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A PRELIMINARY METHODOLOGY FOR
EVALUATING THE COST-EFFECTIVENESS
OF ALTERNATIVE INDOOR AIR
QUALITY CONTROL APPROACHES

Prepared for

Office of Radiation and Indoor Air

Prepared by

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FOREWORD

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E. Timothy Oppelt, Director
National Risk Management Research Laboratory

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A PRELIMINARY METHODOLOGY FOR EVALUATING THE COST-EFFECTIVENESS OF ALTERNATIVE INDOOR AIR QUALITY CONTROL APPROACHES

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NOTICE

ABSTRACT

A simplified methodology is defined that can be used by indoor air quality (IAQ) diagnosticians, architects/engineers, building owners/operators, and the scientific community, for preliminary comparison of the cost-effectiveness of alternative IAQ control measures for any given commercial or institutional building. Such a preliminary analysis could aid the user in initial decision-making prior to retaining experts (such as HVAC engineers and building modelers) who could conduct a rigorous evaluation.

This preliminary methodology consists of text, logic diagrams, and worksheets that are intended to aid the user in:

1) assessing which IAQ control option(s) might be applicable in the specific building being addressed;

2) designing alternative control measure [involving increased outdoor air (OA) ventilation, air cleaning, or source management steps], and developing rough installed and operating costs for these measures;

3) estimating the approximate effectiveness of the alternative control measures in reducing occupant exposure to contaminants of concern; and

4) comparing the cost-effectiveness of the alternative control measures under consideration, to aid in selection of the optimal control approach.

In this report, the term "cost-effectiveness" refers to the incremental increase in annualized cost per unit reduction in exposure by the building occupants. "Exposure" is the number of person-hours per year during which the occupants are exposed to a unit concentration of the contaminant of concern; in this report, the units of exposure are (mg/m^3)-person-hr/yr. The most cost-effective control approach is the one offering the lowest annualized cost per unit reduction in exposure.

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METRIC CONVERSION FACTORS

Although it is EPA's policy to use metric units in its documents, non-metric units have been used in this report consistent with common practice in the heating, ventilating, and air-conditioning industry. Readers more accustomed to the metric system may use the following factors to convert to that system.

Non-Metric	Times	Yields Metric
inch (in.)	0.0254	meter (m)
foot (ft)	0.305	meter (m)
square foot (ft^2)	0.0929	square meter (m^2)
cubic foot (ft^3)	0.0283	cubic meter (m^3)
cubic foot per minute (cfm)	37	liters per second (L/s)
pound (lb)	0.454	kilogram (kg)
pound per cubic foot* (lb/ft^3)	1.60×10^7	milligrams per cubic meter* (mg/m^3)
gallon (gal.)	3.78×10^{-3}	cubic meter (m^3)
inch of water (in. WG)	249	pascals (Pa)
degrees Fahrenheit (°F)	5/9 (°F - 32)	degrees Celsius (°C)
British thermal unit (Btu)	0.293	watt-hour (W-hr)
therm (100,000 Btu)	29.3	kilowatt-hours (kW-hr)
British thermal unit per hour (Btu/h)	0.293	watt (W)
ton (of refrigeration) (12,000 Btu/h)	3,520	watts (W) of cooling capacity
horsepower (hp)	0.746	kilowatt (kW)

* Note: By convention, indoor concentrations are expressed in metric units (mg/m^3) throughout this report.

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SECTION 1

OBJECTIVES AND APPROACH

1.1 INTRODUCTION

The control techniques for reducing the concentrations of indoor air pollutants can be viewed as falling into three broad categories:

1) ***improved ventilation*** -- including increases in the quantity of outdoor air (OA) supplied to a building, and/or improvement in the distribution and mixing of the supply air (OA plus recirculated air) throughout the various zones in the building;

2) ***air cleaning*** -- typically involving devices mounted in the central HVAC ducting, or self-contained devices (having their own fans) mounted in the occupied zones, capable of removing particulate or gaseous contaminants from the circulating air; and

3) ***source management*** -- which can include removal of all or part of the source, replacement of the source by a lower-emitting alternative, treatment of the source to reduce emissions, re-location of the source, re-scheduling of the timing when the source is allowed to be active (to avoid occupied periods), or re-location of the building occupants in order to reduce occupant exposure.

There are different conditions under which each of these approaches is most likely to be included -- or excluded -- as a candidate for IAQ control in a particular building. In some cases, one of the approaches might be the only logical candidate.

Improved ventilation will be an obvious selection in cases where diagnostics in an existing building show that an IAQ problem in one zone of the building results from inadequate distribution of supply air to that zone. Increases in OA to the building as a whole are a logical choice when the indoor pollutants are being generated throughout the building (so that source management is potentially a less attractive option), when only moderate reductions in indoor concentrations are needed (since practical increases in OA rates will likely be capable of only moderate degrees of contaminant dilution), and when there is excess capacity in existing HVAC heating and cooling coils (so that modifications to the existing mechanical system will not be required to accommodate the increased OA). When the pollutant source is isolated in a localized area, localized exhaust of that area -- considered here to fall into the category of "improved ventilation" -- can be a logical selection, serving both to increase the ventilation rate in that area (by drawing increased supply air from adjoining zones inside the building) and to prevent the contaminants in that area from being dispersed throughout the building. But improved ventilation/increased OA will clearly not be a logical choice when the outdoor air is the pollutant source, unless that problem can be addressed by re-locating the OA intake.

Air cleaning will be an obvious candidate whenever the outdoor air is the pollutant source, and this problem cannot be addressed by re-locating the OA intake or the source that is creating the outdoor concentrations. In such cases, increased ventilation is not an option. Air cleaning would also be a clear candidate in those cases where the pollutants are being generated throughout the building (complicating the application of source management), when the pollutant of concern is amenable to air cleaning, and when the required reduction in pollutant concentration is greater than the moderate levels practically achievable by increased ventilation. (In concept, a 100% efficient air cleaner mounted in the central HVAC ducting -- through which the building air is recirculated at a typical rate of 7 air changes per hour -- might be expected to reduce indoor concentrations by about 85% to 90%. By comparison, increasing the OA ventilation rate from 20 cfm/person to, say, 40 or 60 cfm/person would reduce concentrations by only about 50% to 65%.) Where an air cleaner would have to be retrofitted into the ducting of an existing HVAC system, air cleaning will more likely be a candidate when the existing air handler has sufficient excess capacity to handle the increased pressure drop created by the air cleaner.

Source management will be the logical selection whenever the source can be conveniently removed or otherwise managed. This is most likely to occur in cases where the source is in a localized area and is readily accessible, or when the source is an activity that can be easily modified. When a significant portion of the source is amenable to source management, this approach can be the most effective of the three approaches in reducing occupant exposure.

Consideration of the control costs, and of the effectiveness of the controls in reducing occupant exposure to indoor pollutants, can be valuable when selecting and designing the IAQ control approach (or combination of approaches) for a particular building. In cases where the logical control approach appears obvious *a priori*, a cost-effectiveness analysis might reveal that modifications in the design or implementation of this approach -- impacting its effectiveness -- could result in a lower cost per unit reduction in exposure. In cases where the preferred control approach is *not* apparent beforehand, a cost-effectiveness analysis could indicate which of the alternative approaches would provide the lowest cost per unit reduction, and the specific design for that approach that would minimize the cost.

1.2 OBJECTIVE

The objective of this study was to develop a preliminary methodology for utilizing cost-effectiveness considerations in selecting and designing the IAQ control approach (or combination of approaches) for any given commercial or institutional building. This methodology was to be applicable for the variety of different commercial and institutional building types (e.g., offices, retail establishments, schools, hospitals), and for both existing buildings (retrofit) and new construction.

This preliminary methodology guides the user through:

1) an assessment of which IAQ control option(s) might be applicable in the specific building that the user is addressing;

2) a rough estimation of the installed costs, and the operating and maintenance (O&M) costs, associated with the identified control technique(s) in that building, where possible;

3) a rough estimation of the effectiveness of the control technique(s) in that building, where possible; and

4) a comparison of the cost-effectiveness of the control techniques, based on the estimated costs and effectiveness, to enable a preliminary screening of the alternatives.

The potential users of such a methodology were envisioned as including IAQ diagnosticians, architects/engineers, building owners/operators, and the scientific community. From a practical standpoint, this preliminary methodology might assist a building operator or an IAQ diagnostician in assessing the potential cost-effectiveness of, say, increased ventilation before hiring an HVAC engineer to consider modifications to the mechanical system. Or it could aid the scientific community in assessing, e.g., what performance will have to be achieved with air cleaners (in terms of, say, the required carbon lifetime in granular activated carbon units) in order for air cleaning to be more cost-effective than increased ventilation in particular types of applications. It could suggest to an architect how great a premium might be paid for low-emitting materials in constructing and furnishing a new building, before this source management approach becomes less cost-effective than other alternatives.

Only a preliminary methodology was attempted here, involving rough estimates. Many site-specific variables will impact the performance and cost of each control technique (and hence the technique's cost-effectiveness) in any given building. These include variables associated with the building, the HVAC system, the nature and location of the IAQ pollutant source(s), the building occupancy pattern, and the design and operation of the IAQ control system. Moreover, a rigorous estimation of the control system costs, and the system's effectiveness in reducing occupant exposure, would require the expertise of, e.g., HVAC engineers and computer modelers, applied specifically to the building under consideration. A methodology that could guide the user through a rigorous assessment of each of the several classes of variables for any selected building utilizing the required expertise -- and that, based on this assessment, could then provide definitive site-specific guidance regarding control selection and design -- would require a comprehensive compilation of charts and nomographs, and/or a computer-based expert system. Such a rigorous methodology was beyond the scope of this effort.

Given the large number of site-specific variables that determine the cost and effectiveness of IAQ controls in a specific building, it was recognized *a priori* that the preliminary methodology developed here would necessarily be fairly general if it were to be broadly applicable to many different buildings. Accordingly, the preliminary methodology serves as a general framework for site-specific cost-effectiveness analysis by the user, assisting in the thought process but not serving as a "cook-book".

1.3 APPROACH

To assist the user in identifying which IAQ control approaches might be considered in a specific building (Item 1 in Section 1.2 above), a series of logic diagrams has been prepared indicating the conditions under which improved ventilation, air cleaning, and source management are most likely to be candidates. These logic diagrams are presented and discussed in ***Section 2*** of this report.

To aid in estimating the installed, the O&M, and the annualized costs associated with the control techniques (Item 2 in Section 1.2 above), Worksheets 1 through 13 in Appendix A have been prepared, illustrating approaches for:

a) making key design decisions to enable the costing of specific approaches (including, e.g., determination of the amount of additional ventilation air required, or the required per-pass removal efficiency of an air cleaner); and

b) roughly estimating the installed, the operating, and the maintenance costs of specific controls, generally utilizing simplifying "rules of thumb" and default values (for, e.g., equipment and utilities costs).

For more rigorous designs and cost estimates, the user is referred to HVAC engineers and equipment vendors, and to computer modelers familiar with building energy and cost modeling. The simplified cost estimation approach is described in ***Sections 3 through 5***.

To aid in estimating the effectiveness of the techniques in reducing occupant exposure (Item 3 in Section 1.2 above), Worksheets 14 and 15 (in Appendix A) are introduced in ***Section 6***, for approximating these reductions for each of the control approaches. These worksheets assist in the estimate of: *absolute* reductions in exposure, where such an estimate is possible; or *relative* reductions in exposure achieved by one control approach compared to another, where absolute estimates are not feasible. For more rigorous estimates, the user is referred to computer modelers capable of more rigorously computing pollutant concentrations and occupant exposures throughout the building considering building air flows, source decay, etc.

To aid in a preliminary comparison of the cost-effectiveness of the alternative IAQ control measures that are being evaluated (Item 4 in Section 1.2 above), procedures are presented in ***Section 7*** for estimating the *absolute* or *relative* cost-effectiveness of the alternatives (depending upon whether absolute or relative exposure reductions were estimated in Section 6). Methods for presenting and interpreting these cost-effectiveness results are described, to aid in the selection of an optimal IAQ control approach.

In this report, it is assumed that -- prior to the implementation of this methodology -- the necessary diagnostic testing has already been completed to define the nature and source of the IAQ problem that is to be addressed (EPA, 1991). Thus, such "problem-definition" diagnostic testing is not included in this methodology. However, the methodology in some cases suggests additional information gathering to aid in evaluating alternative control approaches.

1.4 CONSIDERATIONS REGARDING "EFFECTIVENESS"

In this methodology, the "effectiveness" of an IAQ control measure refers to the degree to which the control measure reduces occupant exposure to the pollutant of concern. "Exposure" in a given building would take the general form:

the pollutant concentration to which each individual occupant is exposed during any given hour of occupancy in the building

times

the number of hours of occupancy in the building by that occupant over the total period of interest (e.g., over a year)

times

the total number of occupants.

Exposure would thus have units of (concentration) x (persons) x (time). If the period of interest were one year, typical units of cumulative exposure would be

$$(mg/m^3) \bullet \text{person} \bullet \text{hr per year.}$$

[Note: By convention, indoor concentrations are shown in metric units throughout this report.]

The effectiveness of a control measure would be the change in exposure achieved by that control, i.e.,

$$\text{effectiveness} = -\,\Delta(\text{exposure}).$$

The minus sign indicates that a negative change (a reduction) in exposure represents a positive effectiveness.

Correspondingly, the "cost-effectiveness" of the measure would be expressed as:

$$\text{cost-effectiveness} = -\,\Delta(\text{cost})/\Delta(\text{exposure}),$$

i.e., the unit increase in control cost per unit reduction in occupant exposure. A control measure having good cost-effectiveness would charge a (relatively) low cost for a (relatively) large reduction in exposure. Where the effectiveness is expressed as the exposure reduction *per year*, cost is commonly expressed as an average annualized amount, including average annual O&M costs plus an annual capital recovery figure accounting for the installed costs.

As used here, the term "effectiveness" addresses only the reduction in the concentrations to which occupants are exposed over time. It does not address the reductions in actual contaminant uptake by the occupants (the "absorbed dose"), nor any resulting health benefits.

Since both the cost and the effectiveness of a given IAQ control category (e.g., improved ventilation) will depend upon the degree of control that the control was designed to achieve, it is clear *a priori* that the cost-effectiveness will vary as a function of effectiveness. Also, more effective control approaches (such as source management) will sometimes have a higher cost than other, less effective approaches, but could turn out to be more cost-effective at their greater level of effectiveness. Thus, it is apparent that -- in a rigorous analysis -- the cost-effectiveness of a control approach would have to be plotted as a function of effectiveness, in order to enable a fair comparison among alternative approaches at a given level of effectiveness.

It should be noted that the absolute value for occupant exposure in a given building, with and without control measures, will involve a fairly sophisticated computation. This computation would require a mass balance -- addressing source/sink characteristics and building/HVAC flow dynamics -- to determine indoor concentrations as a function of time and as a function of location within the building. The detailed occupancy pattern of the building would then be superimposed on these mass balance results. The concentration at a given location in the building will vary hourly, depending upon, e.g., HVAC operation and pollutant source decay rates. The exposure experienced by any individual occupant will depend upon which hours that occupant spends in which locations within the building, a pattern that will vary from occupant to occupant. A fairly sophisticated computer model will be required to compute and sum the hourly exposures of each individual occupant over the course of a year, if rigorous, absolute exposures are to be determined in computing control effectiveness.

Even where a computer model is used to compute an absolute control effectiveness, one might commonly choose to assess the effectiveness for selected, representative occupants, rather than the total for all occupants in the building. In such cases, the effectiveness might be expressed as the reduction in [(mg/m^3) • hr] per representative person per year.

Where the user wishes to make preliminary estimates of effectiveness (and cost-effectiveness) without a computer model, Worksheets 14 and 15 (Appendix A) are introduced in Section 6 for developing either:

a) rough estimates of the absolute reductions in exposure with a given control approach, which -- using the procedures in Section 7 -- permit estimation of the approximate cost-effectiveness of that approach; or

b) the *relative* reduction in exposure, permitting estimation of the *relative* cost-effectiveness of one control approach vs. another -- e.g., the cost-effectiveness of Control Option 1 divided by that of Control Option 2.

This latter procedure avoids the need to calculate absolute values of exposure.

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SECTION 2

IDENTIFICATION OF CANDIDATE IAQ CONTROL OPTIONS

As indicated by Item 1 in Section 1.2, the first step in this preliminary methodology is the identification of those IAQ control options that might be considered as candidates in any particular building that the user might be addressing.

2.1 SELECTING BETWEEN IMPROVED VENTILATION, AIR CLEANING, AND SOURCE MANAGEMENT

Figures 1A, 1B, and 1C are logic diagrams illustrating the thought process that can be used in deciding which control approaches will be applicable, given any set of circumstances that the user is encountering.

The user begins with Figure 1A, which addresses the case where the source creating the indoor air problem is located outdoors. If the source is not outdoors, the user proceeds to Figure 1B, which addresses the case where the source is indoors but the IAQ problem is localized within the building. If the source is indoors and the IAQ problem is distributed throughout the building, the user proceeds to Figure 1C.

The logic sequence begins in the upper left in each figure. "Yes" responses to questions in the logic sequence lead the user toward the right, and "No" responses lead the user downward, until a suggestion is ultimately reached regarding whether ventilation, air cleaning, or source management appears to be the more logical approach.

Where the logical approach appears to be improved ventilation, the figures walk the user through additional logic steps intended to better define the specific nature of the appropriate improved ventilation step. These additional steps sometimes refer the user to Appendix A worksheets that are introduced in Section 3, to assist in designing and costing the improved ventilation method. Where the logical approach appears to be air cleaning or source management, Figures 1A-1C refer the user to other figures, presented later in Section 2, that assist in the design and costing of these approaches, to the extent possible.

These logic diagrams ask a series of questions. In some cases, the answers to the questions might be readily apparent, or might have been obtained during problem-definition diagnostic testing conducted prior to the application of this methodology. In other cases, where the answers are not known, the questions are suggesting additional information-gathering or diagnostic testing that might be needed to aid in control selection.

2.1.1 Source(s) Located Outdoors

Figure 1A illustrates the logic in cases where the source(s) creating the indoor problem is (are) located outside the building.

The outdoor pollutants will be entering the building either via the outdoor air, or via soil gas. When soil gas is the source, one can consider additional OA supply into the building, either to adjust the indoor pressure on the ground floors of the building (to reduce or prevent soil gas entry), or to dilute the entering soil gas contaminants. In either case, such an increase in OA is considered an "improved ventilation" control approach for the purposes of this methodology.

If neither of these OA-related steps would adequately control the soil gas contaminants, then soil depressurization (and/or perhaps foundation sealing) would be the only alternatives. These are considered to be "source management" approaches.

If the outdoor air is the source of the indoor pollutants, the first question is whether this problem results because the OA intake for the building's mechanical system is located too near to a localized outdoor source (such as a loading dock or a dumpster). If this is the case, the user should explore the possibility of moving the OA intake ("improved ventilation") or re-locating the outdoor source ("source management").

If re-location of the intake or the source is not an option, the primary alternative would seem to be installation of an air cleaner on the incoming OA. For completeness, Figure 1A suggests that one might also consider reducing the OA intake; this will probably not commonly be a practical approach.

Mechanically supplied OA is generally the predominant route by which the contaminated outdoor air will enter the commercial and institutional buildings being addressed in this document. Thus, Figure 1A and the preceding discussion focus on the OA that is being introduced by the mechanical system. In some cases, unacceptable amounts of the outdoor contaminants might also enter the building via uncontrolled infiltration through the building shell. Re-location of the mechanical system's OA intakes, or installation of an air cleaner to treat the incoming OA, will not address this uncontrolled OA entry. If the contaminants in infiltrating air cannot be reduced by re-locating the outdoor source ("source management"), other options to consider would include: a) supplying increased OA through the mechanical system (with an air cleaner treating the intake air), to pressurize the building and thus prevent the infiltration ("improved ventilation" combined with "air cleaning"); or b) an appropriate air cleaning approach. Possible air cleaning approaches could include: installation of a central air cleaner in the mechanical system, treating all of the recirculating building air; or, if the infiltration is occurring only in certain zones, installation of self-contained air cleaners treating those zones.

2.1.2 Localized Problem Resulting from Indoor Sources

Figure 1B illustrates the logic in cases where the pollutant source is indoors, but the IAQ problem is localized within the building (e.g., appears to be limited to a particular zone or room).

In many such cases, the localized problem results from a localized source -- e.g., an improperly vented storage area for chemicals, occupant activities, water damage (and hence biological contamination), or new carpeting or furniture in that zone or room. The first question to ask in such cases is whether in fact there is such a localized source creating the problem, and whether this source can reasonably be removed or reduced. If a local source is responsible, such a source management approach will generally be the most effective at reducing (or eliminating) contaminant concentrations. And, since the source is confined to a fairly limited area, this approach might well be the most conveniently implemented as well.

If a localized source is not responsible for the IAQ problem, some localized problem with the ventilation system must be responsible. For such cases, Figure 1B inquires whether: a) the localized area is receiving proper supply air flow from the HVAC system; and b) whether this supply air is being adequately mixed within the localized area. If inadequate localized ventilation is the cause of the problem, appropriate modifications to the air distribution system ("improved ventilation") would appear to be the logical solution.

In some cases, the source of the localized IAQ problem will be a localized source that is not amenable to being removed or reduced, or that cannot be reduced to a sufficient extent to adequately reduce contaminant levels. For example, the source might be some occupant activity that cannot be curtailed, such as food processing, graphics, or laboratory activities. In cases where source management is not a practical (or cost-effective) complete solution with a localized source, improved ventilation approaches should be considered, increasing air supply to the area. A common method for increasing supply air to a localized area containing a source is to exhaust air from that area to outdoors. This method provides the combined benefit of increasing local ventilation by drawing air from adjoining areas of the building (diluting the contaminant), while also depressurizing the area (preventing the contaminant from dispersing to other zones in the building). Figure 1B also shows the option of modifying the HVAC system to provide more air to the area directly via the supply ducting, an option that might be accompanied by local exhaust (to ensure increased local ventilation). Where source management and/or improved ventilation are not cost-effective, one can also consider the option of air cleaning, perhaps using a self-contained air cleaner (incorporating its own circulating fan, independent of the HVAC system) treating only the localized area.

The logic diagrams necessarily require "yes" or "no" answers, and their layout might thus imply that only one possible ultimate end-point. In practice, the user might find that an answer to certain logic questions is "maybe". For example, source removal might be one possible solution, or partial solution, but must be compared against localized exhaust ventilation as another, possibly more cost-effective alternative.

2.1.3 Building-Wide Problem Resulting from Indoor Sources

Figure 1C illustrates the logic when the pollutant source is indoors, and the IAQ problem is distributed throughout the building.

The first question asked in the figure is whether the building-wide problem results from localized emissions indoors that are being distributed throughout the building by the HVAC system. Where this is the case, source management addressing that localized source, or isolation of the source (including exhaust ventilation of the area where the source is located), would appear to be logical approaches to be considered first.

If the indoor source is not localized, but is building-wide, the next question is whether an approach other than improved ventilation should be considered at the outset. While source management can sometimes be more difficult to implement when the sources are distributed throughout the building, there will be cases when it will be a strong candidate on a building-wide scale. For example, low-emitting building materials and furnishings can be considered when a new building is being planned.

A central question determining whether air cleaning should be considered initially is whether the pollutant of concern is reliably removed by commercially available air cleaners. The pollutant most reliably removed by indoor air cleaners is particulates (ASHRAE, 1996). Technically, some gaseous contaminants can also be removed by indoor air cleaners (ASHRAE, 1995), although gaseous indoor air cleaners have not found such wide application in practice. Where the pollutant emission source is building-wide, it will probably often be most cost-effective to mount the air cleaner in the central HVAC ducting, rather than using self-contained units (discussed previously as an option for localized sources).

If building-wide source management and air cleaning are not clear-cut alternatives at the outset, the next question posed in Figure 1C is whether the HVAC system itself might be the source of the IAQ problem. Most commonly, HVAC-created contaminants will include microbiologicals (growing on moist components in the system) and dust (when the particulate air filters in the system are not functioning properly). The most common control approach in these cases will be to clean the system, or to design and operate the system to avoid biological growth ("source management"). In some cases, maintenance of the particulate filters ("air cleaning") will be the appropriate approach.

The next question in Figure 1C is whether the indoor source is intermittent (e.g., chemical spills in the building or periodic use of chemical cleaners). In general, intermittent sources that occur at widely spaced (and possibly irregular) time intervals would seem to be less amenable to treatment with improved ventilation, since it appears intuitively unattractive to consistently ventilate the building at an increased rate in order to handle the occasional spike in concentration that will occur when the intermittent source becomes active. For completeness, the figure suggests that increased ventilation might be considered in cases where the spikes can be detected by a sensor in the HVAC control system, and the ventilation rate can be designed to automatically increase whenever these spikes are detected. But in practice, such a sensor-controlled approach would not seem to be commonly applicable. In practice, improved ventilation will likely be a candidate for intermittent sources only when: a) the intermittent sources are so frequent that they may be treated as essentially continuous sources; or b) the increased ventilation can be activated manually (e.g., with an exhaust fan in the area where the source occurs) whenever the source becomes active.

If the answers are "no" to all of the questions up to this point in Figure 1C -- i.e., if there is a fairly steady building-wide source for which source management and air cleaning are not obvious solutions at the outset, and which is not being created within the HVAC system -- then improved ventilation (increasing OA to the entire building) would appear to be a logical control approach. The major deterrent to using increased ventilation under these circumstances would be if the contaminant concentrations in the building were so great that OA rates could not cost-effectively be increased sufficiently to provide the needed reductions.

Given that increased OA appears to be a leading candidate at this point in the logic, the next question is whether the HVAC system is in fact supplying the amount of OA for which it was designed, and the amount of OA specified in applicable standards such as ASHRAE 62-1989 (ASHRAE, 1989). If the mechanical system is not providing the proper amount of OA, the appropriate first step would be to make any necessary system modifications to correct this problem. If pollutant concentrations remain too high even after such modifications, then further OA increases might be considered, as discussed in the following paragraphs.

If the HVAC system is providing the proper amount of OA, Figure 1C directs the user to Worksheet 1 in Appendix A, which can be used to estimate the increase in OA that would be required to achieve the desired reduction. The next question is whether the existing HVAC system (in the case of existing buildings) -- or the mechanical system that has been specified for a new building -- has sufficient cooling and heating capacity to accommodate this increase in OA without modifications to the equipment.

If the mechanical system has sufficient heating/cooling coil capacity to handle the required increase in OA, the primary cost impact will be the energy cost for conditioning the increased OA flows and for operating the fans at increased capacity. For this case, Figure 1C refers the user to additional worksheets to aid in a rough estimation of these energy costs. If the existing (or specified) cooling or heating capacity would have to be increased to condition the increased OA, the figure refers to further worksheets that will also assist in rough estimations of installed costs for the enlarged equipment.

2.2 CONSIDERATIONS REGARDING AIR CLEANING

In a number of cases, Figures 1A through 1C suggest that the user consider air cleaning as a candidate control option. Figure 2 is a supplementary logic diagram to assist the user in assessing air cleaning options in these cases.

As indicated previously, a primary consideration when identifying air cleaning as an option is that the pollutant of interest must be amenable to reliable removal by commercially-available air cleaners.

As with Figure 1B, Figure 2 begins by asking if the pollutant source is localized -- i.e., if it impacts only one zone, or a portion of a zone, among a number of zones being treated by a given HVAC unit within the building. Where the problem is localized in this manner, it would commonly be treated by local exhaust ventilation or source management rather than by air cleaning. Accordingly, the discussion of air cleaning in this document focuses on central air cleaners, mounted in the ductwork of the HVAC unit and thus generally treating all of the zones conditioned by that unit. However, there are individual cases -- including, e.g., clean rooms and smoking lounges -- where users might sometimes wish to consider self-contained air cleaners, independent of the HVAC system, as an option for localized treatment (Flanders Filters, 1994; Pierce et al., 1996). Thus, for completeness, Figure 2 includes this option.

2.2.1 Central In-Duct Air Cleaners

If the pollutant source cannot reasonably be addressed by localized self-contained units, Figure 2 refers the user to Worksheet 7 in Appendix A, for estimating the required per-pass removal efficiency of a central, duct-mounted air cleaner for removing particulate or gaseous contaminants. The results from this worksheet -- which will depend upon whether the air cleaner will be treating the recirculating building air or the incoming outdoor air -- will aid in selecting and sizing the air cleaner.

The next questions address whether -- in the case of existing buildings -- there is sufficient space in the existing mechanical room to physically accommodate the air cleaner that would be required, and sufficient excess static pressure capability in the existing central air handler to handle the added pressure drop that the air cleaner will create. In the case of new buildings in the design phase, the analogous questions would be whether the mechanical room or the air handler would have to be enlarged.

The issues of space and pressure drop can be important. A typical particulate filter module capable of treating 2,000 cfm (i.e., about 2,000 ft^2 of floor area at 1 cfm/ft^2) will commonly have dimensions of perhaps 2 by 2 by 1 ft. Many of the granular activated carbon (GAC) modules that are offered commercially to remove gaseous organics are of similar dimensions. A central air handler treating, say, 8,000 ft^2 would require four of these modules combined into a filter bank of a configuration best suited to the available space (e.g., four modules aligned side-by-side, or four modules stacked two by two). These banks, plus the associated ducting, might require more space than will sometimes be available in small mechanical rooms, especially when the additional space required for maintenance is considered.

The pressure drops associated with particulate filters commonly range from perhaps 0.1 to over 1.0 inch of water (in. WG), depending upon air velocity, dust loading on the filter, and design removal efficiency. The pressure drops associated with GAC filters of the common V-bank configuration might range from below 0.5 to above 1.0 in. WG, depending on velocity, carbon particle size, and bed depth. These added pressure drops could impact the performance of an air handler that might have been selected to provide at maximum static pressure of, say, 6 to 8 in. WG.

If the existing mechanical room and air handler (or the new building as designed) can accommodate the required central air cleaner, then Figure 2 directs the user to worksheets that can aid in the rough estimation of installed, O&M, and annualized costs. If the mechanical room and/or the air handler are inadequate, the user must assess the feasibility and costs of installing the air cleaner remote from the air handler, or of enlarging the mechanical room and air handler as necessary.

2.2.2 Self-Contained Air Cleaners

Self-contained air cleaners are independent of the central HVAC system. These air cleaners incorporate their own fan to circulate the air from the occupied space through the unit, and might be mounted, e.g., in the overhead plenum.

Where the source is localized, and where self-contained units appear to be an option, Figure 2 refers the user to Worksheet 12, which will assist in estimating the air cleaner flow capacity required to provide the needed reduction in contaminant concentration. Vendor information on the performance and characteristics of available units can also assist in this assessment.

With this rough estimation of the hardware requirements, the user must then assess whether there is sufficient space, electrical power, etc., in the localized area to accommodate the self-contained air cleaner. If there is, Figure 2 refers the user to the worksheet that can assist in a rough estimation of the installed, O&M, and annualized costs for this approach. If the localized area is not readily amenable to accommodating a self-contained air cleaner, the user must assess the feasibility and costs associated with modifying the space to accommodate the unit(s).

2.3 CONSIDERATIONS REGARDING SOURCE MANAGEMENT

In a number of cases, Figures 1A through 1C suggest that the user consider source management as a candidate control option. Figure 3 is a supplementary logic diagram to assist the user in assessing source management options in these cases.

Figure 3 walks the user through the various classes of activities that are considered "source management", and provides some practical examples of each. Clearly, those source management activities that are applicable in any given building -- and their costs and effectiveness -- will depend heavily on the characteristics of that particular site.

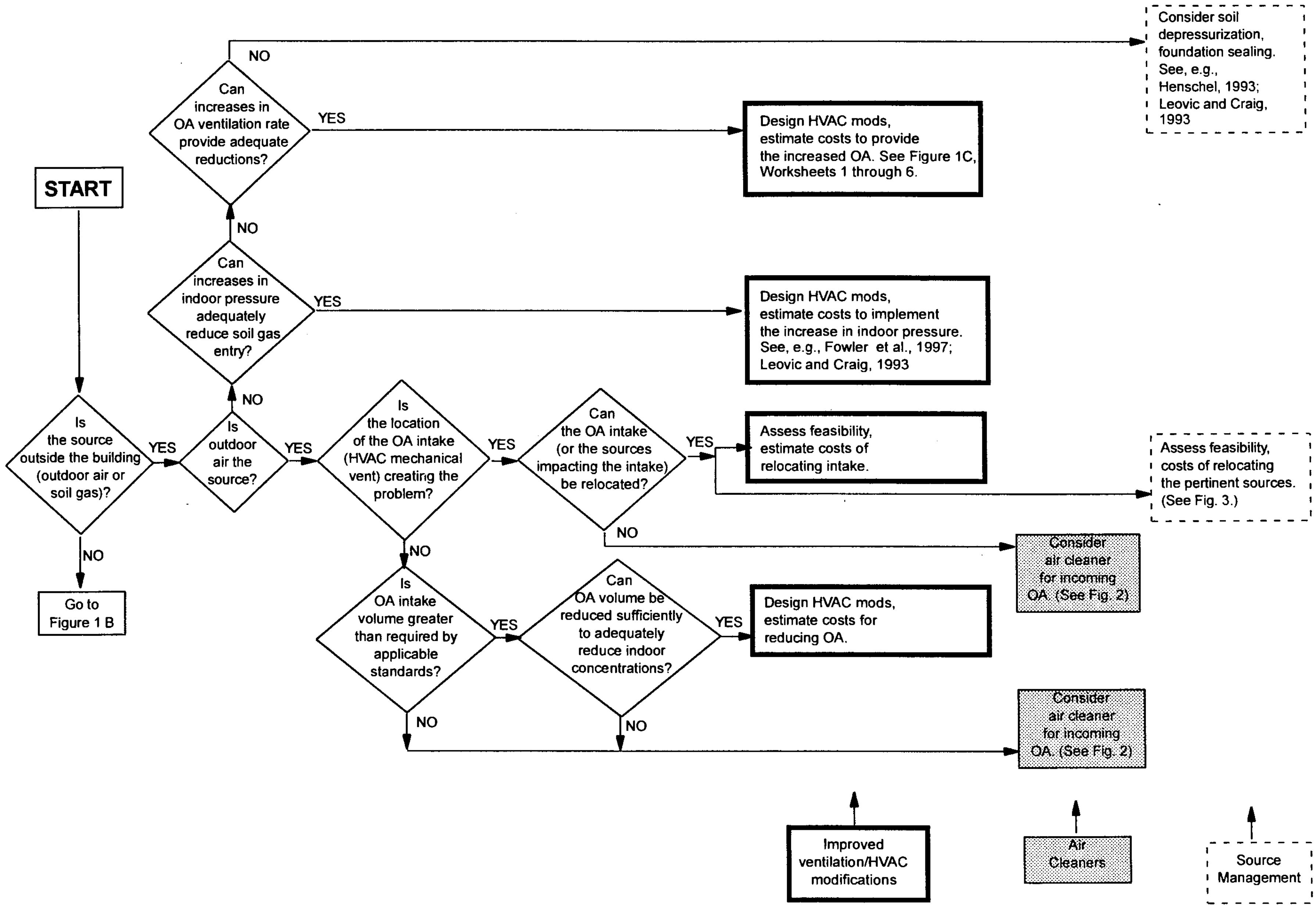

Figure 1A. Logic diagram for selecting an IAQ control approach: Part A (sources outside building).

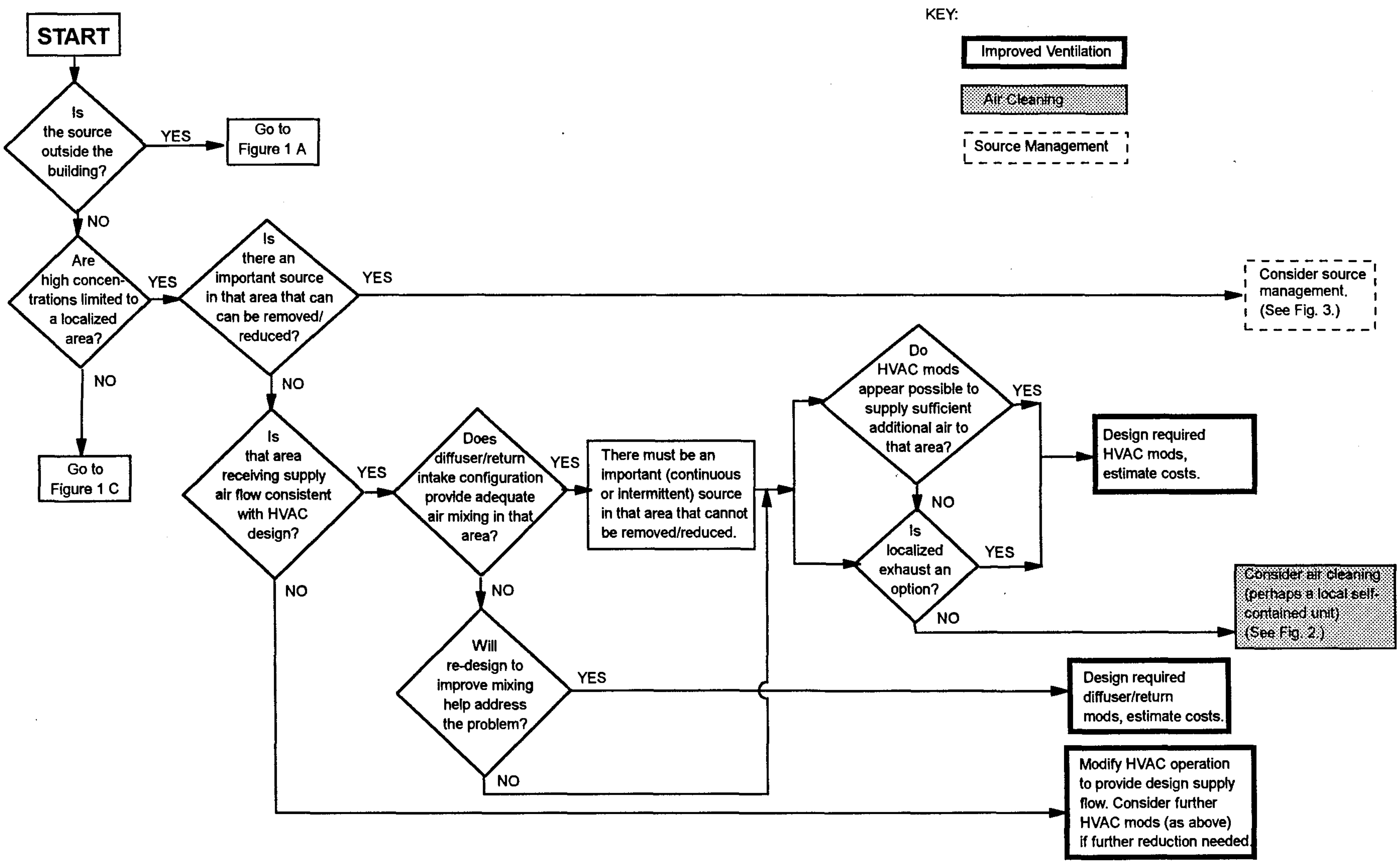

Figure 1B. Logic diagram for selecting an IAQ control approach: Part B (localized problem resulting from sources inside building).

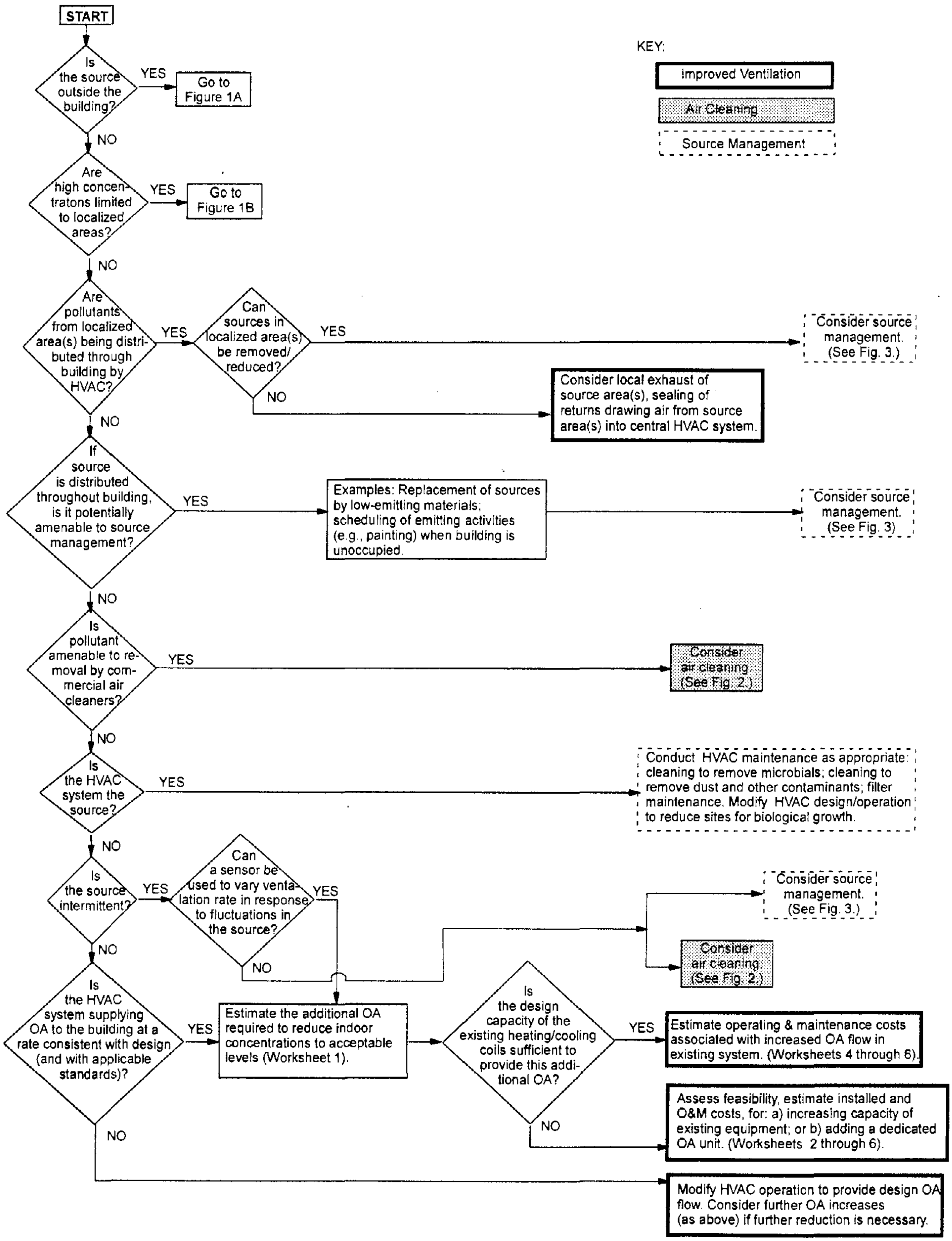

Figure 1C. Logic diagram for selecting an IAQ control approach: Part C (building-wide problem resulting from sources inside building).

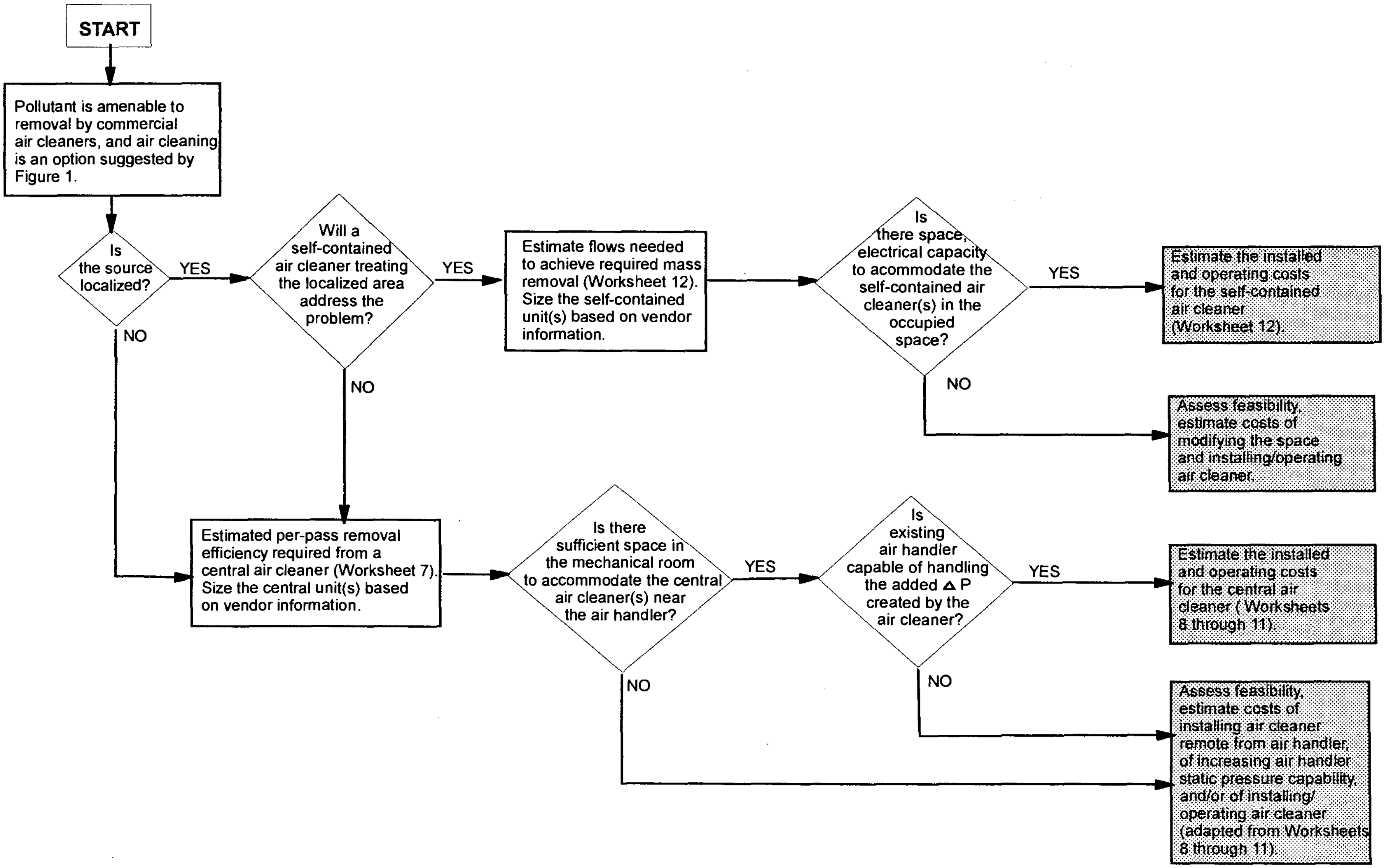

Figure 2. Logic diagram for assessing particulate or gaseous air cleaners as an IAQ control approach where air cleaning is an option.

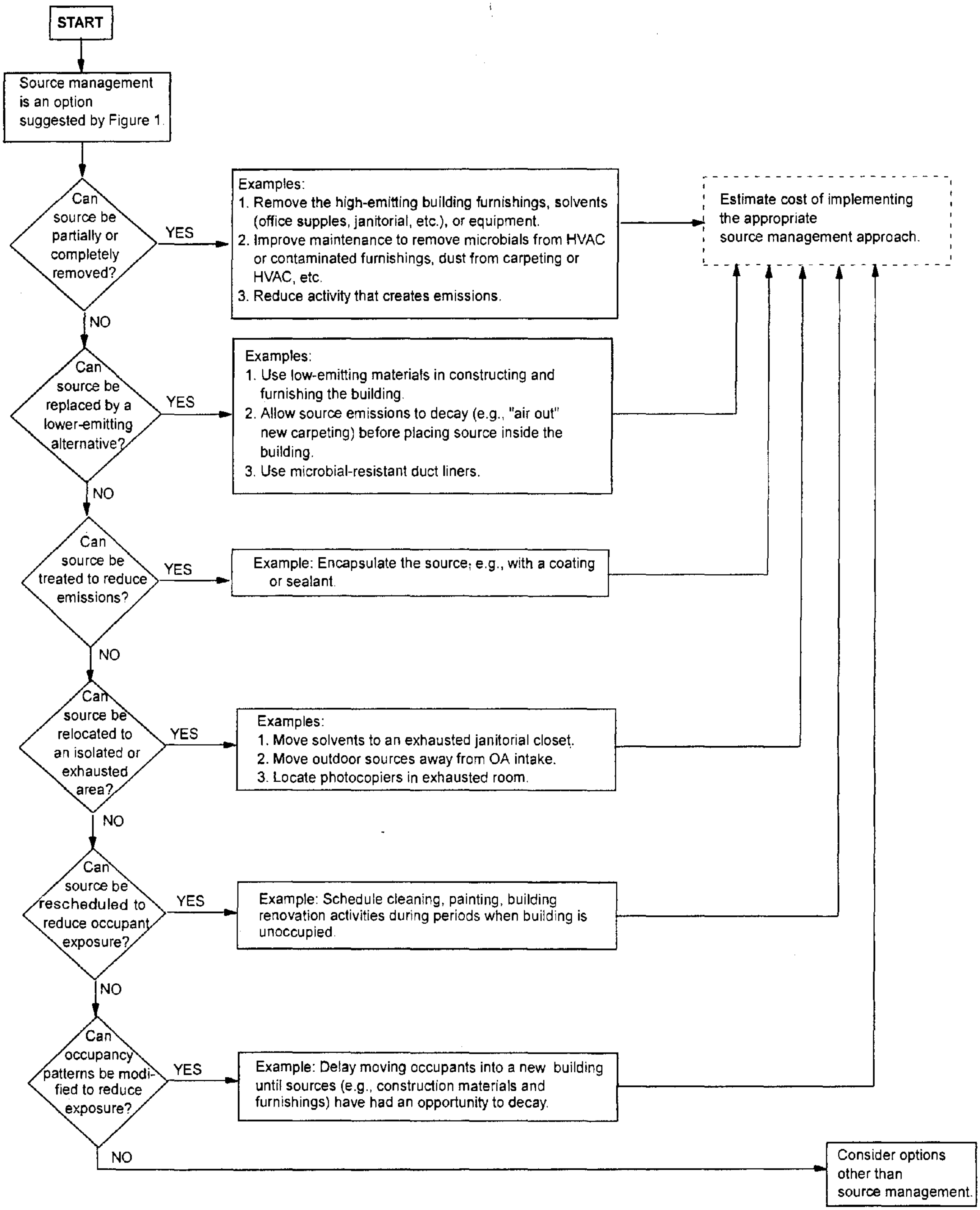

Figure 3. Logic diagram for assessing source management as an IAQ control approach where source management is an option.

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SECTION 3

ESTIMATING THE COSTS OF IAQ CONTROL OPTIONS: IMPROVED VENTILATION

As indicated by Item 2 in Section 1.2, the second step in this preliminary methodology is the development of rough cost estimates for the candidate IAQ control options that have been identified in Section 2.

In this preliminary methodology, these rough estimates are viewed as an initial screening tool to assist the user in making a first cut among the candidates. Of course, better cost estimates could be developed for all of the control options if the required expertise (e.g., in HVAC engineering) were available in-house or on a consulting basis, and if the time and resources were available. The objective of this methodology is to facilitate a fairly quick, inexpensive comparison -- by users who might not possess all of the specialized expertise required for a rigorous cost analysis of each option -- before more substantial efforts are undertaken to develop better estimates.

This section and the two that follow include worksheets to assist the user in making key design decisions (e.g., regarding required ventilation increases or air cleaner effectiveness), and -- where possible -- in roughly estimating installed, O&M, and total annualized costs for the control options. To derive the rough estimates, the worksheets utilize broad assumptions, "rules of thumb", and other shortcuts that sacrifice accuracy but enable a reasonable number to be developed fairly simply for comparative purposes.

The cost number that will be used in the subsequent computation of "cost-effectiveness" is the total annualized cost. This includes the average annual O&M cost plus an annual capital recovery factor applied to the installed cost.

This section addresses cost estimation for control options involving *improved ventilation*. Sections 4 and 5 address the costs for control options involving air cleaning and source management, respectively.

3.1 INTRODUCTION

Four types of control steps are suggested in Figures 1A through 1C that fall under the category of "improved ventilation".

1) *Re-location of the OA intake*, in cases where outdoor contaminants are being drawn into the building because the OA intake is located near an outdoor pollutant source. The cost of implementing this HVAC modification will be so site-specific that meaningful assistance in the general costing of this step cannot be provided here.

2) *Adjustments to the supply air distribution system, and/or the diffuser and return grille configurations*, to improve supply air distribution and mixing. Such modifications can sometimes be fairly simple, for example, adjusting the position of a damper; in other cases, the required modifications could be more complicated. Because the required activities will be so site-specific, and might require specialized diagnostics, meaningful assistance in the general costing of this step cannot be provided here.

3) *Localized exhaust ventilation*, to increase the ventilation rate in a given area and to depressurize the area. The amount of exhaust that is required in a particular building -- and the ease with which that area can be, e.g., manifolded into the central exhaust ducting for the building -- will be very site-specific. Thus, again, it is not felt that meaningful assistance in the general costing of this step can be provided here.

4) *Increased outdoor air*, to dilute the indoor contaminants (or possibly to pressurize the ground floor of the building to prevent soil gas entry). For this improved ventilation step, generalized worksheets appear to be possible that might be of assistance to a user in assessing a site-specific case.

Accordingly, the worksheets that follow focus on the case of increased OA.

For ease of reference, all of the worksheets in this report are presented in Appendix A.

3.2 ESTIMATING THE REQUIRED INCREASE IN VENTILATION RATE

The first step in assessing the costs associated with increasing the OA ventilation rate, is to estimate the OA increase that will be required. ***Worksheet 1*** in Appendix A presents the step-wise procedure for estimating the needed increase, assuming that dilution is the sole mechanism by which the contaminant concentration is reduced.

The standard dilution calculation reflected in Worksheet 1 shows that if one wants to reduce the indoor concentration to, say, one-half of the current concentration, then the OA flow rate must be increased by a factor of 2 above its current value.

This calculation assumes that the concentration of the contaminant of concern is zero in the outdoor air, and that the indoor air is well mixed.

To conduct this calculation, one must know: a) the current pollutant concentration in the indoor air; b) the concentration to which the pollutant must be reduced; and c) the current flow of OA into the building (or into the area of interest). In some cases, these parameters will be known; the indoor concentration of a contaminant, and the OA intake rate, can certainly be measured. However, in practice, there will be occasions where the user will have to make some judgements in making the requested entries into Worksheet 1. For example, exactly which contaminant(s) should drive the calculation? Where the current concentration is not steady, is the time-averaged concentration the best value to enter on Line 1 of the worksheet? On what basis does one select the concentration to which the current levels are to be reduced? Clearly, the simple format of the worksheet has some potentially non-trivial questions embedded within it. This underscores the point made in Section 1.2, that this preliminary methodology functions more to outline a thought process rather than to provide cookbook answers.

The worksheet addresses the case where the contaminant of concern is a consistent problem throughout the entire portion of the building served by a given air handler. The OA being provided by that air handler is correspondingly being increased to treat that entire portion of the building in a uniform manner. Figure 1B suggests that -- when there is a localized source -- one option could be to modify the air handler to provide more total direct *supply* air (OA plus recirculated air) to the area where the source is located. In this case, as a first approximation, one might use Worksheet 1 to estimate the additional "clean" supply air that would have to be provided to adequately reduce the concentration in the local area. The inaccuracy in using the worksheet in that manner is that the added supply air will increase the mixing of the local contaminant throughout the area served by the air handler in question, and the supply air (which is largely recirculated air) will thus increasingly deviate from the assumption that there is zero concentration of contaminant in the ventilating air. If a localized source were indeed to be addressed by an increase in direct supply air, the user would really have to consider the entire portion of the building treated by that air handler, possibly moderately increasing OA flows to that entire portion (as well as increasing supply to the localized problem area). The required mass balance in such a case is more complicated than the simple procedure shown in Worksheet 1.

Figure 1A suggests pressurization of the ground floor of a building (through increased OA to that area) as a means for preventing soil gas entry into the building. The pressurization mechanism is very different from that of dilution, on which Worksheet 1 is based. The amount of additional OA to achieve sufficient pressurization of a building is very site-specific, and cannot be addressed here.

3.3 ESTIMATING INSTALLED COSTS FOR INCREASES IN VENTILATION RATE

Often, the existing HVAC equipment will have to be modified to accommodate an increase in the OA ventilation rate. An installed cost will be incurred for making these modifications.

Where increased OA is to be retrofit into an existing building, the term "existing equipment" will refer to the pre-existing hardware in that existing building. For new buildings yet to be constructed, that term, as used here, refers to the current specifications for the HVAC equipment originally designed to be installed into that new building -- equipment that must now be modified before construction to accommodate increased OA. For the new-building case, the "installed costs" for increased ventilation are in fact the incremental increase in the installed cost of the mechanical system resulting from the adjustments that are made in the specifications to increase the OA rate.

3.3.1 HVAC Components That Will or Will Not Require Modification

Among the equipment components in the HVAC system, only the central supply fan, the return fan (if present), and the supply and return ducting will consistently *not* be impacted by an increase in outdoor air. All of the other components are subject to potential modification, depending upon the design of the HVAC system.

Cooling and heating capacity. The cooling and heating capacity of the existing HVAC units will generally have to be increased to handle the sensible and latent load added by the increased OA, unless the original system was designed with sufficient excess capacity. An increase in capacity will require increases, for example, in: the cooling and heating coil surfaces; the capabilities of the condenser, compressor, and chiller associated with the cooling system; and, depending upon the source of heating, the capacity of the furnace or the electrical service to the resistance heaters.

Central supply fans. It is unlikely that an increase in OA will require modifications to the existing central air handlers that circulate the conditioned air throughout the building. Central air handlers are commonly designed to supply about 1 cfm per ft^2 of floor area (OA plus recirculating air). In office buildings that have been designed according to ASHRAE 62-1989 -- supplying 20 cfm OA per person with 7 persons per 1,000 ft^2 (i.e., 0.14 cfm/ft^2 of OA) -- OA will constitute about 14% of the total supply air being circulated. This OA rate could be increased 7-fold (to 140 cfm/person) before the total supply air reached 100% OA with the existing air handlers. Only if the OA rate had to exceed about 140 cfm/person would it be necessary to increase the flow capacity of the existing central air handlers. Such substantial OA increases will not commonly be considered.

Return fans (if present). Consistent with the supply fans, the return fans will be designed to return about 1 cfm/ft^2 from the zones to the central heating/cooling unit, regardless of the volume of OA being provided to the space. Thus, an increase in OA supply to the zones will not increase the required flow capacities of the return fans, except in the unlikely event that the increased OA rate being considered were greater than 100% OA for the existing system, as discussed above.

Supply and return ducting. An increase in OA rate will not impact the required dimensions of the ducting that delivers supply air from the central units to the zones, and that returns zone air to the central units. As discussed above, the total volume of air moving through this ducting will remain unchanged as the OA rate is increased.

OA intake fans (if present). Many HVAC systems do not include OA intake fans. In systems having economizers -- i.e., in systems dampered to draw in up to 100% OA -- there is commonly no OA fan. In such cases, adjustments to the OA intake dampers will enable the existing central air handler to draw additional OA without modifications to the hardware. However, some HVAC systems -- including some with economizers -- do include OA intake fans. In particular, an intake fan is one option for ensuring a constant minimum OA intake rate in variable volume systems where the rate might otherwise drop below the minimum as system flows vary with load (Kettler, 1998). In these cases, an increase in the minimum OA requirement would necessitate an increase in the capacity of the intake fan. Also, in systems without economizers -- i.e., in systems designed to provide a fixed OA intake rate -- an OA intake fan would have to be added, or the existing intake fan enlarged, if that OA rate were to be increased.

OA intake ducting. In systems having economizers, the existing OA intake ducting will be sized to accommodate up to 100% OA. Thus, no increase in the dimensions of the intake ducting will be needed when OA is increased (from, say, 14% OA to anything less than 100% OA). But in systems without economizers, the OA intake ducting will be sized for the lesser, fixed amount of OA that had been provided previously. In such systems, the duct dimensions would have to be increased (or new ducting added in parallel with the existing ductwork) to provide the required additional OA volume without excessive pressure loss or noise in the ducting.

Some OA intake ducting might be added when a dedicated-OA unit is used to retrofit increased OA into an existing building, as discussed later, even if the central system has an economizer.

Pressure relief (exhaust) fans and ducting. When OA is increased, the amount of air removed from the building must likewise be increased to prevent unacceptable levels of building pressurization. Pressure relief is provided by: a) localized exhausts (from bathrooms and janitorial closets), which would commonly remain unchanged as OA rate is increased; and b) exhaust of some fraction of the recirculating air from the central return ducting, referred to here as "central exhaust". It is the central exhaust that would be increased to accommodate the increased OA intake.

In systems having economizers, the existing central pressure relief component -- the exhaust ducting leading off of the return ducting, and any central exhaust fan, if present -- has been designed to handle up to 100% OA. Thus, an increase in OA rate will necessitate no increase in the existing pressure relief hardware (except in the unlikely event that the increased OA rate exceeds 100% OA on the original system). However, in systems without economizers, the pressure relief component has been sized to handle only the lesser, fixed amount of OA provided by the original system. In these cases, the capacity of any central exhaust fan would have to be increased, and the dimensions of the exhaust/relief ducting would have to be increased to accommodate the greater exhaust flow.

3.3.2 Approaches for Increasing Cooling/Heating Capacity

Two alternative approaches will commonly be considered for increasing HVAC system cooling and heating capacity to handle the loads associated with an increase in OA.

The first approach is to enlarge the central HVAC units -- e.g., adding additional cooling coil surface, installing larger condenser/compressor units and chillers, adding heating elements and electrical (or furnace) capacity. This approach will be most easily applied in new construction, where the capacity increases can be accomplished simply by specifying higher-capacity components at the outset. However, even in retrofit cases, it could be possible to, e.g., replace an existing bank of direct-expansion evaporator coils in the central unit and the corresponding compressor/ condenser unit with components having a greater refrigeration capacity.

The second approach is to install a separate HVAC unit, independent of the central units, that would serve solely to treat the incoming OA and to supply it to the OA intake ducting of the central system. Such separate units are referred to here as "dedicated-OA" units. While a dedicated-OA unit could be considered in either an existing building or in new construction, it offers particular attraction in the retrofit case. In retrofit situations, the new dedicated-OA unit would make it possible for the pre-existing HVAC units to handle the increased OA flow without modifications to the existing equipment.

Dedicated-OA units will generally involve direct-expansion cooling and electric heating elements, making them independent of central system chillers and furnaces. There is no return air to the dedicated-OA unit; the unit might be viewed as an "OA intake fan" with conditioning capability incorporated.

In the discussion that follows, each of these two approaches will be considered under each of two circumstances: a) the OA increase is to be implemented in an existing building (the retrofit case); and b) the OA increase is being considered for a new building not yet constructed.

3.3.3 Installed Costs in Existing Buildings (Retrofit Case)

Enlarged Central Units

Worksheet 2A in Appendix A presents a procedure for estimating the installed costs associated with increasing the capacity of the existing central HVAC units in the retrofit case. This worksheet assumes that the pre-existing HVAC systems do not have sufficient cooling and heating capacity to handle the OA increase without modification.

Worksheet 2A is based on the following scenario (presented in terms of the equipment components discussed in Section 3.3.1).

Cooling and heating capacity. The existing cooling coils, and the associated condenser/compressor units, are removed from each of the HVAC units in the building, and replaced with coils and condenser/compressor units having the required greater refrigeration capacity. Likewise, the heating elements are removed and replaced with higher-capacity elements. Since this simplified worksheet assumes direct-expansion cooling units having electric heat, it will be less accurate for systems involving chillers and furnaces.

OA intake fan (if present). In cases where an OA intake fan is required, the worksheet assumes that the pre-existing fan is retained and is supplemented with a single new fan designed to provide the incremental additional OA that is required by all of the HVAC units in the building. (Where the OA flows are sufficiently great, the user might need to consider multiple new supplemental OA fans, each fan serving some number of the HVAC units in the building.)

OA intake ducting. In systems without economizers -- where the OA increase would require that the pre-existing intake ductwork be supplemented in some manner to handle the increased OA flow -- the worksheet assumes that new ducting is retrofit specifically for the new OA fan discussed above, directing the supplemental OA from that fan to the individual HVAC units.

In systems *with* economizers, no modifications to the existing OA intake ductwork are needed. In systems with an economizer but having an OA intake fan -- e.g., a modern VAV unit having an OA fan to assure constant OA supply -- it is assumed that the new supplemental OA fan delivers its OA into the pre-existing intake ducting.

Central exhaust fan (if present). Systems that have a central exhaust fan but do not have an economizer may require an increase in the capacity of the exhaust fan. The worksheet assumes that, in these cases, the capacity increase is accomplished by installing a new, supplemental exhaust fan designed to exhaust an air volume equal to the incremental increase in the OA supply rate.

Central exhaust ducting. In systems without economizers, the required increase in exhaust flow would necessitate that the pre-existing exhaust ductwork be supplemented in some manner. In these cases, the worksheet assumes that new ducting is retrofit specifically for the new exhaust fan discussed above, drawing the supplemental exhaust air from the zones served by the individual HVAC units.

The size of the required increase in cooling capacity is estimated in the worksheet by computing the sensible and latent energy required to cool the incremental volume of increased OA from the 1% value of outdoor enthalpy for cooling design for the local climate [as defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE, 1997a)], to an indoor enthalpy corresponding to 75 °F and 50% relative humidity. Similarly, the required increase in heating capacity is estimated from the sensible energy required to heat the incremental OA volume from the 99% value of outdoor temperature for heating design for the local climate, as defined by ASHRAE, to an indoor temperature of 70 °F. The worksheet includes a table presenting the tons of additional refrigeration capacity and the kW of additional heating capacity per 1,000 cfm of incremental OA, for a variety of geographical locations based on these ASHRAE data.

The installed cost associated with replacement of the existing cooling coils and the condenser/compressor unit -- $830 per ton of refrigeration capacity -- was derived from Means Mechanical Cost Data (Means, 1996), based upon the costs for new coils and new condenser/compressor units assuming a direct-expansion system, as defined in the worksheet. To account for the retrofit costs (removing the original coils and condenser), the $830/ton figure includes a doubling of the labor costs for installing new units. Likewise, the installed cost associated with replacement of the heating elements ($35/kW) was derived in a similar manner, assuming electric duct heaters.

The installed costs of new supplemental OA and exhaust fans and ducting, if required, were likewise obtained from Means, as defined in the footnotes to Table A-2. To account for retrofit costs, the installed cost of ducting was increased by $40 per linear foot, based on prior experience.

New Dedicated-OA Unit

Worksheet 2B in Appendix A presents a procedure for estimating the installed costs associated with the addition of a new dedicated-OA unit in the retrofit case.

Worksheet 2B is based on the following scenario.

Cooling and heating capacity. A new rooftop direct-expansion system with electric heat is installed having the capacity required to condition the incremental *additional* OA that is to be supplied to the building. The capacities of the pre-existing HVAC units in the building remain unchanged; the existing units continue to be responsible for conditioning the original OA volume. The one new dedicated-OA unit is assumed to provide the conditioned incremental OA for all of the original HVAC units in the building. However, if the incremental OA flows are sufficiently great, the user might need to consider multiple new dedicated-OA units, each serving some number of the original HVAC units.

OA intake fan (if present). The air handler associated with the new dedicated-OA unit is, in effect, the OA intake fan for the incremental OA flow. In systems that require an OA intake fan, the air handler in the new unit fulfills this requirement for the additional flow, and no additional costs are encountered for increased OA intake fan capacity. The pre-existing intake fan is retained, and continues to supply the original OA volume to the original HVAC units.

OA intake ducting. In systems *with* economizers, it is assumed that the incremental additional OA being supplied by the dedicated-OA unit can be delivered into the pre-existing OA intake ducting; no modifications to the ducting are required, since it was designed to handle up to 100% OA. In systems *without* economizers, it is assumed that new intake ducting is retrofit into the building to deliver the incremental OA from the new dedicated-OA unit to the inlets of each of the original HVAC units. This new intake ducting is assumed to consist of a main trunk line from the dedicated-OA unit, splitting into branches leading to each HVAC unit. The original intake ducting remains in place, supplying the original OA volume to the units.

Central exhaust fan (if present). Systems that have a central exhaust fan but do not have an economizer may require an increase in the capacity of the exhaust fan. As in Worksheet 2A above, Worksheet 2B assumes that, in these cases, the capacity increase is accomplished by installing a new, supplemental exhaust fan designed to exhaust an air volume equal to the incremental increase in the OA supply rate. Any pre-existing exhaust fan remains in place, and continues to function as before.

Central exhaust ducting. In systems without economizers, Worksheet 2B (like Worksheet 2A) assumes that new ducting is retrofit specifically for the new exhaust fan, drawing the supplemental exhaust air from the zones served by the individual HVAC units. The original exhaust ducting continues to function as before.

The installed costs of the new dedicated-OA unit as a function of cooling capacity were derived from Means (Means, 1996), considering single-zone rooftop direct-expansion units having cooling capability only, as described in the footnotes to Table A-3. The cost of adding heating capacity to these new units was likewise derived from Means based on electric duct heaters, as discussed in Table A-4.

The required cooling and heating capacity for the new dedicated-OA unit, and the costs of new supplemental intake and exhaust fans and of retrofit exhaust ducting (if needed), are estimated in the same manner as described previously in connection with Worksheet 2A.

3.3.4 Installed Costs in the New Construction Case

Enlarged Central Units

Worksheet 3A in Appendix A presents a procedure for estimating the installed costs associated with increasing the capacity of the central HVAC units to handle increased OA in the new construction case. In this case, it is assumed that a system capable of handling and conditioning the increased OA flow is now to be installed *in lieu of* the system that had originally been designed for the as-yet unconstructed building.

Worksheet 3A is based on the following scenario.

Cooling and heating capacity. The originally designed cooling and heating capacities are increased for each of individual HVAC units in the building, to handle the increased OA flow to each. The air handler, cooling coils, condenser, compressor, heating elements, and controls of each unit are re-designed as required before construction. Since this simplified worksheet assumes direct-expansion cooling units having electric heat, it will be less accurate for systems involving chillers and furnaces.

OA intake fan (if present). In cases where one or more OA intake fans are required in the new building, the worksheet assumes that intake fans of greater capacity are installed in lieu of the lower-capacity, originally designed fans.

OA intake ducting. In systems without economizers -- where the OA increase would require that the intake ductwork be supplemented in some manner to handle the increased OA flow -- the worksheet assumes that intake ducting of larger dimensions is installed in lieu of the original intake ducting. The basic configuration of the original intake ducting is otherwise retained. In systems *with* economizers, no modifications to the originally designed OA intake ductwork are needed.

Central exhaust fan (if present). In systems that have one or more central exhaust fans but do not have economizers, Worksheet 3A assumes that exhaust fans of greater capacity are installed in lieu of the originally designed, lower-capacity fans.

Central exhaust ducting. In systems without economizers, the worksheet assumes that exhaust ducting of larger dimensions is installed in lieu of the original exhaust ducting. The basic configuration of the original exhaust ducting is otherwise retained. In systems *with* economizers, no modifications to the originally designed exhaust ductwork are needed.

The incremental installed cost of the enlarged HVAC units, fans, and ductwork are estimated in this worksheet in a manner similar to that discussed previously for Worksheets 2A and 2B (based upon the cost data in Means), with one significant difference. In the two retrofit worksheets, the costs are the *total* costs of new dedicated-OA HVAC units, new fans, and new ducting. In Worksheet 3A, by comparison, the costs are the *incremental* costs associated with installing a larger unit in lieu of the originally designed unit.

In addition, in Worksheet 3A, the ductwork costs do not reflect the additional $40 per linear foot installation cost associated with retrofitting ducting into an existing building.

<u>New Dedicated-OA Unit</u>

Worksheet 3B in Appendix A presents a procedure for estimating the installed costs associated with the use of a dedicated-OA unit in the new construction case. In this case, it is assumed that -- since a dedicated-OA unit is to be installed in a new building -- it will be designed to condition *all* of the OA entering the building, rather than just the incremental increase in OA.

Worksheet 3B is based on the following scenario.

Cooling and heating capacity. One or more rooftop direct-expansion systems with electric heat, dedicated to treating the incoming OA, are added to the original design. These added units have the capacity required to condition *all* of the OA that is now to be supplied to the building. The dedicated-OA units provide conditioned OA to the inlets of the originally designed HVAC units. The cooling and heating capacities of all of the originally designed HVAC units in the building are reduced, since the original units will no longer be required to condition OA, providing a cost savings that partially offsets the cost of the dedicated-OA units.

OA intake fan (if present). The air handlers associated with the dedicated-OA units become, in effect, the intake fans for the entire OA flow into the building. In systems that included OA intake fans in the original design, these intake fans can now be eliminated, resulting in a cost savings.

OA intake ducting. In systems *with* economizers, it is assumed that the increased total volume of OA being supplied by the dedicated-OA units is delivered into the originally designed OA intake ducting with no modifications to the original ducting design. In systems *without* economizers, the worksheet assumes that intake ducting of larger dimensions -- but otherwise of the same configuration as the original -- is installed in lieu of the original intake ducting.

Central exhaust fan (if present). For systems that have central exhaust fans but do not have economizers, Worksheet 3B assumes that exhaust fans of greater capacity are installed in lieu of the originally designed fans.

Central exhaust ducting. In systems without economizers, the worksheet assumes that exhaust ducting of larger dimensions is installed in lieu of the original exhaust ducting.

3.4 ESTIMATING OPERATING AND MAINTENANCE COSTS FOR INCREASES IN VENTILATION RATE

3.4.1 Annual Operating Costs

The annual operating cost associated with an increase in ventilation rate will be the incremental energy cost resulting from: 1) cooling and heating the increased flow of outdoor air; and 2) where applicable, operating the enlarged or new intake or exhaust fans.

Worksheet 4 in Appendix A presents a method for estimating these energy costs, when rigorous modeling of building energy consumption and costs is not possible.

Cooling and heating energy. The incremental energy consumption associated with increased ventilation will depend not only on the local climate, but on the times of day when this OA is being supplied and conditioned. For example, a calculation of heating energy consumption that is based solely on the total heating degree-days in a given climate, could be misleading; the mechanical system may in fact not be supplying OA to the building during the middle of the night, when the coldest hours (that significantly impact the heating degree-day figure) occur. In addition, the nature of the mechanical system can impact the actual energy that is required to provide the needed heating and cooling of the incremental OA.

Accordingly, the DOE-2 building energy computer model has been used to compute the required energy output from the mechanical system per incremental cfm of OA in a variety of climates with alternative mechanical systems, assuming that OA is being supplied 13 hours per day, 5 days per week. The results -- in the form of the average Btu of cooling energy output and Btu of heating energy output per incremental cfm for the different cities -- are tabulated for the user to draw upon. The details are summarized in the footnotes to Table A-6 in Worksheet 4. Where the user's system is supplying OA for a different period than that assumed in the DOE-2 modeling, the worksheet makes a correction in the tabulated energy requirements, assuming that consumption will change proportionally with the change in the number of hours per day, or the number of days per week. It is felt that this approach will be more accurate than would be calculations based on cooling and heating degree-days -- which would assume that the OA is being supplied 24 hours per day, 365 days per year -- followed by a correction downward to the reduced number of hours per year during which the user's system is actually supplying OA.

Using the required energy output from the mechanical system, obtained as discussed in the preceding paragraph, the annual incremental cost of energy is then computed accounting for the system efficiency and the unit cost of fuel or electricity.

Energy for new or enlarged fans. Worksheet 4 assumes that the incremental additional OA or exhaust air being handled by the fan is being supplied into ductwork sized such that -- at the total flow that will exist in the ducting -- the pressure loss will be 0.1 in. WG per linear foot. If the fan is new, the new ductwork is sized to provide this duct loss. If the fan is enlarged, the ducting is likewise assumed to be enlarged, such that the enlarged fan, like the original fan it replaces, would have this same duct loss.

From the average length of ductwork and the average number of fittings and other flow obstructions in the ducting (including the coils and filters, in the case of the dedicated-OA air handlers), the total required pressure differential across the fan can be determined. The total incremental fan output power is then computed as being equal to the incremental flow rate times the pressure differential. The required annual input energy requirements are determined from the output power, accounting for the fan efficiency and the hours per year of fan operation.

3.4.2 Annual Maintenance Costs

A procedure for estimating annual maintenance costs for increased ventilation is presented in ***Worksheet 5*** in Appendix A.

For the purposes of this rough estimate, it is assumed that increases in ventilation cause an increase in maintenance costs only when: a) a new intake or exhaust fan is added; or b) a new dedicated-OA HVAC unit is added. No increase in maintenance is assumed to result from enlargements of existing equipment.

Worksheet 5 prompts the user to enter an estimate for the number of additional maintenance labor hours per year that is expected per fan or per dedicated-OA unit added to the building. As a default, the worksheet suggests arbitrary but reasonable figures of 5 hr/yr for each fan, and 20 hr/yr for each dedicated-OA unit. A labor rate of $35/hr (including overhead) is suggested, based upon the hourly rate data in Means (Means, 1996).

3.5 ESTIMATING TOTAL ANNUALIZED COSTS FOR INCREASES IN VENTILATION RATE

The total annualized cost can be determined using ***Worksheet 6*** in Appendix A.

The total annualized cost consists of two components:

1) an annualized amount that amortizes the total installed cost derived in Section 3.3; plus

2) the total annual operating and maintenance cost derived in Section 3.4.

The annualized amount to be charged for the installed costs is determined using the Capital Recovery Factor (CRF), a standard approach in costing calculations. The user selects the number of years, n, over which the installed cost is to be amortized, and the interest rate, i, that is to be charged. The value of n will commonly be the estimated lifetime of the equipment. The value of i may be the rate that is being paid on money borrowed to install the equipment, or the interest rate that could have been obtained on the money had it been invested rather than used for the installation. Based on the selected values of n and i, the CRF is calculated using an equation derived from standard compound interest considerations (Humphreys and Wellman, 1996):

$$CRF = [i(1+i)^n] / [(1+i)^n - 1].$$

The CRF is the fraction of the initial installed cost that must be amortized each year if -- after n years, i.e., after n equal "payments" -- the initial cost is to be recovered with an i percent annual interest rate being charged on the unpaid balance.

Accordingly, the total annualized cost computed in Worksheet 6 for the increase in OA ventilation rate is the sum of:

1) the CRF multiplied by the incremental total installed cost derived from Worksheet 2A, 2B, 3A, or 3B, as appropriate; plus

2) the incremental annual operating cost, derived in Worksheet 4; plus

3) the incremental annual maintenance cost, derived in Worksheet 5.

To assist the user, a table of values for the CRF (as a function of the selected values of n and i) is included in the worksheet.

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SECTION 4

ESTIMATING THE COSTS OF IAQ CONTROL OPTIONS: AIR CLEANING

4.1 INTRODUCTION

As indicated in Figures 1 and 2, and as discussed in Section 2.2, it will sometimes be appropriate to consider the use of air cleaners to remove the contaminant(s) of concern. From a practical standpoint, air cleaners are most likely to be considered in cases where ventilation or source management are not clear options (e.g., when the outdoor air is the contaminant source), and where indoor air cleaning technology is well demonstrated for the contaminant(s) of concern (such as particulate matter and perhaps VOC molecules of sufficiently high molecular weight).

Two classes of indoor particulate air cleaners are considered: "media" air cleaners; and electronic air cleaners (ASHRAE, 1996). For the purposes here, media air cleaners include: pleated filter panels, commonly enclosed in cartridges; bag filters; and variations of these types (e.g., pocket filters). Electronic air cleaners are electrostatic precipitators. Only particulate air cleaners having an average removal efficiency of 65% or greater, as measured using ASHRAE Standard 52.1-1992 (ASHRAE, 1992), are considered here for IAQ purposes; it is assumed that lower-efficiency filters are already present on the HVAC system, to protect the fan and coils. High-efficiency particulate air (HEPA) filters -- offering 99.97% or greater removal efficiencies on 0.3 μm particles -- are included here in the event that the user wishes to consider maximum particulate control. HEPA filters, generally high-efficiency media cartridge filters, are commonly used in clean-room applications.

The air cleaners considered here for gaseous contaminants involve the use of beds of dry, granular material acting by physical adsorption (e.g., granular activated carbon), chemical absorption (e.g., activated alumina impregnated with potassium permanganate), or catalysis. Such air cleaners can be considered for the control of a variety of gaseous contaminants (ASHRAE, 1995), although the focus here is on the removal of VOCs.

The discussion here focuses on the case where the air cleaners are centrally mounted, in the ducting of one (or more) of the HVAC units serving the building. In this situation, the air cleaners will be treating all of the building air being recirculated by the HVAC unit (or all of the intake OA, depending on where the cleaners are mounted within the ducting); all of the zones being conditioned by that HVAC unit will be impacted proportionally. Central, in-duct mounting is the configuration most commonly considered when treatment of a significant source is required.

In some cases, there may be a source which impacts only one zone (or a portion of one zone) among the multiple zones being conditioned by a given HVAC unit. Often in such cases, it will be preferable to consider local exhaust ventilation or source management for such sources, rather than air cleaning. However, in some cases, the user might wish to consider localized air cleaning, using self-contained air cleaners within the affected zone (Flanders Filters, 1994; Pierce et al., 1996). Self-contained units include their own fan to circulate air through the unit, and operate independently of the HVAC system. Accordingly, Section 4.6 provides a costing approach for the case of self-contained air cleaners.

As illustrated in Figure 2 and discussed in Section 2.2, the addition of a central, in-duct air cleaner will result in an increased pressure drop, necessitating a more powerful motor on the central air handler. This will in turn result in increased fan heat, which will have to be removed by the cooling system when the system is operating in the cooling mode. Further, there is the issue regarding the availability of space for the central air cleaners within the mechanical room (or at a location remote from the mechanical room). The costing worksheets provided in this section address, to the extent possible, the first two of these issues: the incremental costs of a larger fan motor and of removing the heat generated by the larger motor. The worksheets do not attempt to address any extraordinary costs associated with, e.g., modifying the mechanical room or the HVAC hardware to accommodate the air cleaner, since these costs will be so site-specific.

Accordingly, the installed costs for the air cleaners computed in the worksheets here assume that there are no particular complications in the installation which would significantly increase installation labor hours and materials. In addition, the installed costs for the larger fan motor address only the *incremental* cost for the larger motor, beyond the cost of the smaller motor that would otherwise be sufficient; these costs do not include any costs associated with the replacement of a smaller, pre-existing motor with a new, larger one. No installation cost impact is included for any required increase in the cooling capacity of the HVAC unit, to remove the increased fan heat. Thus, the approximate installed costs estimated here will be more representative of a new installation, rather than a retrofit installation with complications.

4.2 ESTIMATING THE REQUIRED AIR CLEANER PERFORMANCE

To enable estimation of the installed and O&M costs of the air cleaner, it is first necessary to determine the required contaminant removal performance of the unit. ***Worksheet 7*** in Appendix A presents a method for estimating the required fractional removal efficiency, η, of central, in-duct air cleaners. (A method for estimating the required performance of self-contained air cleaners is presented in a later worksheet addressing such units.)

The calculations in Worksheet 7 are based on a simple mass balance around the zone(s) being conditioned by the HVAC unit into which the air cleaner is being mounted. The exact nature of the mass balance equation is determined by where in the ducting the air cleaner is mounted: in the incoming outdoor air (for cases where the OA is the pollutant source); or in the recirculating building air, either prior to or following mixing with OA (for cases where the source is in the zones). See Figure A-1 in Worksheet 7.

For each of these locations, the worksheet determines the air cleaner efficiency that is required if the average concentration in the zone(s) is to be reduced to the desired value. For particulate air cleaners, this efficiency will dictate the nature of the air cleaner that is selected, potentially impacting the installed cost -- especially if the requirements lead to the selection of an electronic air cleaner or a HEPA filter rather than a media filter of lesser efficiency. Efficiency requirements can also impact operating costs -- increasing power consumption if media filters creating greater pressure drops are needed, reducing consumption if electronic air cleaners are used having modest pressure drops and moderate power consumption by the corona wires and collection plates [~30 W/1,000 cfm (ASHRAE, 1996)]. And high efficiency requirements will increase maintenance costs by increasing the required replacement frequencies for media filters or cleaning frequencies for electrostatic precipitators.

For air cleaners that remove gaseous contaminants using granular sorbents -- where removal efficiency is essentially 100% when the sorbent is fresh, but progressively deteriorates once breakthrough begins -- increased efficiency requirements can be met either through an increase in sorbent mass, or an increase in sorbent replacement frequency, or some combination of the two. Higher efficiency requirements for gaseous air cleaners would increase the installed cost, if the designer elects to increase sorbent mass. Increased sorbent mass would also increase operating costs (power consumption), by increasing the pressure drop through the deeper sorbent beds. But in the worksheets that follow here, it is assumed that increased efficiency is achieved solely by increasing sorbent replacement frequency. With this approach, only maintenance costs are increased (though potentially significantly); installed and operating costs remain unchanged.

To conduct the calculation in Worksheet 7, one must know a number of things -- the target contaminant concentration (C_{IN}) to which the indoor levels should be reduced, the concentration (C_{OA}) of this contaminant in the outdoor air, the flows of outdoor air (Q_{OA}) and total supply air (Q_S) into the space, and the rate (S) at which the contaminant is being generated indoors. These parameters would require some measurements, and will sometimes be difficult to determine. Adding to the complexity of this assessment are issues such as: which contaminant(s) should drive the calculation (determining C_{IN}); the basis on which C_{IN} should be selected; and the likely variation with time of some of the key parameters (C_{OA}, S). So the relatively simple worksheet format incorporates some non-trivial questions on which the user will have to make some judgements. But the worksheet does illustrate the theory that must be considered in making this analysis.

4.3 ESTIMATING INSTALLED COSTS FOR CENTRAL AIR CLEANERS

Installation of a central air cleaner in the HVAC ducting will require: 1) the procurement and installation of the air cleaner itself; 2) potentially, for media particulate filters and for gaseous air cleaners, a larger motor for the central air-handling fan, to compensate for the pressure drop across the cleaner; and 3) potentially, increased cooling coil capacity, to remove, at peak load, the additional heat produced by the power being supplied to the larger fan or to the electronic air cleaner. There will be an installed cost associated with this equipment.

For convenience in the worksheets here, the installed cost of increasing the cooling system capacity is neglected. [According to one estimate (Henschel, 1998), this component could be perhaps 10% of the total installed cost for the air cleaner.] Accordingly, only the installed costs of the air cleaner itself and of the enlarged fan motor are considered.

As discussed in Section 4.1, the installed costs for air cleaners computed in the worksheet here assume that there are no particular complications in the installation. Thus, the estimates here will be more representative of a new installation, rather than a retrofit installation with complications.

4.3.1 Installed Costs for Central Particulate Air Cleaners

A procedure for estimating the installed costs for either media or electronic particulate air cleaners is presented in the first sections of ***Worksheet 8*** in Appendix A.

In this procedure, Worksheet 8 first assists the user in selecting the appropriate air cleaner, based upon the performance requirements computed in Worksheet 7. To aid in this selection, available data are tabulated giving the fractional efficiencies that might be expected for various media and electronic air cleaners in removing particles of several sizes (0.01, 0.1, and 1 μm).

With this selection made, the user may then either obtain an estimate from a vendor for this type of air cleaner, or may use a simplified table (Table A-10) included with the worksheet. The table presents rough installed costs per 1,000 cfm air throughput for each of the several types of air cleaners. These installed costs include the cost of the air cleaner and of the increase in fan motor horsepower, but exclude any costs for increased cooling capacity, as indicated above.

As indicated in the footnotes to Table A-10, the uninstalled costs for the media air cleaners themselves -- including pleated panel cartridges and the frame to support the cartridge bank -- were derived for vendor quotes. Installation labor was estimated assuming no complications in the installation, and was costed using labor rates from Means (1996) for sheet metal workers.

The incremental installed cost for the increase in fan motor capacity per 1,000 cfm throughput were obtained from data in Means, assuming that the average pressure drop across the media filter over its lifetime is 1 in. WG. (In practice, the pressure drop across the filter will generally increase from a fraction of an inch when the filter cartridges are new, depending on filter efficiency, to something greater than 1 in. WG at the time the cartridges are replaced, based upon vendor literature.) These incremental fan motor costs address only the incremental increase in horsepower required to overcome the added 1 in. WG pressure drop. In retrofit cases, it might sometimes be necessary to replace a smaller, pre-existing motor with a larger one, requiring that an entire new motor be purchased; this situation is not addressed in the Table A-10 numbers.

As shown in the table, there is little variation in the installed cost of cartridge filters as the efficiency is increased from ASHRAE 65 to ASHRAE 95.

The installed costs for electronic air cleaners were obtained from Means.

4.3.2 Installed Costs for Central Air Cleaners for Gaseous Contaminants

A procedure for estimating the installed costs for air cleaners for gaseous contaminants is presented in the last section of ***Worksheet 8***.

The worksheet directs the user either to obtain an installed cost estimate for the air cleaner from a vendor, based upon the expected air throughput, or to compute the installed cost directly assuming a unit cost of $680 per 1,000 cfm throughput. Since variations in required removal efficiency are addressed entirely through adjustment of the sorbent replacement frequency, as discussed earlier, the efficiency results from Worksheet 7 do not impact the installed cost estimated here.

The $680 per 1,000 cfm unit installed cost includes the cost of the air cleaner itself, plus the incremental cost of an enlarged fan drive motor to handle the increased pressure drop. The cost of the air cleaner -- $660 per 1,000 cfm -- is obtained from a rigorous cost estimate for a granular activated carbon unit, derived from vendor quotes (Henschel, 1998). The air cleaner costed in that study was of a typical design, with the granular carbon being contained within 1-inch-deep panel beds mounted in a V-bank configuration, marketed in modules having a capacity of 2,000 cfm each. The same unit air cleaner cost is obtained from Means (1996) for full-flow activated charcoal air cleaners.

The incremental installed cost of the enlarged motor for the air handler -- $20 per 1,000 cfm -- was derived in the same manner as described in Section 4.3.1 for the case of particulate air cleaners. A pressure drop of 1 in. WG was assumed across the 1-inch-thick carbon panel beds (Henschel, 1998) -- the same as the average pressure drop expected across the media particulate filters -- dictating the incremental additional fan horsepower that is needed. This is the approximate pressure drop that would be calculated for 1-in.-thick beds of 8 x 16 mesh granular material, at the face velocity of 80 ft/min representative of some commercial V-bank panel reactors. Thinner beds, coarser carbon particles, or lower face velocities would reduce the pressure drop.

4.4 ESTIMATING OPERATING AND MAINTENANCE COSTS FOR CENTRAL AIR CLEANERS

4.4.1 Annual Operating Costs

The annual operating cost associated with central air cleaners will consist of the incremental energy cost for: 1) the increase in power consumption by the fan motor to accommodate the added pressure drop, in the case of media particulate filters and gaseous air cleaners; 2) power consumption by the corona wires and plates, in the case of electronic air cleaners; and 3) added power consumption by the cooling system in removing the incremental heat added to the air stream by the enlarged fan motor or the electronic air cleaner, when the HVAC system is operating in the cooling mode.

Worksheet 9 in Appendix A presents a method for estimating these energy costs, for each of the types of central air cleaners.

Increased fan horsepower. Worksheet 9 estimates the incremental additional fan horsepower requirements by multiplying the total airflow through the air cleaner times the average pressure drop across it, accounting for fan/motor efficiency, and applying the appropriate conversion factors. The annual energy consumption (kWh/yr) is then computed by multiplying this power requirement times the number of hours per year that the fan will be operating. The annual operating cost for the larger fan motor is determined from this energy consumption, based on the unit cost of electricity.

Default values are provided for all of the parameters -- pressure drop, fan efficiency, hours of fan operation, and unit energy costs -- if the user does not have values readily available. As discussed in Sections 4.3.1 and 4.3.2, the default pressure drop across media particulate filters and gaseous air cleaners is 1 in. WG. The pressure drop across the electronic air cleaners is assumed to be small.

Electronic air cleaner power consumption. The power to the corona wires and plates of electrostatic precipitators is computed by defining a power consumption per unit air throughput. The default value for this parameter, suggested in the worksheet, is 30 W per 1,000 cfm throughput. This figure is the mean of the typical range (20 to 40 W per 1,000 cfm) cited in the literature (ASHRAE, 1996).

Increased cooling costs. The incremental increase in power input to the fan motor, and the power input to the electronic air cleaner, will appear in the building as heat. Some fraction of this incremental heat will have to be removed by the cooling coils, when the system is operating in the cooling mode. Likewise, when the system is in the heating mode, one might expect the heating load to be correspondingly reduced.

Calculations were made using the DOE-2 computer model, to assess the building energy impacts resulting from the installation of air cleaners in a variety of climates. These calculations suggest that, on average, a high percentage of the incremental heat introduced by the enlarged fan motor or the electronic air cleaner will have to be removed by the cooling system. Only a few percent of the added heat seems to contribute to a reduction in building heating energy requirements, even in cold climates.

Thus, Worksheet 9 assumes that -- for the purposes of this rough estimate -- all of the energy input to each of the air cleaners will appear as heat that has to be removed by the cooling coils. This added energy is multiplied by the electric input ratio (EIR) for the cooling system -- the default value of which is 0.34 kW of electric input to the system per kW of cooling provided to the air stream -- to determine the incremental additional electric input required to the compressor/condenser. This result is then multiplied by the unit cost of electricity to give estimated annual energy costs for increased cooling.

4.4.2 Annual Maintenance Costs

Worksheet 10 in Appendix A presents a method for estimating the annual maintenance costs for each of the types of central air cleaners.

Maintenance costs are assumed to include:

a) the materials and labor costs associated with periodic replacement of the filter media, in the case of media particulate air cleaners;

b) the labor costs associated with periodic cleaning of the corona wires and plates, in the case of electronic air cleaners; and

c) the materials and labor costs associated with periodic replacement of the granular sorbent, in the case of air cleaners for gaseous contaminants.

For each type of air cleaner, Worksheet 10 first computes the mass of contaminant per year that the air cleaner will be removing, based upon the volumetric flow through the unit, the average contaminant concentration in the air stream, and the removal efficiency. The worksheet then computes the mass of contaminant that can be accumulated on the air cleaner before maintenance is required, and, from this, derives the number of times per year that maintenance is necessary. Multiplying this frequency times the cost per maintenance event yields the annual maintenance cost.

The mass of contaminant that can be accumulated before maintenance is required must be obtained from the vendor for media air filters; the filter must be replaced before the pressure drop created by the increasing dust cake becomes unacceptably high. Likewise, the allowable mass of particulate that can be collected by electronic air cleaners must be obtained from the vendor; cleaning is required before the depth of the dust layer impacts the electrostatic properties sufficiently to degrade precipitator performance below specifications.

For gaseous air cleaners, the user may obtain an estimate from the vendor regarding the mass of the particular organic compound(s) of concern that can be accumulated per unit mass of sorbent, before the organics will break through the sorbent bed in unacceptable amounts. Alternatively, the user is provided with a table (based upon independent data on sorption capacities on granular activated carbon) that presents the mass of organic compound per unit mass of carbon. These values depend heavily on the nature of the specific organic compounds of interest, and on their inlet concentrations into the air cleaner. Once the mass of organics per unit mass of sorbent is thus estimated, the replacement frequency will be determined by the mass of sorbent present in the air cleaner per unit air throughput.

The cost per maintenance event in Worksheet 10 for particulate media filters is based on vendor quotes for replacement filter cartridges; the labor cost associated with replacing the cartridges is assumed to be small. The cost per event for electronic air cleaners is based on the labor hours required for the cleaning operation, a number that the user must estimate. For gaseous air cleaners, the cost per event is computed from: the unit cost of replacement sorbent (default $3/lb for carbon, based on vendor quotes); the mass of sorbent in the air cleaner (commonly about 45 lb per 1,000 cfm air throughput for carbon); the labor required to replace the carbon (default 1 labor hour per 1,000 cfm); and the cost for disposal of the spent sorbent (default $0.05/lb, assuming the waste material can be sent to a standard landfill).

In all cases, the default labor rate in the worksheet is the rate obtained from Means (1996) for building laborers.

4.5 ESTIMATING TOTAL ANNUALIZED COSTS FOR CENTRAL AIR CLEANERS

The total annualized cost for central air cleaners can be determined using ***Worksheet 11*** in Appendix A.

Worksheet 11 uses the costs derived in Worksheets 8, 9, and 10 to compute the total annualized cost for air cleaners, following the same format used in Worksheet 5 for increases in ventilation rate (see Section 3.5).

4.6 ESTIMATING COSTS FOR SELF-CONTAINED AIR CLEANERS

Sections 4.2 through 4.5 -- and Worksheets 7 through 11 -- address central, in-duct air cleaners. This section addresses the case of self-contained air cleaners.

The procedure for estimating the costs of self-contained units is presented in ***Worksheet 12*** in Appendix A. Figure A-2 at the end of that worksheet provides a generic schematic diagram for the self-contained case.

Worksheet 12 begins by estimating the value for the key parameter that will be used in sizing and costing the self-contained unit, analogous to the computation in Section 4.2 for central air cleaners. For the central units, the flow through the air cleaner is dictated by the total flows around the HVAC unit, and depends only on where the air cleaner is located within the HVAC system. Thus, in Section 4.2, the key parameter being computed is the required air cleaner efficiency, given the flow rate. But with self-contained units, the key parameter is the flow rate of air from the affected space, Q_C, that must be circulated through the air cleaner; this will dictate the size and number of self-contained units that must be installed in the space. Accordingly, in Worksheet 12, the user is asked to estimate *a priori* what the efficiency of the self-contained units will be -- e.g., based on vendor literature -- and the focus is then on computing the necessary flows.

The analysis shown for self-contained units in Figure A-2 is similar to that in Figure A-1 and Table A-8 for central units (see Worksheet 7). Of course, the mass balance equation for self-contained units is somewhat different, and, as discussed above, is solved for Q_C rather than for η. For simplicity, the mass balance equation in Figure A-2 ignores the effect of the other zones being conditioned by the HVAC system, either as sources of the contaminant of concern, or as sources of dilution air, to the zone of interest.

The computed flow Q_C is then used in Worksheet 12 to determine the number of self-contained units that will be required in the zone, considering the flow capacity of the individual units available from the vendor. Depending upon the size of the affected zone and the contaminant reductions that are necessary, it might be expected that multiple self-contained units will commonly be required in the zone to provide the desired performance. The installed cost for each air cleaner is determined from the vendor's quote for the uninstalled unit plus the user's estimate of the cost of installation in the occupied space (e.g., mounting and wiring), which will be highly site-specific. The total installed cost for the set of air cleaners will then be obtained by multiplying the installed cost per air cleaner times the number of air cleaners needed.

The annual operating (electricity) costs for self-contained air cleaners arise from the same sources as in the case of the central unit, namely, power consumption by: a) the fan; b) the electronic air cleaner, if applicable; and c) the cooling system, in removing the heat introduced by a) and b). The only difference is that, with the self-contained units, the fan power consumption arises from the separate fan contained within each unit, rather than from the incremental increase in consumption by the central HVAC air handler. With that difference, the computational approach in Worksheet 12 for the annual operating costs of self-contained units is essentially the same as that for central units in Worksheet 9, discussed in Section 4.4.1.

Likewise, the estimation of annual maintenance costs in Worksheet 12 follows exactly the procedure used in Worksheet 10 for central air cleaners (discussed in Section 4.4.2). And the estimation of the total annualized costs follows the same procedure used in Worksheet 11 for central units.

SECTION 5

ESTIMATING THE COSTS OF IAQ CONTROL OPTIONS: SOURCE MANAGEMENT

5.1 INTRODUCTION

As illustrated in Figure 3, the IAQ control methods that fall into the category of "source management" cover a wide array of different procedures: use of low-emitting materials, removal or relocation of sources, maintenance activities, source treatment, and adjustments to occupancy patterns. Furthermore, the difficulty and costs involved in implementing any one of these methods -- in fact, the determination *if* and exactly *how* the method can be implemented -- will be highly site-specific. Thus, for source management, it is generally difficult to define rigorous worksheets similar to those presented in Sections 3 and 4 for the ventilation and air cleaning cases.

Accordingly, this section is not subdivided in the same manner as the preceding two (installed costs, operating costs, etc.), but rather, is subdivided according to the types of source management options as defined by the diamonds on the left side of Figure 3. Within each subsection, the specific control methods that represent that type of source management option are discussed in terms of the types of issues that the user will need to address in assessing installed and annualized costs. But often, no attempt will be made to provide a rigorous worksheet, except in cases where such a worksheet is feasible and potentially helpful.

5.2 ESTIMATING THE REQUIRED EXTENT OF SOURCE MANAGEMENT

5.2.1 Constant Sources

Some sources might be viewed as having an essentially steady emission rate, for the purposes of this analysis. The best example of a truly constant source would be a continuous occupant activity -- e.g., constant operation of a photocopier or a printer -- that releases contaminants at a steady rate during occupied hours. Even where the activity is not continuous, but is frequent and consistent -- e.g., repetitive use of solvent-containing office supplies during occupied hours, causing periodic concentration spikes -- the resulting average concentration over the duration of the work day might be represented as relatively constant within the uncertainties of this analysis. Sources which are not continuous, where the emission rate irreversibly decays over time -- typical, e.g., of building materials and furnishings -- might simulate a constant source over moderate time intervals in cases where the particular source decays at a slow rate. (For example, composite wood office furniture have such a slow decay rate in some cases.) Microbiological contamination on building or HVAC surfaces may release airborne biologicals and VOCs at a relatively constant rate.

In cases where the source is essentially constant, the effect of a source management step might be approximated using a simple mass balance. Such a mass balance around a zone containing the source (using the flow diagram illustrated in Figure A-1, Worksheet 7, in the Appendix) yields the relationship

$$C_{sm}/C_o = [Q_A C_A K + S_{sm}]/[Q_A C_A K + S_o] \qquad \text{(Equation 5-1)}$$

where

- C_{sm} = the concentration of the contaminant of concern in the zone after source management is applied (mg/m^3);
- C_o = the concentration in the zone before source management (mg/m^3);
- Q_A = the outdoor air flow rate into the zone (cfm);
- C_A = the concentration of that contaminant in the outdoor air (mg/m^3);
- K = concentration conversion factor, 6.2×10^{-8} $(lb/ft^3)/(mg/m^3)$;
- S_{sm} = the emission rate from all sources of that contaminant in the zone after source management (lb/min); and
- S_o = the emission rate from all sources before source management (lb/min).

In cases where the outdoor concentration of the contaminant of concern is zero, the above equation naturally reduces to one of direct proportionality:

$$C_{sm}/C_o = S_{sm}/S_o. \qquad \text{(Equation 5-2)}$$

Where there are multiple types of constant sources emitting the same contaminant, then S_o in the above equations would be represented by

$$S_o = S_{o\text{-}a} + S_{o\text{-}b} + S_{o\text{-}c} + \ldots \qquad \text{(Equation 5-3)}$$

where the subscripts a, b, and c represent the different sources. S_{sm} would be represented similarly.

For any generic source, the emission rate S would be defined by the expression

$$S = s_u A \qquad \text{(Equation 5-4)}$$

where

s_u = unit emission rate, i.e., the rate per some unit measure of the amount of source present (e.g., lb/min per ft^2 of source surface, or lb/min per photocopier or other device); and

A = amount of source present (e.g., ft^2 of source area, or number of emitting devices).

Source management involves reduction of the values of s_u and/or A during periods when the building is occupied. This could be achieved by some combination of: reducing the inherent value of s_u in one of several ways; eliminating some of the source (i.e., reducing A); or modifying the time at which the source is active, or the occupancy pattern of the building, so that s_u has decayed to a reduced level by the time the space is occupied.

Estimation of the extent of source management required for constant sources would involve the following steps.

1) Estimate or determine: the required reduction in the indoor concentration (yielding the required value of C_{sm}/C_o); and, if $C_A \neq 0$, the values of S_o, Q_A, and C_A.

2) Using Equation 5-1 or 5-2, compute S_{sm}/S_o.

3) Depending upon the nature of the source and the source management step being considered, use Equation 5-4 to assess how s_u and/or A will be reduced to achieve the desired value of S_{sm}/S_o computed in Step 2, i.e., so that

$$(s_{u\text{-}sm}A_{sm})/(s_{u\text{-}o}A_o) = S_{sm}/S_o \qquad \text{(Equation 5-5)}$$

where $s_{u\text{-}sm}$ and $s_{u\text{-}o}$ are the values of s_u with and without source management, respectively. If, for example, the source management were to consist solely of reducing the amount A of source while s_u remains unchanged, then A_{sm} would have to equal $A_o \times (S_{sm}/S_o)$. If A were to remain unchanged, then $s_{u\text{-}sm}$ would have to equal $s_{u\text{-}o} \times (S_{sm}/S_o)$. Where there are multiple sources (a, b, and c) emitting the same contaminant, then differing adjustments could be made to $S_{o\text{-}a}$, $S_{o\text{-}b}$, and $S_{o\text{-}c}$ in Equation 5-3 to achieve the desired overall value of S_{sm}.

The reasoning illustrated in the above steps will be cited in Sections 5.3 through 5.8, indicating how this analysis might be applied under the various source management scenarios to assess the extent of source management required in cases where the source is constant.

5.2.2 Decaying Sources

Many sources decay over time, at rates dependent on the nature of the source. For example, the emissions from newly applied latex paints -- after a substantial spike immediately following application -- may decay to near zero within days, or perhaps a week or two. Emissions from new carpeting might be expected to decay to near zero within a few months. Liquid products used in the building -- e.g., floor wax, janitorial cleaner, personal hygiene products -- decay very rapidly, within hours; in fact, the contaminants may be released into the air almost instantaneously after application, with the "decay" period being more a measure of how long it takes for the ventilation system to flush the spike of contaminants out of the space.

Estimating the required extent of source management for these sources -- to achieve some desired reduction in average indoor concentrations or annual occupant exposure -- cannot be computed as simply as is possible in Section 5.2.1 for constant sources. Because emissions vary with time, computer modeling would be required, incorporating appropriate mathematical expressions for the source's emission and decay characteristics, including the required experimentally determined constants. A number of models are available that enable such modeling (Sparks, 1991; FSEC, 1992; Walton, 1994; Guo, 1999). However, such modeling is beyond the scope of this simple methodology.

The inability to estimate simply the total or time-averaged effects of modifying decaying sources will not necessarily prevent some consideration of source management with such sources. It is known that such sources often decay to near-zero emissions in days, weeks, or, in the case of carpeting, months. Sources, such as paint or carpeting, that are introduced into the building on a one-time basis and that decay relatively quickly will probably have a minimal effect on the long-term exposure of the occupants (although peak short-term exposures could be significant). Thus, computer modeling to assess long-term, chronic occupant exposures from these sources -- and the effects of source management steps to reduce these long-term exposures -- is probably unnecessary. If the objective is to reduce short-term, acute exposures -- one of the most likely objectives of managing quickly decaying sources -- then one might roughly estimate the relative reduction in peak exposure as being proportional to the relative reduction in emission factors expected to be achieved by implementing the source management step.

Where the source management step is to involve some delay in the exposure of occupant to the source -- by delaying occupancy of a new building while sources decay, or by "airing out" a product before introducing it into the building -- general knowledge of the decay periods for the different types of sources would be sufficient, without any modeling, to define what an appropriate delay period might be. Of course, modeling would still be required if one wished to rigorously compute the reduction of occupant exposure achieved by this step, for the purposes of quantifying cost-effectiveness.

Some decaying sources may simulate a constant source. For example, the decay period for composite wood furniture -- at least for some contaminants -- may be a couple years. Thus, as indicated in Section 5.2.1, it may be reasonable to treat the furniture during its first couple years as a constant source emitting at its average rate during the year. Likewise, liquid supplies that are used frequently and consistently during occupied periods might be assumed to be a constant source having an average emission factor, even though they are in reality a sequence of spikes that occur during each use. However, liquid supplies that are used infrequently during periods of low occupancy -- e.g., floor wax -- could not be analyzed in this manner.

5.3 SOURCE REMOVAL

5.3.1 Remove High-Emitting Furnishings, Solvents, or Equipment

This step involves the permanent removal of part or all of the source. This is distinguished from replacement of the source (Section 5.4) or relocation of the source (Section 5.6), and suggests that at least some of the materials/equipment that are generating the emissions are not really necessary on-site.

Referring to Equation 5-5 in Section 5.2.1, this source management step would involve making A_{sm} sufficiently small relative to A_o.

Some of the issues that the user will need to address in costing these source management options are listed below.

The source is a furnishing

1) Exactly where, and in what quantity, are these furnishings located throughout the building?

2) Which portion of these furnishings are to be removed? Can a sufficient amount of the furnishings be removed, so that A_{sm} becomes sufficiently small to provide the desired reduction in exposure?

3) In existing buildings (retrofit cases), what will be involved in removing the portion of the furnishings that are to be removed? For example, if the furnishing is carpeting, is it covered with extensive furniture that will have to be moved? Is there molding that will have to be removed/re-installed? How is the carpeting attached to the floor? Will any refinishing of the underlying flooring be required before the space can be re-occupied?

4) Estimate the cost of removing the furnishing. In existing buildings, this will involve an estimation of the one-time renovation costs for the type of efforts suggested in 3) above. For new construction, this cost may in fact be an installed cost savings, since it will translate into a reduction in the originally planned furnishings in the new building (e.g., fewer square yards of carpeting).

The source is a solvent (janitorial products, etc.)

5) Can a sufficient amount of this source in fact be removed to provide the required reductions in exposure?

6) How will the removal of this source impact day-to-day activities in the building? For example, will contract janitorial service personnel who used to store cleaning products in the building now have to transport them into the building daily?

7) Estimate the annual maintenance (or operating) costs for implementing these changes.

The source is equipment (reproduction equipment, photo-finishing equipment, etc.)

8) Can a sufficient amount of this equipment in fact be removed from the site, to provide the required reductions in exposure?

9) How will the removal of this equipment impact day-to-day activities in the building? For example, will some task which was previously performed in the building now have to contracted out to an off-site supplier?

10) Estimate the cost of removing the equipment (in existing buildings) and, as necessary, the net annual costs for conducting the tasks with this equipment off-site. For new construction, there may be some savings in installed or annual costs from not having to purchase or lease the equipment in the first place.

5.3.2 Improve Maintenance to Remove Contamination

This step includes maintenance/cleaning activities designed to remove contamination (such as biocontaminants) that is present, e.g., in the HVAC system or on other surfaces within the building, and that is acting as an emission source. Again, the objective of this step is to reduce the value of A_{sm} in Equation 5-5.

Some of the issues that the user will need to address in costing these source management option are:

1) Exactly where in the building is the emitting contamination located?

2) How extensive is the contamination in these locations? Can the contaminated surface reasonably be cleaned, or does it have to be replaced (Section 5.4)?

3) Estimate the cost of the maintenance/cleaning effort, perhaps with the aid of vendor quotes. Will this cost be a one-time renovation cost, resulting from, e.g., water damage that is not expected to recur? Or will it be have to be repeated periodically (e.g., periodic cleaning of the HVAC system), representing a continuing, annual cost?

5.3.3 Reduce Activity Generating Emissions

Some emissions result from occupant activities -- e.g., smoking, the use of personal care products, or the use of office supplies and equipment.

Reductions in the on-site use of office supplies or equipment were addressed in Section 5.3.1 above. Elimination, e.g., of smoking on-site is a policy issue that cannot be addressed in this economic analysis.

5.4 SOURCE REPLACEMENT

5.4.1 Use of Low-Emitting Materials (LEMs)

One approach commonly considered for source management is the replacement of an existing or planned "high-emitting" source -- carpeting, furniture, paint, photocopier, etc. -- with a comparable material or equipment item having lower emissions.

Referring to Equation 5-5, this source management step would involve making the unit emission rate after source management, $s_{u\text{-}sm}$, sufficiently small relative to the rate prior to source management, $s_{u\text{-}o}$.

Because this approach is commonly considered -- and because it is somewhat more amenable to a worksheet format than are many other source management methods -- ***Worksheet 13*** in Appendix A has been prepared for this LEM replacement case. While this worksheet is not as rigorous as those addressing ventilation and air cleaning -- requiring more effort by the user in deriving some of the entries -- it illustrates the thought process that would be used in comparing the costs of LEM replacement against the costs of the competing alternatives of ventilation or air cleaning.

Worksheet 13 is subdivided into sections for the retrofit and the new construction cases, since the calculational process is somewhat different between the two. In both cases, the user is first asked to estimate the unit cost for the low-emitting material or product versus the originally planned, higher-emitting material. As estimate is also requested for the differences, if any, in the useful lifetime of the low- vs. higher-emitting materials. While this analysis seems to imply that the low-emitting material may be more expensive or shorter-lived, this will not necessarily be the case.

For the retrofit case, the installed cost of the LEM is derived in the worksheet from: a) the installed cost that would be incurred if the LEM were being installed in a new building without complications; plus b) the additional installation costs resulting from the complications of retrofit, i.e., clearing the work area, removing and disposing of the old material, any required surface preparation, and restoration of the space after installation. Due to the highly site-specific nature of this effort, it is left to the user to define the costs of the LEM (e.g., based on vendor quotes) and to define the additional costs for retrofit for the particular building under consideration. The annualized costs for this LEM replacement effort are computed from this total installed cost utilizing a Capital Recovery Factor (CRF) that is based on the number of years, n_L, representing the expected lifetime of the LEM.

For the new construction case, the cost of the LEM replacement approach will be the incremental cost of installing the LEM in lieu of the originally planned material in the first place. In this case, the appropriate cost is the incremental difference between: the annualized cost of installing the LEM (i.e., the total installed cost for the LEM times the CRF based on the expected lifetime, n_L, of the LEM); and the annualized cost of installing the original material (i.e., the total installed cost for the original material times the CRF based on its expected lifetime, n_O).

The above calculational approach assumes that the user knows the cost of the LEM beforehand, and wishes to compute the resulting annualized cost. From that annualized cost, and from the reductions in exposure (i.e., the "effectiveness") resulting from the LEM replacement (see Section 6), the user could then proceed to compute the cost-effectiveness of this approach (see Section 7).

As an alternative, Worksheet 13 also addresses the reverse of this calculation: the user is assumed to know what reduction in exposure is needed, and the cost-effectiveness with which this required exposure reduction can be achieved using alternative, competing approaches involving increased ventilation or air cleaning. The question then becomes, What is the maximum premium that could be paid for a LEM (compared to the original material) before LEM replacement becomes less cost-effective than ventilation or air cleaning? From the required effectiveness and cost-effectiveness, the maximum allowable annualized cost for LEM replacement is determined, and the worksheet then helps the user back-calculate what the cost of the LEM can be. The user would then have to determine whether a suitable low-emitting material is available at this price that can provide the required exposure reductions.

As discussed in Section 5.2.2, it can be difficult to quantify the long-term reductions in occupant exposures that can be achieved through source management steps (such as the use of LEMs) unless: a) the source is a constant source; or b) the source is a decaying source, but it recurs frequently and consistently during occupied hours, or it decays very slowly (over a period greater than a year), in which case it may simulate a constant source. The exposure effects from managing constant sources can be estimated using a simple mass balance (Section 5.2.1). But if the source does not recur frequently and if it decays completely over a relatively short period (days, weeks, or a few months), quantification of long-term exposure effects requires computer modeling of the building, plus sufficient information on the emission and decay characteristics of the material to serve as input to this computer model (Section 5.2.2). Such computer models will not be available to many users of this document; and, in many cases, the necessary data on LEM emission characteristics will not be available.

Thus, it will often not be straightforward for the user to perform the reverse calculations discussed in the preceding paragraph, if the source is non-recurring and decays in a period shorter than a few months (as will commonly be the case). It will not be easy for the average user to determine what reduction in annual occupant exposure a given LEM product on the market will provide, or to quantitatively compare this reduction against that achievable with ventilation or air cleaning.

From modeling that has been performed, it appears that -- with non-recurring emission sources that decay to become non-sources within a few months or less, such as carpeting or paints -- the primary benefit of substituting LEMs is a reduction in acute exposures when the sources are new. The reduction in chronic, annual exposures -- of the type used in computing cost-effectiveness in this document -- will often be modest with this type of source. The greatest impact on chronic exposure using LEM replacement is likely to be achieved with constant sources (or sources which simulate constant sources), such as slow-decaying materials (perhaps such as composite wood furniture), or such as products that are in continual use in the building -- e.g., photocopiers, office supplies, or janitorial cleaning products.

5.4.2 Allowing Source to Decay Before Use

For non-recurring emission sources that decay relatively quickly, one option that is sometimes considered is to allow the source to decay before being introduced into the building. This could be done with furnishings that are brought into the building, e.g., with carpeting or furniture. This approach is being considered "source replacement" here, in that a higher-emitting source (the new product) is being replaced by a lower-emitting (aged) product. (One might also consider this procedure to be a variation of "Source Treatment", Section 5.5.)

Referring to Equation 5-5, this source management step would involve leaving the source outside the building until such time as the unit emission rate of the new product (without source management), s_{u-o}, decays to a suitably lower value (after source management), s_{u-sm}.

Issues that can be considered in costing this approach are:

1) How long should the product be thus "aired out", in order to provide the needed reduction in acute (or chronic) exposure? Computer modeling, with data input on the decay characteristics of this source, would enable this calculation.

2) Will the supplier air out the product for this time period? Will the supplier estimate an incremental cost for this procedure?

3) If building owner/operators are going to perform this procedure themselves, is the labor and off-site space available? Can a cost be associated with this labor and space?

4) Will any costs be incurred as a result of the delay in introducing the product into the building? For example, will furniture have to be rented to address an on-going need during the time that the new, purchased furniture is being aired out?

5.4.3 Use of Contamination-Resistant Materials

Where the emission source is not an emission source at the time of installation -- but may develop into a source (e.g., by contamination) following installation -- then one possible source management option would be to install a material which is resistant to such contamination. The classic example of this scenario is the bio-contamination of building or mechanical system surfaces. The use of microbial-resistant duct liners for the mechanical system would be a specific example of this source management approach.

This is the same LEM concept discussed in Section 5.4.1, with the exception that, in Section 5.4.1, the source was assumed to be an emitter at the time of installation. In the current section, the material is assumed to develop into a source *after* installation, and the objective is to install a material less prone to do so.

Some of the issues to be addressed in costing this source management approach are listed below.

1) What quantity of material in the current or designed building is subject to replacement by the contamination-resistant material? For example, what lengths and diameters of ducting are being considered for modification with

microbial-resistant duct liners? In retrofit cases, what portion of the existing material is reasonably accessible for replacement or modification?

2) To what extent is the contamination-resistant material expected to reduce emissions relative to the original material (i.e., what is s_{u-sm} relative to s_{u-o})? Given the amount of resistant material to be installed, will that provide the desired reductions in occupant exposures?

3) In a new building, what are the uninstalled cost and installation cost of this resistant material, relative to the original material?

4) In retrofit cases, what will be the uninstalled cost of the resistant material and what will be the cost associated with: clearing space as necessary to gain access to the materials to be replaced; removing, modifying, and/or disposing of the original materials that are to be replaced; and restoring the space?

5.5 SOURCE TREATMENT

One source management approach that could be considered would be to treat an emission source in some manner so that it would no longer be a source. One example would be encapsulation of existing contaminated duct liners, to prevent the release of emissions from biocontaminants in the liners. One might also postulate coatings on certain product or building surfaces, to trap contaminants that would otherwise be released.

There are other specific source management activities that might be considered "source treatment", depending on the user's semantics. For example, improved maintenance to remove contaminants (considered as source removal, Section 5.3.2) or allowing materials to decay before use (considered as source replacement, Section 5.4.2) might be considered to be source treatment. In this document, a step is termed "source treatment" only when the original contaminants are allowed to remain in the source, but the source is treated in some manner to prevent their release.

Some of the issues that would impact the costing this generic source management approach are suggested below.

1) What material or product is being considered for treatment, and what is the nature of the treatment? Must the treatment be performed on site, or can the treatment of the materials/products be performed off-site by a supplier?

2) What quantity of material in the current or designed building is subject to treatment? In retrofit cases, what portion of the existing material is reasonably accessible for treatment?

3) To what extent is treatment expected to reduce emissions relative to the original material (i.e., what is s_{u-sm} relative to s_{u-o})? Given the amount of material that can be treated, will that provide the desired reductions in occupant exposures?

4) For treated materials/products to be obtained from an off-site supplier for a new building, what are the uninstalled cost and installation cost of this treated material, relative to untreated material? For treatment to be performed on-site in a new building, how will this add to installation costs?

5) In retrofit cases, what will be the costs associated with: clearing space as necessary to gain access to the materials to be treated; removing (if necessary) and treating the original materials; and restoring the space?

5.6 SOURCE RELOCATION

In some cases, it might be possible to retain the emitting source on-site -- avoiding the need for removal, replacement, or treatment -- if the source can be relocated such that the emissions no longer contribute to occupant exposure (or contribute only to a reduced extent). Examples include relocation of indoor sources to an exhausted space within the building (such as a janitorial closet); or relocation of outdoor sources such that their emissions no longer appear in the outdoor air intake into the building.

The costs of source relocation will be very site-specific. Among the general issues that the user would consider in costing this option would be:

1) To what location(s) might the source be relocated?

2) What would be the costs of preparing the new location to accommodate the source?

3) What would be the cost of moving the source to the new location, in the case of existing buildings? For new buildings, what would be the incremental cost of installing the source in the new location in lieu of the previously planned location?

5.7 SOURCE RESCHEDULING

With non-recurring sources that decay fairly quickly, it will sometimes be possible to reschedule the time during which the source is active, such that occupant exposure is reduced. A classic example is scheduling of interior painting to occur over weekends, when the building has a much lower occupancy. Depending on the emission and decay characteristics of the paint, the high contaminant peaks seen during the painting activity might have decayed by perhaps 90% by the time occupants re-enter the building, if the painting is completed 48 hours before the occupants return.

Among the general issues impacting the cost of this option would be:

1) What are the complications of rescheduling? Is the source expected to decay sufficiently quickly -- and does the indoor space remain unoccupied for sufficiently long intervals -- to warrant the effort involved in rescheduling?

2) What cost items will increase by virtue of rescheduling, and by how much? (For example, what overtime premium will have to be paid for the painters to work overnight and on weekends?)

5.8 ADJUSTMENT OF OCCUPANCY PATTERNS

Another option for reducing exposure to non-recurring, decaying sources is to keep the occupants out of the affected portion of the building during the time that the source is active. Examples of the option are: a) to delay moving occupants into a newly constructed building until the new sources in the building have had an opportunity to decay; and b) to keep occupants of an existing building out of a wing of the building during the time that renovations are underway.

Issues to be considered in costing this approach are:

1) Is it practical to keep the occupants out of the space -- e.g., by renting alternative space, or preventing access to the renovated portion of the building -- for the duration required to permit sufficient decay of the source(s)? For the concentration spikes from freshly applied paints, this period could involve several days for significant (e.g., 90%) reductions, and a week or two for essentially complete decay. For carpeting, this period could involve a month or two for moderate (e.g., 50%) reductions, and a number of months for essentially complete decay.

2) If alternative, temporary space is to be used while the sources in the main space decay, what will be the costs of leasing and furnishing this temporary space, and of providing utilities and maintenance, as applicable? Will these costs for the temporary space be offset in any way by a reduction in utilities, maintenance, etc., for the main space while it is unoccupied?

3) In an existing building under renovation, will costs be incurred in installing temporary alternative routes for pedestrian traffic, resulting from the need to avoid the area under renovation?

SECTION 6

ESTIMATING THE EFFECTIVENESS OF IAQ CONTROL OPTIONS

In Sections 3 through 5, simplified methods were presented for estimating the incremental increase in cost resulting from implementation of each of the three IAQ control approaches. This number represents the term "Δ(cost)" in the expression defining "cost effectiveness" (see Section 1.4), i.e.,

$$\text{cost-effectiveness} = - \Delta(\text{cost})/\Delta(\text{exposure}). \qquad \text{(Equation 6-1)}$$

In the current section, a procedure is discussed for estimating the other term in the equation, Δ(exposure), i.e., the effectiveness of the control step in reducing occupant exposure.

As discussed in Section 1.4, "exposure" is expressed as the number of person-hours of exposure to a unit concentration of contaminant per year. The units are thus of the form $(mg/m^3) \bullet$ person $\bullet$ hr per year. If one wishes instead to consider the exposure of an average building occupant, the total occupant exposure can be divided by the number of occupants, and unit exposure will then be expressed in units of $(mg/m^3) \bullet$ hr per average person per year. Alternatively, the exposure calculation may be performed for a selected typical person, in which case the units would be $(mg/m^3) \bullet$ hr per typical person per year. The user may employ any of the above definitions of exposure (total exposure of all occupants, or exposure per average or typical occupant), as long as the same definition is used consistently in comparing the effectiveness (and cost-effectiveness) of alternative IAQ control approaches.

Section 6 is subdivided into two subsections. The first subsection addresses methods for estimating the absolute reductions in exposures that will be achieved with a given control approach [Δ(exposure)]. The second addresses a simpler procedure for estimating the *relative* reduction in exposure that can be achieved by one control approach compared to another [i.e., $\Delta(\text{exposure})_1/\Delta(\text{exposure})_2$].

6.1 ABSOLUTE EXPOSURE VALUES

6.1.1 Rigorous (Computer-Assisted) Calculations

From a practical standpoint, only users who have access to a suitable computer model will be in a position to rigorously estimate absolute reductions in occupant exposure resulting from IAQ control measures. It is anticipated that many users of this document will not be readily able to utilize such a model. In fact, this document is intended for use by persons who are not in a position to perform such modeling, to enable rough estimates of cost-effectiveness before someone is retained who can conduct this modeling. Section 6.1.1 is included here for the purpose of illustrating the logic behind such rigorous calculations.

Consider the case where one of the building occupants spends one hour in a zone within the building, and where, during that particular hour, the concentration of the contaminant of concern within that zone is 1 mg/m^3. The total exposure during that hour is

$$(1\ mg/m^3) \bullet (1\ person) \bullet (1\ hr) = 1\ (mg/m^3)\text{-person-hr.}$$

If one tracked this person throughout a year -- recording the zone occupied by this person and the average concentration in that zone during each hour of occupancy -- the above calculation could be repeated for each hour that this person was in the building during the year. The sum of all of these hourly exposures would be the total exposure experienced by this person during the year. Repeating this annual calculation for every occupant of the building, and summing over every person, would yield the total (mg/m^3)-person-hours of exposure in the building per year.

The concentrations that a given occupant might see could vary from hour to hour. For one thing, the person might move from one zone within the building to another having a different concentration, or might leave the building altogether. Thus, occupancy pattern plays a role. In addition, the concentration within a given zone can vary from hour to hour: an existing source can be decaying; a new source might be introduced (e.g., use of some office supply or cleaning product); or the cycling of the HVAC system might be creating fluctuations in concentration. An example of this latter effect is overnight or weekend shutdown of the HVAC system, which can result in higher-than-average zone concentrations during the first hour or two after startup at the beginning of the work day.

To rigorously perform this tedious hour-by-hour computation of exposures with changing concentrations, one needs a suitable computer model. There are several types of models available for estimating these exposures, varying in complexity.

The simplest type of model is referred to here as a "mass balance" model, and is represented by the models of Sparks (1991) and Guo (1999). This type of model uses a simple mass balance approach for computing hour-by-hour concentrations in each zone of the building -- assuming that each zone is separate and internally well-mixed -- based on the following input from the user.

1) The distribution of sources and sinks among the zones, and the exact characteristics of each source and sink. The model includes various equations that define the emission/decay characteristics for various types of sources (first-order decay, second-order decay, etc.); the user must select the type of equation to be used to represent each source, and values of the specific constants to be used in each equation (determining, e.g., initial emission rate, the decay rate, and the sink sorption/desorption characteristics).

2) Flows of air from one zone to another, and from the outdoors to each zone. This would include building air recirculation and OA supply by the HVAC system, OA infiltration directly into the zone, and interzonal air movement independent of any HVAC system. These flows must all be specified as input to the model; the model is not able to calculate these flows independently.

The mass balance models then use the hour-by-hour concentrations in each zone of the building, and the occupancy patterns of each zone, to compute the total exposure in the building for the period of interest, e.g., over the course of a year.

A somewhat more complicated type of model is referred to here as a "building simulation" model, represented by the models of FSEC (1992) and Walton (1994). This type of model is similar to mass balance models, with one important exception: the air flows between zones, and between the outdoors and each zone, do not have to be specified as model inputs. These models compute building energy requirements and HVAC system performance, and, in doing so, compute the mechanically induced flows to the different zones and the flows induced by pressure differences between zones.

A third type of model, referred to here as a "computational fluid dynamics" (CFD) model, is the most sophisticated of the alternative model types. Both the mass balance and the building simulation model types assume the zones to be internally well-mixed units; CFD models avoid this need, allowing consideration of gradients within zones. However, this level of sophistication and computational effort is beyond what is necessary for the exposure calculations used in IAQ cost-effectiveness analysis, even in those cases where building modeling experts become involved.

6.1.2 Simplified Calculations

From a practical standpoint, a computer model is necessary to compute absolute exposure if the user is to rigorously account for the variations in indoor concentrations with time, as discussed in Section 6.1.1. Accordingly, if absolute exposure is to be estimated without such a model, it will be necessary to simplify the calculation by assuming that the occupants are exposed to a steady, average indoor concentration over the course of the year, and that the occupancy pattern is simple and consistent.

Worksheet 14 in Appendix A presents a simplified method for estimating the effectiveness (the change in exposure) that will result from applying an IAQ control measure, considering the reduction achieved in the annual average concentration.

Worksheet 14 first asks the user to estimate the average annual concentrations of the contaminant of concern in each of the zones of interest, with and without implementation of the IAQ control measure. The difference between these two represents the reduction in concentration achieved by the control step. This difference is then multiplied by the average number of occupants and the average hours of occupancy per year in each zone, to provide the reduction in the annual exposure in each zone. Summing these reductions over all of the zones of interest yields the total reduction in exposure for all of these zones (e.g., for the entire building).

It will generally not be straightforward to estimate the annual average concentrations with and without the control measure, which the worksheet requires as a surrogate for the time-varying concentrations that will exist in reality. In cases where such average concentrations cannot reasonably be estimated, the user may wish to consider the approach used in Section 6.2 below, which avoids the need to compute absolute concentrations, either with or without the control measure. Instead, the approach in the next section uses simply the fractional reduction expected from a control measure, and compares it against the fractional reductions achieved by other measures.

Even if the uncertainties in estimating absolute concentrations might make Worksheet 14 difficult to use in some cases, the worksheet still useful in illustrating the concept of the exposure/effectiveness calculation.

As discussed in Section 1.4, the "effectiveness" of a control measure is described by the equation

$$\text{effectiveness} = - \Delta(\text{exposure}).$$

Worksheet 14 computes the value of Δ(exposure) created by implementation of the control step. Because the control step presumably will reduce the concentration and hence reduce the exposure, the change in exposure will be negative. According to the equation above, a negative change in exposure translates into a positive effectiveness for the control measure.

6.2 RELATIVE EXPOSURE VALUES

The difficulties involved in estimating the average contaminant concentrations, discussed in Section 6.1.2 above, can be avoided in cases where it is sufficient for the user to estimate only the *relative* reductions in exposure achieved by one control measure compared to another. In this situation, where only the relative performance of alternative techniques is of interest, it is not necessary to know the actual before-and-after concentrations with either technique. Nor is it necessary to estimate the occupancy pattern of the building, as Worksheet 14 requires.

The estimation of *relative* reductions in exposure still requires the user to estimate the fractional (or percentage) reduction achieved by each of the control measures being considered. But such an estimation of reduction will commonly be much more reliable than will be an estimation of the absolute concentrations involved. For example, the estimate that a doubling of OA ventilation rate will provide a 50% reduction in exposure will generally be more reliable than will be estimates of the actual indoor concentrations before and after that estimated 50% reduction.

Of course, if one computes only the *relative* effectiveness of one measure versus another in this section, that will permit the calculation in Section 7 only of relative *cost-effectiveness* values for the measures being compared. But that may often be sufficient, given that the user's objective will commonly be to select the most cost-effective of the alternative measures under consideration.

Worksheet 15 in Appendix A presents a method for estimating the relative reductions in exposure that can be achieved with one IAQ control measure in comparison against other measures under consideration.

Worksheet 15 simply asks the user to estimate the fractional change in the annual average exposure for each of the control measures under consideration. For example, doubling the OA ventilation rate would likely provide a 50% reduction in indoor concentrations (resulting in a fractional change of -0.5 in total occupant exposure), according to the approach in Worksheet 1. Perhaps an air cleaner might be designed that can reduce concentrations by 75%, using the mass balance considerations in Worksheet 7 (providing a fractional change in exposure of -0.75). Removing 80% of a source might be expected to reduce indoor concentrations by about 80% (a fractional change of -0.8). Based on Equation 6-2 above, the *effectiveness* of these three measures would thus be +0.5, +0.75, and +0.8, respectively.

The relative effectiveness of these control measures in this hypothetical case is readily computed. The doubling of the ventilation rate is 0.5/0.75 = 0.67, or 67% as effective as the postulated air cleaner; and it is 0.5/0.8 = 0.62, or 62% as effective as the postulated source management step. These ratios can be estimated without any knowledge of absolute indoor concentrations or occupancy patterns.

For the purposes of the discussion of relative cost-effectiveness in Section 7.2, it is useful here to express mathematically the intuitive ratio that is being computed in the preceding paragraph. Assume that:

E_o = total annual occupant exposure in the building prior to implementing any IAQ control measure [(mg/m^3)-person-hr];
E_1 = total annual exposure if Measure #1 is implemented;
E_2 = total annual exposure if Measure #2 is implemented;
X_1 = fractional reduction in annual average indoor air concentration if Measure #1 is implemented; and
X_2 = fractional reduction in annual average indoor air concentration if Measure #2 is implemented.

The total annual exposures with the two control measures, E_1 and E_2, are related to the uncontrolled exposure E_o by the expressions

$$E_1 = (1-X_1)E_o = E_o - X_1E_o$$

and

$$E_2 = (1-X_2)E_o = E_o - X_2E_o.$$

Thus, the change in exposure being achieved by the two measures are

$$\Delta(\text{exposure})_1 = E_1 - E_o = -X_1E_o$$

and

$$\Delta(\text{exposure})_2 = E_2 - E_o = -X_2E_o.$$

The effectiveness of the two measures is

$$(\text{effectiveness})_1 = -\Delta(\text{exposure})_1 = X_1E_o$$

and

$$(\text{effectiveness})_2 = -\Delta(\text{exposure})_2 = X_2E_o.$$

Accordingly, the *relative* effectiveness of the two measures is

$$(\text{effectiveness})_1/(\text{effectiveness})_2 = X_1E_o/X_2E_o = X_1/X_2. \quad \text{(Equation 6-1)}$$

Thus, E_o -- the absolute parameter that is difficult to estimate -- cancels out. The relative effectiveness is simply the ratio of the fractional reductions of the two measures.

SECTION 7

ASSESSING THE COST-EFFECTIVENESS OF IAQ CONTROL OPTIONS

With the annualized cost estimates from Sections 3 through 5, and the effectiveness estimates from Section 6, it is now relatively straightforward to compute the cost-effectiveness of the IAQ control options that are being considered.

An issue to be considered when making decisions based upon the cost-effectiveness results, is that cost-effectiveness will be a function of the effectiveness of the control measure. A given control measure designed to provide, say, a 50% reduction in exposure may be more or less cost-effective than the same measure designed to provide a 75% reduction. Accordingly, when alternative control measures are compared, the comparison will be fairest when the alternatives are compared at a consistent level of effectiveness. This issue is discussed in Section 7.3.

7.1 ABSOLUTE VALUES FOR COST-EFFECTIVENESS

If absolute values for Δ(exposure) are estimated from Section 6.1 (Line 8 of Worksheet 14), then these values can be used in the expression

$$\text{cost-effectiveness} = -\ \Delta(\text{cost})/\Delta(\text{exposure})$$

to compute the absolute cost-effectiveness for the particular control measure being considered. The value for Δ(cost) in the expression would be the total annualized cost for the measure, obtained from: Line 9 of Worksheet 6, for ventilation measures; Line 9 of Worksheet 11, or Line 29 or Worksheet 12, for air cleaning measures; or Line 11 or Line 23 of Worksheet 13, for source management measures.

The units of cost-effectiveness would be \$ per (mg/m^3)-person-hr/yr, based on the units that have been used throughout this document.

This simple calculation would be performed for each of the control measures being considered. Since this computation normalizes the total annualized cost for each measure to account for the measure's effectiveness, these results permit the alternative measures to be directly compared even when the measures have different levels of effectiveness.

The interpretation of these results -- to compare (and select between) alternative control measures -- is further discussed in Section 7.3.

7.2 RELATIVE VALUES FOR COST-EFFECTIVENESS

As discussed in Section 6.2, it will often be more convenient to estimate the *relative* effectiveness of one control measure versus another, rather than the absolute effectiveness of either measure. This approach avoids the difficulties and uncertainties involved in estimating the average annual concentrations and the occupancy patterns in the building. But if the user estimates only *relative* effectiveness, the cost-effectiveness calculations here are likewise limited to relative values.

As discussed at the end of Section 6.2, the relative effectiveness of two control measures is the ratio of the fractional reductions that they can achieve in indoor concentrations:

$$(\text{effectiveness})_1/(\text{effectiveness})_2 = X_1/X_2. \qquad \text{(Equation 6-1)}$$

If C_1 is defined as the total annualized cost of Measure #1 in dollars (from Worksheet 6, 11, 12, or 13), and C_2 as the annualized cost of Measure #2, then the *relative* cost-effectiveness of the two measures will be:

$$(\text{cost-effectiveness})_1/(\text{cost-effectiveness})_2 =$$

$$\{C_1/[-\Delta(\text{exposure})_1]\}/\{C_2/[-\Delta(\text{exposure})_2]\} =$$

$$[C_1/(\text{effectiveness})_1]/[C_2/(\text{effectiveness})_2] =$$

$$(C_1/C_2) \times [(\text{effectiveness})_2/(\text{effectiveness})_1] =$$

$$C_1X_2/C_2X_1 = (C_1/X_1)/(C_2/X_2). \qquad \text{(Equation 7-1)}$$

Where multiple IAQ control measures were being considered, pairs of alternative measures would be compared in this manner to identify the one offering the best relative cost-effectiveness (i.e., the lowest cost per unit reduction in exposure, or the lowest value of C_x/X_x in the above equation).

7.3 INTERPRETATION OF COST-EFFECTIVENESS RESULTS

As indicated previously, the cost-effectiveness of any given IAQ control measure will generally depend on the effectiveness that the measure has been designed to achieve. This needs to be considered when evaluating the results from the cost-effectiveness analysis, and when making decisions based on these results.

Many of the IAQ control measures can be designed or operated to achieve alternative degrees of reduction in occupant exposure. Where the measure involves an increase in OA ventilation rate, the system can be designed for greater increased in the OA rate, to provide increased effectiveness. Where the measure involves, e.g., activated carbon air cleaners to reduce VOC exposure, system operation can be modified to reduce the frequency of carbon replacement, a step that would reduce effectiveness but also reduce annualized costs. The costs (and the cost-effectiveness) of these measures will vary if these design or operating changes are implemented.

7.3.1 Required Effectiveness Is Known

Where the user has defined the level of effectiveness that must be achieved -- and where there is this flexibility in designing/operating each of the various control options to achieve this desired reduction in indoor concentrations and exposure -- the approach for comparing the options may be relatively straightforward. The cost analysis in Sections 3, 4, and/or 5 would be conducted for the various control measures, each designed/operated to achieve the defined level of effectiveness. In such cases, $(\text{effectiveness})_1 = (\text{effectiveness})_2$ (and $X_1 = X_2$) in Equation 6-1, and Equation 7-1 above reduces to

$$(\text{cost-effectiveness})_1/(\text{cost-effectiveness})_2 = C_1/C_2. \qquad \text{(Equation 7-2)}$$

That is, the user is seeking the control measure that will provide that desired effectiveness at the least annualized cost.

7.3.2 Effectiveness to Be Achieved Is Open to Judgement

In other cases, the precise level of exposure reduction that is to be achieved may be more of a judgement call. In those cases, the cost-effectiveness analysis here may aid the user in deciding what level of exposure reduction to pay for.

In such cases, it can be useful to plot cost-effectiveness as a function of effectiveness for the various control measures under consideration, to aid in this decision process. Figure 4 is an illustrative example of how such a plot might appear, for the case where the contaminant of concern is VOCs.

Note that Figure 4 is largely qualitative, and is for a hypothetical building. The exact positions and slopes of the curves could vary significantly from building to building. "Effectiveness" on the abscissa is expressed, not as an absolute change in VOC exposure [in (mg/m^3)-person-hr/yr], but as the dimensionless fractional reduction in exposure, X, relative to the uncontrolled case.

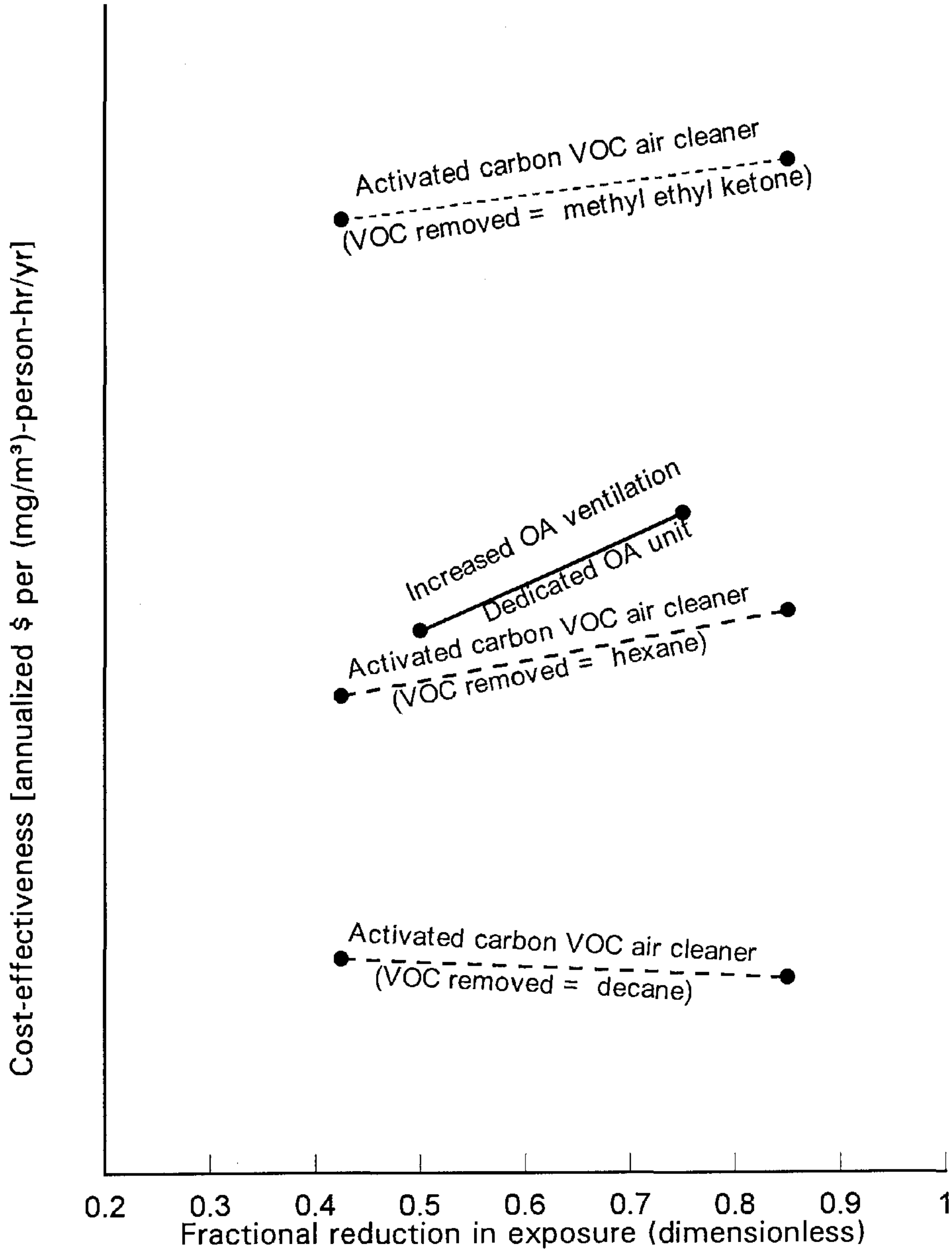

Figure 4. Illustrative plot of cost-effectiveness vs. effectiveness for one particular building.

Four curves are shown in the figure. The solid curve is for increased OA ventilation, in the case where this increase is accomplished utilizing a dedicated-OA unit. (The option of using a dedicated-OA unit to condition the increased OA, versus enlargement of the central HVAC unit, is discussed in Section 3.) The dashed curves are for VOC air cleaners utilizing granular activated carbon.

The bottom-most dashed curve in Figure 4 is for the case where the specific VOC compound of concern is decane, which is effectively sorbed on carbon; for this building, the estimated carbon replacement frequency is once every 24 months to maintain full air cleaner removal performance for decane. The middle dashed curve represents hexane (estimated carbon lifetime of 4 months); and the upper curve represents methyl ethyl ketone (MEK) (estimated carbon lifetime of 2 months). Some individual VOCs (e.g., formaldehyde) are sorbed more weakly than MEK, in which case carbon lifetime would be even shorter and the cost higher per unit reduction in exposure. (See Table A-12 in Worksheet 10.) The left-hand (lesser-reduction) points on each of the air cleaner curves represent the case where the carbon replacement frequencies estimated above have been reduced by half for each of the organic compounds, such that breakthrough through the carbon bed is allowed to occur for some period before the carbon is replaced, reducing the average efficiency.

A plot such as Figure 4 could enable the user to draw several conclusions, assisting in the selection of the more cost-effective IAQ control approach for this particular (hypothetical) building.

For one thing, the relative cost-effectiveness of air cleaning vs. increased ventilation will depend heavily on the specific organic compounds of concern. If the compounds are strongly sorbed on carbon -- such as decane -- then a GAC air cleaner would appear to be more cost-effective than increased ventilation (i.e., to involve a lower cost per unit reduction in exposure), at all levels of effectiveness. If the compounds have a moderate affinity for carbon -- such as hexane -- carbon sorption and increased ventilation will be of roughly comparable cost-effectiveness. And if the compound is more weakly sorbed than hexane, GAC air cleaning will be less cost-effective than ventilation.

This result illustrates the importance of defining the specific organic compounds of concern before evaluating the cost-effectiveness of GAC air cleaning. From Table A-12 (Worksheet 10), it should be noted that inlet concentration, as well as the identity of the specific compound, can also impact GAC sorption capacity (and hence carbon replacement frequency and costs). Thus, where the nature and/or concentrations of the specific VOCs may vary with time in a given building, it may be useful to plot a family of air cleaner curves as in Figure 4, reflecting these varying compounds and/or inlet concentrations, to provide the perspective required for assessing the cost-effectiveness.

Another conclusion that can be drawn from Figure 4 is that, for most of the control measures in this hypothetical building, the cost per unit reduction in exposure becomes modestly higher at greater levels of effectiveness, as might intuitively be expected. That is, the control measures become modestly less cost-effective at greater levels of contaminant removal. The user would have to make a judgement regarding whether to pay the additional price to achieve the greater reduction in exposure.

Again, it is re-emphasized that the cost curve relationships in Figure 4 are for one particular, hypothetical building, and would be different for different buildings.

7.3.3 Effectiveness Is Not Subject to Adjustment

In Sections 7.3.1 and 7.3.2, it is assumed that the user has some flexibility in designing and operating the IAQ control measures, to achieve alternative levels of performance from any given control measure. There may be some situations where this flexibility will not exist, or will be limited.

For example, the pre-existing HVAC system in a particular building may accommodate a certain maximum incremental increase in the OA ventilation rate (which will provide a fractional exposure reduction X_1). In this same building, there may be a certain amount of a given pollutant source that can practically be considered for removal (which will provide a fractional reduction X_2), and logic dictates that this entire amount be removed, if in fact source removal is to be implemented. In this building, the user does not have much practical flexibility of increasing or decreasing the incremental additional OA or the amount of source to be removed, in an effort to compare both of these measures at the same level of effectiveness. Rather, the user is constrained to compare two fixed approaches having inherently different levels of effectiveness ($X_1 \neq X_2$).

In such cases, the cost-effectiveness of the alternative measures would be computed according to Section 7.1 or 7.2. If the measure which is the least expensive also happens to be the one providing the greatest reduction in exposure -- and is thus necessarily the most cost-effective -- then the selection between the options is obvious. Where the less effective measure happens to be the least expensive -- and perhaps the most cost-effective as well -- then the user is required to make the judgement regarding whether to pay additional for the greater reduction in exposure.

SECTION 8

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APPENDIX A

Worksheets

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WORKSHEET 1

Estimation of Outdoor Air Increase Required to Achieve Desired Reduction in Contaminant Concentration Using Increased Ventilation

1. Enter the current average concentration of the contaminant of concern in the building (or in that portion of the building served by a given air handler) -- in suitable units (e.g., ppmv) __________ ppmv

2. Enter the average concentration to which the level in Line 1 above should be reduced -- in the same concentration units as above __________ ppmv

3. Calculate the desired concentration as a fraction of the current concentration (Line 2 divided by Line 1) __________

4. Enter the current flow of OA into the building (or into the portion served by the air handler in question) -- in suitable units (e.g., cfm) __________ cfm

5. Compute the total OA flow that is required if the desired concentration (Line 2) is to be achieved (Line 4 divided by Line 3) -- in the same units as Line 4 __________ cfm

6. Compute the incremental increase in outdoor air flow rate required to achieve the desired reduction in concentration (Line 5 minus Line 4) __________ cfm

WORKSHEET 2A

Estimation of Installed Costs for Increased OA: Enlarged Central Units - Retrofit Case

Enter Basic Data

1. Enter the incremental increase in OA intake rate that is required for the entire building, in cfm (from Line 6 of Worksheet 1). __________ cfm

2. Enter the incremental increase in OA to each of the HVAC units serving the building:

2(1). Increase in OA to Unit #1 __________ cfm
2(2). Increase in OA to Unit #2 __________ cfm
2(3). Increase in OA to Unit #3 __________ cfm
etc.

[Note: The sum of Lines 2(1) through 2(x) should sum to the total on Line 1.]

3. Enter the original cooling capacity for each of the HVAC units serving the building:

3(1). Cooling capacity of Unit #1 __________ tons
3(2). Cooling capacity of Unit #2 __________ tons
3(3). Cooling capacity of Unit #3 __________ tons
etc.

4. Enter the original heating capacity for each of the HVAC units serving the building:

4(1). Heating capacity of Unit #1 __________ kW
4(2). Heating capacity of Unit #2 __________ kW
4(3). Heating capacity of Unit #3 __________ kW
etc.

(continued)

Estimate Cost of Increased Cooling/Heating Capacity

5. Refer to Table A-1 at the end of this worksheet. Locate in Column A the city having the climate most closely representing the user's.

6. From Columns B and C of Table A-1, enter the required cooling and heating capacity per 1,000 cfm OA for the climate of this city.

6a. Cooling capacity:	________	tons/1,000 cfm
6b. Heating capacity:	________	kW/1,000 cfm

7. Compute the *incremental* additional cooling capacity for each of the HVAC units in the building, to treat the increased OA.

7(1). Unit #1 [Line 2(1) x Line 6a ÷ 1,000]	________	tons
7(2). Unit #2 [Line 2(2) x Line 6a ÷ 1,000]	________	tons
7(3). Unit #3 [Line 2(3) x Line 6a ÷ 1,000]	________	tons
etc.		

8. Compute the *incremental* additional heating capacity for each of the HVAC units in the building, to treat the increased OA.

8(1). Unit #1 [Line 2(1) x Line 6b ÷ 1,000]	________	kW
8(2). Unit #2 [Line 2(2) x Line 6b ÷ 1,000]	________	kW
8(3). Unit #3 [Line 2(3) x Line 6b ÷ 1,000]	________	kW
etc.		

9. Compute the revised total cooling capacity required for each of the HVAC units in the building, increased to handle the increased OA load.

9(1). Unit #1 [Line 3(1) + Line 7(1)]	________	tons
9(2). Unit #2 [Line 3(2) + Line 7(2)]	________	tons
9(3). Unit #3 [Line 3(3) + Line 7(3)]	________	tons
etc.		

(continued)

10. Compute the cost of replacing the pre-existing cooling coils and cooling equipment in each HVAC unit, with enlarged components having the capacity determined in Item 9 above.

10(1). Unit #1 [Line 9(1) x $830/ton]	$ ________
10(2). Unit #2 [Line 9(2) x $830/ton]	$ ________
10(3). Unit #3 [Line 9(3) x $830/ton]	$ ________
etc.	

[**Note:** The cost of $830/ton, derived from Means (1996), includes: a) removal of the old coils and the old condenser/compressor ($130/ton, assumed to equal the labor charges in Section 157-230 of the citation for installation of new coils and condensers); b) installation of new coils in the central unit (including more rows and/or more fins/inch), to increase capacity ($100/ton, from Section 157-201-0470 to -0640); and c) installation of a new, higher-capacity condenser/ compressor ($600/ton, from Section 157-230). This installed cost per ton is roughly independent of the total tons of capacity. Since this estimate assumes a direct-expansion cooling system, it will be less accurate for systems involving chillers.]

11. **Compute the total cost of replacing the cooling coils and equipment** [sum of Lines 10(1) through 10(x)] $ ________

12. Compute the revised total heating capacity required for each of the HVAC units in the building, increased to handle the increased OA load.

12(1). Unit #1 [Line 4(1) + Line 8(1)]	________ kW
12(2). Unit #2 [Line 4(2) + Line 8(2)]	________ kW
12(3). Unit #3 [Line 4(3) + Line 8(3)]	________ kW
etc.	

13. **Compute the cost of replacing the pre-existing heating elements in each HVAC unit,** with enlarged components having the capacity determined in Item 12 above.

13(1). Unit #1 [Line 12(1) x $30/kW]	$ ________
13(2). Unit #2 [Line 12(2) x $30/kW]	$ ________
13(3). Unit #3 [Line 12(3) x $30/kW]	$ ________
etc.	

[**Note:** The cost of $30/kW, derived from Means (1996), includes: a) removal of the old heating elements ($1-$2/kW, assumed to equal the average labor charges in Section 155-408 of the citation for installation of new coils having a heating capacity of 20 kW or greater); and b) installation of new heating elements of increased wattage in the central unit, to increase capacity ($25-$30/kW, the average installed cost from Section 155-408 for coils of 20 kW or greater). Since this estimate assumes electric resistance heating, it will be less accurate for systems involving furnaces.]

(continued)

Worksheet 2A (continued)

14. **Compute the total cost of replace all of the heating elements** [sum of Lines 13(1) through 13(x)] $ ________

15. **Enter the total cost for increasing the cooling and heating capacity** [Line 11 + Line 14] $ ________

Estimate Cost of Increased OA Intake Fan Capacity (if applicable)

[**Note**: The following portion of Worksheet 2A applies *only in those cases* where an OA intake fan is already present, or must be added in connection with the OA increase. The following assumes that a new OA fan is added, sized to provide the OA increment. See text.]

16. Enter the total incremental increase in OA to the building (Line 1 above) ________ cfm

17. Refer to Table A-2 at the end of this worksheet. Locate in Column A the fan flow rate corresponding to the total additional OA flow on Line 16. Interpolate as necessary.

18. From Column B of Table A-2, **enter the installed cost of the air handler** required to provide this additional OA flow. $ ________

Estimate Cost of Retrofitting Additional OA Intake Ductwork (if applicable)

[**Note**: The following portion of Worksheet 2A applies *only in systems without economizers*, where the required OA increase cannot be achieved without supplementing the OA intake duct. The following assumes that new ducting is installed to direct the incremental OA from the new intake fan to each central HVAC unit, with a main trunk line from the fan splitting into branches leading to each unit. See text.]

(continued)

19. Estimate the linear feet of ductwork that would be required to direct the incremental additional OA [in Lines 2(1) through 2(x) above] from the new OA intake fan to each of the HVAC units in the building:

19(T).	Length of OA trunk line	________ ft
19(1).	Branch from trunk line to Unit #1	________ ft
19(2).	Branch from trunk line to Unit #2	________ ft
etc.		

20. Refer to Table A-2. Locate in Column A the incremental OA flow rates to the entire building (Line 1), and to each HVAC unit [Lines 2(1) through 2(x)].

21. From Column D of Table A-2, enter the installed cost per linear foot of retrofitted *insulated* duct, based on the OA flows in the trunk line and in the branches to each HVAC unit:

21(T).	OA trunk line [flow on Line 1]	________ $/ft
21(1).	Unit #1 branch [flow on Line 2(1)]	________ $/ft
21(2).	Unit #2 branch [flow on Line 2(2)]	________ $/ft
etc.		

22. Compute the installed cost of each element of the ductwork:

22(T).	OA trunk line [Line 19(T) times Line 21(T)]	$ ________
22(1).	Unit #1 branch [Line 19(1) times Line 21(1)]	$ ________
22(2).	Unit #2 branch [Line 19(2) times Line 21(2)]	$ ________
etc.		

23. **Compute the total installed cost of the new OA supply ductwork** [sum of Lines 22(T) through 22(x)] $ ________

(continued)

Estimate Cost of Increased Exhaust Fan Capacity (if applicable)

[**Note**: The following portion of Worksheet 2A applies *only in those cases* where a central exhaust fan is already present, or must be added in connection with the OA increase. This will usually be the case only in *systems without economizers*. The following assumes that a new central exhaust fan is added, sized to exhaust an amount of building air equal to the OA increment. See text.]

24. Refer to Table A-2 at the end of this worksheet. Locate in Column A the fan flow rate corresponding to the total additional OA flow on Line 1 (or 16). Interpolate as necessary.

25. From Column B of Table A-2, **enter the installed cost of the air handler** required to exhaust this volume of building air. $ __________

Estimate Cost of Retrofitting Additional Exhaust Ductwork (if applicable)

[**Note**: The following portion of Worksheet 2A applies *only in systems without economizers*, where the required increase in exhaust air cannot be achieved without supplementing the central exhaust ducting. The following assumes that, in systems without economizers, new ducting is installed to draw exhaust air from one zone near each central HVAC unit, with the branches from the zones combining into a main trunk line leading to the exhaust fan. See text.]

26. Estimate the linear feet of ductwork that would be required to direct exhaust air -- equal to the incremental additional OA in Lines 2(1) through 2(x) -- to the new exhaust fan, from zones near each of the central HVAC units:

26(T). Length of exhaust air trunk line __________ ft
26(1). Branch from Unit #1 zone to trunk line __________ ft
26(2). Branch from Unit #2 zone to trunk line __________ ft
etc.

27. Refer to Table A-2. Locate in Column A the incremental OA flow rates to the entire building (Line 1), and to each HVAC unit [Lines 2(1) through 2(x)].

(continued)

28. From Column C of Table A-2, enter the installed cost per linear foot of retrofitted *uninsulated* duct, based on the exhaust air flows in the trunk line and in the branches from the zones near each HVAC unit:

28(T). Exhaust trunk line [flow on Line 1] __________ $/ft
28(1). Branch from Unit #1 zone [flow on Line 2(1)] __________ $/ft
28(2). Branch from Unit #2 zone [flow on Line 2(2)] __________ $/ft
etc.

29. Compute the installed cost of each element of the ductwork:

29(T). Exhaust trunk line [Line 26(T) times Line 28(T)] $ __________
29(1). Unit #1 branch [Line 26(1) times Line 28(1)] $ __________
29(2). Unit #2 branch [Line 26(2) times Line 28(2)] $ __________
etc.

30. **Compute the total installed cost of the new exhaust ductwork** [sum of Lines 29(T) through 29(x)] $ __________

Estimate Total Installed Cost (retrofit enlarged central unit plus, as applicable, added OA and exhaust fans and ductwork)

31. **Compute the total installed cost of the retrofitted enlarged HVAC system** (Line 15 plus, as applicable, Lines 18, 23, 25, and 30). $ __________

(continued)

TABLE A-1

Incremental Increases in Cooling and Heating Capacities
Necessitated by Increases in Outdoor Air Ventilation Rates
(by Geographical Location)

Column A City	*Column B* Required Increase in Cooling Capacity[1] (tons per 1,000 cfm OA)	*Column C* Required Increase in Heating Capacity[2] (kW per 1,000 cfm OA)
Albuquerque, NM	~0	16
Atlanta, GA	3.3	15
Boston, MA	2.7	18
Chicago, IL	3.3	22
Cincinnati, OH	3.9	18
Cleveland, OH	2.7	20
Dallas-Fort Worth, TX	3.9	14
Denver, CO	~0	21
Houston, TX	4.6	12
Los Angeles, CA	0.5	8
Miami, FL	4.6	6
Minneapolis, MN	2.7	26
New York, NY	3.3	17
Omaha, NE	3.9	23
Pittsburgh, PA	2.1	20
Raleigh, NC	3.9	16
St. Louis, MO	3.9	20
San Francisco, CA	~0	10
Seattle, WA	0.5	13
Washington, D.C.	3.9	16

Notes:

1 Computed using the 1% design values for the cooling dry-bulb/mean wet-bulb temperatures for the various cities, as defined by ASHRAE (ASHRAE, 1997a). The refrigeration capacity presented here is the incremental power required to reduce 1,000 cfm of outdoor air from the 1% value of outdoor enthalpy to an indoor enthalpy corresponding to 75 °F and 50% relative humidity.

2 Computed using the 99% heating dry-bulb temperatures for the various cities, as defined by ASHRAE (ASHRAE, 1997a). The heating capacity presented here is the incremental power required to increase 1,000 cfm of outdoor air from the 99% value of outdoor temperature to an indoor temperature of 70 °F.

(continued)

TABLE A-2

Approximate Installed Costs of Air Handlers and Retrofit Ducting[1]

Column A Flow Rate (cfm)	*Column B* Installed Cost of Fan[2] ($)	*Column C* Retrofit Installed Cost of Uninsulated Duct[3] ($/linear ft)	*Column D* Retrofit Installed Cost of Insulated Duct[3] ($/linear ft)
500	900	66	72
1,000	1,300	77	86
2,000	1,600	91	104
4,000	2,800	113	130
6,000	3,000	128	150
8,000	3,200	143	168
10,000	4,000	155	183

Notes:

1 Includes all materials (with markup), installation labor, and installation contractor overhead and profit.

2 Derived from Means (1996). Each figure is the average for the various categories of air handlers (centrifugal, vaneaxial, etc.) at the specified capacity, from Section 157-290 of that citation.

3 Derived from Means (1996). The ducts are assumed to have a square cross-section, and are sized to create 0.1 in. WG pressure loss per 100 linear feet (ASHRAE, 1997b). The uninsulated ducts were costed using the data from Sections R157-100 and 157-250 of the citation, assuming the use of 24-gauge galvanized steel. Retrofit costs (including chase work and cutting the flooring) were estimated to add $40/linear foot above the values from Means, based on prior experience (Elder, 1998). A typical cost for insulation of $\$2/ft^2$ was derived from Section 155-651. OA intake ducting is assumed to be insulated, and exhaust ducting to be uninsulated.

WORKSHEET 2B

Estimation of Installed Costs for Increased OA: Dedicated-OA Unit - Retrofit Case

[For this case, it is assumed that a single new rooftop direct-expansion HVAC unit is installed, dedicated to treating the additional OA increment being supplied to the building. If there are multiple existing central HVAC units serving the building and if the OA to each unit is being increased, this one new dedicated-OA unit would supply the required OA increment to all of the existing central units. *If the building requires such a substantial increase in OA volume that multiple dedicated-OA units would be needed, the user should repeat the computations in this worksheet for each dedicated-OA unit.*]

Enter Basic Data

1. Enter the incremental increase in OA intake rate that is required for the entire building, in cfm (from Line 6 of Worksheet 1). __________ cfm

2. Enter the incremental increase in OA to each of the HVAC units serving the building:

2(1). Increase in OA to Unit #1 __________ cfm
2(2). Increase in OA to Unit #2 __________ cfm
2(3). Increase in OA to Unit #3 __________ cfm
etc.

[**Note:** The sum of Lines 2(1) through 2(x) should sum to the total on Line 1.]

Estimate Cost of Dedicated-OA Rooftop Unit

3. Refer to Table A-1 at the end of Worksheet 2A. Locate in Column A the city having the climate most closely representing the user's.

4. From Column B of Table A-1, enter the required cooling and heating capacities per 1,000 cfm OA for the climate of this city.

4a. Cooling capacity __________ tons/1,000 cfm
4b. Heating capacity __________ kW/1,000 cfm

(continued)

5. Compute the incremental additional cooling capacity required to treat the total increase in OA to the building (Line 1 x Line 4a ÷ 1,000). __________ tons

   [**Note:** This is the required cooling capacity of the new dedicated-OA unit.]

6. Refer to Table A-3 at the end of this worksheet. Locate in Column A the cooling capacity defined in Line 5 above.

7. From Column B of Table A-3, enter the total installed cost per ton of a packaged dedicated-OA unit having the cooling capacity in Line 5 above. $ __________ /ton

8. **Compute the total installed cost (excluding heating)** of the dedicated-OA unit having the required cooling capacity (Line 5 x Line 7). $ __________

9. Compute the incremental additional heating capacity required to treat the total increase in OA to the building (Line 1 x Line 4b ÷ 1,000). __________ kW

10. Refer to Table A-4 at the end of this worksheet. Locate in Column A the heating capacity defined in Line 9 above.

11. From Column B of Table A-4, enter the total installed cost per kW of installing the required heating capacity into the dedicated-OA unit. __________ /kW

12. **Compute the total installed cost of incorporating heating capacity** into the new dedicated-OA unit (Line 9 x Line 11). $ __________

13. **Compute the total installed cost of the new dedicated-OA unit (cooling and heating)** (Line 8 plus Line 12). $ __________

(continued)

Estimate Cost of Retrofitting Additional OA Intake Ductwork Associated with the Dedicated-OA Unit (if applicable)

[**Note**: The following portion of Worksheet 2B applies *only in systems without economizers*, where the increased OA being supplied by the dedicated-OA unit cannot simply be delivered into the pre-existing OA intake duct. The following assumes that, in systems without economizers, new ducting is installed to direct the incremental OA from the dedicated-OA unit to each central HVAC unit, with a main trunk line from the dedicated-OA unit splitting into branches leading to each HVAC unit. See text.]

14. Estimate the linear feet of ductwork that would be required to direct the necessary amount of OA from the dedicated-OA unit to all of the HVAC units in the building:

14(T). Length of OA trunk line	________ ft
14(1). Branch from trunk line to Unit #1	________ ft
14(2). Branch from trunk line to Unit #2	________ ft
etc.	

15. Refer to Table A-2 at the end of Worksheet 2A. Locate in Column A the incremental OA flow rates to the entire building (Line 1 above) and to each HVAC system in the building [Lines 2(1) through 2(x).]

16. From Column D of Table A-2, enter the installed cost per linear foot of retrofitted *insulated* duct, based on the OA flows in the trunk line and in the branches to each HVAC unit:

16(T). OA trunk line [flow on Line 1]	________ $/ft
16(1). Unit #1 branch [flow on Line 2(1)]	________ $/ft
16(2). Unit #2 branch [flow on Line 2(2)]	________ $/ft
etc.	

17. Compute the installed cost of each element of the additional OA ductwork:

17(T). OA trunk line [Line 14(T) times Line 16(T)]	$ ________
17(1). Unit #1 branch [Line 14(1) times Line 16(1)]	$ ________
17(2). Unit #2 branch [Line 14(2) times Line 16(2)]	$ ________
etc.	

(continued)

Worksheet 2B (continued)

18. **Compute the total installed cost of retrofitting the new OA supply ductwork** [sum of Lines 17(T) through 17(x)] $ __________

Estimate Cost of Increased Exhaust Fan Capacity (if applicable)

[**Note:** The following portion of Worksheet 2B applies *only in those cases* where a central exhaust fan is already present, or must be added in connection with the OA increase. This will usually be the case only in *systems without economizers*. The following assumes that a new central exhaust fan is added, sized to exhaust an amount of building air equal to the OA increment. See text.]

19. Refer to Table A-2 at the end of Worksheet 2A. Locate in Column A the fan flow rate corresponding to the total additional OA flow on Line 1 above. Interpolate as necessary.

20. From Column B of Table A-2, **enter the installed cost of the new air handler** required to exhaust this volume of building air. $ __________

Estimate Cost of Retrofitting Additional Exhaust Ductwork (if applicable)

[**Note:** The following portion of Worksheet 2A applies *only in systems without economizers*, where the required increase in exhaust air cannot be achieved without supplementing the central exhaust ducting. The following assumes that, in systems without economizers, new ducting is installed to draw exhaust air from one zone near each central HVAC unit, with the branches from the zones combining into a main trunk line leading to the exhaust fan. See text.]

21. Estimate the linear feet of ductwork that would be required to direct exhaust air -- equal to the incremental additional OA in Lines 2(1) through 2(x) -- to the new exhaust fan, from zones near each of the central HVAC units:

21(T). Length of exhaust air trunk line __________ ft
21(1). Branch from Unit #1 zone to trunk line __________ ft
21(2). Branch from Unit #2 zone to trunk line __________ ft
etc.

(continued)

22. Refer to Table A-2 at the end of Worksheet 2A. Locate in Column A the incremental OA flow rates to the entire building (Line 1 above), and to each HVAC unit [Lines 2(1) through 2(x)].

23. From Column C of Table A-2, enter the installed cost per linear foot of retrofitted *uninsulated* duct, based on the exhaust air flows in the trunk line and in the branches from the zones near each HVAC unit:

23(T). Exhaust trunk line [flow on Line 1] ________ $/ft
23(1). Branch from Unit #1 zone [flow on Line 2(1)] ________ $/ft
23(2). Branch from Unit #2 zone [flow on Line 2(2)] ________ $/ft
etc.

24. Compute the installed cost of each element of the ductwork:

24(T). Exhaust trunk line [Line 21(T) times Line 23(T)] $ ________
24(1). Unit #1 branch [Line 21(1) times Line 23(1)] $ ________
24(2). Unit #2 branch [Line 21(2) times Line 23(2)] $ ________
etc.

25. **Compute the total installed cost of retrofitting the new exhaust ductwork** [sum of Lines 24(T) through 24(x)] $ ________

Estimate Total Installed Cost (new dedicated-OA unit plus, as applicable, added OA ductwork, exhaust fans, and exhaust ductwork)

26. **Compute the total installed cost of the retrofitted dedicated-OA system** (Line 13 plus, as applicable, Lines 18, 20, and 25). $ ________

(continued)

TABLE A-3

Approximate Total and Incremental Installed Costs
for a New Rooftop Cooling System[1]

Column A	*Column B*	*Column C*
Cooling Capacity Range (tons)	Total Installed Cost per Ton[2] ($/ton)	Incremental Installed Cost[2,3] ($/ton)
0 - 5	1,200	1,000
6 - 20	1,000	1,000
>20	1,000	900

Notes:

1 Includes all materials (with markup), installation labor, and installation contractor overhead and profit. Systems include cooling capability only, with no heating coils.

2 Derived from Means (1996). The figure for each capacity range is the average for the various single-zone, cooling-only rooftop packaged units shown in Section 157-180-5000 through -6070 of that citation, within the specified range. Costs include the air handler, cooling coils, condenser/compressor, and the associated housing. Costs do not include any ductwork.

3 The *incremental* installed cost is the slope of the cost-vs.-capacity curve, i.e., the derivative d($)/d(tons). The *total* installed cost (Column B) would be used to compute the cost of a new unit of a given capacity. The *incremental* installed cost (Column C) would be used to compare the incremental cost of one unit versus another, i.e., the incremental cost of installing a unit of greater capacity *in lieu of* a unit of lesser capacity within the Column A capacity range.

TABLE A-4

Approximate Total and Incremental Installed Costs for Heating Capacity in a New Rooftop HVAC System[1]

Column A	*Column B*	*Column C*
Heating Capacity Range (kW)	Total Installed Cost per kW[2] ($/kW)	Incremental Installed Cost[2,3] ($/kW)
0 - 10	100	75
11 - 20	65	60
21 - 40	40	40
41 -100	25	25
>100	15	15

Notes:

1 Includes all materials (with markup), installation labor, and installation contractor overhead and profit. These figures represent the costs associated with incorporating heating capacity into the cooling units shown in Table A-3.

2 Derived from Means (1996). The figure for each capacity range is the average for the electric duct heaters shown in Section 155-408-0100 through -3300 of that citation, within the specified range.

3 The *incremental* installed cost is the slope of the cost-vs.-capacity curve, i.e., the derivative d($)/d(kW). The *total* installed cost (Column B) would be used to compute the cost of incorporating a given heating capacity into a new unit. The *incremental* installed cost (Column C) would be used to compare the incremental cost of one heating element versus another, i.e., the incremental cost of installing an element of greater capacity *in lieu of* an element of lesser capacity within the Column A capacity range.

WORKSHEET 3A

Estimation of Installed Costs for Increased OA: Enlarged Central Units - New Construction Case

[In this case, it is assumed that an HVAC system of increased cooling/ heating capacity is installed in the new building in lieu of an originally planned, lower-capacity system.]

Enter Basic Data

1. Enter the incremental increase in OA intake rate that is required for the entire building, beyond the originally designed rate, in cfm (from Line 6 of Worksheet 1). __________ cfm

2. Enter the incremental increase in OA to each of the HVAC units serving the building, beyond the originally designed OA rate to that unit:

2(1). Increase in OA to Unit #1 __________ cfm
2(2). Increase in OA to Unit #2 __________ cfm
2(3). Increase in OA to Unit #3 __________ cfm
etc.

[Note: The sum of Lines 2(1) through 2(x) should sum to the total on Line 1.]

3. Enter the originally designed cooling and heating capacities for each of the central HVAC units in the building.

3(1a). Original cooling capacity - Unit #1 __________ tons
3(1b). Original heating capacity - Unit #1 __________ kW

3(2a). Original cooling capacity - Unit #2 __________ tons
3(2b). Original heating capacity - Unit #2 __________ kW

3(3a). Original cooling capacity - Unit #3 __________ tons
3(3b). Original heating capacity - Unit #3 __________ kW
etc.

(continued)

Worksheet 3A (continued)

Estimate Cost of Increased Cooling/Heating Capacity

4. Refer to Table A-1 at the end of Worksheet 2A. Locate in Column A the city having the climate most closely representing the user's.

5. From Columns B and C of Table A-1, enter the required cooling and heating capacity per 1,000 cfm OA for the climate of this city.

5a. Cooling capacity: __________ tons/1,000 cfm
5b. Heating capacity: __________ kW/1,000 cfm

6. Compute the *incremental* additional cooling capacity required for each of the HVAC units in the building, to treat the increased OA.

6(1). Unit #1 [Line 2(1) x Line 5a ÷ 1,000] __________ tons
6(2). Unit #2 [Line 2(2) x Line 5a ÷ 1,000] __________ tons
6(3). Unit #3 [Line 2(3) x Line 5a ÷ 1,000] __________ tons
etc.

7. Refer to Table A-3 at the end or Worksheet 2B. Locate in Column A of Table A-3 the cooling capacity ranges for each of the units in the building.

8. From Column C in Table A-3, enter the *incremental* cost per ton of increased cooling capacity corresponding to the capacity of each unit.

8(1). Incremental cost for Unit #1 [based on capacity on Line 3(1a) above]. $ __________ /ton
8(2). Incremental cost for Unit #2 [based on capacity on Line 3(2a)]. $ __________ /ton
8(3). Incremental cost for Unit #3 [based on capacity on Line 3(3a)]. $ __________ /ton
etc.

(continued)

9. Compute the estimated incremental increase in the installed cost of each HVAC unit.

9(1). Unit #1 [Line 6(1) x Line 8(1)]	$ ________
9(2). Unit #2 [Line 6(2) x Line 8(2)]	$ ________
9(3). Unit #3 [Line 6(3) x Line 8(3)]	$ ________
etc.	

[Because the costs on Line 8(x) are based on rooftop direct-expansion units, these estimates will be less accurate for systems involving chillers.]

10. Determine the total estimated increase in installed HVAC cost resulting from the incremental increase in specified cooling capacity [sum of Lines 9(1) through 9(x)] $ ________

11. Compute the *incremental* additional heating capacity for each of the HVAC units in the building, to treat the increased OA.

11(1). Unit #1 [Line 2(1) x Line 5b ÷ 1,000]	________ kW
11(2). Unit #2 [Line 2(2) x Line 5b ÷ 1,000]	________ kW
11(3). Unit #3 [Line 2(3) x Line 5b ÷ 1,000]	________ kW
etc.	

12. Refer to Table A-4 at the end or Worksheet 2B. Locate in Column A of Table A-4 the cooling capacity ranges for each of the units in the building.

13. From Column C in Table A-4, enter the *incremental* cost per ton of increased heating capacity corresponding to the capacity of each unit.

13(1). Incremental cost for Unit #1 [based on capacity on Line 3(1b) above].	$ ________ /kW
13(2). Incremental cost for Unit #2 [based on capacity on Line 3(2b)].	$ ________ /kW
13(3). Incremental cost for Unit #3 [based on capacity on Line 3(3b)].	$ ________ /kW
etc.	

(continued)

14. Compute the estimated incremental increase in the installed cost of each HVAC unit to provide increased heating capacity.

    14(1). Unit #1 [Line 11(1) x Line 13(1)] $ ________
    14(2). Unit #2 [Line 11(2) x Line 13(2)] $ ________
    14(3). Unit #3 [Line 11(3) x Line 13(3)] $ ________
    etc.

[Because the costs on Line 13(x) are based on electric duct heaters, these estimates will be less accurate for systems involving furnaces.]

15. **Determine the total estimated increase in installed HVAC cost resulting from the incremental increase in specified heating capacity** [sum of Lines 14(1) through 14(x)] $ ________

16. **Enter the total incremental increase in installed cost resulting from the specification of an HVAC system having a greater cooling and heating capacity** compared to the original design [Line 10 + Line 15] $ ________

Estimate Cost of Increased OA Intake Fan Capacity (if applicable)

[**Note**: The following portion of Worksheet 3A applies *only in those cases* where an OA intake fan has been planned for the new building. The following assumes that a larger OA fan is installed in lieu of the originally planned fan.]

17. Enter the total incremental increase in OA to the building (Line 1 above) ________ cfm

18. Enter the original total OA flow to the building (or to the portion of the building under consideration), prior to the increase (Line 4 of Worksheet 1) ________ cfm

19. Refer to Table A-5 at the end of this worksheet. Locate in Column A the fan flow rate corresponding to the total original OA flow on Line 18.

(continued)

20. From Column B of Table A-5, enter the *incremental* installed cost per 1,000 cfm of added fan capacity, corresponding to the total fan capacity on Line 18. __________ $/1,000 cfm

21. Compute the incremental cost resulting from the need to install a larger OA intake fan (Line 17 x Line 20 ÷ 1,000). $ __________

Estimate Cost of Enlarging the OA Intake Ductwork (if applicable)

[**Note**: The following portion of Worksheet 3A applies *only in systems without economizers*, where the required OA increase cannot be achieved without enlarging the OA intake duct. The following assumes that OA intake ducting of larger dimensions is installed in lieu of the originally planned intake ducting.]

22. Enter the linear feet of OA intake ductwork that has been specified in the original system design, delivering OA to each of the HVAC units in the building:

22(T). Length of OA trunk line __________ ft
22(1). Branch from trunk line to Unit #1 __________ ft
22(2). Branch from trunk line to Unit #2 __________ ft
etc.

[**Note**: The above format assumes that the OA is delivered from an OA intake fan to a main trunk line, from which branches lead to each unit.]

23. Enter the originally designed OA flow in each branch of the OA intake ducting:

23(T). Trunk line (flow on Line 18 above) __________ cfm
23(1). Branch to Unit #1 (original OA to Unit #1) __________ cfm
23(2). Branch to Unit #2 __________ cfm
etc.

24. Refer to Table A-5. Locate in Column A the original total OA flow rates to the entire building (Line 18) and to each HVAC unit [Lines 23(1) through 23(x)].

(continued)

25. From Column D of Table A-5, enter the incremental installed cost per linear foot of *insulated* duct per 1,000 cfm *increase* in flow, corresponding to these original OA flows in the trunk line and in the branches to each HVAC unit:

25(T).	OA trunk line [flow on Line 18]	________	$/ft/1,000 cfm
25(1).	Unit #1 branch [flow on Line 23(1)]	________	$/ft/1,000 cfm
25(2).	Unit #2 branch [flow on Line 23(2)]	________	$/ft/1,000 cfm
etc.			

26. Compute the incremental increase in the installed cost of each element of the ductwork:

26(T).	OA trunk line [Line 22(T) x Line 25(T) x Line 1 ÷ 1,000]	$ ________
26(1).	Unit #1 branch [Line 22(1) x Line 25(1) x Line 2(1) ÷ 1,000]	$ ________
26(2).	Unit #2 branch [Line 22(2) x Line 25(2) x Line 2(2) ÷ 1,000]	$ ________
etc.		

27. **Compute the total incremental installed cost resulting from the need to install OA supply ductwork having larger dimensions** [sum of Lines 26(T) through 26(x)]. $ ________

Estimate Cost of Increased Exhaust Fan Capacity (if applicable)

[**Note**: The following portion of Worksheet 3A applies *only in those cases* where a central exhaust fan has been planned for the new building. This will usually be the case only in *systems without economizers*. The following assumes that a larger central exhaust fan is installed in lieu of the originally planned fan.]

28. Enter the originally planned capacity of the building exhaust fan. [It should approximately equal the original OA intake rate minus the rates of localized (e.g., bathroom) exhaust fans.] ________ cfm

(continued)

29. Refer to Table A-5 at the end of this worksheet. Locate in Column A the fan flow rate corresponding to the total exhaust flow on Line 28.

30. From Column B of Table A-5, enter the *incremental* installed cost per 1,000 cfm of fan capacity corresponding to the total fan capacity on Line 28. __________ $/1,000 cfm

31. Compute the incremental cost resulting from the need to install a larger central exhaust fan (Line 1 x Line 30 ÷ 1,000). $ __________

Estimate Cost of Enlarging the Exhaust Ductwork (if applicable)

[**Note**: The following portion of Worksheet 3A applies *only in systems without economizers*, where the required increase in exhaust air cannot be achieved without increasing the dimensions of the central exhaust ducting. The following assumes that, in new systems without economizers, central exhaust ducting of larger dimensions is installed in lieu of the originally planned exhaust ducting.]

32. Enter the linear feet of ductwork that has been specified in the original system design, removing air from the zones conditioned by each of the HVAC units in the building:

32(T). Length of exhaust air trunk line __________ ft
32(1). Branch from Unit #1 zones to trunk line __________ ft
32(2). Branch from Unit #2 zones to trunk line __________ ft
etc.

33. Enter the original design exhaust flow in each branch of the central exhaust ducting:

33(T). Trunk line flow __________ cfm
33(1). Flow in branch from Unit #1 zones __________ cfm
33(2). Flow in branch from Unit #2 zones __________ cfm
etc.

(continued)

34. Refer to Table A-5. Locate in Column A the original total central exhaust flow rates from the entire building [Line 33(T)] and from the zones served by each HVAC unit [Lines 33(1) through 33(x)].

35. From Column C of Table A-5, enter the incremental installed cost per linear foot of *uninsulated* duct per 1,000 cfm *increase* in flow, corresponding to these original exhaust air flows in the trunk line and in the branches from the zones served by each HVAC unit:

35(T). Exhaust trunk line
[flow on Line 33(T)] ________ $/ft/1,000 cfm
35(1). Branch from Unit #1 zone
[flow on Line 33(1)] ________ $/ft/1,000 cfm
35(2). Branch from Unit #2 zone
[flow on Line 33(2)] ________ $/ft/1,000 cfm
etc.

36. Compute the incremental increase in the installed cost of each element of the ductwork:

36(T). Exhaust trunk line
[Line 32(T) x Line 35(T) x Line 1 ÷ 1,000] $ ________
36(1). Unit #1 branch
[Line 32(1) x Line 35(1) x Line 2(1) ÷ 1,000] $ ________
36(2). Unit #2 branch
[Line 32(2) x Line 35(2) x Line 2(2) ÷ 1,000] $ ________
etc.

37. Compute the total incremental installed cost resulting from the need to install central exhaust ductwork having larger dimensions
[sum of Lines 36(T) through 36(x)] $ ________

(continued)

Estimate Total Installed Cost (enlarged central unit plus, as applicable, enlarged OA and exhaust fans and ductwork)

38. **Compute the total incremental installed cost of the enlarged HVAC system, installed in lieu of the originally planned system** (Line 16 plus, as applicable, Lines 21, 27, 31, and 37). $ ________

(continued)

TABLE A-5

Incremental Installed Costs of Air Handlers and Ducting in a New Building[1]

Column A Total Flow Rate (cfm)	*Column B* Incremental Installed Fan Cost[2,3] ($/1,000 cfm)	*Column C* Incremental Installed Cost of Uninsulated Duct[3,4] ($/linear ft/1,000 cfm)	*Column D* Incremental Installed Cost of Insulated Duct[3,4] ($/linear ft/1,000 cfm)
500 - 1,500	1,300	20	26
1,501 - 2,500	800	13	17
2,501 - 5,000	700	9	11
>5,000	400	7	8

Notes:

1 Includes all materials (with markup), installation labor, and installation contractor overhead and profit.

2 Derived from Means (1996). Each figure is the average incremental installed cost (per 1,000 cfm) for the various categories of air handlers (centrifugal, vaneaxial, etc.) within the specified capacity range, from Section 157-290 of that citation.

3 *Incremental* costs are the costs for installing a fan or ducting accommodating a flow 1,000 cfm greater than the originally designed rate, *in lieu of* the originally designed fan or ducting. This incremental cost per 1,000 cfm *increase* in flow is distinguished from the *total* cost of the fan or ducting.

4 Derived from Means (1996). The ducts are assumed to have a square cross-section, and are sized to create 0.1 in. WG pressure loss per 100 linear feet (ASHRAE, 1997b). The uninsulated ducts were costed using the data from Sections R157-100 and 157-250 of the citation, assuming the use of 24-gauge galvanized steel. A typical cost for insulation of $2/ft^2$ was derived from Section 155-651. OA intake ducting is assumed to be insulated, and exhaust ducting to be uninsulated.

WORKSHEET 3B

Estimation of Installed Costs for Increased OA: Dedicated-OA Unit - New Construction Case

[For this case, it is assumed that a single rooftop direct-expansion HVAC unit is installed, dedicated to treating the total OA flow being supplied to the building. If there are multiple central HVAC units serving the building, this one dedicated-OA unit would supply the total required OA to all of the central units, and the original design capacity for each HVAC unit could be reduced accordingly. *If the building requires such a substantial OA volume that multiple dedicated-OA units would be needed, the user should repeat the computations in this worksheet for each dedicated-OA unit.*]

Enter Basic Data

1. Enter the total OA intake rate that will now be required for the entire building, after the OA rate is increased (from Line 5 of Worksheet 1). __________ cfm

2. Enter the originally designed OA rate to each of the HVAC units serving the building:

   2(1). Original OA rate to Unit #1 __________ cfm
   2(2). Original OA rate to Unit #2 __________ cfm
   2(3). Original OA rate to Unit #3 __________ cfm
   etc.

3. Enter the original cooling capacity for each of the HVAC units serving the building:

   3(1). Original cooling capacity of Unit #1 __________ tons
   3(2). Original cooling capacity of Unit #2 __________ tons
   3(3). Original cooling capacity of Unit #3 __________ tons
   etc.

4. Enter the original heating capacity for each of the HVAC units serving the building:

   4(1). Original heating capacity of Unit #1 __________ kW
   4(2). Original heating capacity of Unit #2 __________ kW
   4(3). Original heating capacity of Unit #3 __________ kW
   etc.

(continued)

Worksheet 3B (continued)

Estimate Cost of Dedicated-OA Rooftop Unit

5. Refer to Table A-1 at the end of Worksheet 2A. Locate in Column A the city having the climate most closely representing the user's.

6. From Column B of Table A-1, enter the required cooling capacity per 1,000 cfm OA for the climate of this city. ________ tons/1,000 cfm

7. Compute the total cooling capacity required to treat the total (increased) OA flow into the building (Line 1 x Line 6 ÷ 1,000). ________ tons

[**Note**: This is the required cooling capacity of the dedicated-OA unit.]

8. Refer to Table A-3 at the end of Worksheet 2B. Locate in Column A the cooling capacity defined in Line 7 above.

9. From Column B of Table A-3, enter the total installed cost per ton of a packaged rooftop unit having the cooling capacity in Line 7 above. $ ________ /ton

10. **Compute the total installed cost (excluding heating)** of the dedicated-OA unit having the required cooling capacity (Line 7 x Line 9). $ ________

11. From Column C of Table A-1, enter the required heating capacity per 1,000 cfm OA for the climate of the user's city. ________ kW/1,000 cfm

12. Compute the total heating capacity required to treat the total (increased) OA flow into the building (Line 1 x Line 11 ÷ 1,000). ________ kW

13. Refer to Table A-4 at the end of Worksheet 2B. Locate in Column A the heating capacity defined in Line 12 above.

(continued)

14. From Column B of Table A-4, enter the total installed cost per kW of installing the required heating capacity into the dedicated-OA unit. $ ________ /kW

15. **Compute the total installed cost of incorporating the required heating capacity** into the dedicated-OA unit (Line 13 x Line 14). $ ________

16. **Compute the total installed cost of the new dedicated-OA unit (cooling and heating)**, treating the total (increased) OA flow entering the building (Line 10 + Line 15). $ ________

Estimate the Cost Savings Achieved by Reducing the Capacities of the Central HVAC Units (since they will no longer have to condition the OA)

17. Compute the *incremental* decrease in cooling capacity that will be experienced by each of the HVAC units in the building, by virtue of their no longer having to condition the OA.

17(1). Reduced cooling capacity - Unit #1 [Line 2(1) x Line 6 ÷ 1,000]. ________ tons
17(2). Reduced cooling capacity - Unit #2 [Line 2(2) x Line 6 ÷ 1,000]. ________ tons
17(3). Reduced cooling capacity - Unit #3 [Line 2(3) x Line 6 ÷ 1,000]. ________ tons
etc.

18. Refer to Table A-3 at the end of Worksheet 2B. In Column A, locate the cooling capacity for each HVAC unit. From Column C, enter the *incremental* installed savings per ton of decreased cooling capacity corresponding to the capacity of each unit.

18(1). Incremental cost for Unit #1 [based on capacity on Line 3(1) above]. $ ________/ton
18(2). Incremental cost for Unit #2 [based on capacity on Line 3(2) above]. $ ________/ton
18(3). Incremental cost for Unit #3 [based on capacity on Line 3(3) above]. $ ________/ton
etc.

(continued)

19. Compute the estimated incremental savings in the installed cost of each HVAC unit due to reduced cooling requirements.

19(1).	Unit #1 [Line 17(1) x Line 18(1)].	$ ________
19(2).	Unit #2 [Line 17(2) x Line 18(2)].	$ ________
19(3).	Unit #3 [Line 17(3) x Line 18(3)].	$ ________
etc.		

[Because the costs on Line 18(x) are based on rooftop direct-expansion units, these estimates will be less accurate for systems involving chillers.]

20. **Determine the total estimated savings in installed HVAC cost resulting from the incremental reduction in specified cooling capacity** [sum of Lines 19(1) through 19(x)]. $ ________

21. Compute the *incremental* decrease in heating capacity that will be experienced by each of the HVAC units in the building, by virtue of their no longer having to condition the OA.

21(1).	Reduced heating capacity - Unit #1 [Line 2(1) x Line 11 ÷ 1,000].	________ kW
21(2).	Reduced cooling capacity - Unit #2 [Line 2(2) x Line 11 ÷ 1,000].	________ kW
21(3).	Reduced cooling capacity - Unit #3 [Line 2(3) x Line 11 ÷ 1,000].	________ kW
etc.		

22. Refer to Table A-4 at the end of Worksheet 2B. In Column A, locate the heating capacity for each HVAC unit. From Column C, enter the *incremental* installed savings per kW of decreased heating capacity corresponding to the capacity of each unit.

22(1).	Incremental cost for Unit #1 [based on capacity on Line 4(1) above].	$ ________/kW
22(2).	Incremental cost for Unit #2 [based on capacity on Line 4(2) above].	$ ________/kW
22(3).	Incremental cost for Unit #3 [based on capacity on Line 4(3) above].	$ ________/kW
etc.		

(continued)

23. Compute the estimated incremental savings in the installed cost of each HVAC unit due to reduced heating requirements.

23(1). Unit #1 [Line 21(1) x Line 22(1)]. $ ________
23(2). Unit #2 [Line 21(2) x Line 22(2)]. $ ________
23(3). Unit #3 [Line 21(3) x Line 22(3)]. $ ________
etc.

[Because the costs on Line 22(x) are based on electric duct heaters, these estimates will be less accurate for systems involving furnaces.]

24. **Determine the total estimated savings in installed HVAC cost resulting from the incremental reduction in specified heating capacity** [sum of Lines 23(1) through 23(x)]. $ ________

25. **Enter the total incremental savings in installed cost resulting from reducing the cooling and heating requirements of the original HVAC units** [Line 20 + Line 24]. $ ________

Estimate Cost Savings from Elimination of OA Intake Fan (if applicable)

[**Note**: The following portion of Worksheet 3B applies *only in those cases* where an OA intake fan had originally been planned for the new building. The following assumes that the fan can now be eliminated, being replaced by the air handler associated with the dedicated-OA unit.]

26. Enter the estimated installed cost for the OA intake fan, from the estimates developed by the designer of the mechanical system (if available). $ ________

27. If the designer's estimate is not available, refer to Table A-2 at the end of Worksheet 2A. Locate in Column A the flow rate corresponding to the original total OA intake rate to the building (Line **4** of Worksheet 1).

(continued)

28. From Column B of Table A-2, enter the installed cost of the fan having this capacity. $ ________

29. **Enter the installed cost of the original OA intake fan** (from either Line 26 or Line 28, as applicable). $ ________

Estimate Cost of Enlarging the OA Intake Ductwork (if applicable)

[**Note:** The following portion of Worksheet 3B applies *only in systems without economizers,* where the increased volume of OA being supplied by the dedicated-OA unit cannot simply be delivered into the originally designed OA intake duct. The following assumes that, in systems without economizers, the originally designed intake ducting retains its original configuration (presumed to be a main trunk line splitting into branches that lead to each HVAC unit), but that ducting of enlarged dimensions is installed in lieu of the originally designed ducting, as necessary to handle the greater OA flow.]

30. Enter the linear feet of OA intake ductwork that has been specified in the original system design, delivering OA to each of the HVAC units in the building:

30(T). Length of OA trunk line ________ ft
30(1). Branch from trunk line to Unit #1 ________ ft
30(2). Branch from trunk line to Unit #2 ________ ft
etc.

31. Enter the originally designed OA flow in each branch of the OA intake ducting:

31(T). Trunk line (Line 4 of Worksheet 1) ________ cfm
31(1). Branch to Unit #1 [from Line 2(1)] ________ cfm
31(2). Branch to Unit #2 [from Line 2(2)] ________ cfm
etc.

32. Enter the *incremental increase* in OA flow that must be accommodated in each branch of the ducting.

32(T). OA increase to bldg. (Line 6, Worksheet 1). ________ cfm
32(1). Increase in OA to Unit #1 ________ cfm
32(2). Increase in OA to Unit #2 ________ cfm
etc.

(continued)

33. Refer to Table A-5 at the end of Worksheet 3A. Locate in Column A the original total OA flow rates to the entire building [Line 31(T)] and to each HVAC unit [Lines 31(1) through 31(x)].

34. From Column D of Table A-5, enter the incremental installed cost per linear foot of *insulated* duct per 1,000 cfm *increase* in flow, corresponding to these original OA flows in the trunk line and in the branches to each HVAC unit:

34(T). OA trunk line [flow on Line 31(T)] ________ $/ft/1,000 cfm
34(1). Unit #1 branch [flow on Line 31(1)] ________ $/ft/1,000 cfm
34(2). Unit #2 branch [flow on Line 31(2)] ________ $/ft/1,000 cfm
etc.

35. Compute the incremental increase in the installed cost of each element of the ductwork:

35(T). OA trunk line
[Line 30(T) x Line 34(T) x Line 32(T) ÷ 1,000] $ ________
35(1). Unit #1 branch
[Line 30(1) x Line 34(1) x Line 32(1) ÷ 1,000] $ ________
35(2). Unit #2 branch
[Line 30(2) x Line 34(2) x Line 32(2) ÷ 1,000] $ ________
etc.

36. **Compute the total incremental installed cost resulting from the need to install OA supply ductwork having larger dimensions** [sum of Lines 35(T) through 35(x)]. $ ________

Estimate Cost of Increased Exhaust Fan Capacity (if applicable)

[**Note**: The following portion of Worksheet 3B applies *only in those cases* where a central exhaust fan had originally been planned for the new building. This will usually be the case only in *systems without economizers*. The following assumes that a larger central exhaust fan is installed in lieu of the originally designed fan.]

(continued)

37. Enter the originally planned capacity of the building exhaust fan. [It should approximately equal the original OA intake rate minus the rates of localized (e.g., bathroom) exhaust fans.] __________ cfm

38. Refer to Table A-5 at the end of Worksheet 3A. Locate in Column A the fan flow rate corresponding to the total exhaust flow on Line 37.

39. From Column B of Table A-5, enter the *incremental* installed cost per 1,000 cfm of fan capacity corresponding to the total fan capacity on Line 37. __________ $/1,000 cfm

40. Compute the incremental cost resulting from the need to install a larger central exhaust fan [Line 32(T) x Line 39 ÷ 1,000]. $ __________

Estimate Cost of Enlarging the Exhaust Ductwork (if applicable)

[**Note:** The following portion of Worksheet 3B applies *only in systems without economizers*, where the required increase in exhaust air cannot be achieved without increasing the dimensions of the central exhaust ducting. The following assumes that, in new systems without economizers, the exhaust ducting retains its original design configuration, but that ducting of enlarged dimensions is installed in lieu of the originally designed ducting, as necessary to handle the greater exhaust flow.]

41. Enter the linear feet of ductwork that has been specified in the original system design, removing air from the zones conditioned by each of the HVAC units in the building.

41(T). Length of exhaust air trunk line __________ ft
41(1). Branch from Unit #1 zones to trunk line __________ ft
41(2). Branch from Unit #2 zones to trunk line __________ ft
etc.

(continued)

Worksheet 3B (continued)

42. Enter the original design exhaust flow in each branch of the central exhaust ducting:

42(T). Trunk line flow	________	cfm
42(1). Flow in branch from Unit #1 zones	________	cfm
42(2). Flow in branch from Unit #2 zones	________	cfm
etc.		

43. Refer to Table A-5 at the end of Worksheet 3A. Locate in Column A the original total central exhaust flow rates from the entire building [Line 42(T)] and from the zones served by each HVAC unit [Lines 42(1) through 42(x)].

44. From Column C of Table A-5, enter the incremental installed cost per linear foot of *uninsulated* duct per 1,000 cfm *increase* in flow, corresponding to these original exhaust air flows in the trunk line and in the branches from the zones served by each HVAC unit:

44(T). Exhaust trunk line [flow on Line 42(T)]	________	\$/ft/1,000 cfm
44(1). Branch from Unit #1 zone [flow on Line 42(1)]	________	\$/ft/1,000 cfm
44(2). Branch from Unit #2 zone [flow on Line 42(2)]	________	\$/ft/1,000 cfm
etc.		

45. Compute the incremental increase in the installed cost of each element of the ductwork:

45(T). Exhaust trunk line [Line 41(T) x Line 44(T) x Line 32(T) ÷ 1,000]	\$ ________
45(1). Unit #1 branch [Line 41(1) x Line 44(1) x Line 32(1) ÷ 1,000]	\$ ________
45(2). Unit #2 branch [Line 41(2) x Line 44(2) x Line 32(2) ÷ 1,000]	\$ ________
etc.	

(continued)

46. **Compute the total incremental installed cost resulting from the need to install central exhaust ductwork having larger dimensions** [sum of Lines 45(T) through 45(x)] $ ________

Estimate Total Installed Cost (new dedicated-OA unit plus, as applicable, added OA ductwork, exhaust fans, and exhaust ductwork)

47. **Compute the total incremental installed cost of the dedicated-OA system, installed in lieu of the originally designed system** (Line 16 minus Line 25; minus, if applicable, Line 29; plus, as applicable, Lines 36, 40, and 46). $ ________

WORKSHEET 4

Estimation of Annual Operating Costs for Increased OA

Enter Basic Data

1. Enter the incremental increase in OA intake rate that is required for the entire building, beyond the originally designed rate, in cfm (from Line 6 of Worksheet 1). __________ cfm

2. Enter the overall Energy Efficiency Ratio (EER) for the cooling system in the building, i.e., the Btu/h of cooling output per W of electric input. (As a default, assume EER = 10 Btu/h/W.) __________ Btu/h/W

   [**Note:** If the compressor/condenser of the cooling system is driven by a source other than an electric motor (e.g., by a gas or diesel engine, or a gas or steam turbine) -- or if an absorption chiller is used -- the cooling system efficiency should be expressed in the appropriate units, of Btu/hr cooling output per unit energy input.]

3. Enter the overall efficiency of the heating system in the building, i.e., the Btu/h of heating output per Btu/h of fuel or electricity input. (As a default, assume and efficiency of 1.0 for electricity and 0.7 for gas or oil.) __________ Btu/h per Btu/h

4. Enter the unit costs of the applicable utilities used as energy sources in the building:

   4a. Cost of electricity, if applicable (Default: $0.08/kWh). __________ $/kWh
   4b. Cost of natural gas, if applicable (Default: $0.60/therm). __________ $/therm
   4c. Cost of fuel oil, if applicable (Default: $1.00/gal). __________ $/gal

   [**Note:** Utility costs will sometimes not be a simple function of the amount used. For example, costs of electricity will commonly include a demand charge based on peak kW usage, in addition to the unit cost per kWh. For this simple estimation, the user should utilize an average cost per unit consumed.]

(continued)

5. Enter the average number of hours per day, and days per week, that OA is being supplied to the building.

5a. Hours per day ________ hours/day
5b. Days per week ________ days/week

Estimate Annual Cost of Cooling and Heating the Incremental Increased OA

6. Refer to Table A-6 at the end of this worksheet. Locate in Column A the city having the climate closest to that of the user.

7. From Column B of Table A-6, enter the value for the annual cooling energy that is required by the air stream, per incremental cfm of OA. ________ Btu/yr/cfm

8. The annual cooling energy from Table A-6 is based on operation at 13 hours/day, 5 days/week. If the user's system operates on a significantly different cycle, correct the figure on Line 7:

(Line 7) x (Line 5a ÷ 13) x (Line 5b ÷ 5) ________ Btu/yr/cfm

9. Calculate the total energy input required to the cooling system, considering system efficiency:

(Line 1) x (Line 8) ÷ (Line 2) ÷ 1,000 W/kW ________ kWh/yr

[**Note:** The form of this equation assumes that the cooling system is driven by a compressor having an electric motor, and that Line 9 thus has the units of kWh/yr. If this is not the case, modify the units of Line 2 (and thus of Line 9) accordingly.]

10. **Calculate the annual energy cost associated cooling the incremental additional OA** (Line 9 x Line 4a). $ ________ /yr

11. From Column C of Table A-6, enter the value for the annual heating energy that is required by the air stream, per incremental cfm of OA. ________ Btu/yr/cfm

(continued)

12. Correct the annual heating energy on Line 11 if the user's system operates on a significantly different cycle from 13 hr/day, 5 days/wk:

(Line 11) x (Line 5a ÷ 13) x (Line 5b ÷ 5) __________ Btu/yr/cfm

13. Calculate the total energy input required to the heating system, considering system efficiency:

(Line 1) x (Line 12) ÷ (Line 3) __________ Btu/yr

14. Compute the amount of input energy to the system that is required to provide the Btu's indicated on Line 13:

14a. Line 13 x (1 kWh/3413 Btu) (for electric heat) __________ kWh/yr

14b. Line 13 x (1 therm/100,000 Btu) (for gas heat) __________ therms/yr

14c. Line 13 x (1 gal./140,000 Btu) (for fuel oil heat) __________ gal./yr

15. **Calculate the annual energy cost associated heating the incremental additional OA** (Line 14a x Line 4a for electric; Line 14b x Line 4b for gas; Line 14c x Line 4c for oil). $ __________ /yr

16. **Calculate the total annual energy cost associated with cooling *and* heating the incremental additional OA** (Line 10 plus Line 15). $ __________ **/yr**

Estimate Incremental Annual Energy Cost for New or Enlarged OA Intake Fans (if applicable)

17. Enter the flow rate for any new *OA intake* fan, or the incremental increase in flow through any enlarged intake fan, if applicable. __________ cfm

(continued)

Note: Obtain this value on Line 17 from:
Worksheet 2A, Line 14; *or*
Worksheet 2B, Line 1; *or*
Worksheet 3A, Line 17; *or*
Worksheet 3B, Line 32(T).
In the cases of the dedicated-OA units (Worksheets 2B and 3B), the "OA intake fan" addressed here is the air handler associated with the new dedicated-OA unit.

18. Enter the actual linear feet of ducting through which the OA must flow. __________ ft

Note: Obtain this value from:
Worksheet 2A, Line 17(T) plus the average of Lines 17(1) through 17(x); *or*
Worksheet 2B, Line 14(T) plus the average of Lines 14(1) through 14(x); *or*
Worksheet 3A, Line 22(T) plus the average of Lines 22(1) through 22(x); *or*
Worksheet 3B, Line 30(T) plus the average of Lines 30(1) through 30(x).

19. Enter the additional *equivalent* linear feet of intake ducting, beyond the *actual* linear feet, created by elbows and other fittings in the ducting:

Average number of fittings between the intake fan and the typical HVAC unit in the building (__________) times 20 equivalent feet per fitting. __________ ft

20. Compute the total equivalent linear feet of intake ducting (Line 18 + Line 19). __________ ft

21. Compute the total static pressure increase required across the OA intake fan:

21a. Due to duct loss (Line 20 x 0.1 in. WG/ft). __________ in. WG
21b. Due to HVAC coils and air filter (applies to dedicated-OA cases only) -- enter design value, if available.
(Default: 0.5 in. WG) __________ in. WG
21c. Total (Line 21a + Line 21b). __________ in. WG

(continued)

22. Enter the overall fan energy efficiency.
(Defaults: 0.50 for fans < 1,000 cfm;
0.65 for fans > 1,000 cfm) __________ hp out/hp in

23. Compute the required power input to the fan, to provide the output power required raise the incremental OA flow on Line **17** by the pressure increment on Line 21:

(Line 17) x (Line 21) x [5.19 (lb/ft^2)/(in. WG)]
x [(1 hp)/(33,000 ft-lb/min)] ÷ (Line 22) __________ hp in

24. Enter the number of hours that the fan will be operating per year.
(Default: 3,276 hr/yr, for 13 hr/day, 5 day/wk excluding holidays.) __________ hr/yr

25. **Compute the annual energy consumption by any new *OA intake* fan, or by the incremental increase in flow through any enlarged intake fan.**
(Line 23) x (0.746 kW/hp) x (Line 24) __________ kWh/yr

[**Note**: This calculation assumes that the OA intake fan will be operating at full load whenever it is operating.]

26. **Calculate the incremental annual energy cost associated with the operation of this new or incrementally enlarged OA intake fan**
(Line 25) x (Line 4a) **$** __________ **/yr**

Estimate Incremental Annual Energy Cost for New or Enlarged Exhaust Fans (if applicable)

27. Enter the flow rate for any new *exhaust* fan, or the incremental increase in flow through any enlarged exhaust fan, if applicable. __________ cfm

Note: Obtain this value from:
Worksheet 2A, Line 1, *or*
Worksheet 2B, Line 1; *or*
Worksheet 3A, Line 1; *or*
Worksheet 3B, Line 32(T).

(continued)

28. Enter the actual linear feet of ducting through which the exhaust air must flow. __________ ft

Note: Obtain this value from:
Worksheet 2A, Line 24(T) plus the average of Lines 24(1) through 24(x); *or*
Worksheet 2B, Line 21(T) plus the average of Lines 21(1) through 21(x); *or*
Worksheet 3A, Line 32(T) plus the average of Lines 32(1) through 32(x); *or*
Worksheet 3B, Line 41(T) plus the average of Lines 41(1) through 41(x).

29. Enter the additional *equivalent* linear feet of exhaust ducting, beyond the *actual* linear feet, created by elbows and other fittings in the ducting:

Average number of fittings between the exhaust fan and the typical HVAC zones in the building (__________) times 20 equivalent feet per fitting. __________ ft

30. Compute the total equivalent linear feet of exhaust ducting (Line 28 + Line 29). __________ ft

31. Compute the total static pressure increase required across the exhaust fan, due to duct loss (Line 30 x 0.1 in. WG/ft). __________ in. WG

32. Enter the overall exhaust fan energy efficiency. (Defaults: 0.50 for fans < 1,000 cfm; 0.65 for fans > 1,000 cfm) __________ hp out/hp in

33. Compute the required power input to the fan, to provide the output power required raise the exhaust flow on Line 27 by the pressure increment on Line 31:

(Line 27) x (Line 31) x [5.19 (lb/ft^2)/(in. WG)] x [(1 hp)/(33,000 ft-lb/min)] ÷ (Line 32) __________ hp in

(continued)

34. Enter the number of hours that the exhaust fan will be operating per year.
(Default: 3,276 hr/yr, for 13 hr/day, 5 day/wk excluding holidays.) __________ hr/yr

35. Compute the annual energy consumption by any new *exhaust* fan, or by the incremental increase in flow through any enlarged exhaust fan.
(Line 33) x (0.746 kW/hp) x (Line 34) __________ kWh/yr

[**Note:** This calculation assumes that the exhaust fan will be operating at full load whenever it is operating.]

36. Calculate the incremental annual energy cost associated with the operation of this new or incrementally enlarged exhaust fan
(Line 35) x (Line 4a) $ __________ /yr

Estimate Total Incremental Annual Operating Cost (increased cooling and heating energy plus, as applicable, increased energy for OA and exhaust fans)

37. Compute the total incremental annual operating cost associated with the increase in OA ventilation rate (Line 16 plus, as applicable, Lines 26 and 36). $ __________ /yr

(continued)

TABLE A-6

Incremental Annual Cooling and Heating Energy Requirements
per Unit Increase in OA Ventilation Rate[1,2]
(by Geographical Location)

Column A City	*Column B* Incremental Additional Annual Cooling Energy Required per Incremental Increase in Outdoor Air Intake Rate (Btu/yr per incremental cfm)	*Column C* Incremental Additional Annual Heating Energy Required per Incremental Increase in Outdoor Air Intake Rate (Btu/yr per incremental cfm)
Chicago, IL	13,000	41,000
Miami, FL	67,000	200
Minneapolis, MN	13,000	63,000
Northern Virginia	20,000	25,000
Raleigh, NC	26,000	16,000
Seattle, WA	3,000	28,000

Notes:

1 Computed using the DOE-2 computer model for simulating building energy consumption (York, 1981), assuming a small office building for which an input file was already available (Henschel, 1997). The figure for each geographical location is an average for alternative variable-volume and constant-volume mechanical systems, and for OA flow rates over the range of 5 to 60 cfm/person at an occupant density of 7 persons per 1,000 ft^2. The modeling assumed that OA was supplied to the building 13 hours/day (6 am to 7 pm) on weekdays only (excluding holidays).

2 Addresses the energy that must be supplied to the incremental outdoor air. The energy that must be supplied as input to the cooling and heating equipment (in the form of fuel or electricity), to provide this cooling/heating of the incremental OA, will depend on the efficiency of the equipment.

WORKSHEET 5

Estimation of Annual Maintenance Costs for Increased OA

1. Enter the number of *new* OA intake fans assumed in Worksheets 2A or 3B, if applicable. __________ fans

   [**Note**: Intake fans that have been *enlarged*, as assumed in Worksheet 3A, should not be included here; only fans that have been *added* are assumed to add to maintenance costs. Only Worksheet 2A assumes the addition of new intake fans; in Worksheet 3B, any previously designed intake fans would be *deleted*, in which case the number entered here would be negative. The formats of Worksheets 2A and 3B assume that only a single intake fan is being added (or deleted); in larger buildings, this number might be greater than one. As noted in those prior tables, there will often not be any intake fan, in which case the number entered here would be zero.]

2. Enter the number of *new* central exhaust fans assumed in Worksheets 2A or 2B, if applicable. __________ fans

   [**Note**: Exhaust fans that have been *enlarged*, as assumed in Worksheets 3A and 3B, should not be included here. As noted in the prior tables, central exhaust fans will usually be required only in systems without economizers.]

3. Enter the total number of new fans (sum of Line 1 plus Line 2). __________ fans

4. Enter the estimated additional maintenance labor hours per year per new fan. (Default: 5 hours/year/fan) __________ hr/yr/fan

5. Enter the estimated hourly labor rates for fan maintenance personnel. (Default: $35/hour, including overhead) $ __________ /hr

6. **Compute the annual maintenance cost increase for the additional fans** (Line 3 x Line 4 x Line 5). $ __________ /yr

(continued)

Worksheet 5 (concluded)

7. Enter the number of new dedicated-OA units assumed in Worksheets 2B or 3B, if applicable. __________ units

[**Note**: HVAC units that have been *enlarged*, as assumed in Worksheets 2A and 3A, are not be included here; only units that have been *added* are assumed to add to maintenance costs. The formats of Worksheets 2B and 3B assume that only a single dedicated-OA unit is being added; in larger buildings, this number might be greater than one.]

8. Enter the estimated additional maintenance labor hours per year per new dedicated-OA unit. (Default: 20 hours/year/unit) __________ hr/yr/unit

9. Enter the estimated hourly labor rates for HVAC maintenance personnel. (Default: $35/hour, including overhead) $ __________ /hr

10. **Compute the annual maintenance cost increase for the new dedicated-OA units** (Line 7 x Line 8 x Line 9). $ __________ /yr

Estimate Total Annual Maintenance Costs (for new OA and exhaust fans and dedicated-OA units, as applicable)

11. **Compute the total incremental annual maintenance cost associated with the increase in OA ventilation rate** (Line 6 plus Line 10, as applicable). $ __________

WORKSHEET 6

Estimation of Total Annualized Costs for Increased OA

Enter Results from Other Worksheets

1. Enter the **total installed cost** of the equipment required for the increase in ventilation rate. $ ________

   Note: Obtain this value from:
   Worksheet 2A, Line 29; *or*
   Worksheet 2B, Line 26; *or*
   Worksheet 3A, Line 38; *or*
   Worksheet 3B, Line 47.

2. Enter the **total incremental annual operating cost** associated with the increase in ventilation rate (Worksheet 4, Line 37). $ ________ /yr

3. Enter the **total incremental annual maintenance cost** associated with the increase in ventilation rate (Worksheet 5, Line 11). $ ________ /yr

Determine the Capital Recovery Factor (CRF)

[**Note:** The CRF is the fraction of the initial installed cost that must be amortized each year if, after n years (i.e., after n equal "payments"), the initial cost is to be recovered with an i percent annual interest rate charged on the unpaid balance.]

4. Enter the equipment lifetime, n, that will be assumed for these calculations (commonly 10 to 20 years). ________ yr

5. Enter the annual interest rate, i, that will be assumed for these calculations. ________ %

6. From these values for n and i, identify the appropriate value of the CRF from Table A-7 at the end of this worksheet. ________

(continued)

Worksheet 6 (continued)

Compute the Total Annualized Cost for Increased Ventilation

7. Compute the average annual capital charge (Line 1 x Line 6). $ _________ /yr

8. Compute the annual operating and maintenance (O&M) costs associated with the increase in ventilation rate (Line 2 + Line 3). $ _________ /yr

9. **Compute the total annualized cost associated with the increase in OA ventilation rate** (Line 7 plus Line 8). $ _________ /yr

(continued)

Worksheet 6 (concluded)

TABLE A-7

Capital Recovery Factors[1]

Number of Years, n, Over Which the Initial Investment Is to Be Amortized	Compound Interest Rate, i, to Be Charged on the Unpaid Balance				
	5%	6%	7%	8%	10%
1	1.0500	1.0600	1.0700	1.0800	1.1000
2	0.5378	0.5454	0.5531	0.5608	0.5762
3	0.3672	0.3741	0.3811	0.3880	0.4021
4	0.2820	0.2886	0.2952	0.3019	0.3155
5	0.2310	0.2374	0.2439	0.2505	0.2638
6	0.1970	0.2034	0.2098	0.2163	0.2296
7	0.1728	0.1791	0.1856	0.1921	0.2154
8	0.1547	0.1610	0.1648	0.1740	0.1874
9	0.1407	0.1470	0.1535	0.1601	0.1736
10	0.1295	0.1359	0.1424	0.1490	0.1628
11	0.1204	0.1268	0.1334	0.1401	0.1540
12	0.1128	0.1193	0.1259	0.1327	0.1468
13	0.1065	0.1130	0.1196	0.1265	0.1408
14	0.1010	0.1076	0.1143	0.1213	0.1358
15	0.0963	0.1030	0.1098	0.1168	0.1315
16	0.0923	0.0990	0.1059	0.1130	0.1278
17	0.0887	0.0954	0.1024	0.1096	0.1247
18	0.0856	0.0924	0.0994	0.1067	0.1219
19	0.0828	0.0896	0.0968	0.1041	0.1196
20	0.0802	0.0872	0.0944	0.1018	0.1175

Note:

[1] The figures presented in the table above are the values of the Capital Recovery Factor (CRF), computed from the specified values of n and i using the equation:

$$CRF = [i(1+i)^n] / [(1+i)^n - 1].$$

WORKSHEET 7

Estimation of Air Cleaner Efficiency Required to Achieve Desired Reduction in Contaminant Concentration Using a Central Indoor Air Cleaner

Enter Basic Data

1. Enter the current average indoor concentration, C_{IN_o}, of the contaminant of concern in the building (or in that portion of the building served by a given air handler), with no air cleaner in place. ________ mg/m^3

2. Enter the average concentration, C_{IN}, to which the level in Line 1 above should be reduced after the air cleaner is installed. ________ mg/m^3

3. Enter the average concentration, C_{OA}, of the contaminant in the outdoor air. ________ mg/m^3

4. Enter the volumetric flow of outdoor air, Q_{OA}, into the building (or into that portion of the building being addressed here). ________ cfm

5. Enter the total volume of air, Q_S, being supplied to the space within the building, including the outdoor air Q_{OA} plus the recirculating air, Q_R. ________ cfm

6. Compute the rate, Q_R, at which building air is being recirculated (Line 5 minus Line 4). ________ cfm

7. Quantify the rate, S, at which the contaminant of concern is being generated by sources inside the building, in lb/min. ________ lb/min

(continued)

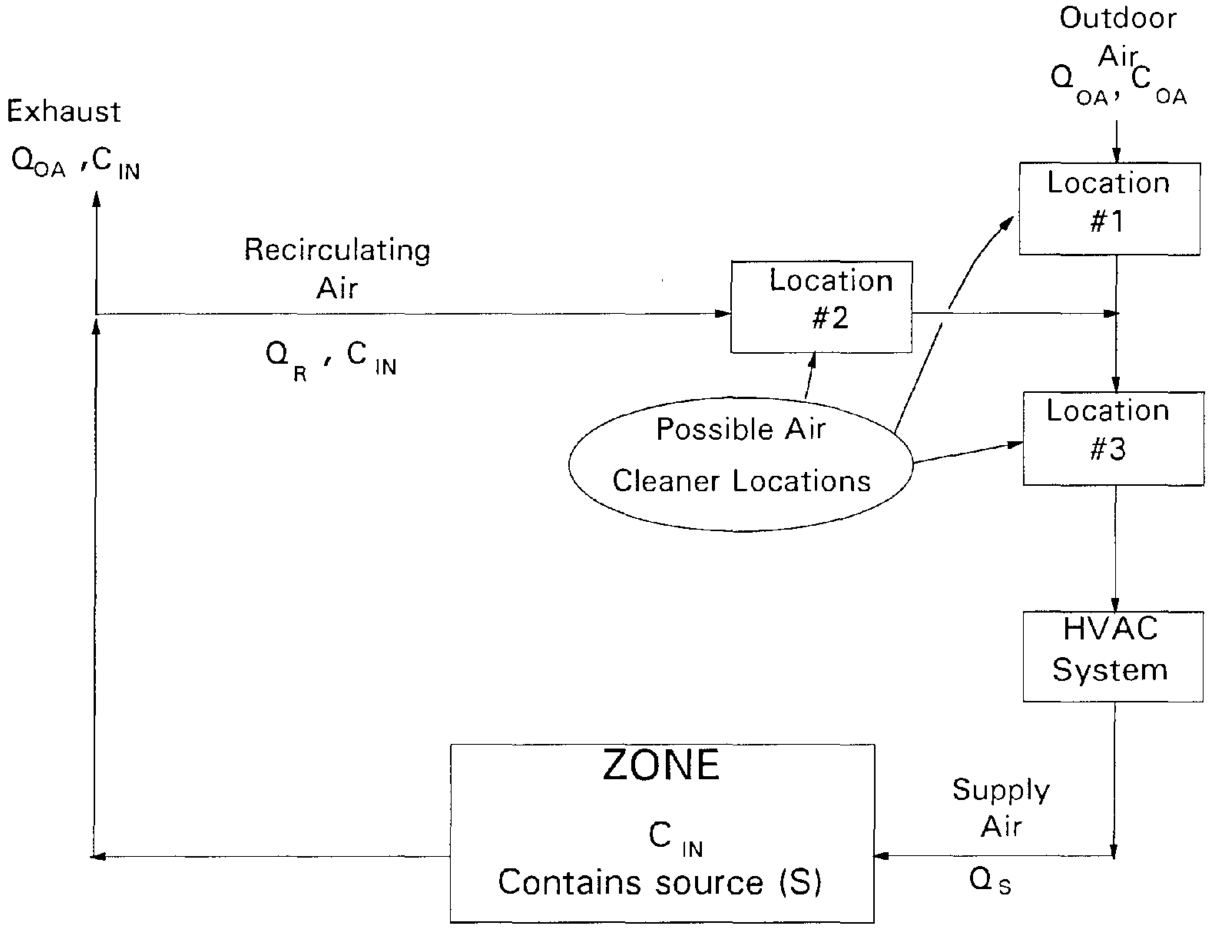
Calculate the Required Air Cleaner Efficiency

8. Refer to Figure A-1 at the end of this worksheet. Select which alternative location in that figure is to be used for the air cleaner.

9. Refer to Table A-8 at the end of this worksheet. For the selected air cleaner location, identify in the table the equation that defines the required air cleaner efficiency, η, as a function of C_{IN}, C_{OA}, Q_{OA}, Q_R, and S.

10. Compute the required air cleaner efficiency, η, using the appropriate equation selected on Line 9, using the parameters defined on Lines 2, 3, 4, 6, and 7. __________

(continued)



Key:
- Q = air flow rate (cfm)
- C = contaminant concentration (mg/m^3)
  [Note: 1 mg/m^3 = 6.2 x 10^{-8} lb/ft^3]
- S = source term for contaminant generated indoors (lb/min)

Subscripts:
- OA = outdoor air
- S = supply air to zone
- R = recirculating air
- IN = desired indoor concentration with air cleaner in place

Figure A-1. Alternative locations for central indoor air cleaners within the HVAC system.

(continued)

Worksheet 7

TABLE A-8

Equations [1,2] to Compute Air Cleaner Efficiency, η,
Required to Achieve Desired Indoor Concentration, C_{IN}

Air cleaner Location #1[3]:

$$\eta = \frac{Q_{OA}(C_{OA} - C_{IN})K + S}{Q_{OA}C_{OA}K}$$

Air cleaner Location #2:

$$\eta = \frac{Q_{OA}(C_{OA} - C_{IN})K + S}{Q_R\, C_{IN}K}$$

Air cleaner Location #3:

$$\eta = \frac{Q_{OA}(C_{OA} - C_{IN})K + S}{Q_{OA}C_{OA}K + Q_R C_{IN}K}$$

Notes

1. Air cleaner locations, and terms in equations, as defined in Figure A-1. K = concentration conversion factor = 6.2×10^{-8} $(lb/ft^3)/(mg/m^3)$.
2. Equations derived based upon a mass balance around the zone. See text.
3. Equation for Location #1 applies only when outdoor air is a meaningful contributor to indoor concentrations.

WORKSHEET 8

Estimation of Installed Costs for Central Indoor Air Cleaners

Enter Basic Data

1. Enter the required per-pass removal efficiency for the air cleaner (from Line 10 of Worksheet 7). __________

2. Enter the total flow through the air cleaner. __________ cfm

   Note: Obtain this value from the following lines on Worksheet 7:
   Line 4 (Q_{OA}) for Location #1; *or*
   Line 6 (Q_R) for Location #2; *or*
   Line 5 (Q_S) for Location #3.

Estimate Installed Cost for Particulate Air Cleaners

[**Note:** The following portion of Worksheet 8 applies only when the air cleaner is being installed to remove particulate matter. It is assumed that the HVAC system already includes basic particulate air cleaners for protecting the fan and coils and for controlling coarse particles, and that any air cleaner being costed here is to remove greater amounts of finer particulate.]

3. Refer to Table A-9 at the end of this worksheet. Considering the air cleaner efficiency defined in Line 1 above and the size range of the particulate to be removed, select an air cleaner from the table that will provide the desired efficiency.

4. Estimate the installed cost per unit air flow for a particulate air cleaner of the type selected in Line 3 above.

[**Note:** This would include the installed cost of the cleaning device itself plus any housing required to mount the device in the ductwork, plus any increase in the horsepower of the central fan drive motor necessary to handle the increase in pressure drop created by the air cleaner.]

(continued)

4a. Obtain a quote from a vendor, including installation. $ __________ /1,000 cfm

or

4b. Refer to Table A-10 at the end of this worksheet. Identify in Column A the air cleaner closest to the one selected in Line 3. From Column B of the table, enter the unit installed cost of this cleaner. $ __________ /1,000 cfm

5. **Compute the estimated installed cost for the particulate air cleaner** (Line 2 x Line 4a or 4b ÷ 1,000). $ __________

6. If there are multiple HVAC units in the building requiring an air cleaner, repeat the procedure on Lines 3 through 5 for each unit.

Estimate Installed Cost of Air Cleaners for Gaseous Contaminants

[**Note:** The following portion of Worksheet 8 applies only when the air cleaner is being installed to remove gaseous contaminants.]

7. Estimate the installed cost per unit air flow for a gaseous contaminant air cleaner, suitable for removing the contaminant(s) of concern.

7a. Obtain a quote from a vendor, including installation. $ __________ /1,000 cfm

or

7b. Enter $680/1,000 cfm $ __________ /1,000 cfm

[**Note:** The default value of $680/1,000 cfm consists of the following components: 1) $660/1,000 cfm for an installed granular activated carbon filter, derived independently from vendor quotes (Henschel, 1998) and also obtained from Section 157-401-0050 of Means (1996); and 2) $20/1,000 cfm as the incremental cost for an enlarged motor to drive the central air handler, to accommodate an assumed 1 in. WG pressure loss across the air cleaner, derived from Section 163-140 of Means (1996).] The installed cost of increased cooling capacity, to remove the additional heat generated by the larger fan motor, is neglected. Complications in installation, such as inadequate space to accommodate the new air cleaner within the existing mechanical room, are not included in these costs.

(continued)

8. **Compute the estimated installed cost for the gaseous air cleaner** (Line 2 x Line 7a or 7b ÷ 1,000). $ __________

9. If there are multiple HVAC units in the building requiring an air cleaner, repeat the procedure on Lines 3 through 5 for each unit.

(continued)

TABLE A-9

Approximate Fractional Efficiency of
Various In-Duct Particulate Indoor Air Cleaners[1,2]

Type of Air Cleaner	Air Cleaner Efficiency in Removing Particles Having the Following Diameters[3] 0.01 μm	0.1 μm	1.0 μm
Media Air Cleaners			
Pleated panel cartridge filter; 6 in. deep; paper media; ASHRAE 65[4]	90	20	40
Pleated panel cartridge filter; 6 in. deep; paper media; ASHRAE 85	90-95+	40-50	80-90
Pleated panel cartridge filter; 6 in. deep; paper media; ASHRAE 95	95+	50-60	95
Pocket filter; 22 in. deep; non-woven fiber media; ASHRAE 95	95+	70-95+	90-95+
High-efficiency particulate air (HEPA) pleated panel filter; 12 in. deep; glass fiber media; DOP 99.97[5]	99.97% efficient on particles of 0.3 μm		
Electronic Air Cleaners			
Electrostatic precipitator; 2 stages			
- 90-180 ft/min face velocity	40-70	80-90	80-90
- 350 ft/min face velocity	40	60	70

(continued)

TABLE A-9 (concluded)

Approximate Fractional Efficiency of
Various In-Duct Particulate Indoor Air Cleaners

Notes:

[1] The particulate air cleaners addressed here are designed for mounting in the HVAC ductwork, as illustrated in Figure A-1, as distinguished from self-contained or in-room stand-alone units. Only air cleaners having an ASHRAE dust spot average efficiency of 65% or greater (ASHRAE, 1992) are addressed, assuming that less efficient filters to control coarse particles are already incorporated into the system.

[2] The fractional efficiency data presented in this table (excluding the value for the HEPA filter) were obtained from Hanley et al. (1994).

[3] Fractional efficiencies on the various particle sizes vary, to greater or lesser extents, with air velocity through the air cleaner and, for media air cleaners, with filter loading. The value shown here represents a typical value. The air cleaners are consistently least efficient for particles around 0.1 to 0.3 μm; efficiencies improve for smaller as well as larger particles.

[4] The ASHRAE specification (e.g., ASHRAE 65) refers to the dust spot average efficiency determined using the procedure for testing air cleaning devices defined in ASHRAE Standard 52.1-1992 (ASHRAE, 1992).

[5] The DOP (dioctyl phthalate) specification for the performance of HEPA filters refers to the percentage removal of 0.3 μm DOP particles using the procedure defined in U. S. Military Standard MIL-STD-282 (U. S. Department of Defense, 1956).

TABLE A-10

Approximate Installed Costs of
Various In-Duct Particulate Indoor Air Cleaners

Column A Type of Air Cleaner	*Column B* Total Unit Installed Cost ($/1,000 cfm)
Pleated panel cartridge filter, ASHRAE 65[1,2]	115
Pleated panel cartridge filter, ASHRAE 85[1,2]	115
Pleated panel cartridge filter, ASHRAE 95[1,2]	120
Pleated panel HEPA filter	*[3]
Electronic air cleaner[2,4]	400

Notes:

1 Installed costs for ASHRAE 65 through 95 media filters are based on cartridge filter units, and thus might be less accurate for bag or pocket filters. Costs include: the cartridge ($35-$40/1,000 cfm for 2,000 cfm cartridges), based on vendor quotes (Flanders Filters, Inc., Washington, NC) and Section 157-401-3000 of Means (1996); the frame, based on vendor quotes of about $50/1,000 cfm for a unit capable of supporting four 2,000 cfm cartridges (Air Seal Filter Housing, Houston, TX); installation labor for the frame into the ductwork (assumed to require 2 labor hours at the rate charged for a sheet metal worker in Means, 1996); and the incremental installed cost for an enlarged drive motor for the air handler, to handle the increased pressure drop across the filter (estimated to be about 1 in. WG on average over the filter lifetime). The incremental cost for enlarged drive motors (about $20/1,000 cfm) was derived from Section 163-140 of Means (1996). The installed cost of increased cooling capacity, to remove the additional heat generated by the larger fan motor, is neglected.

2 Complications resulting from, e.g., inadequate space to accommodate the new air cleaner within the existing mechanical room, are not considered in these costs.

3 Quotes for HEPA filters should be obtained directly from the vendor. Due the quality required in materials and fabrication, HEPA units will cost significantly more than the other media filters.

4 Installed cost per 1,000 cfm for an electronic air cleaner was obtained from Section 157-401-2000 of Means (1996), based on a 2,000 cfm unit.

WORKSHEET 9

Estimation of Annual Operating Costs for Central Indoor Air Cleaners

Enter Basic Data

1. Enter the total flow through the air cleaner. __________ cfm

Note: Obtain this value from the following lines on Worksheet 7:
Line 4 (Q_{OA}) for Location #1; *or*
Line 6 (Q_R) for Location #2; *or*
Line 5 (Q_S) for Location #3.

2. Enter the number of hours per year that the central air handler (and the indoor air cleaner) will be operating.
(Default: 3,276 hr/yr, for 13 hr/day, 5 day/wk, excluding holidays). __________ hr/yr

3. Enter the unit cost of electricity.
(Default: $0.08/kWh). $ __________ /kWh

[**Note**: Electricity costs will sometimes not be a simple function of the number of kWh used. For example, a demand charge based on the peak kW usage rate will commonly be included. For this simple estimation, the user should utilize an average cost per kWh consumed.]

4. Enter the Electric Input Ratio (EIR) for the cooling system on which the air cleaner is to be installed, i.e., the kW of electric input per kW of cooling input.
(Default: EIR = 0.34 kW/kW.) __________ kW/kW

[**Note**: If the compressor/condenser of the cooling system is driven by a source other than an electric motor (e.g., by a gas or diesel engine, or a gas or steam turbine) -- or if an absorption chiller is used -- the cooling system efficiency should be expressed in the appropriate units, of Btu/hr cooling output per unit energy input.]

(continued)

5. Enter the overall energy efficiency of the central air handler (fan/motor combination). (Defaults: 0.50 for fans $<$ 1,000 cfm; 0.65 for fans $>$ 1,000 cfm) __________ hp out/hp in

Estimate Annual Operating Cost of Media Air Cleaners for Particulate Matter

[**Note:** The following portion of Worksheet 9 applies for particulate air cleaners utilizing media cartridges, pockets, or bags. The annual operating costs consist of: the increased fan energy required to overcome the pressure drop associated with the new filter; and the incremental increase in cooling energy required to remove the heat produced by this increase in fan power.]

6. Enter the average pressure drop across the filter over its lifetime (ranging from unloaded at the outset, to completely loaded with collected particulate prior to replacement of the media). (Default: 1 in. WG). __________ in. WG

7. Compute the required incremental additional power input to the fan/motor, required to enable the flow on Line 1 to overcome the added pressure drop identified in Line 6:

   (Line 1) x (Line 6) x [(5.19 lb/ft^2)/(in. WG)] x [(1 hp)/(33,000 ft-lb/min)] ÷ (Line 5) __________ hp in

8. Compute the incremental annual energy consumption resulting from this added fan power:

   (Line 7) x (0.746 kW/hp) x (Line 2) __________ kWh/yr

9. **Compute the incremental annual energy cost associated with the increased fan power required to handle the filter pressure drop** (Line 8 x Line 3). $ __________ /yr

10. Compute the incremental additional energy input required to the cooling system, to remove the additional heat created by this increase in fan power. (*Assume that, on average over the cooling and heating seasons, essentially all of the heat added to the air stream by the fan must be removed by the cooling system.*) (Line 8 x Line 4) __________ kWh/yr

(continued)

11. **Compute the incremental annual energy cost associated with the increased cooling energy consumption necessitated by the increase in fan power** (Line 10 x Line 3). $ ________ /yr

12. **Compute the total incremental annual operating cost associated with the addition of a media filter for indoor particulate control** (Line 9 plus Line 11). $ ________ /yr

Estimate Annual Operating Cost of Electronic Air Cleaners for Particulate Matter

[**Note:** The following portion of Worksheet 9 applies for particulate air cleaners utilizing electrostatic precipitation. The annual operating costs consist of: the electrical energy required to operate the precipitator; and the incremental increase in cooling energy required to remove the heat produced by this electrical input. It is assumed that there is no pressure drop across the precipitator.]

13. Enter the average electric power consumption by the precipitator per unit air flow, as stated by the vendor.
[Default: 30 W/1,000 cfm (ASHRAE, 1996)] ________ W/1,000 cfm

14. Compute the total annual power consumption to operate the electrostatic precipitator:

(Line 13) x (Line 1) ÷ (1,000 cfm/MCFM)
x (Line 2) ÷ (1,000 W/kW) ________ kWh/yr

15. **Compute the annual electrical power cost associated with operating the precipitator** (Line 14 x Line 3). $ ________ /yr

16. Compute the incremental additional energy input required to the cooling system, to remove the additional heat generated by the power input to the precipitator. (*Assume that, on average over the cooling and heating seasons, essentially all of the heat added to the air stream by the precipitator must be removed by the cooling system.*) (Line 14 x Line 4) ________ kWh/yr

(continued)

17. Compute the incremental annual energy cost associated with the increased cooling energy consumption necessitated by the power input to the precipitator (Line 16 x Line 3). $ __________ /yr

18. Compute the total incremental annual operating cost associated with the addition of an electronic air cleaner for indoor particulate control (Line 15 plus Line 17). $ __________ /yr

Estimate Annual Operating Cost of Air Cleaners for Gaseous Contaminants

[**Note:** The following portion of Worksheet 9 applies for air cleaners designed to remove gaseous contaminants, utilizing dry granular sorbents or catalysts (e.g., granular activated carbon or activated alumina). The annual operating costs consist of: the increased fan energy required to overcome the pressure drop across the granular bed; and the incremental increase in cooling energy required to remove the heat produced by this increase in fan power.]

19. Enter the estimated pressure drop across the air cleaner, based on vendor specifications. (Default: 1 in. WG). __________ in. WG

20. Compute the required incremental additional power input to the fan/motor, required to enable the flow on Line 1 to overcome the added pressure drop identified in Line 19:

(Line 1) x (Line 19) x [(5.19 lb/ft^2)/(in. WG)] x [(1 hp)/(33,000 ft-lb/min)] ÷ (Line 5) __________ hp in

21. Compute the incremental annual energy consumption resulting from this added fan power:

(Line 20) x (0.746 kW/hp) x (Line 2) __________ kWh/yr

22. Compute the incremental annual energy cost associated with the increased fan power required to handle the air cleaner pressure drop (Line 21 x Line 3). $ __________ /yr

(continued)

Worksheet 9 (concluded)

23. Compute the incremental additional energy input required to the cooling system, to remove the additional heat created by this increase in fan power. (*Assume that, on average over the cooling and heating seasons, essentially all of the heat added to the air stream by the fan must be removed by the cooling system.*) (Line 21 x Line 4). ________ kWh/yr

24. **Compute the incremental annual energy cost associated with the increased cooling energy consumption necessitated by the increase in fan power** (Line 23 x Line 3). $ ________ /yr

25. **Compute the total incremental annual operating cost associated with the addition of an air cleaner for indoor gaseous contaminant control** (Line 22 plus Line 24). $ ________ /yr

Summation of Annual Operating Costs for All Air Cleaners

26. **If multiple air cleaners must be installed in a given building, repeat the calculations above for each one as necessary. Sum the total annual operating costs (on Lines 12, 18, and/or 25) for all air cleaners, and enter the sum here.** **$ ________ /yr**

WORKSHEET 10

Estimation of Annual Maintenance Costs for Central Indoor Air Cleaners

[**Note:** For this estimation, it is assumed that the only maintenance costs are those associated with: replacing the filter media in media filters for particulate matter; removing the collected particulate matter from an electronic air cleaner; or replacing the granular sorbent/catalyst in air cleaners for gaseous contaminants.]

Compute the Mass of Contaminant to Be Removed by the Air Cleaner

1. From Worksheet 7, enter:

   1a. The flow rate entering the air cleaner. __________ cfm

   [Q_{OA} (Line 4) for Location #1;
   Q_R (Line 6) for Location #2;
   $Q_S = Q_R + Q_{OA}$ (Line 5) for Location #3]

   1b. The contaminant concentration entering the air cleaner. __________ mg/m^3

   [C_{OA} (Line 3) for Location #1;
   C_{IN} (Line 2) for Location #2;
   $(Q_R C_{IN} + Q_{OA} C_{OA})/(Q_R + Q_{OA})$ for Location #3]

   1c. The fractional efficiency, η, of the air cleaner (Line 10). __________

2. From Worksheet 9, Line 2, enter the number of hours per year that the central air cleaner will be operating. __________ hr/yr

3. Compute the mass of contaminant that will be removed per year by the air cleaner:

   (Line 1a) x (Line 1b) x [6.2 x 10^{-8} (lb/ft^3)/(mg/m^3)] x (Line 1c) x (60 min/hr) x (Line 2). __________ lb/yr

(continued)

Estimate Annual Maintenance Cost of Media Air Cleaners for Particulate Matter

4. From the vendor of the media air cleaner, obtain an estimate of the mass of particulate that can be collected on the filter under consideration, before the pressure drop would be expected to exceed the vendor's (or the user's) specifications. ________ lb

5. Compute the number of times per year that the filter media will need to be replaced:

(Line 3) ÷ (Line 4) ________ /yr

6. Refer to Table A-11 at the end of this worksheet. Identify in Column A the ASHRAE dust spot efficiency of the media filter. From Column B, enter the unit cost per replacement filter cartridge. [MCFM = 1,000 cfm] $ ________ /MCFM

[**Note:** Since these cost estimates are based on cartridge filters, they will be less accurate for bag or pocket filters. These replacement costs include the cost of the cartridge only, assuming that the labor costs involved in physically replacing the cartridges is small for the purposes of this rough estimate.]

7. **Compute the annual cost of replacing the media in particulate media filters:**

(Line 6) x (Line 1a) ÷ 1,000 cfm/MCFM x (Line 5). $ ________ /yr

Estimate Annual Maintenance Cost of Electronic Air Cleaners for Particulate Matter

8. From the vendor of the electronic air cleaner, obtain an estimate of the mass of particulate that can be collected on the plates of the precipitator under consideration, before precipitator performance would be expected to drop below the vendor's (or the user's) specifications. ________ lb

(continued)

9. Compute the number of times per year that the precipitator will need to be cleaned:

(Line 3) ÷ (Line 8) __________ /yr

10. Estimate the number of labor hours that will be required to clean the precipitator. __________ hr/cleaning

11. Enter the labor rate for the personnel who will clean the precipitator.
[Default: $32/hr for building laborers, incl. overhead, from Means (1996)] $ __________ /hr

12. Compute the annual cost of cleaning the electronic air cleaners:

(Line 9) x (Line 10) x (Line 11). $ __________ /yr

Estimate Annual Maintenance Cost of Air Cleaners for Removing Gaseous Contaminants

[**Note**: The following is based on gaseous air cleaners utilizing dry granular sorbents and catalysts.]

13. From the vendor or from vendor literature, define the mass of sorbent (or catalyst) that is present in the air cleaner, per unit air throughput. __________ lb sorbent/MCFM

14. Compute the lb/yr of gaseous contaminant that is removed by the air cleaner, per unit air throughput:

(Line 3) ÷ (Line 1a) x (1,000 cfm/MCFM). __________ lb contam./yr/MCFM

15. For the specific gaseous compounds to be removed by the air cleaner, determine the mass of contaminant that can be removed per unit mass of sorbent, before the sorbent must be replaced:

(continued)

15a. Obtain a rigorous estimate from the vendor. __________ lb contam./lb sorbent

or

15b. Refer to Table A-12 at the end of this worksheet. Identify in Column A the contaminant that is closest to the one that must be removed in the case at hand. Select from Column B the corresponding sorbent capacity for the contaminant concentration that the user is anticipating. __________ lb contam./lb sorbent

[**Note**: Table A-12 is based on the performance of 8 x 16 mesh coconut shell granular activated carbon in removing individual organic compounds. Thus, the figures in this table will be less accurate for other sorbents (impregnated carbons, impregnated activated alumina, etc.) and for compound mixtures. See table footnotes.]

16. Compute the number of times per year that the sorbent/catalyst in the air cleaner will have to be replaced:

(Line 14) ÷ (Line 13) ÷ (Line 15a or 15b). __________ /yr

17. Enter the unit cost of replacement sorbent or catalyst purchased from the supplier.
(Default: $3/lb for activated carbon) $ __________ /lb

18. Enter the number of labor hours required to replace the sorbent, per unit air throughput.
(Default: 1 labor hr/MCFM) __________ hr/MCFM

19. Enter the labor rate for the personnel who will replace the sorbent.
[Default: $32/hr for building laborers, incl. overhead, from Means (1996)] $ __________ /hr

(continued)

20. Enter the cost per unit mass for disposing of the spent sorbent that is removed from the air cleaner.
[Default: $0.05/lb for landfilling (Henschel, 1998)] $ _________ /lb

21. Compute the cost incurred per unit air throughput each time the sorbent is replaced:

[(Line 13) x (Line 17)] + [(Line 18) x (Line 19)] + [(Line 13) x (Line 20)]. $ _________ /MCFM/replacement

22. Compute the annual cost of replacing the sorbent in air cleaners for gaseous contaminants:

(Line 21) x (Line 16) x (Line 1a) ÷ 1,000 cfm/MCFM. $ _________ /yr

Summation of Annual Maintenance Costs for All Air Cleaners

23. If multiple air cleaners must be installed in a given building, repeat the calculations above for each one as necessary. Sum the total annual maintenance costs (on Lines 7, 12, and/or 22) for all air cleaners, and enter the sum here. **$ _________ /yr**

TABLE A-11

Approximate Replacement Costs of Media Cartridges for Particulate Media Air Cleaners

Column A Type of Air Cleaner	*Column B* Unit Cost of Replacement Cartridges ($/MCFM[1])
Pleated panel cartridges, ASHRAE 65[2]	35
Pleated panel cartridges, ASHRAE 85[2]	35
Pleated panel cartridges, ASHRAE 95[2]	40
Pleated panel HEPA filter, DOP 99.97	*[3]

Notes:

1 MCFM = 1,000 cfm.

2 Replacement costs for ASHRAE 65 through 95 media filters based on cartridge filter units, and thus might be less accurate for bag or pocket filters. Costs include the cartridge ($35-$40/MCFM for 2,000 cfm cartridges), based on vendor quotes (Flanders Filters, Inc., Washington, NC) and based on Section 157-401-3000 of Means (1996). For this rough estimate, it is assumed that only minimal labor is required to install the replacement cartridges.

3 Obtain quotes for HEPA filters directly from the vendor. Due the quality required in materials and fabrication, HEPA units will cost more than the other media filters.

Worksheet 10 (concluded)

TABLE A-12

Sorption Capacity of Granular Activated Charcoal Air Cleaners for Various Organic Compounds[1,2,3,4]

Column A	*Column B* Sorption Capacity (lb organic compound per lb carbon), at the following inlet concentrations		
Organic Compound	0.1 ppmv	1 ppmv	10 ppmv
Decane	0.14	0.15	0.16
1,1-Dichloroethane	0.0004	0.004	0.01
Hexane	0.02	0.04	0.10
Methyl ethyl ketone	0.01	0.03	0.06
Toluene	0.05	0.09	0.17

Notes:

1 Figures derived from logarithmic extrapolation of data obtained with the indicated organic compounds in the concentration range of 0.1 to 10 ppmv, reported by VanOsdell et al. (1996).

2 The figures shown here represent the lb of organic compound that will be adsorbed per lb of 8 x 16 mesh coconut shell carbon, at the point where 10% of the compound in the inlet stream breaks through the carbon bed, appearing in the outlet. The figures are based on a feed stream containing only the indicated organic compound in otherwise pure air at room temperature and 50% relative humidity. Carbon sorption capacity will likely be reduced for coarser carbon or higher relative humidities than the values used here. Also, performance for a given compound will likely be reduced when other compounds are simultaneously present in the inlet stream.

3 Capacities are based on activated coconut shell carbon without any impregnant. Performance would likely be different with, e.g., carbons impregnated with activating agents, or other sorbents or catalysts (e.g., impregnated activated alumina).

4 Any attempt to interpolate to organic compounds not on the above list should be generally based on the size of the molecule and the functional groups that are present. Non-impregnated activated carbon is not a good sorbent for compounds having fewer than four atoms (exclusive of hydrogen). Note that sorption capacity can vary substantially with inlet concentration to the air cleaner.

WORKSHEET 11

Estimation of Total Annualized Costs for Central Indoor Air Cleaners

Enter Results from Other Worksheets

1. Enter the **total installed cost** of the equipment required for the central indoor air cleaner(s). $ ________

   Note: Obtain this value from:
   Worksheet 8, Line 6; *and/or*
   Worksheet 8, Line 9.

2. Enter the **total incremental annual operating cost** associated with the central indoor air cleaner(s) (Worksheet 9, Line 26). $ ________ /yr

3. Enter the **total incremental annual maintenance cost** associated with the central indoor air cleaner(s) (Worksheet 10, Line 23). $ ________ /yr

Determine the Capital Recovery Factor (CRF)

[**Note:** The CRF is the fraction of the initial installed cost that must be amortized each year if, after n years (i.e., after n equal "payments"), the initial cost is to be recovered with an i percent annual interest rate charged on the unpaid balance.]

4. Enter the equipment lifetime, n, that will be assumed for these calculations (commonly 10 to 20 years). ________ yr

5. Enter the annual interest rate, i, that will be assumed for these calculations. ________ %

6. From these values for n and i, identify the appropriate value of the CRF from Table A-7 at the end of Worksheet 6. ________

(continued)

Worksheet 11 (concluded)

Compute the Total Annualized Cost for Indoor Air Cleaners

7. Compute the average annual capital charge (Line 1 x Line 6). $ ________ /yr

8. Compute the annual operating and maintenance (O&M) costs associated with the indoor air cleaner(s) (Line 2 + Line 3). $ ________ /yr

9. **Compute the total annualized cost associated with the central indoor air cleaner(s)** (Line 7 plus Line 8). $ ________ /yr

WORKSHEET 12

Estimation of Costs for Self-Contained Indoor Air Cleaners

Enter Basic Data

1. Enter the current average indoor concentration, $C_{INo\text{-}Z}$, of the contaminant of concern in the zone that is to be treated by the self-contained air cleaner, with no air cleaner in place. __________ mg/m^3

2. Enter the average concentration, $C_{IN\text{-}Z}$, to which the level on Line 1 above should be reduced after the air cleaner is installed. __________ mg/m^3

3. Enter the average concentration, C_{OA}, of the contaminant in the outdoor air. __________ mg/m^3

4. Enter the total volume of air, $Q_{S\text{-}Z}$, being supplied to the zone of interest, including the outdoor air to the zone, $Q_{OA\text{-}Z}$, plus the recirculating air, $Q_{R\text{-}Z}$. __________ cfm

5. Enter the volumetric flow of outdoor air, $Q_{OA\text{-}Z}$, into the zone being addressed here. __________ cfm

[**Note:** This OA flow to this zone will be a fraction of the total OA being supplied by the HVAC system, proportional to the ratio of the supply air flow to this zone, $Q_{S\text{-}Z}$, to the total supply air being provided by the system to all of the zones it is serving.]

6. Quantify the rate, S_Z, at which the contaminant of concern is being generated by sources inside the zone, in lb/min. __________ lb/min

7. Enter the fractional efficiency, η, of the air cleaner in removing the contaminant of concern, based on data from the vendor or independent sources. __________

(continued)

Calculate the Required Flow, Q_C, Through the Air Cleaner

8. Refer to Figure A-2 at the end of this worksheet. Using the equation in that figure, compute the required total rate, Q_C, at which zone air must be circulated through the air cleaner in order to achieve the desired zone concentration, C_{IN-Z}. __________ cfm

Estimate the Installed Cost for Self-Contained Air Cleaners

9. Enter the flow capacity for the self-contained air cleaners being considered. __________ cfm/air cleaner

10. Compute the number of air cleaners that will be required to provide the total capacity calculated on Line 8 (Line 8 ÷ Line 9). __________ air cleaners

11. Enter the uninstalled cost per air cleaner, based on vendor quotes. $ __________ /air cleaner

12. Estimate the installation cost for each air cleaner, including the cost for mounting and electrical wiring. $ __________ /air cleaner

13. Calculate the total installed cost per air cleaning unit (Line 11 + Line 12). $ __________ /air cleaner

14. **Compute the total installed cost of the self-contained air cleaning system:**

(Line 13) x (Line 10). $ __________

Estimate the Annual Operating Cost for Self-Contained Air Cleaners

15. Enter the electric power consumption by each self-contained air cleaner, based on vendor specifications. __________ kW/air cleaner

[**Note:** This power consumption will include, as a minimum, the power to operate the air circulation fan within the air cleaner.]

(continued)

16. Enter the number of hours per year that the self-contained air cleaner will be operating.
(Default: 3,276 hr/yr, for 13 hr/day, 5 day/wk, excluding holidays). __________ hr/yr

17. Enter the unit cost of electricity.
(Default: $0.08/kWh). $ __________ /kWh

18. **Compute the incremental annual energy cost associated with the electricity to operate the self-contained air cleaner(s):**

(Line 15) x (Line 10) x (Line 16) x (Line 17). $ __________ /yr

19. Enter the Electric Input Ratio (EIR) for the cooling system serving the zone in which the air cleaner is to be installed, i.e., the kW of electric input per kW of cooling input.
(Default: EIR = 0.34 kW/kW.) __________ kW/kW

20. Compute the incremental additional energy input required to the cooling system, to remove the additional heat created by the power input to the air cleaner. (*Assume that, on average over the cooling and heating seasons, essentially all of the heat added to the space by the air cleaner must be removed by the cooling system.*)

(Line 15) x (Line 10) x (Line 16) x (Line 19) __________ kWh/yr

21. **Compute the incremental annual energy cost associated with the increased cooling energy consumption necessitated by the power input to the air cleaner(s)** (Line 20 x Line 17). $ __________ /yr

22. **Compute the total incremental annual operating cost associated with the addition of self-contained indoor air cleaner(s)** (Line 18 plus Line 21). $ __________ /yr

(continued)

Estimate the Annual Maintenance Cost for Self-Contained Air Cleaners

23. Compute the mass of contaminant that will be removed per year by the air cleaner system:

(Line 8) x (Line 2) x (Line 7). __________ lb/yr

24. Complete Lines 4 through 22, as applicable, in Worksheet 10 for central air cleaners. To adapt that worksheet to self-contained air cleaners, make the following adjustments:

- use Line 8 above in lieu of Line 1a of Worksheet 10;
- use Line 23 above in lieu of Line 3 of Worksheet 10;
- for media filters, use vendor quotes in lieu of the filter costs in Table A-11 on Line 6 of Worksheet 10.

25. Based on the use of Worksheet 10, as specified on Line 24 above, **enter the total incremental annual maintenance cost associated with the addition of self-contained indoor air cleaner(s)** (from Line 7, 12, or 22 of Worksheet 10). $ __________ /yr

Estimate the Total Annualized Cost for Self-Contained Air Cleaners

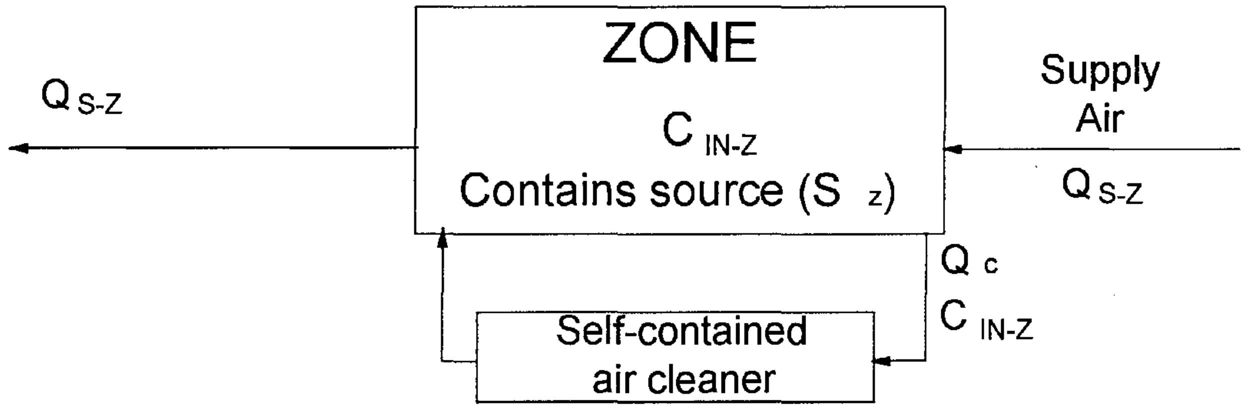
26. Determine the CRF, according to Lines 4 through 6 of Worksheet 11. __________

27. Compute the average annual capital charge (Line 14 x Line 26). $ __________ /yr

28. Compute the annual operating and maintenance (O&M) costs associated with the self-contained air cleaner(s) (Line 22 plus Line 25). $ __________ /yr

29. **Compute the total annualized cost associated with the self-contained indoor air cleaner(s)** (Line 27 plus Line 28). $ __________ /yr

(continued)



$$Q_C = \frac{Q_{OA-Z}(C_{OA} - C_{IN-Z})K + S_Z}{\eta\ C_{IN-Z}K}$$

Key:

Q_{S-Z} = supply air flow to the zone to be treated using a self-contained air cleaner (cfm)

Q_C = flow rate of zone air being circulated through the air cleaner (cfm)

Q_{OA-Z} = flow rate of outdoor air into the zone (cfm)

C_{OA} = contaminant concentration in outdoor air (mg/m^3)

C_{IN-Z} = desired contaminant concentration in the zone (mg/m^3)

K = concentration conversion factor = 6.2×10^{-8} (lb/ft^3)/(mg/m^3)

S_Z = source term for contaminant generated in zone (lb/min)

η = fractional efficiency of the air cleaner

Figure A-2. Schematic diagram and mass balance equation for a zone being treated using a self-contained air cleaner.

WORKSHEET 13

Estimation of Costs for Source Management: Source Replacement by Low-Emitting Materials (LEMs)

[**Note:** For simplicity, this worksheet addresses a single type of source that is to be replaced by a lower-emitting substitute -- e.g., carpeting, wall paint, or a specific item of furniture (such as office desks) -- where the emission characteristics of the original product and of the lower-emitting substitute are known. Where multiple source types are being considered for replacement, this worksheet would have to filled out for each source type.]

Enter Basic Data

1. Enter the source type that is being addressed in this analysis (carpeting, wall paint, furniture item, photocopiers, etc.). __________

2. Enter amount of source area/number of sources for sources of this type (ft^2 of carpeted floor area, ft^2 of painted wall surface, number of furniture items or photocopiers, etc.). __________ ______ (units)

3. Enter the installed cost per unit area, or the cost per item, for the originally planned high-emitting materials/equipment items, *assuming that the materials are being installed in a new building (no retrofit complications).* $ __________ /(unit)

4. Enter the installed cost per unit area, or the cost per item, for the low-emitting materials with which the original units are to be replaced, *assuming that the LEM is being installed in a new building (no retrofit complications).* $ __________ /(unit)

[**Note:** Line 4 will not necessarily be greater than Line 3. The installed costs on these two lines should include: the uninstalled cost of the material; and the labor/supplies required for installation in a new building, where there are no installation complications associated with retrofit. These costs would be expressed, for example, as $/$ft^2$ or $/furniture item, depending upon the material/equipment item being addressed.]

(continued)

Worksheet 13 (continued)

5. Enter the estimated useful lifetime of the originally planned high-emitting materials/ equipment items. __________ yr

6. Enter the estimated useful lifetime of the low-emitting materials with which the original units are to be replaced. __________ yr

[**Note**: Line 5 will not necessarily be greater than Line 6. As a default, assume that Line 6 equals Line 5.]

RETROFIT CASE

[**Note**: For the case of new construction, skip directly to Line 17.]

Compute the Installed Cost for the LEMs - Retrofit Case

7. For existing buildings (retrofit cases), estimate the cost per unit for removing the original materials or equipment items, if applicable. $ __________ /(unit)

[**Note**: This removal cost could include, for example: clearing the area to provide working access to the original material; physical removal of the old material; disposal of the old material, as applicable; any repairs or surface preparation required before new material can be installed; and, as applicable, moving back into place any furniture, etc., that had been cleared to allow access to the original material.]

8. Estimate the total unit installed cost of the LEM, including the complications of installation in the retrofit case (Line 4 plus Line 7). $ __________ /(unit)

9. **Compute the total installed cost of retrofitting a LEM into the existing building:**

   (Line 8) x (Line 2). $ __________

(continued)

Compute the Total Annualized Cost for Retrofitting the LEM

10. Refer to Table A-7 at the end of Worksheet 6 (page A-52). Identify the Capital Recovery Factor for the number of years, n_L, corresponding to the expected LEM lifetime entered on Line 6 (and for the interest rate, i, selected by the user). Enter that CRF here. ________ /yr

11. **Compute the total annualized cost for retrofitting the LEM into this building** (Line 9 times Line 10). $ ________ /yr

Back-Calculation of Premium That Could Be Paid for LEMs (Retrofit)

[**Note**: The preceding calculations assume that the price of the LEM is known, and the objective is to compute the annualized cost that will enable the subsequent calculation of the cost-effectiveness of this approach (see Section 7). The following calculations consider the reverse situation, where the absolute cost-effectiveness of ventilation and/or air cleaning is known (Section 7.1), and the user wishes to determine what premium could be paid for a LEM that will accomplish the same contaminant reduction, before this source management approach becomes less cost-effective than those competing alternatives. That is, the user wishes to back-calculate what the acceptable entry would be on Line 4.]

12. Enter the incremental reduction in exposure [Δ(exposure)] that is desired to protect the occupants [in units of (mg/m^3)-person-hr per year]. (See Section 1.4, page 1-5.) ________ (mg/m^3)-p-hr/yr

[**Note**: Computer modeling may be necessary to determine whether LEM replacement may in fact be capable of providing this degree of reduction. See Section 6.1.]

13. Enter the cost-effectiveness [CE = - Δ(cost)/ Δ(exposure)] with which ventilation or air cleaning can provide this desired reduction in exposure [in annualized dollars expended per (mg/m^3)-person-hr per year reduction]. ________ \$/(mg/m^3)-p-hr/yr

(continued)

14. Compute the maximum annualized cost that can be paid for LEM replacement before this approach becomes less cost-effective than the competing alternatives (Line 12 x Line 13). $ _________ /yr

15. Back-calculate the maximum allowable total installed cost for retrofitting a LEM into the building, that will not exceed the maximum annualized cost on Line 14:

(Line 14) ÷ (Line 10). $ _________

16. **Back-calculate the maximum allowable unit installed cost of the LEM** (under the no-retrofit-complication case) that can be entered on Line 4 without exceeding the allowable total installed cost on Line 15:

[(Line 15) ÷ (Line 2)] - (Line 7). $ _________ /(unit)

[**Note**: The user must now determine whether a suitable low-emitting material can be obtained for this unit price.]

NEW CONSTRUCTION CASE

Compute the Incremental Installed Cost for the LEMs in New Construction

17. Compute the cost that would have been incurred had the originally planned material been installed in the new building:

(Line 3) x (Line 2). $ _________

18. Compute the cost that will be incurred if the LEM is installed instead:

(Line 4) x (Line 2). $ _________

(continued)

19. Compute the total incremental installed cost of installing a LEM into a new building during construction:

(Line 18) - (Line 17). $ ________

Compute the Incremental Annualized Cost of Substituting a LEM in New Construction

20. Refer to Table A-7 at the end of Worksheet 6 (page A-52). For the interest rate, i, selected by the user, enter:

20a. The CRF for the number of years, n_O, corresponding to the expected lifetime entered on Line 5 *for the originally planned high-emitting material.* ________ /yr

20b. The CRF for the number of years, n_L, corresponding to the expected lifetime entered on Line 6 *for the LEM.* ________ /yr

21. Compute the total annualized cost that would have been incurred with the originally planned material:

(Line 17) x (Line 20a). $ ________ /yr

22. Compute the total annualized cost that will be incurred with LEM:

(Line 18) x (Line 20b). $ ________ /yr

23. Compute the incremental increase in the total annualized cost for installing the LEM into this new building (Line 22 minus Line 21). $ ________ /yr

(continued)

Back-Calculation of Premium That Could Be Paid for LEMs (New Construction)

[**Note:** The following procedure back-calculates the maximum unit price for a LEM that can be entered on Line 4, if the cost-effectiveness of the LEM replacement approach is to match that for ventilation or air cleaning steps achieving the same reduction in exposure.]

24. Enter the incremental reduction in exposure [Δ(exposure)] that is desired to protect the occupants [in units of (mg/m^3)-person-hr per year]. __________ (mg/m^3)-p-hr/yr

[**Note:** Computer modeling may be necessary to determine whether LEM replacement may in fact be capable of providing this degree of reduction. See Section 6.1.]

25. Enter the cost-effectiveness [CE = - Δ(cost)/ Δ(exposure)] with which ventilation or air cleaning can provide this desired reduction in exposure [in annualized dollars expended per (mg/m^3)-person-hr per year reduction]. __________ $/$(mg/m^3)$-p-hr/yr

26. Compute the maximum annualized cost that can be paid for LEM replacement before this approach becomes less cost-effective than competing alternatives (Line 24 x Line 25). $ __________ /yr

27. Back-calculate the maximum allowable total annualized cost for using a LEM in the new building (i.e., the maximum allowable entry on Line 22), that will ensure that the incremental annualized cost for using a LEM (the value on Line 23) does not exceed the maximum annualized cost on Line 26:

(Line 26) + [(Line 17) x (Line 20a)]. $ __________ /yr

(continued)

28. **Back-calculate the maximum allowable unit installed cost of the LEM** in the new building, that can be entered on Line 4 without exceeding the allowable total annualized cost for using a LEM on Line 27:

[(Line 27) ÷ (Line 20b)] ÷ (Line 2). $ ________ /(unit)

[**Note**: The user must now determine whether a suitable low-emitting material can be obtained for this unit price.]

WORKSHEET 14

Absolute Reduction in Exposure Resulting from Implementation of an IAQ Control Measure: Simplified Calculation

1. Enter the annual average concentration of the contaminant of concern in each individual zone of interest during working hours, *prior to implementation of the IAQ control measure*:

1(1). In Zone #1	________	mg/m^3
1(2). In Zone #2	________	mg/m^3
1(3). In Zone #3	________	mg/m^3
etc.		

[**Note:** Obtain these average concentrations from: Line 1 of Worksheet 1; Line 1 of Worksheet 7; or C_o in Section 5.2.1, if those entries represent annual average concentrations.]

2. Enter the annual average concentration of the contaminant of concern in each individual zone of interest during working hours, *after implementation of the IAQ control measure*:

2(1). In Zone #1	________	mg/m^3
2(2). In Zone #2	________	mg/m^3
2(3). In Zone #3	________	mg/m^3
etc.		

[**Note:** Obtain these average concentrations from: Line 2 of Worksheet 1; Line 2 of Worksheet 7; or C_{em} in Section 5.2.1, if those entries represent annual average concentrations.]

3. Compute the incremental change in concentration being achieved in each zone of interest by implementing the IAQ control measure:

3(1). In Zone #1 [Line 2(1) minus Line 1(1)]	________	mg/m^3
3(2). In Zone #2 [Line 2(2) minus Line 1(2)]	________	mg/m^3
3(3). In Zone #3 [Line 2(3) minus Line 1(3)]	________	mg/m^3
etc.		

[**Note:** These numbers should be negative -- i.e., Line 2(x) should be smaller than Line 1(x) -- reflecting a *reduction* in the concentration to which occupants are being exposed.]

(continued)

4. Enter the number of occupied hours during days when the building is occupied. __________ hr/day

[**Note:** If there are hours when very few persons are in the building -- e.g., overnight or on weekends -- the user may wish to consider, for this simplified calculation, only those hours when the number of occupants is significant.]

5. Enter the average number of persons in each zone during the occupied hours in Line 4 above:

5(1). In Zone #1 __________ persons
5(2). In Zone #2 __________ persons
5(3). In Zone #3 __________ persons
etc.

[**Note:** If, for example, 10 persons worked in Zone X during the 9-hour period between 8 am and 5 pm, but each left for a 1-hour lunch break on a staggered schedule around mid-day, the user might wish to simply enter "8 hr" on Line 4 above, and enter "10 persons" on Line 5(X). Alternatively, the user could enter "9 hr" on Line 4 and, on Line 5(X),

(10 x 8) person-hr total occupancy/day ÷ 9 hr/day =
8.9 persons per hour on average.]

6. Compute the total number of occupied hours per year:

{[(number of occupied days/week) x (52 weeks/yr)]
- (number of holidays/yr)} x Line 4. __________ hr/yr

7. Compute the change in occupant exposure in each of the individual zones of interest:

7(1). In Zone #1
[Line 3(1) x Line 5(1) x Line 6] __________ (mg/m^3)-person-hr/yr
7(2). In Zone #2
[Line 3(2) x Line 5(2) x Line 6] __________ (mg/m^3)-person-hr/yr
7(3). In Zone #3
[Line 3(3) x Line 5(3) x Line 6] __________ (mg/m^3)-person-hr/yr
etc.

(continued)

8. **Compute the total change in occupant exposure summed over all zones of interest**
[Line 7(1) + Line 7(2) + . . Line 7(x)]. _________ (mg/m^3)-person-hr/yr

[**Note:** If one wishes instead to express this exposure result in terms of the change in exposure for the average person in the zones of interest, divide the figure on Line 8 by the total number of persons in the zones, i.e., the sum of Lines 5(1) through 5(x). The figures on Lines 7 and 8 should be negative, representing a reduction in exposure achieved by implementing the IAQ control measure.]

WORKSHEET 15

Relative Reductions in Exposure Achieved by One IAQ Control Measure Compared Against Alternative Measures

1. For each of the IAQ control measures under consideration, enter the ratio of the annual average indoor concentration expected to be achieved by implementing the control ($C_{control}$) divided by the annual average concentration without this control ($C_{no\ control}$):

    1(1). $C_{control}/C_{no\ control}$ with Alternative Measure #1 ________
    1(2). $C_{control}/C_{no\ control}$ with Alternative Measure #2 ________
    1(3). $C_{control}/C_{no\ control}$ with Alternative Measure #3 ________
    etc.

    [**Note**: For example, if a given control measure reduced the indoor concentration to 20% of the level it would otherwise have been without control, enter 0.2 here for that measure. These fractional efficiencies could be obtained from the preceding worksheets as follows:

(Line 3)	in Worksheet 1;
[(Line 2) ÷ (Line 1)]	in Worksheet 7;
(C_{sm}/C_o)	in Section 5.2.1.]

2. Compute the fractional change in annual exposure resulting from implementing each of the alternative control measures [($C_{control}/C_{no\ control}$) - 1].

    2(1). $(C_{control}/C_{no\ control})_1 - 1$ (Measure #1) ________
    2(2). $(C_{control}/C_{no\ control})_2 - 1$ (Measure #2) ________
    2(3). $(C_{control}/C_{no\ control})_3 - 1$ (Measure #3) ________
    etc.

    [**Note**: For example, if $(C_{control}/C_{no\ control})_x = 0.2$, then $(C_{control}/C_{no\ control})_x - 1 = -0.8$, reflecting an 80% reduction in annual exposure with Measure x, relative to the case of no control.]

(continued)

3. Enter the fractional effectiveness of each alternative control measure:

3(1). Effectiveness of Measure #1 {-[Line 2(1)]} ________
3(2). Effectiveness of Measure #2 {-[Line 2(2)]} ________
3(3). Effectiveness of Measure #3 {-[Line 2(3)]} ________
etc.

[**Note**: This step is intended simply to emphasize the relationship, effectiveness = - Δ(exposure). A control measure causing a fractional change in annual exposure of -0.8 would have an effectiveness of +0.8.]

4. Compute the relative effectiveness of any one of these control measures (e.g., Measure #1) relative to each of the others:

4(1). Measure #1 relative to Measure #2 [Line 3(1)]/[Line 3(2)]. ________
4(2). Measure #1 relative to Measure #3 [Line 3(1)]/[Line 3(3)]. ________
etc.

[**Note**: For example, if Measure #1 had an effectiveness of 0.8 and Measure #2 an effectiveness of 0.6, the effectiveness of Measure #1 relative to Measure #2 would be 0.8/0.6 = 1.33, indicating that Measure #1 is 33% more effective in reducing exposure than Measure #2.]