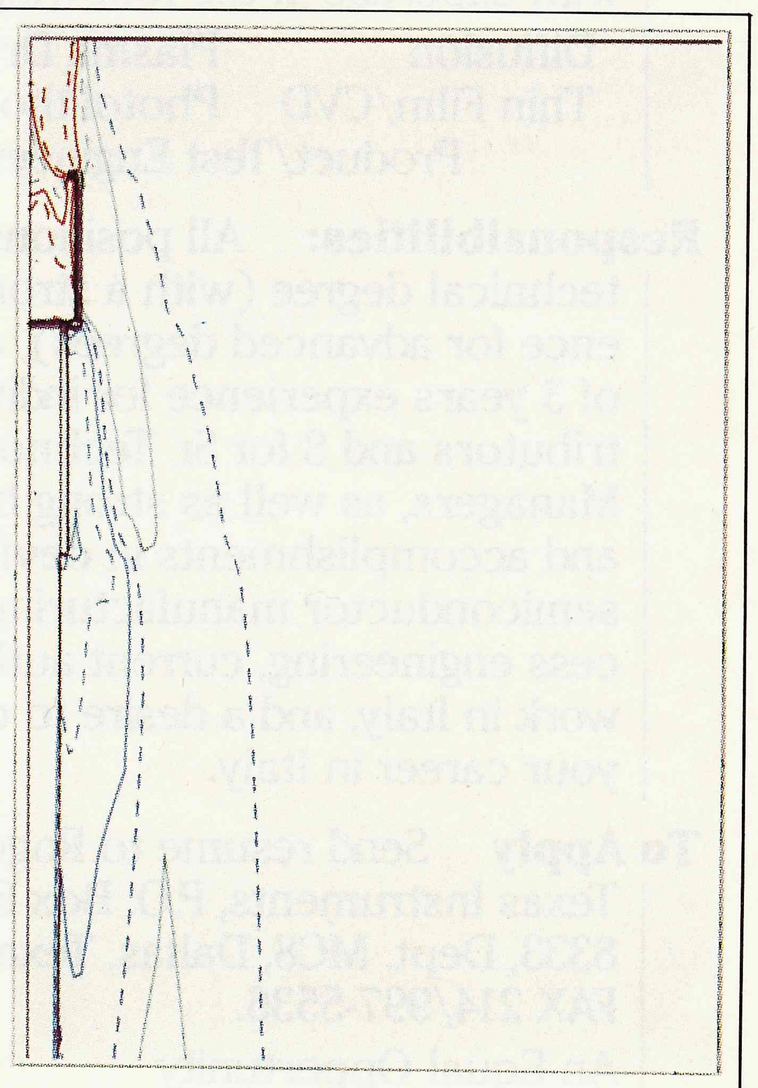


Figure 19: Iso-turbulence-intensity contours near a ceiling/wall interface in a wet-sealed cleanroom. Turbulence is relatively high compared with that shown in Figure 18.

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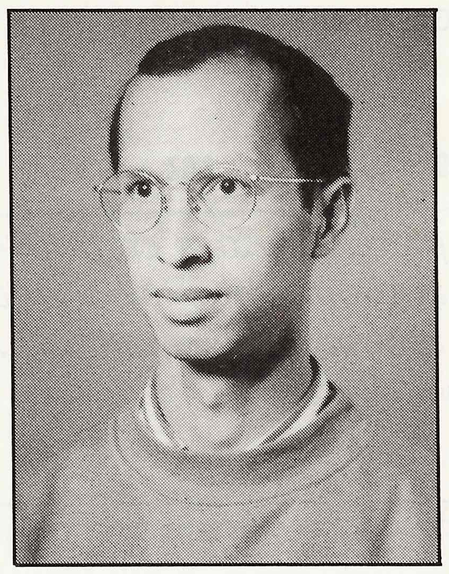
TEXAS INSTRUMENTS

the simulations represents a line of symmetry. The results presented in Figures 16 and 17 show there was little difference between the sealing methods with regard to overall flow fields. But the turbulence mappings presented in Figures 18 and 19 indicate higher turbulence levels near the interface in the cleanroom that was sealed using the wet technique.

CONCLUSION

Computer modeling of the airflow and air-turbulence patterns of various cleanroom designs can be a useful tool for predicting, and thereby preventing, contamination problems. The computer program used in our study of this technique is limited to rectangular geometries. However, efforts have begun on implementing a method of "boundary-fitted coordinates" to account for objects with curved surfaces. Also, faster solution methods—e.g., multigrid—will be applied. With regard to cleanroom airflow modeling, an extension of the program into particle-behavior modeling, including gravity and drag forces, is planned.



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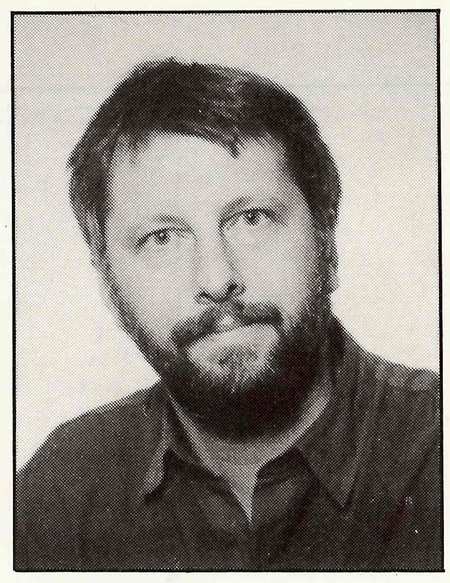

Luscuere

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