LA-UR- 03-0946

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Submitted to: Proceedings of ASME FEDSM'03, ASME 2003 Fluids Engineering Division Summer Meeting, Honolulu, Hawaii, USA, July 6-11, 2003

FEDSM2003-45176

Los Alamos
NATIONAL LABORATORY

Proceedings of FEDSM'03
4th ASME_JSME Joint Fluids Engineering Conference
Honolulu, Hawaii, USA, July 6-11, 2003

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COMPUTATIONAL MODELING AND ANALYSIS OF AIRFLOW IN A TRITIUM STORAGE ROOM

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ABSTRACT

In this study, a commercial computational fluid dynamics (CFD) code, CFX-5.5, was utilized to assess flow field characteristics, and to simulate tritium gas releases and subsequent transport in a storage room in the tritium handling facility at Los Alamos. This study was done with mesh refinement and results compared. The results show a complex, ventilation-induced flow field with vortices, velocity gradients, and stagnant air pockets. This paper also explains the time-dependent gas dispersion results. The numerical analysis method used in this study provides important information that is possible to be validated with an experimental technique of aerosol tracer measurement method frequently used at Los Alamos. Application of CFD can have a favorable impact on the design of ventilation systems and worker safety with consideration to facility costs.

INTRODUCTION

The accidental release of radioactive material could occur in Department of Energy research and production facilities, such as those located at Los Alamos, Savannah River Site, Sandia, and other National Laboratories. In such facilities, Federal Regulation 10 CFR 835 (DOE 1999a) requires real-time air monitoring of radioactive materials using Continuous Air Monitors (CAMs), including tritium gas detectors, in work areas where an individual is likely to receive an exposure of 40 or more Derived Air Concentration-hours (DAC-hours) in a year (which relates to an annual radiation dose of 100 mRem). Such CAMs or tritium detectors are needed to alert individuals to unexpected increases in airborne radioactivity.

Tritium detectors are used to protect workers by monitoring the level of airborne radioactive material within a room. Once a preset radioactivity level is exceeded, a detector alarm is triggered, which alerts workers to a potential hazard and directs them to evacuate the room promptly. Knowledge of airflow and dispersion patterns in work areas is important to ensuring the tritium detectors are located in sufficient quantities and in positions that provide adequate worker protection. Research has demonstrated that effective placement of real-time air monitors in large nuclear facilities is critical to radioactive safety of workers (Whicker et al, 1996, 1997, 2001; Konecni et al. 2000, 2002). The importance of effective placement of tritium detectors in nuclear facilities is also noted in DOE regulations (DOE 1999b).

For many years, the Engineering Sciences and Applications Division (ESA) and Health Physics Measurements (HSR-4) Group at Los Alamos National Laboratory (LANL) have been studying and developing new technologies using analytical and experimental tools to aid in the design of nuclear facilities. These technologies can be utilized to guide ventilation system design and detector placement decisions. The two objectives of this study were to 1) numerically evaluate and compare ventilation-induced flow fields determined using a coarse and a fine mesh density, and 2) to evaluate predicted dispersion of gas releases in terms of worker protection. Specifically, this report discusses the numerical analysis that was used to evaluate a ventilation-induced flow field and to investigate gas dispersion from four tritium release sources. A mesh refinement technique was utilized in order to assess the influence of the finer room mesh on the steady state flow field. In addition, the results of the numerical analysis provide a predicted gas concentration time history detected at six potential sampling locations that can be used in the evaluation of worker exposures and placement of tritium detectors.

NOMENCLATURE

- u x-velocity component
- v y-velocity component
- w z-velocity component
- p pressure

CFD APPLICATION

Computational fluid dynamics analyses offer some advantages over the experimental techniques in investigating fluid flow. These advantages include savings in time and cost associated with the alternative, namely, constructing and performing large-scale experiments. In addition, CFD codes allow detailed flow visualization, as well as the ability to conveniently perform parametric sensitivity and optimization studies. It also provides the ability to evaluate room and equipment re-configurations. Finally, CFD analysis is the only possible approach to investigate flow field and aerosol/gas dispersion in rooms in the design phase. (Konecni et al. 2000, 2002).

The flow field and gas dispersion in the room studied here was simulated using CFX5.5, a commercially available CFD code developed by AEA Technology. CFD models provide a simultaneous numerical solution of continuity, Navier-Stokes, and energy equations for a flow field geometry with specified boundary conditions. CFX-5.5 uses a coupled solver, which solves the hydrodynamic equations (for u, v, w, p) as a single system. This reduces the number of iterations required for convergence to a steady state, and to a transient analysis solution for each time step in time-dependant gas dispersion.

ROOM CONFIGURATION AND BOUNDARY CONDITIONS

An isometric view of the full-scale tritium storage room is shown in Figure 1. The room size is 10.16 m by 3.98 m and 3.9 m high. The solid model of the room contains the major room details, such as the exposed beams, lights, ventilation hardware, wiring conduit, shelves, and the door. The tritium release sources are shown with the red spots in Figure 1.

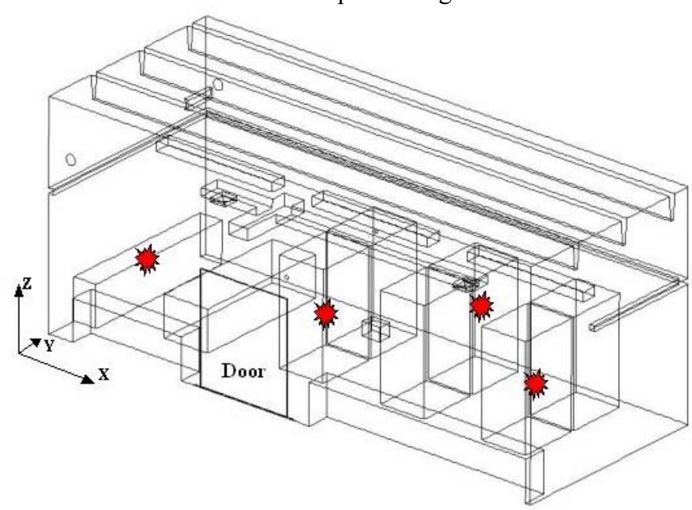

Figure 1. Isometric view of tritium storage room, the red spots show four gas release locations.

Figure 2 shows the top view of the room. The storage room has two square inlet diffusers on the ceiling and one outlet register on the left wall near the ceiling. Four release sources labeled with a number near the red spot, six tritium detectors are noted with D1 to D6. The coordinates of the release sources and monitor points are listed in Table 1.

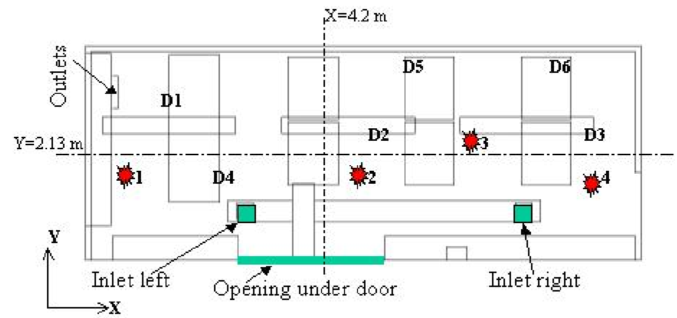

Figure 2. Top view of the storage room

Table 1. Locations of the release sources and monitors

Items	X (m)	Y (m)	Z (m)
Source 1	0.500	1.990	1.473
Source 2	4.809	1.993	1.473
Source 3	6.808	2.100	1.473
Source 4	9.008	1.850	1.473
D1	1.727	2.666	2.464
D2	4.978	2.361	2.867
D3	9.220	2.361	2.413
D4	2.489	1.080	2.032
D5	5.740	3.594	2.032
D6	8.890	3.594	2.032

As shown in the Table 1, all release sources are in the region of the chest high plane, elevated 1.47 m from the room floor. This plane is also “the breathing zone plane” since its position is at the average inhaling height of a standing worker. The detectors are distributed around the suspended lights in the room.

Boundary conditions were applied according to the flow measurements taken in the room. The airflow rates at the inlets were measured with a volumetric hood and the direction of the air flowing into the room through the diffusers was measured with a thermal anemometer. The flow rates at the inlets and outlet measured were found to correspond to about 8.4 air exchanges per hour (ACH). Inlet air was modeled as a constant velocity inlet at an angle of 25 degrees relative to the ceiling. Outlet air was modeled as a constant velocity as well. The other source of air in the room is the gap under the door that allows air to flow in. The room is kept at negative pressure. This is achieved by withdrawing more air out of the room than what the ventilation supplies. The shelves, conduit, lights and other equipment were modeled as blocks, which surfaces were treated as solid walls. Some fine detail (pipes, furniture, conduit, etc.) was ignored in the model and the effects of this simplification were not evaluated. The computational flow domain is the open space in the room with two inlets, one outlet, and the gap underneath the door. The air was treated as incompressible, and adiabatic flow. Each release source was modeled as a cube with 1 cm^3 volume. They were modeled as sub-domains in the main flow domain. Effects from people or other heat sources inside the room were not considered in this study.

EFFECT OF THE MESH SIZE ON THE FLOW FIELD

A parametric model of the room was constructed in Unigraphics (UG 16) and a parasolid file of the 3-D model was created from it. The parasolid file was exported from UG and imported into an advanced meshing tool of the CFX-5.5 pre-processor, called CFX-Build. This step in preprocessing saves considerable time in geometry clean-up correction and mesh generation. Two unstructured meshes were created using the parasolid as the baseline geometry of the room (Figures 3 and 4). The first mesh has over 2.0 million tetrahedron elements and it is called in this study the “coarse mesh” (Figure 3). The second mesh has about 6.6 million tetrahedron elements and it is referred as the ”fine mesh” (Figure 4). The solutions were obtained on an 866 MHz dual processor, Dell Workstation PWS420 machine as a host processor machine. For the coarse mesh, the steady state solution required about 2 days and 5 hours using 4 processors.. The transient analysis required about 2 days of continuous operation using four distribute parallel processors to obtain all concentration profiles for six detectors with four gas release sources. For the fine mesh, we a used parallel run with 8 processors from 4 dual processor machines. The steady state analysis required almost 2 days to compete, while the transient solution needed 2 and half days to provide the results.

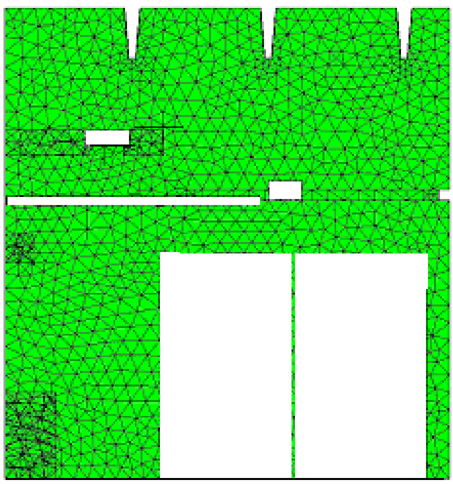

Figure 3. Mesh density for the Coarse Mesh, 2 million elements.

Figure 4. Mesh density for the Fine Mesh, 6.6 million elements.

The three-dimensional steady-state flow field was computed using the k-ε two-equation turbulence model for two meshes. Figures 3 and 4 show a slice of the mesh for x=4.2 m (through the door). The average element length in the coarse mesh is 0.06 m, and in the fine mesh is 0.04 m. Inlets and outlets have a finer mesh density to resolve the complex flows in those regions.

The steady state flow solutions for the two meshes show differences in some areas of the room. Figures 5 and 6 show velocity contours on a plane through the door (x=4.2m). The position of the x=4.2 m plane is shown in Figure 2. From these figures the difference can be seen in the shape of the higher velocity contours around the shelves. Figure 6 shows the velocity contours for the fine mesh and suggests the high velocity flow follows the shape of the storage shelf more closely than that predicted by the coarse mesh (Figure 5).

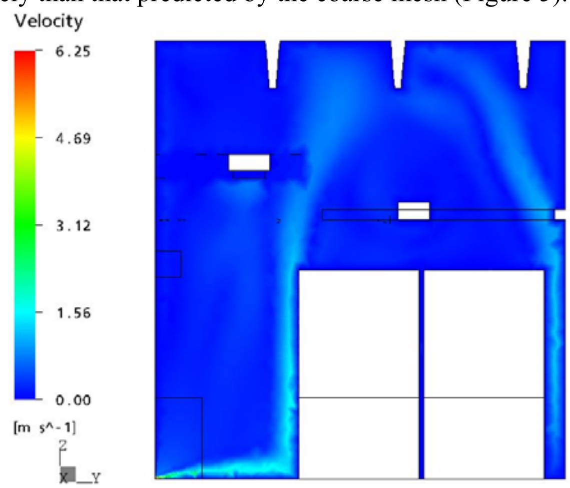

Figure 5. Velocity contours in a vertical plane, Coarse Mesh (x =4.2 m)

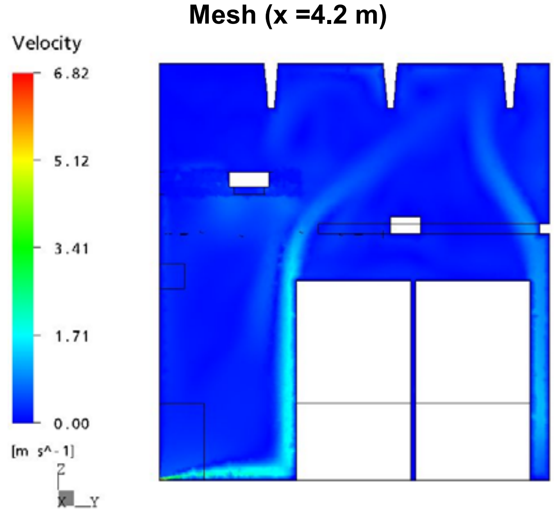

Figure 6. Velocity contours in a vertical plane, Fine Mesh (x =4.2 m)

Figures 7 and 8 compare predictions of low velocity airflow (< 10 cm/s) for each of the grid densities in the breathing zone plane. These areas of low velocity airflow, or stagnant air pockets, are important to worker protection because of the gas releases in these areas may remain concentrated for longer times, thus potentially increasing worker exposures to unsafe levels unless the releases are rapidly detected by local air monitors. For both grid densities, the lowest velocities in the breathing zone plane were found between the shelves and in the back left room corner. Comparing airflow between the two mesh densities, the area away from the door and the ventilating outlet has the most similarities. The airflow in the area between the right wall and the last row of the shelves compare well for both meshes.

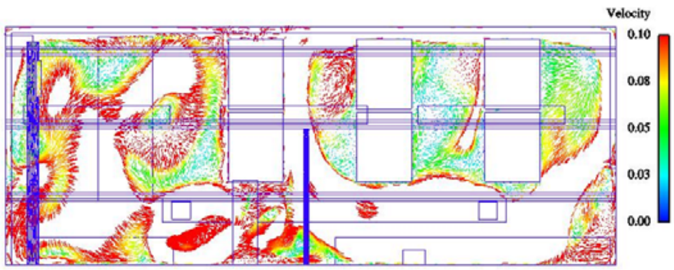

Figure 7. Velocity vectors for plane z=1.47, Fine Mesh

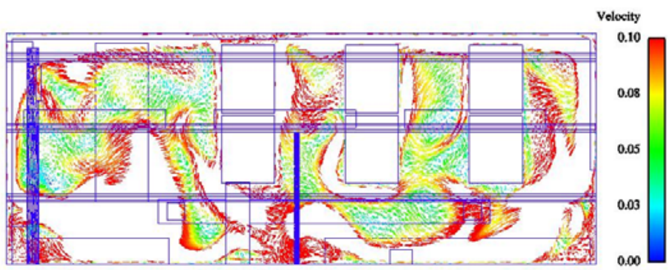

Figure 8. Velocity vectors for plane z=1.47 m, Coarse Mesh, velocity vectors bellow 10 cm/s are plotted

The flow around the door and the open space between the left wall and first row of the shelves differ in both meshes.

Figures 9 and 10 compare the velocity vectors for the coarse and the fine mesh at a plane y=2.13 m which run through the middle of the room. The red vectors show velocities higher than 50 cm/s. These high velocities are predominant in the area under the door, along the first tall shelf and along the ceiling. The difference in the solution between the two meshes is mainly in the area between the left wall and the first row of shelves. High velocity flow crosses over the first shelf in the case of the coarse mesh. It goes straight up in the case of the fine mesh solution.

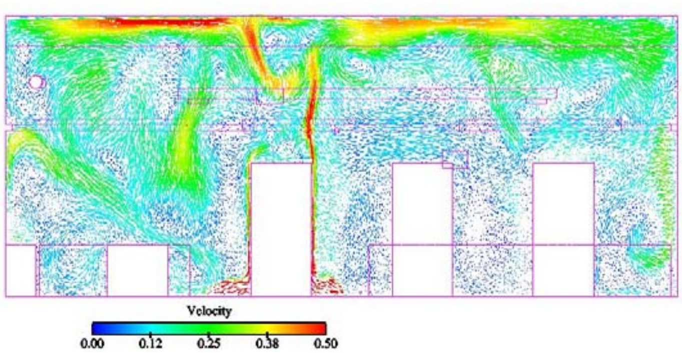

Figure 9. Velocity vectors for plane y=2.13 m, Fine Mesh

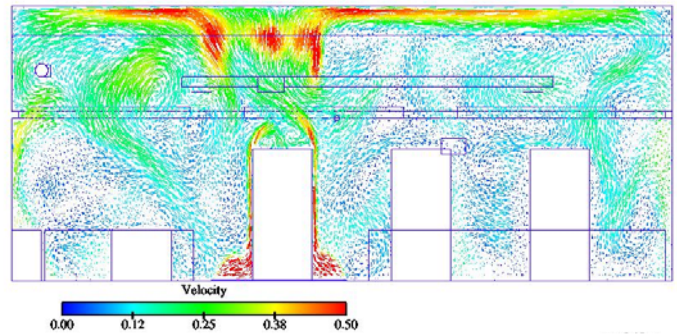

Figure 10. Velocity vectors for plane y=2.13, Coarse Mesh

Figures 7, 8, 9 and 10 show that the re-circulation zones are developed between two right shelves and close to tritium release source 3. Such zones can trap aerosols and gases released nearby. Velocities as high as 6.2 to 6.8 m/s were predicted at the gap underneath the door and 2.4 m/s at the inlets are recorded from the coarse and the fine meshes, but in general the velocities are in the 0.25 m/s range. The flow field predictions show that gas dispersion was dominated by ventilation-driven advections (average about 0.25 m/s) compared to hydrogen diffusion, which occurs at about 0.01 m/s.

GAS DISPERSION SIMULATION

The steady-state CFD solution of the flow in the room was used as an input in solving the time-dependant dispersion pattern of the spread of released tritium in the room. Figure 11 is an example that shows the 3-dimentional nature of gas dispersion. The gas was simulated assuming dilute, mono-disperse, and neutrally buoyant particles. Transient calculations of the gas dispersion by advection, turbulent diffusion, and molecular diffusion over a five-minute period were performed and gas concentration versus time was recorded at six potential sampling locations.

The molecular diffusivity of the release was specified to be 0.41E-4 m^2/s, and the release rate was 1.0E4 kg/m^3s. Four locations were determined for the releases close to the shelves. The release duration was 10 seconds simulating short bursts of the gas in the room. Dispersion of the gas was calculated for a total of 300 seconds. Calculated concentration of the gas was obtained at six sampling locations as shown in Figure 2.

Figure 11 shows isosurfaces of the four releases at 10 seconds after the release. This figure is for the coarse mesh. From this figure it can be seen that the clouds of gas do not disperse isotropically as is assumed in some room dispersion models, but in this case the gas disperses sideways and slightly upwards for release location 2. Figure 11 also suggests that while there is considerable mixing of air in the room before it exits, not all of the room air may exchange 8 times per hour. For example, isolated stagnant mixing zones, with air exchange rates less than 8 air exchanges per hour, seem to be in place between the shelves and the ceiling which may slow mixing into the rest of the room.

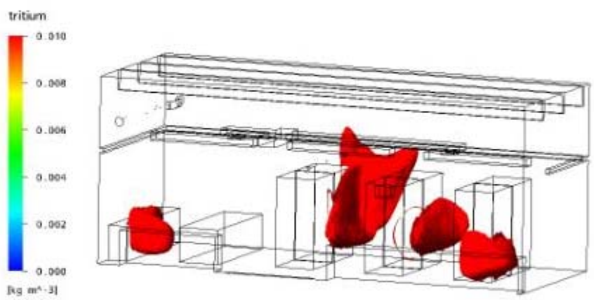

Figure 11: Isosurface plot of gas dispersion from four release sources at elapsed time of 10 second, Coarse Mesh

Figure 12 shows gas dispersion from four release locations at different times for the coarse mesh. The results are shown as concentration contours at the breathing zone height of 1.47 m from the floor.

Figure 13 shows the concentration of release contours for the fine mesh at the breathing zone plane. In general, the fine mesh predicts higher concentrations in the breathing zone as is seen in the time-dependent concentration profiles.

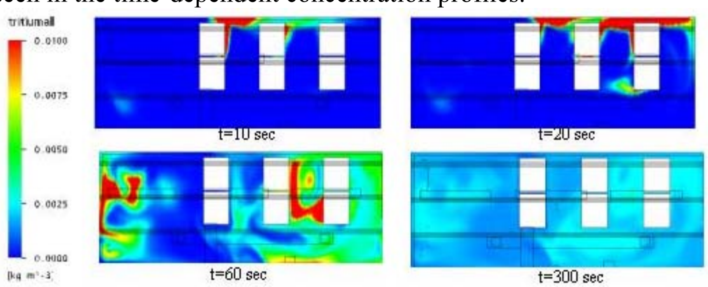

Figure 12: Predicted tritium dispersion at times of 10s, 20s, 60s, and 300s at the breathing zone (height 1.47 m) –Coarse Mesh

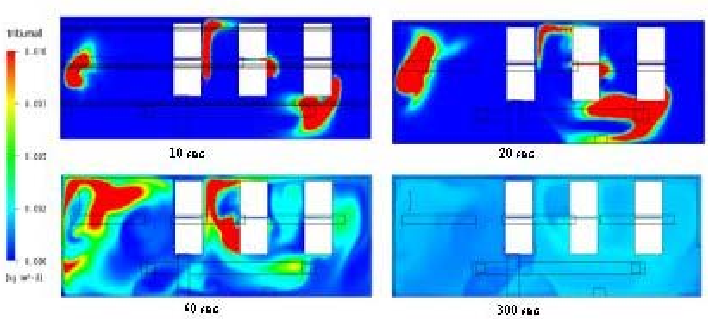

Figure 13. Predicted tritium dispersion at times of 10s, 20s, 60s, and 300s at the breathing zone (height 1.47 m) –Fine Mesh

The time-dependent concentration profiles at six potential tritium detector locations for four release sources are obtained from CFD time-dependant dispersion solver. Figure 14 shows the concentration over time obtained by CFX5.5 for detecting the Release 1. This figure compares the detection times for both meshes. The fine mesh detectors have a shorter time to detection of Release 1 0f about 25 sec.

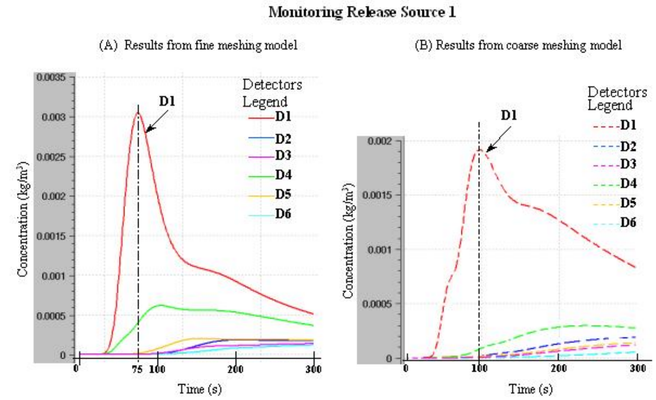

Figure 14. The concentration profiles at six potential tritium detector locations for Release 1

The results of the concentration profiles show that the concentrations predicted by the fine mesh were slightly greater than the coarse mesh and that the profiles were sharper for the fine mesh. Figure 2 also shows the importance of placement of tritium monitors in the room. Specifically, locations D1 and D2 would provide significantly better worker protection for a release at location 1 relative to the other tested locations. Clearly, accurate CFD analysis can provide valuable information toward determining optimal placement of air quality monitors.

CONCLUSION

CFD studies were carried out for a tritium storage room at Los Alamos National Laboratory and the results are presented in this report. Mesh study results are also compared. Two meshes were developed for the room and flow field calculated using the same boundary condition. Differences were noted in the flow pattern described. Gas was released and monitored for 300 s. A mesh independent solution was not obtained because an equipment limit for the mesh size was reached. Measurements that can be used for model validation.

The CFD-derived velocity field shows complex airflow patterns. This can complicate decisions about detector placement. Although we are planning a tracer release study for model validation and additional monitor placement evaluation, computed and measured aerosol lag time data were compared in the past and showed general agreement (Whicker et al. 2000) in the test room at the Los Alamos. Group HSR-4 operated test facility has also shown general agreement between simulations and empirical measurements, as has the work presented in Baker (1999) and Konecni et al. (2000). These findings establish that, once adequately parameterized, CFD modeling accurately represents room airflow and contaminant transport patterns and is a useful tool for evaluating the number and placement of radiation detectors during facility design phases. In addition, the CFD process should provide a better understanding of any spatial flexibility that operations personnel might have when placing the CAMs in an optimal configuration.

In conclusion, analytical (CFD) tools have been combined to form the basis of a new technology that is useful in the design and operation of nuclear facilities. Applications include ventilation system design, equipment layout, detector placement, and accident analysis. We believe that, with development, the techniques presented here can contribute toward safer facilities through (1) improvements in ventilation design which create more protective airflow pattern, (2) optimization of the number and placement of aerosol or gas detectors in nuclear facilities, and (3) determination of optimal egress routes.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the interest and support of Stephen Blake, Rick Hemphill at Tritium Engineering Science Group, and Brian Smith, Debbie Montoya, and Sonja Manzanares at Engineering Design Group of Engineering Science and Application Division of Los Alamos National Laboratory, and CFD technical support from AEA Technology Engineering Software, Inc, and Jim Peirce for editorial support.

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