EXECUTIVE SUMMARY

Since the 1980's, tuberculosis (TB) has re-emerged as a major cause of death globally. This is primarily due to the emergence of drug resistant strains of the disease. TB is an infectious disease primarily transmitted through the air. The bacterium involved, Mycobacterium tuberculosis, becomes aerosolized in small droplets of water or bodily fluid when an infected person coughs, sneezes or laughs. Many of these droplets dry into droplet nuclei, and becoming airborne following room air currents, and cause infection when they are inhaled. While the lungs are primarily affected by the disease, other affected organs include the brain, bones, kidneys and lymph nodes. A group particularly susceptible to infection are those with weakened immune systems, most notable people suffering from Human Immunodeficiency Virus (HIV), the virus which causes Acquired Immunodeficiency Syndrome (AIDS).

Individuals who are at greatest risk are those in close contact with infected people, such as healthcare workers. Others at risk include:

- Homeless people. Homeless shelters are particularly likely to need TB control measures.
- Nursing home residents.
- Intravenous drug users.
- Diabetics or cancer sufferers.
- HIV/ AIDS sufferers.
- Anybody breathing air in a confined space with an infected person, such as family members or caregivers.

As drug resistant forms of TB are extremely expensive to treat (the cost can run up to $125,000), preventative measures are a more realistic option. There are several techniques that can be utilized in healthcare facilities to provide control of the spread of the disease:

- Negative pressurization of the isolation room relative to the rest of a healthcare facility. This only acts as a means to prevent spread however: it does not remove infectious particles from the area of an infected person.
- High efficiency particulate air (HEPA) filters are used in air ducts to disinfect the air, especially if the ventilation system recirculates the air in a room, rather than providing fresh air. However, proper installation, maintenance and monitoring of the HEPA filters is essential.
- High ventilation rates, in terms of high values of air changes per hour (ACH), which control the particles by removal through ventilation. Current Center for Disease Control and Prevention (CDC) guidelines indicate that a value of 12 ACH is necessary for new facilities, while 6 ACH is the absolute minimum. The problem with this means of control is that increasing the ventilation rate results in diminishing returns in terms of removal.

- Upper room Ultraviolet Germicidal Irradiation (UVGI) is frequently used to supplement minimum ACH in both isolation rooms and other types of spaces where individuals with undiagnosed cases of TB may be present. The lamps providing radiation are located relatively high up in the room to prevent exposure to occupants.

The latter option is increasingly seen as a cost effective measure to supplement the general ventilation system in a room. However, a combination of the general ventilation system and UV lamps may not necessarily be implemented correctly within a room. For example, if the ventilation rate is high, then the particles may not spend enough time within the UV zone. Further, if the ventilation system does not provide good mixing within the room, the particles may not be transported into the UV zone.

This study is therefore intended as a means of determining the most effective use of UVGI, as well as determining ventilation system configurations, which will provide higher removal effectiveness. To do this, the airflow pattern needs to be fully understood and well organized, with important parameters being studied, such as:

- Ventilation flow rate
- Locations of air supplies/exhausts
- Supply air temperature
- Location of the UVGI
- Room configuration

Previous research has been almost entirely based on empirical methods (Chang et al. (1985), Macher et al. (1992), Vortimer et al. (1995)), which are time consuming and are limited by the cost of modifying physical installations of the ventilation systems. It also demonstrated the limitations imposed by absence of U-V treatment systems. The design guidance for isolation rooms basically relied on gross simplifications without fully understanding the effect of the complex interaction of room airflow and U-V treatment systems.

In this study, Computational Fluid Dynamics, CFD, (sometimes known as airflow modelling) has been employed. CFD has been proven to be very powerful and efficient in research projects involving parametric study on room airflow and contaminant dispersion (Jiang et al. (1997), Jiang et al.(1995), Haghighat et al. (1994) and Anderson et al. (1984)). The output of the CFD simulations can be used to examine field distributions, as well as provide overviews on the effects of parameters involved. CFD is employed as a main approach in this study. Further, an algorithm was developed in this study which allowed the particles to be tracked through the room studied, and allowed the UV dosage to be calculated for the particle. From this data, information such as the number of particles vented by the ventilation system, the number of particles killed by UV, and the number of viable particles in the room at any time could be established.

In this study, airflow modeling was used to evaluate the effects of following parameters on minimizing the risk from airborne organism in isolation rooms:

- Ventilation flow rate
- Supply temperature and external ambient condition
- Exhaust location
- Baseboard heating (in winter scenarios)
- Pressurization of the room relative to the external rooms
- Location and intensity of UV lamps in the room

Forty different cases of room configuration were considered in this study, with three different combinations of lamp location and intensity combinations. There is very little literature to suggest what is an appropriate level of deposition of particles on surfaces in an isolation room setting. However, general consciences among experts suggest that the particle deposition is extremely low. For the purpose of this research, deposition of particles on surfaces was neglected.

An assessment was made on the effectiveness of:

- The removal of bacteria via the ventilation system, through exhaust grilles, and
- Killing bacteria with UVGI.

In its totality, this document is intended to provide an architectural / engineering tool for good design practice that is generally applicable to conventional isolation room use.

The key conclusions from the research are:

- The number of particles vented out of the room increases with ACH. The variation with ACH is more pronounced for winter cases with no baseboard heating than summer cases. This is demonstrated in Figure 0.1 and 0.2.

- Cases with high exhaust grilles vent out more particles than low exhaust grille systems for the particle release points considered in this study for the low to medium ACH values considered. This trend is not present at the higher values of ACH considered.

- The results show that there is little advantage in increasing the ventilation rate in the room beyond 6 ACH for summer cases, or winter cases with baseboard heating in terms of increasing the effectiveness of the UVGI. This value is also consistent with the results of a concurrent study done by Memarzadeh and Manning (2000) examining thermal comfort and uniformity in patient rooms. In particular, this study suggests that the optimum ventilation rate for similar winter conditions considered in this study is 6 ACH to provide good levels of thermal comfort and uniformity. This value is also suitable for summer condition cases. This can be clearly seen in Figures 0.3 and 0.4.

- The number of viable particles in the room is generally lower for high exhaust grille system compared with low exhaust grille system cases for the low to medium ACH values considered.

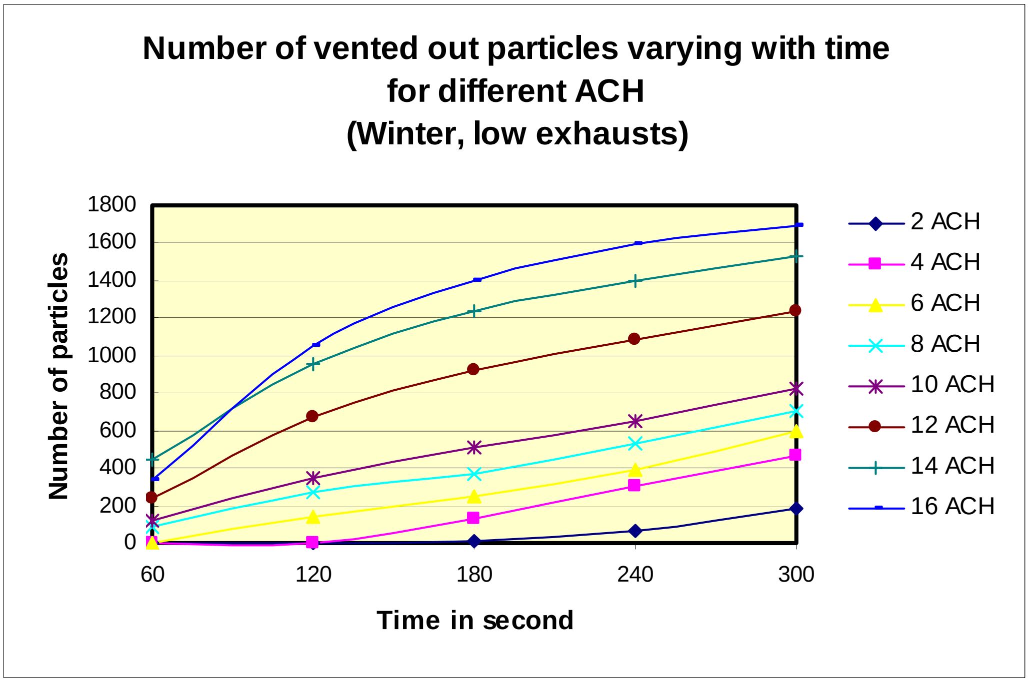

Figure 0.1. *Number of vented out particles with ACH change (Winter)*

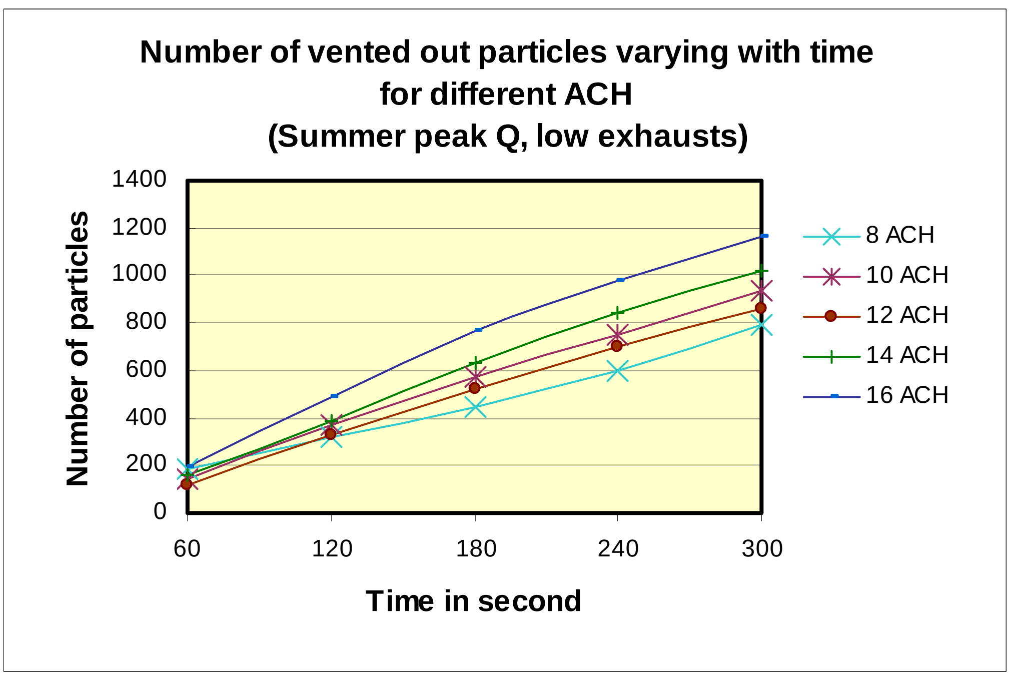

Figure 0.2. *Number of vented out particles with ACH change (Summer)*

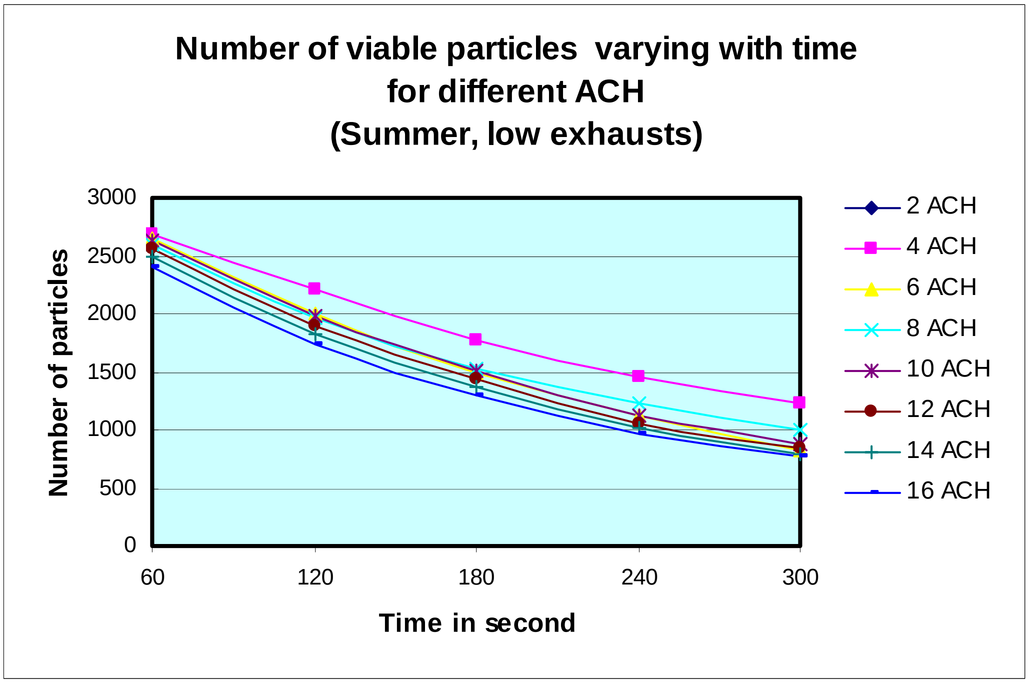

Figure 0.3. *Number of viable particles with ACH change (Summer, peak T).*

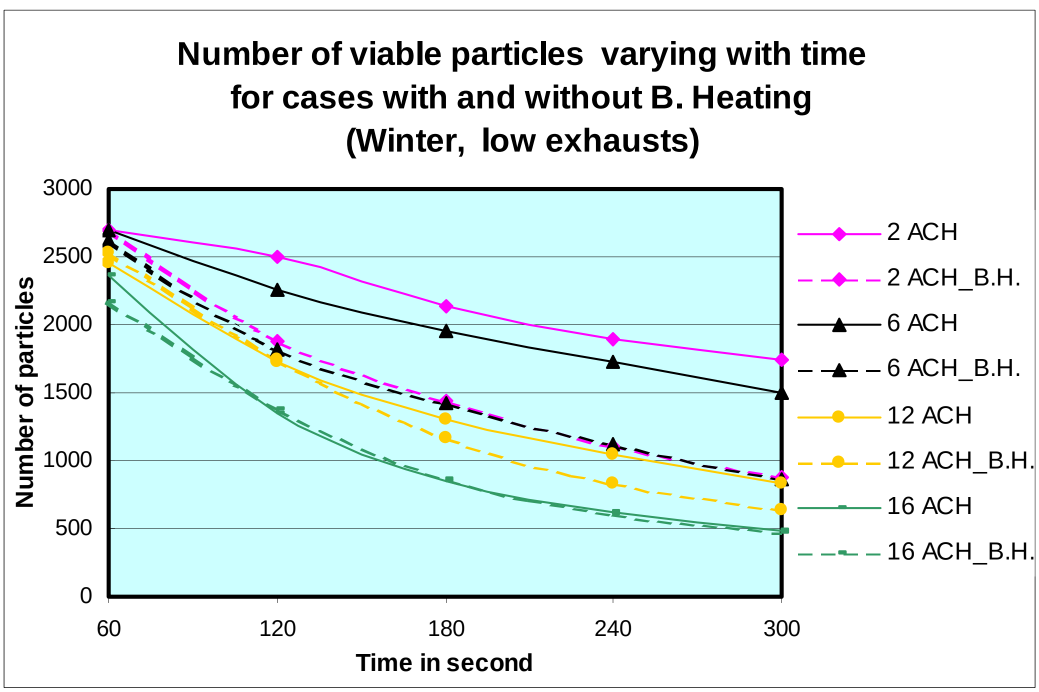

Figure 0.4. *Number of viable particles with /without Baseboard Heating*

- For the effectiveness of UVGI, the best ventilation rates seem to fall in the range of 10-12 ACH for winter (no baseboard heating) and at 6ACH for summer with the UVGI location being studied. This is demonstrated in Figures 0.5 and 0.6.

- UVGI does result in the killing of a significant percentage of the viable particles in the room.

- Changing the location of the UV lamp and increasing its intensity result in a higher percentage of particles being killed. However, further increases in UV intensity show diminishing returns. This is demonstrated in Figures 0.7 to 0.9.

- The addition of baseboard heating results in better kill UVGI rates irrespective of ACH. Baseboard heating should therefore be used in winter cases, especially at low ACH.

- The winter plots show that there is an increase, then a reduction in the number of killed particles by increasing ACH. For the summer case, there is a general reduction in the number of killed particles on increasing ACH. The reason for this is that, as the ACH is increased and mixing is improved, the particles dwell less time in the UV zone.

- The addition of UVGI offers a clear advantage over increasing the ACH in the ventilation system. For example, for the UV1 case, an increase from 6 to 16 ACH results in a drop of 30% in the viable particle total if UVGI was not present for summer cases. However, the introduction of UVGI results in a reduction of 68% in the number of viable particles at 6 ACH. At current costs, the inclusion of UVGI is also considerably cheaper ($1742 compared with $9000 over a ten year period for a 200 ft^2 room).

- The reduction in the number of viable particles on doubling the UV intensity for summer cases and winter cases with baseboard heating at 6 ACH is around 20%. This indicates that increasing the UV intensity is not necessarily cost effective. At current costs, this would mean an increase of $1615 ($4844 for the UV3 system compared with $3229 for the UV2 system over a ten year period for a 200 ft^2 room), the majority of which is associated with installation, not running costs.

While the emphasis here has been on the use of UV, if UV was not included, some of the conclusions listed above are still applicable. The reason for this is that the heat dissipated from the UV lamp is not significant, enough to affect the airflow pattern. In particular:

- Baseboard heating should be used in winter cases to improve mixing in the room. This reduces the influence of ACH.

- High level exhausts are generally better than low level exhausts in terms of vented percentage for the particle release points considered in this study, particularly at low to medium ACH. This trend is not present at the higher values of ACH. However, note that patient rooms display better air conditions for low exhausts at low to medium ACH, as demonstrated by Memarzadeh and Manning (2000).

Further, it should be noted that, although this study looks specifically at isolation rooms, the principles could be applied to other areas within a health care facility where infection from TB is a possibility, such as waiting rooms, diagnostic rooms and toilets.

Based on the above, the following design recommendations are made:

1/ Baseboard heating is included in winter scenarios. The addition of baseboard heating is roughly equivalent to an increase of 6 ACH.

2/ UVGI offers significant advantages in terms of reducing the number of viable particles, and should be included.

3/ It is recommended that a value of 6 ACH be utilized as a ventilation rate for extreme summer conditions, and winter conditions with baseboard heating. There are three reasons for this recommendation:

i/ Above 6 ACH, the number of particles killed by UVGI is not increased significantly except for very high values of ACH.
ii/ The cost of each additional ACH is very expensive at current costs, in particular, around \$90 per year per ACH for a single $1800 ft^3$ room. For the same figure of \$90 per year, an extremely efficient UVGI lamp can be located in the room. (Per assumptions in Section V)
iii/ The value of 6 ACH is also sufficient to provide good thermal comfort and uniformity in the room.

4/ Doubling the UV intensity only results in a further 20% reduction in the number of viable particles, and is expensive in terms of the initial outlay of equipment. From this viewpoint, expensive UV systems are not that cost effective, and the current recommendation of 30W per $200\ ft^2$ (First et. al Part II (1999)), which represents the UV1 location scenario in this study, is adequate.

5/ The UV lamp should be located 7.5’ above floor level. No clear conclusion can be drawn as to its location in the room because of the cases considered. However, the placement of the UV lamp immediately above the bed is reasonable so that it is directly out of eye contact with the patient.

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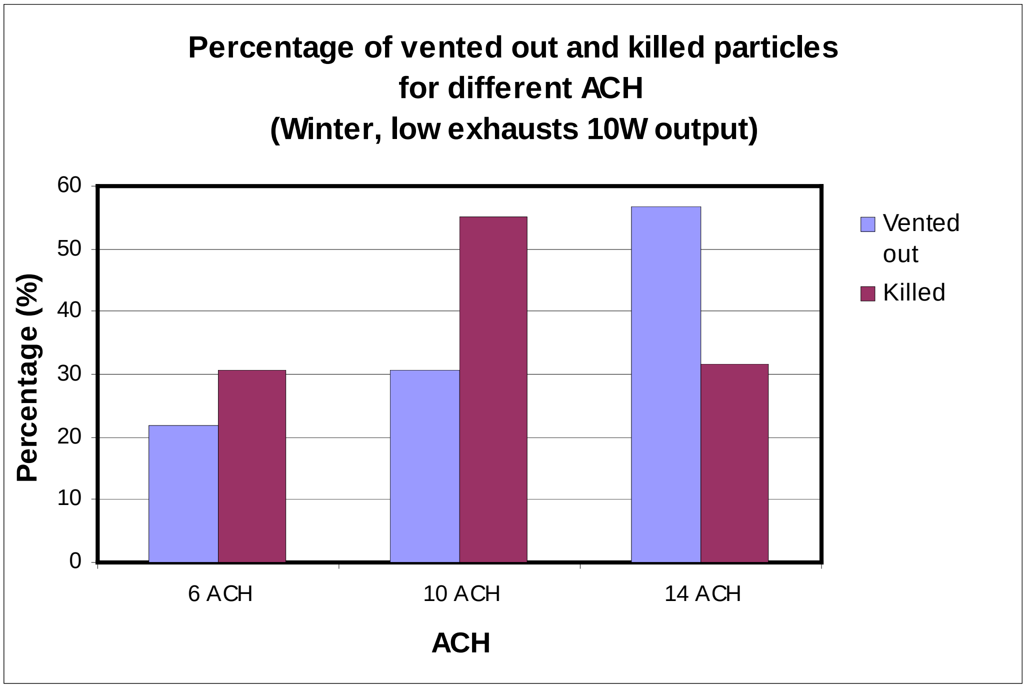

Figure 0.5. *Comparison of killed and vented particles at 300s for winter condition*

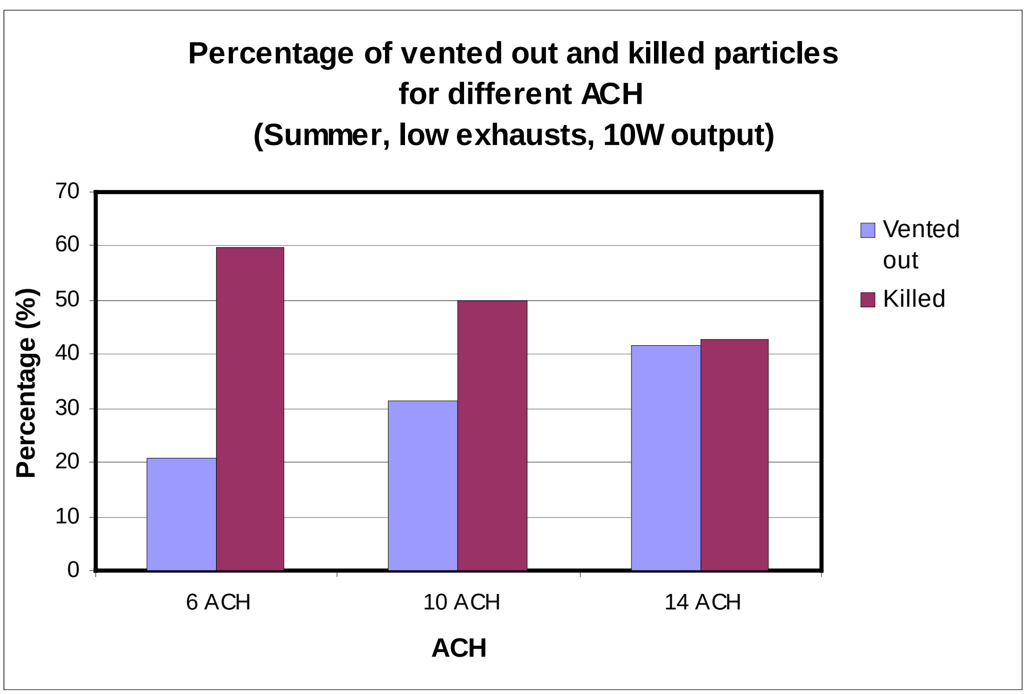

Figure 0.6. *Comparison of killed and vented particles at 300s for summer condition*

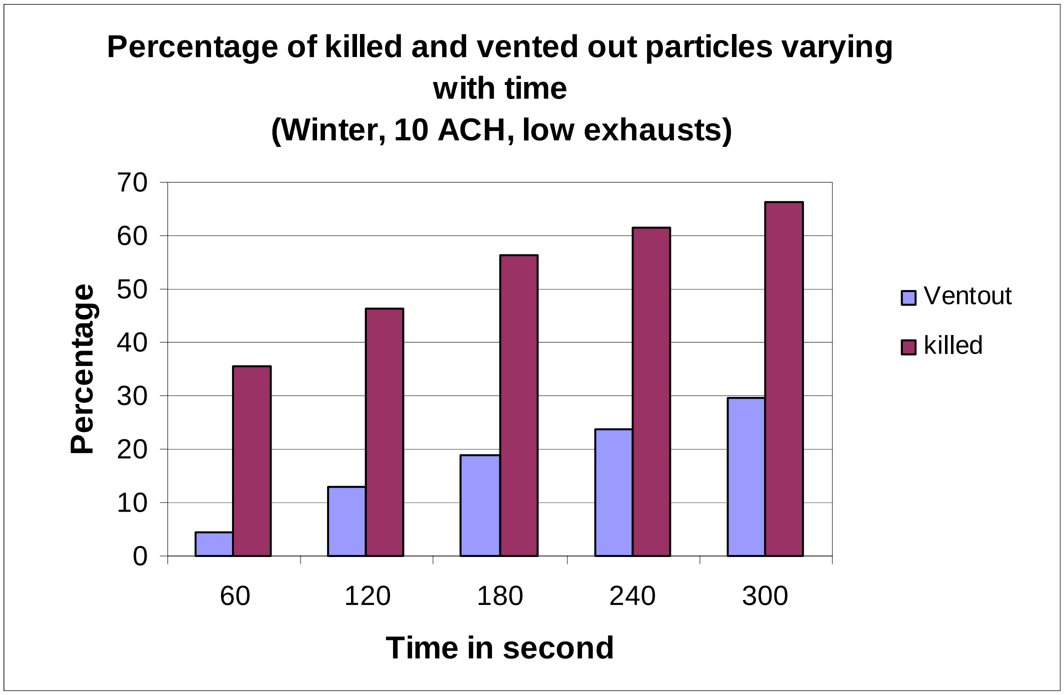

Figure 0.7. *Killed/ vented particle percentages: 10W UV output*

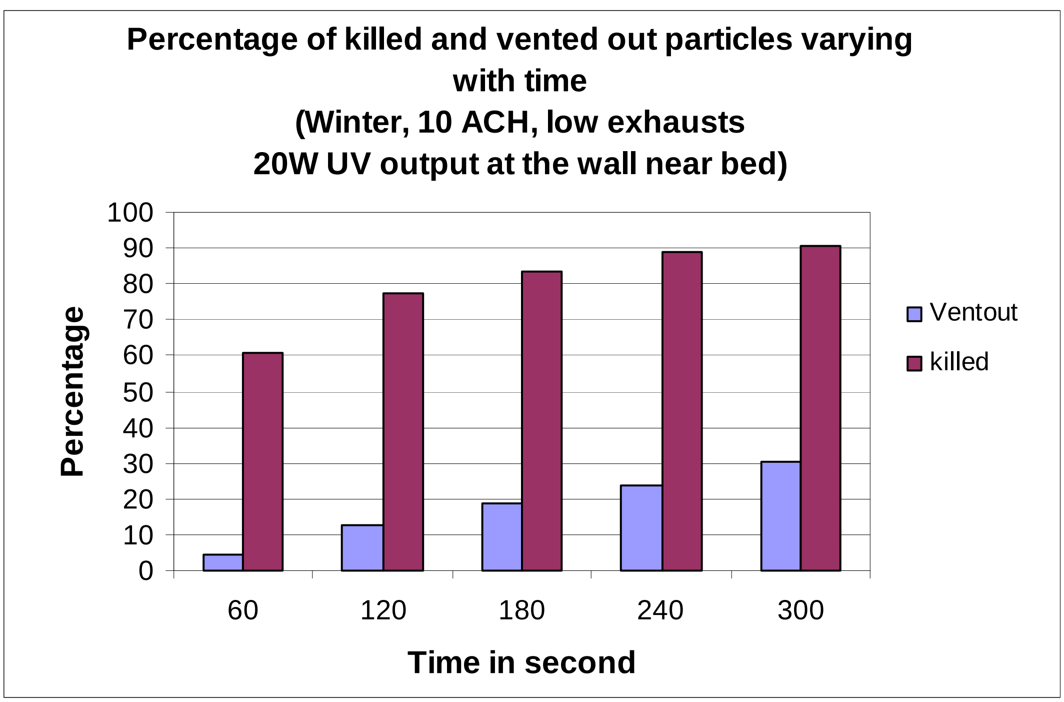

Figure 0.8. *Killed/ vented particle percentages: 20W UV output*

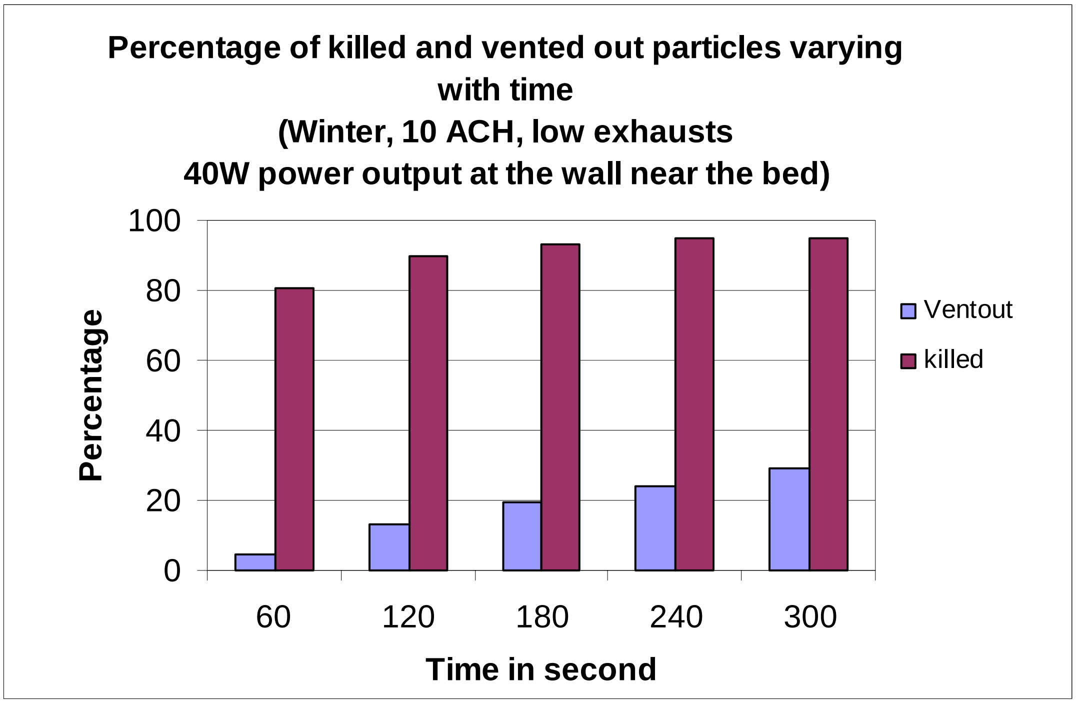

Figure 0.9. *Killed/ vented particle percentages: 40W UV output*

ACKNOWLEDGEMENTS

I wish to express my special thanks to Dr. Melvin First of Harvard University School of Public Health, for his generous assistance in reviewing this document, and providing advice and assistance throughout the development of the project.

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Also, I am grateful to everyone who participated in progress meetings for their valuable input.

Farhad Memarzadeh
Principal Investigator

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FOREWORD

Upper room UVGI holds promise of greatly lowering the concentration of airborne bacteria in a hospital isolation room. As it is designed to kill bacteria that enter the upper irradiated zone, the efficiency of the UVGI is highly reliant on vertical room air currents. An isolation room should be equipped with ventilation system that provides flow pattern not only with balanced thermal comfort and air quality, but also ensures bacteria to stay in the UV zone sufficient time to be killed.

In this project, a systematic study on minimizing the risk from airborne organisms in hospital isolation rooms with the important parameters, as listed below, was conducted.

- Ventilation flow rate
- Locations of air supplies/exhausts
- Supply air temperature and external temperature
- Location of the UV fixture(s)
- The power of the UV output

The study proved that increasing ventilation rate does not necessarily guarantee effective control of the spread of airborne infection, and that the design guidance for isolation rooms should rely on fully understanding the effect of the complex interaction of room airflow and U-V treatment systems.

Why You Should Read and Refer to This Document

Current CDC guidelines indicate that a ventilation rate of 12 ACH is recommended for new isolation room facilities, and 6 ACH for the ones already built. Recent studies, however, indicate that the thermal comfort of the patient can be severely compromised through an inappropriate ventilation system (Memarzadeh and Manning (2000)). Further, these values of ACH do not guarantee that the ventilation system will effectively remove TB particles from the room through venting, nor do they guarantee that the particles will be delivered to UV zones effectively.

This document is intended to provide valuable information to aid the design of isolation room ventilation system in conjunction with UV lamps, so that the maximum number of particles are killed or removed as quickly as possible. As the heat dissipated by the lamps themselves is small, and can effectively be ignored from the calculations, the document also offers guidelines for the most appropriate ventilation system and flow rate when no UVGI is present.

How To Use This Document

This document describes the isolation room project and its findings. The various appendices at the end of the document present relevant summary data and comparisons of parameters considered.

The document is divided into nine major sections:

1. Introduction	6. Summary
2. Purpose of the Study	7. Glossary of Terms
3. Numerical Methodology	8. References
4. Model Set-Up	
5. Results	

Section I:
Provides background information that will aid the understanding of the project. This should be read by all.

Section II:
Provides outline of objectives of project.

Section III:
Provides an explanation of the methodology used. It provides a basis for those with no knowledge of computational fluid dynamics (CFD) or particle tracking techniques. It includes description of Navier-Stokes equations, Lagrangian particle tracking equations and boundary condition used in this project. It also includes the results of particle tracking tests used to establish the validity of the approach, and outlines the application of the UV field to the room, and the description of the locations and intensities of the lamps. Finally, the bacteria killing methodology is outlined.

Section IV:
Outlines the CFD baseline model, including such details as the physical geometry chosen, the weather conditions considered, and an explanation of the ventilation system. The section also includes a table summarizing the description of 40 isolation room configurations considered in this project.

Section V:
Provides a description of the results presentation, notes on how the different totals were counted, as well as the analysis results.

Section VI
Provides a summary of the results from the project, including recommendations with regards to ventilation rate and UV location.

Section VII
Glossary of terms

Section VIII
Complete list of references.

Road Map for Book