# TECHNICAL GUIDE

## Demonstration/Validation of More Cost-Effective Methods for Mitigating Radon and VOC Subsurface Vapor Intrusion to Indoor Air

## Mitigation System Optimization

## ESTCP Project ER-201322

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This technical guide provides a description of suggested activities associated with planning, designing, operating, and decommissioning a mitigation system to address Radon or volatile organic compound (VOC) vapor intrusion to indoor air. This guide provides a comprehensive list of considerations, and the user is encouraged to apply professional judgement to select the relevant and appropriate elements for each building, based on the site-specific conceptual model, and building-specific conditions. Prior to this research, conventional mitigation system design was typically based only on achieving a specified level of applied vacuum below the floor slab (e.g. ASTM E2121, AARST/ANSI Standards, State Guidance documents for VOC Vapor Intrusion and radon posted at: https://www.geosyntec.com/vapor-intrusion-guidance), with verification via indoor air sampling ad analysis. This research provides additional lines of evidence including radial profiles of vacuum, velocity, travel time, and leakage across the floor slab as well as the mass emissions rate, which increase the level of understanding and confidence in the system design and operation and can identify the presence and potentially also the location of preferential pathways from the subsurface to indoor air.

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# TECHNICAL GUIDE FOR ESTCP ER 2013-22 - MITIGATION SYSTEM OPTIMIZATION

This technical guide provides a description of suggested activities associated with planning, designing, operating, and decommissioning a mitigation system to address Radon or volatile organic compound (VOC) vapor intrusion to indoor air. This guide is intended to be used as a refresher after the user has read the Final Report for ESTCP ER201322, which is posted at: https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-201322/ER-201322. This guide provides a comprehensive list of considerations, and the user is encouraged to apply professional judgement to select the relevant and appropriate elements for each building, based on the site-specific conceptual model, and building-specific conditions. Prior to this research, conventional mitigation system design was typically based only on achieving a specified level of applied vacuum below the floor slab (e.g. ASTM E2121, AARST/ANSI Standards, State Guidance documents for VOC Vapor Intrusion and radon posted at: https://www.geosyntec.com/vapor-intrusion-guidance), with verification via indoor air sampling ad analysis. This research provides additional lines of evidence including radial profiles of vacuum, velocity, travel time, and leakage across the floor slab as well as the mass emissions rate, which increase the level of understanding and confidence in the system design and operation and can identify the presence and potentially also the location of preferential pathways from the subsurface to indoor air. Many of these lines of evidence have a low incremental cost and are recommended. Some are considered optional because they may not be cost effective for all buildings. For large buildings, the recommended additions to the conventional scope are likely to reduce costs by a factor much larger than their incremental cost. Economies of scale are not as favorable for small buildings.

| **Suggested Activities** | **Rationale, Special Considerations, Details** |
|---|---|
| Step 1: Planning | |
| a) Contracting | Routine requirement. |
| b) Establish the system design objective(s) after careful consideration of conceptual site model (CSM). | Design objectives should be established after careful consideration of the CSM, including building design and construction, build quality, building age, occupancy, ventilation, subsurface utilities, regulatory requirements, nature and extent of chemicals of concern in the vicinity of the building, acute vs chronic health effects, system longevity, geologic conditions, water table depth, seasonal temperature ranges, wind loads, occupants habits, and other factors specific to individual buildings. Possible objectives include one or more of the following: reduce soil gas entry to a building, reduce radon (Rn) or VOC concentrations in indoor air below health-based criteria or regulatory guidelines; maintain a measurable vacuum below the floor; maintain adequate subfloor ventilation to reduce subslab concentrations below levels of concern; maintain a rate of mass removal adequate to be protective of indoor air quality for target compounds; remove mass of contaminants beneath the building; maintain effectiveness until mitigation is no longer needed; and accommodate future site conditions. Consider the magnitude of the factor of safety for system design and operations based on site specific conditions (for example, greater factor of safety for sites with higher concentrations, higher mass loadings and sensitive receptors. |

| Suggested Activities | Rationale, Special Considerations, Details |
|---|---|
| c) Scoping | Not all activities/components are necessary for all systems. Professional judgement is required. Refer to the ESTCP ER-201322 Final Report for more information. For small buildings and simple cases, the conventional approach (see left side of the flowchart in Figure 1) may be sufficient. For large buildings or cases where the conventional approach provides ambiguous or confounding results, additional lines of evidence are very helpful. Generally, it is appropriate to employ more of the recommended and optional activities in larger buildings. The scope will include considerations that were not specifically developed in this research and are therefore not discussed in detail here, for example, health and safety plan, licensing of sub-trades (electricians, etc.), insurance coverage and investigation-derived waste management. |
| d) Workplan development | As needed for client and regulatory review and approval. |
| e) Regulatory review and approval | Review local, state, or federal regulations and guidance for VOC and radon mitigation. Comply with regulations, and use the technologies discussed in this guide as additional lines of evidence, as needed. Guidance is inherently more flexible than regulations, so it may or may not be necessary or appropriate to comply with all aspects of guidance documents. Engage regulators in discussion regarding new lines of evidence to design and assess the efficacy of mitigation systems where appropriate. Submit workplan for regulatory review and approval as needed. |
| f) Stakeholder Communication | Consider Factsheet, town hall-style meetings or other activities as needed for stakeholder relations. Discuss mitigation system design considerations with building owner, manager, mechanical engineer, or agent responsible for heating, ventilating, and air conditioning (HVAC) system. Clarify pipe routing options, access to electrical power, extraction point locations, monitoring point locations, access agreement, schedule constraints, noise considerations, occupancy frequency and duration, convenient timing for pilot testing and full-scale system installation, and any other related concerns. |
| Step 2: Building Reconnaissance | |
| a) Initial Review | Review any existing reports describing environmental conditions and consider the CSM as needed to evaluate the root cause of vapor/gas entry (for example, preferential pathways, utility penetrations, expansion joints and floor cracks). Review building drawings to identify the extent and potential influence of features such as footers, water vapor barriers, underground utilities, HVAC air zones and the specifications on the slab (e.g., post-tensioned rebar) and subgrade materials. Check for existing air discharge permits that the mitigation system may need to comply with. Identify surrounding land uses, particularly very nearby buildings that could be affected by or be a source of emissions. |
| b) Building HVAC review, Mechanical Engineer interview, Test & Balance report review | Assess range of air exchange rates, target cross-building pressure differentials, regularity of maintenance of filters, duty cycles (daily, weekly, seasonally), presence of other active and passive ventilation systems (e.g., exhaust fans, fume hoods, utility stacks). HVAC systems control building pressure and ventilation, both of which have important implications for vapor intrusion and each building has unique design features and operating characteristics. |
| c) Visual inspection | Identify floor condition (cracks, degraded concrete, etc), floor coverings, penetrations, asbestos tile and other potential asbestos containing materials (ACM), expansion joints, and condition of sealants. Assess presence of background VOC sources (remove when practicable before sampling indoor air). |
| d) Screening observable entry points | Consider depressurizing building with door fan or adjustment to HVAC system and check drains (floor, sink, toilet, etc.), utility penetrations, large aperture cracks, weathered caulking in expansion joints, etc. with photoionization detector (PID) (for chlorinated VOCs [Cl-VOCs]), flame ionization detector (FID) (for petroleum hydrocarbons), or smoke pen noting any elevated concentrations or smoke pattern changes. A thermal imaging camera can also potentially identify points of gas entry if there is sufficient indoor/outdoor temperature contrast. |

| Suggested Activities | Rationale, Special Considerations, Details |
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| e) Cross-slab and cross-building pressure monitoring | Select locations representative of each air zone within the area of concern, install a representative number of subslab probes, deploy a micromanometer with data-logging capabilities, and log differential pressure across the floor slab for as long as practicable. Review differential pressure data to assess ambient building pressure trends. Instantaneous reading may show considerably more fluctuation than time weighted averages, so consider calculating 1-minute to 5-minute rolling averages from the instantaneous readings (this is still a short duration relative to typical air exchange rates, but long enough to allow more appreciable gas flow across the floor slab than instantaneous pressure gradients). Seal subslab probes effectively to prevent leaks. |
| f) Seal selected floor penetrations in areas targeted for mitigation | Use caulking or other appropriate methods to seal visible openings in concrete (unsealed expansion joints, utility penetrations, etc.) in floor and subsurface walls within areas targeted for mitigation, especially any that show elevated PID or FID readings. Use one-way air traps to seal floor drains. Consider adding vapor barriers over crawlspaces; adding epoxy coatings over concrete floors with extensive cracks; installing aerated flooring where there is sufficient headroom; or pouring a new slab on top of the old slab where justified. |
| g) Select locations for pilot tests | Typically prefer locations far (a minimum of 15 ft) from exterior walls to minimize short circuiting of outdoor air unless a perimeter drain could be used to enhance soil vapor extraction with minimal short-circuiting of indoor air. Avoid underground utilities, target areas of highest subslab vapor or radon concentrations. Consider aesthetics and access limitations imposed by building owners, occupants, or visitors. Avoid high traffic areas. |
| h) Geophysical check for utilities and rebar | Ground penetrating radar is usually effective at identifying rebar. Building managers may have utility drawings. |
| i) Check potential test point locations for asbestos-containing material (ACM) | Required by state and federal regulations for worker protection. ACM inspection and mitigation must be performed by certified/licensed contractors. |

| Step 3: Pilot Testing | |
|---|---|
| a) Install sump(s) for pilot testing | Core hole in concrete (ideally 5-inch [13 cm] diameter for a 4-inch [10 cm] pipe or 4 inch [10 cm] hole for a 3-inch [7.6 cm] pipe), excavate approximately 3-5 gallons of subsurface material, install backer rod in annulus between concrete floor and pipe, set in place using fast setting anchor cement, cap pipe with air-tight temporary cap. Photograph subsurface materials (fill and native soil) and make notes on thickness, grain size (sand, slit, clay and gravel fractions) and moisture of fill layer. |
| b) Install communication test points (CTPs) | Probes used for pressure monitoring and potential sub-slab sampling (a.k.a. CTPs) should have an air-tight seal to the concrete floor during testing, using putty, flexible gaskets, or anchor cement. Consider the length of the monitoring period when selecting seal materials (putty may dry out or separate after several hours). Include probes in far corners of area of concern to a radial distance of about 30 ft (10 m), or farther for large buildings with floor slabs in good condition. Consider also including at least one probe in close proximity to the suction pit (radius of about 3 ft or 1 m) to help calibrate the vacuum versus distance model (Equation 4 in the Final Report). Consider having additional probe locations available (i.e., cleared and ready to drill) for probe installation as needed based on data review during pilot testing. Consider the potential for short circuiting through granular utility backfill or cracks in the floor when selecting locations for CTPs. After pilot testing, make a decision for each CPT whether to maintain for future monitoring (take steps to assure robust construction and longevity) or not (seal hole with fast-setting anchor cement, flush to grade). |

| Suggested Activities | Rationale, Special Considerations, Details |
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| c) Arrange for discharge of extracted soil vapor to outdoors or filtration/purification | Select fan, blower, or vacuum for pilot testing (e.g., a Radon fan or large Shop-Vac), and arrange for power and gas-tight fittings. Use 4-inch diameter vacuum hose or lay flat tubing between fan/blower and outdoor air or existing exhaust fan with sufficient capacity. Polyethylene (PE) tubing is easily available but VOCs permeate through PE and may generate indoor air concentrations of concern, so less permeable tubing such as Mylar is preferred when VOC concentrations are high (>100 parts per million by volume [ppmv] total VOCs). Extend tubing at least 15 ft (5 m) outside building, away from potential points of exposure such as windows or doors or use carbon filters to purify extracted gas as needed considering the concentrations expected, test duration, building volume and specific chemicals; add potassium permanganate impregnated zeolite if vinyl chloride is present at concentrations of potential health concern in the discharge. |
| d) Assess extracted gas | For VOCs, screen effluent with a photoionization detector (for Cl-VOCs) and/or a flame ionization detector (for petroleum hydrocarbons). Consider multiple readings if the pilot test duration is more than about 10 minutes to enable interpretation of trends in concentration as a function of volume extracted. Consider collecting a sample for laboratory analysis of individual compounds. Consider also monitoring oxygen, carbon dioxide, and methane with a landfill gas meter to provide additional information to support a more comprehensive CSM. For radon, consider real time monitoring or collecting a Tedlar® bag sample for analysis of Rn concentration. |
| e) Specific Capacity Testing (Section 4.3.1 of Final Report) | Consider monitoring flow rate and vacuum field under multiple applied vacuum settings to aid in fan selection for final system design. |
| f) Static Vacuum vs Distance monitoring and analysis (Section 4.3.3 of Final Report) | Measure flow rate and steady vacuum vs distance for comparison to Equation 4 in Final Report. Monitor rate of change in subslab vacuum to assure steady readings (may require less than a minute or up to an hour), and after stabilization, measure subslab vacuum in all available subslab probes in proximity to the suction point. Monitor extraction flow rate (consider using thermal anemometer, pitot tube, vane anemometer or orifice plate).<br>Enter vacuum vs distance data into spreadsheet model based on Equation 4 in Final Report (Hantush-Jacob Model equation for steady vacuum vs radial distance). Adjust transmissivity (T) and leakance (B) values to provide best fit between Equation 4 results and measured steady vacuum vs distance data. Consider calculating minimum and maximum values of T and B to bracket the range of data where there are enough measurements. |
| g) Transient vacuum testing and analysis (Section 4.3.2 of Final Report) | Set dataloggers to record one reading every second at nearby (3-30 foot) CTPs, then turn the fan off until vacuum dissipates, turn the fan on until vacuum is re-established and stabilizes, then turn fan off again. Choose a location with at least 100 Pascals (Pa) of response if possible. Transient response is often fast enough to allow more than one cycle of drawdown and recovery to check for consistency. Download dataloggers in the field and verify data was captured. Allow at least one minute of readings before turning fan on to establish baseline conditions. Visually inspect readings during each cycle to assure steady conditions are achieved before switching fan from on to off or back. Record flow rate.<br>Data analysis options include: 1) qualitative assessment (fast response [i.e., 10 to 20 seconds] generally corresponds to higher values of T and B, whereas a slow response [several minutes or more] generally corresponds to lower values of T and B), or 2) quantitative assessment (convert vacuum data to feet of air head (1 pascal = 0.27 ft air), import to modeling software (e.g., AQTESOLV), and analyze with Hantush-Jacob leaky aquifer model according to user manual instructions to derive T and B values (Equation 1), then iterate between vacuum vs time and vacuum vs distance to identify T and B values that match both the steady state vacuum vs distance data and the transient vacuum vs time data. |

| Suggested Activities | Rationale, Special Considerations, Details |
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| h) Consider subslab tracer tests (Sections 4.3.4 and 4.3.5 of Final Report) | Consider inter-well tracer tests to verify flow velocities and travel times as additional lines of evidence where appropriate. Use calibrated Hantush-Jacob Model to calculate best estimate and upper/lower estimates of radial distance for a travel time of 1 to 3 minutes. Consider installing additional probes if none are already within this target radius. Inject 5 to 10 L of helium rapidly (5-10 seconds), monitor and record helium concentration in vent-pipe as function of time and note time/concentration of maximum concentration. Record vent pipe flow rate.<br>For larger radial distances, the inter-well tracer test can show a low and flat breakthrough curve that is difficult to interpret so a helium flood test is preferred in those situations.<br>Match model for travel time vs distance (Equations 5 and 6) to inter-well tracer test data by adjusting b and n. Initial estimate for b should be thickness of fill layer. Initial estimate for n should be about 20%. |

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| i) Select radius of influence (ROI) based on Multiple Lines of Evidence (Section 4.1 of Final Report) | Vacuum > conservative site-specific delta P (Section 4.1.1 of Final Report) | Analyze ambient cross-slab gradient with appropriate integration over time (i.e., rolling average of instantaneous readings over 1 to 5-minute intervals) and use judgement to select the target vacuum level (see Equation 4 in the Final Report). Consider seasonal effects on building pressure and the stack effect (which depends on the building height and difference between indoor and outdoor temperature). |
| | Velocity > 3 ft/day (Section 4.1.2 of Final Report) | Use Equation 5 in the Final Report to calculate the profile of vacuum vs radius with T and B values derived from fitting measured vacuum vs time, vacuum vs distance, and subslab tracer test data. See rationale for a 3 ft/day target velocity in the Final Report and adjust if appropriate for building-specific conditions. |
| | Travel Time < 3 to 4 hours (Section 4.1.3 of Final Report) | Use Equation 6 in the Final Report to calculate the profile of travel time versus radial distance from the suction point (travel time) with the T and B values derived from fitting measured vacuum vs time, vacuum vs distance, and subslab tracer test data. See rationale for a 3 to 4-hour target travel time in the Final Report, and adjust if appropriate for building-specific conditions. |
| | Proportion of flow below floor > 5L/min/1000 $ft^2$ (Section 4.1.4 of Final Report) | Calculate incremental proportion of flow from the subsurface as a function of radial distance (Equation 7)–i.e., multiply total extracted flow rate by proportion given by Equation 7 for a certain radius (r1) and a nearby larger radius (r2). The difference between these values is the incremental flow from the subsurface within a ring between r1 and r2. Calculate the area ($A=\pi r^2$) for both r1 and r2, the difference between these is the incremental area. Divide the incremental flow by the incremental area to determine the vertical downward flow across the floor slab per unit area of floor that is induced by the venting system. Plot this value as a function of radial distance. The ROI can be estimated as the radius at which the incremental flow from the subsurface equals the generic default of 5L/min per 1000 $ft^2$. |
| j) Derive Building-Specific Attenuation Factor and subslab screening level (SSSL)s | | Use identified T and B values, conservative site-specific cross-slab pressure gradient, building height and AER to calculate a building-specific AF (Equation 17) and SSSL. Compare measured subslab concentrations to the building-specific SSSL to assess potential vapor intrusion risks. Where concentrations are much (orders of magnitude) higher than the building-specific SSSL, consider additional mitigation effort (e.g., higher flow rates, more suction points) or additional monitoring to provide a margin for safety. Where concentrations are much (orders of magnitude) lower than the building-specific SSSL, consider downsizing (e.g., smaller fans, passive venting), or cyclic operations to assess potential rebound or support closure options. |

| Suggested Activities | Rationale, Special Considerations, Details |
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| Step 4: Full-Scale System Design/Installation | |
| a) Design number and locations of suction points and number and size of fans based on analysis of pilot test data | Review data collected during the Pilot Test and select number and locations of suction points needed to provide appropriate coverage of the target mitigation area. Assess mass loadings from each vent pipe and maximize flow rate from vent pipes with the highest loadings. |
| b) Install vent pipes, fans, pipe hangers, roof/wall penetrations, and additional communication test points as needed | Core concrete and excavate sump as described above in additional locations as needed to provide sufficient suction points for spatial coverage, and add communication test points at strategic locations around new suction points. Vent pipe diameter should be sufficient to maintain a flow velocity below about 1,500 ft/min (500 m/min) to avoid a whistling noise. Seal vent pipe(s) to bottom of slab with cement up to 1/2 in (1.5 cm) below top of slab and polyurethane caulking to top of slab. Plumb piping to a nearby wall or column and run to rooftop or exterior wall for discharge. Use sweep elbows to minimize frictional resistance at bends in pipe header. Set height of discharge from pipe to meet or exceed local codes and radon mitigation guides or a minimum of 10-ft above grade or 0.5-ft above roofline, whichever is higher. Consider whether there are aesthetic requirements and accommodate to the extent necessary. Consider the potential for re-entrainment of exhaust vapor to indoor air intakes when the mass emission rate is >10 times higher than the mass flux screening level (MFSL) (Indoor Air Screening Level (IASL) multiplied by the building ventilation rate [$Q_{building}$]) and assess whether adjustments are needed to the stack height or discharge location, or where those options are limited consider off-gas treatment. Consider installing inline valves for balancing where multiple suction points are connected to one fan. Consider variable frequency drives (VFDs) where high powered fans are selected. Use pipe hangers as per plumbing code and as needed to provide support, especially around connections such as elbows and couplings. Protect vent pipes with bollards or other measures, as needed, to prevent damage from facility operations. Select locations for wall or roof penetrations to minimize risk of damage, avoid re-entrainment in HVAC air handling units (AHU) and minimize visibility. Discharge should be a minimum of 10-ft from any air intake. Riser pipe material should be polyvinyl chloride (PVC), cast-iron, or galvanized steel based on local building code requirements (ultra violet [UV] light can make PVC brittle over time, so consider UV resistant pipe, paint or add pipe checks to Operation, Maintenance, and Monitoring [OM&M]). |
| c) Condensation | Install horizontal pipe with slope (1/8 inch per foot) back to a nearby suction point. Avoid traps in pipes. Where possible, avoid long runs of exterior pipe, particularly in cold climates. |
| d) Electrical hook-up | Use a licensed electrician to complete connection to fan(s), which should be on a dedicated breaker and comply with all applicable local codes. |
| e) Placards and warning alarms | Place labels/placards on each vent pipe at eye level. Include contact information for the person(s) responsible for the system operation on the placard. Install alarm(s) with battery back-up or wired to a breaker different than the fan to indicate any instance where fans stop operating. Notification signage should be provided at alarm with contact information for alarm response. |
| f) Install manometers and sample port | Install manometers or vacuum gauge on vent pipe to provide an immediate visual indication the system is operating. Install sample port for flow measurement and sample collection. Target vacuum should be indicated on the manometer/vacuum gauge. |

| Suggested Activities | Rationale, Special Considerations, Details |
|---|---|
| g) Commissioning/balancing/verification testing | Measure flow and vacuum from each suction point upon system commissioning and compare to pilot test values to assess consistency and interpret optimal settings for long-term operation. Use inline valves to adjust flow from multiple suction points attached to a single fan (where present) to maximize flow in areas of highest mass removal rate where conditions warrant. Mark set-points on valves and make notes to deter inadvertent adjustments. Test pipe connections for leaks and repair as needed. Verify fan is stable during operation and noise level is acceptable or adjust fan and/or add enclosure as needed. Measure static and transient cross-slab pressure differential at all available communication test points and confirm consistency with expectations from pilot test data and analysis and consider design modifications accordingly. Consider collecting indoor air samples for analysis in select locations after system has been operating for at least 3 days and ideally longer. |
| h) Measure flow, vent pipe vacuum, and collect samples from all vent pipes | Measure flow in vent pipe using pitot tube, thermal anemometer, critical orifice or similar device (install a port or hardware as appropriate) and measure vacuum from U-tube manometer or Magnehelic gauge installed on vent pipe. Collect sample using installed port for laboratory analysis. Make these measurements after at least one hour of operation. |
| i) Calculate mass removal rates, compare to MFSL, Building Emissions during building depressurization testing (if available) | Multiply concentrations of target compounds measured by laboratory analysis by the flow rate to calculate the mass removal rate (Equation 10) and compare to the MFSL (Equation 12 in Final Report) and mass emissions from building during building pressure cycling tests (where available, see ESTCP Projects ER201119 and ER201503 for more details). |
| j) Adjust Full-Scale design as appropriate based on new data | Review all data collected after the Commissioning/Balancing/Verification and assess whether the system is meeting objectives. If not, further balancing or additional suction points may be needed (e.g., increase flow rate from vent pipes with the highest concentrations). Consider diminished operations or decommissioning if mass removal rate for an individual extraction point is lower than the mass flux screening level, subject to regulatory review and approval. |
| k) As-Built Drawings/Report | Consider generating as-built drawings to document the system design. Consider adding a report to tabulate pilot test data, describe the analysis of locations, spacing and size of vent-pipes, fan sizes, and valve settings. |

| Step 5: Operation, Maintenance, and Monitoring | |
|---|---|
| a) Design OM&M Plan | Consider the available data from pilot testing and startup testing, regulatory policies and guidance, occupant preferences and activities, potential health risks in the event of system malfunction, damage, power failure or mechanical malfunction, logistics, access agreements and potential future changes in exposure scenarios. Select appropriate number, locations, frequency and quality assurance/quality control (QA/QC) for monitoring, criteria for adjustments to operation, schedule for routine maintenance, implementation plan for unscheduled maintenance. Consider whether short-term measures for protection against acute health risks are important and prepare contingencies where appropriate. |

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| b) Routine inspection, equipment replacement and damage repair | Periodically inspect the system to verify the fan is running, the vent-pipe vacuum is similar to the set-point and no damage has occurred to system components. Make any repairs or replacements needed. Inspection frequency should be selected based on consideration of magnitude of potential risks, sensitive receptors, acute health effects, and other site-specific factors. Identify who will have the responsibility/contract vehicle to do future operation and monitoring and develop a long-term plan for education and communication in the event that building ownership or key personnel change. |
| **Suggested Activities** | **Rationale, Special Considerations, Details** |
| c) Indoor air sampling | Consider indoor air verification samples, especially where subslab concentrations >>SSSLs or Mass Flux from venting system >> MFSL.<br>Consider collecting indoor air samples for laboratory analysis to verify concentrations are below regulatory screening levels. Select sampling time periods to be representative of long-term averages (e.g., quarterly samples for a year) or conservative time frames (e.g., heating season in areas with cold climates). Monitor cross slab differential pressure during sample collection periods (preferred using a data-logger to provide sufficient data for a 1 to 5-minute rolling average of multiple instantaneous readings throughout the sampling period). Compare measured concentrations to risk-based screening levels and typical background levels and consider system modifications as needed if concentrations attributable to vapor intrusion exceed screening levels. |
| d) System monitoring | Consider measuring flow, vacuum, and concentrations in vent pipes over time.<br>Monitor extracted flow rate, vent-pipe vacuum levels and concentration over time provides data that can be used to assess and document consistency in mitigation performance. Use initial monitoring results (first year) to predict loading trends and develop a long-term monitoring program. Negotiate sample frequency with regulators. More frequent monitoring may be appropriate where concentrations and mass removal rates are much higher than risk-based target levels, sensitive populations are present, and/or compounds of interest pose acute health risks. Less frequent monitoring may be appropriate where concentrations and mass removal rates are closer to risk-based target levels. Where off-gas treatment is included in the system, monitor using protocols similar to soil vapor extraction systems, or as needed to meet any permit requirements.<br>Review monitoring data in the context of the CSM and assess whether the data are consistent with expectations, and if not, consider additional assessment to resolve discrepancies (e.g., potential focused assessment for a preferential pathway). |
| e) Replace fans when needed | Fans typically have a service life of about 10 years but are replaced on an as needed basis. Where fans are exposed to freezing temperatures, it is particularly important to avoid ice accumulation from condensation and freezing. For scenarios with potential acute risks, consider pre-purchasing replacement fans to allow for more rapid replacement. Consider whether automated alarms are warranted, or whether visual inspection of a U-tube manometer is sufficient. |
| f) Adjustments as needed to balance flows between vent-pipes, where applicable | Consider increasing flow rate in vent-pipes with higher rates of mass removal and potentially reducing flow rates in vent-pipes with lower rates of mass removal, where flow and vacuum monitoring in vent pipe and sampling and analysis for concentrations in extracted gas is performed to enable calculations of mass removal rate. Balance as needed with valves on individual pipes. |
| g) Prepare periodic reports as needed (regulatory input on schedule) | Report finding to regulatory agencies at an agreed-upon schedule, including documentation of data collected, particularly when diminishing operations or decommissioning mitigation. |

| Suggested Activities | Rationale, Special Considerations, Details |
|---|---|
| h) Assess System Effectiveness | Consider expanding system if data indicate inadequate protection. Additional extraction points or increased flow may be appropriate if mass removal rate does not exceed mass emissions from the pre-mitigation building conditions when the building was negatively pressurized, or if flow rates diminish during operations, or building occupancy changes to include sensitive receptors, etc. Avoid expanding systems based on indoor air sampling and analysis data alone without a forensic assessment of potential background sources.<br><br>Consider downsizing equipment if data indicate indoor air quality can be adequately protected with lower flow rates, fewer suction points, or adjustments can be made to improve energy efficiency such as reduced electrical power draw, reduced loss of conditioned air from inside the building, etc. Reduced (or no flow) from wells may be appropriate if mass removal rate falls below mass flux screening level after some period of operations, if the mass removal rate from certain fan(s) or vent pipe(s) is negligible, if building occupancy changes to less sensitive scenario (e.g., from residential to commercial), etc. Changes of this type may be subject to regulatory review and approval. Consider targeted monitoring after any downsizing to provide data to verify continued health protection. |
| Step 6: Decommissioning Strategy | |
| a) Consider cyclic operation to assess rebound if data indicate there is insufficient mass loading to pose a potential health concern | In cases where the rate of mass removal is much less than the minimum required to sustain indoor air concentrations above screening levels (i.e., the MFSL) and all other lines of evidence indicate the system is capturing the available mass loading, the system may no longer be needed. As part of a petition for closure, perform a short-term shutdown, and measure the mass removal rate again at startup to assess the magnitude of rebound in the mass removal rate. Consider the thickness and diffusivity of the vadose zone to guide selection of an appropriate duration for cyclic operations. Indoor air sampling should be considered to verify that shutdown does not lead to unacceptable concentrations of radon or VOCs in indoor air. |

**Acronym and Abbreviation List**

| | |
|---|---|
| A | area |
| ACM | asbestos containing material |
| AF | attenuation factor |
| AHU | air handling unit |
| b | thickness of active flow zone |
| B | leakance |
| Cl-VOCs | chlorinated volatile organic compounds |
| Cm | centimeter |
| CSM | conceptual site model |
| CTP | communication test point |
| FID | flame ionization detector |
| Ft | feet |
| HVAC | heating, ventilation, air conditioning |
| In | inch |
| L | liter |
| M | Meter |
| MFSL | mass flux screening level |
| Min | minute |
| n | effective porosity |
| OM&M | Operation, Maintenance, and Monitoring |
| P | pressure |
| Pa | Pascal |
| PE | Polyethylene |
| PHC | petroleum hydrocarbons |
| PID | photoionization detector |
| ppmv | parts per million by volume |
| PVC | polyvinyl chloride |
| QA/QC | quality assurance/quality control |
| r | radius |
| Rn | radon |
| ROI | radius of influence |
| SSSL | subslab screening level |
| T | transmissivity |
| UV | Ultra Violet |
| VFD | variable frequency drive |
| VOC | volatile organic compound |

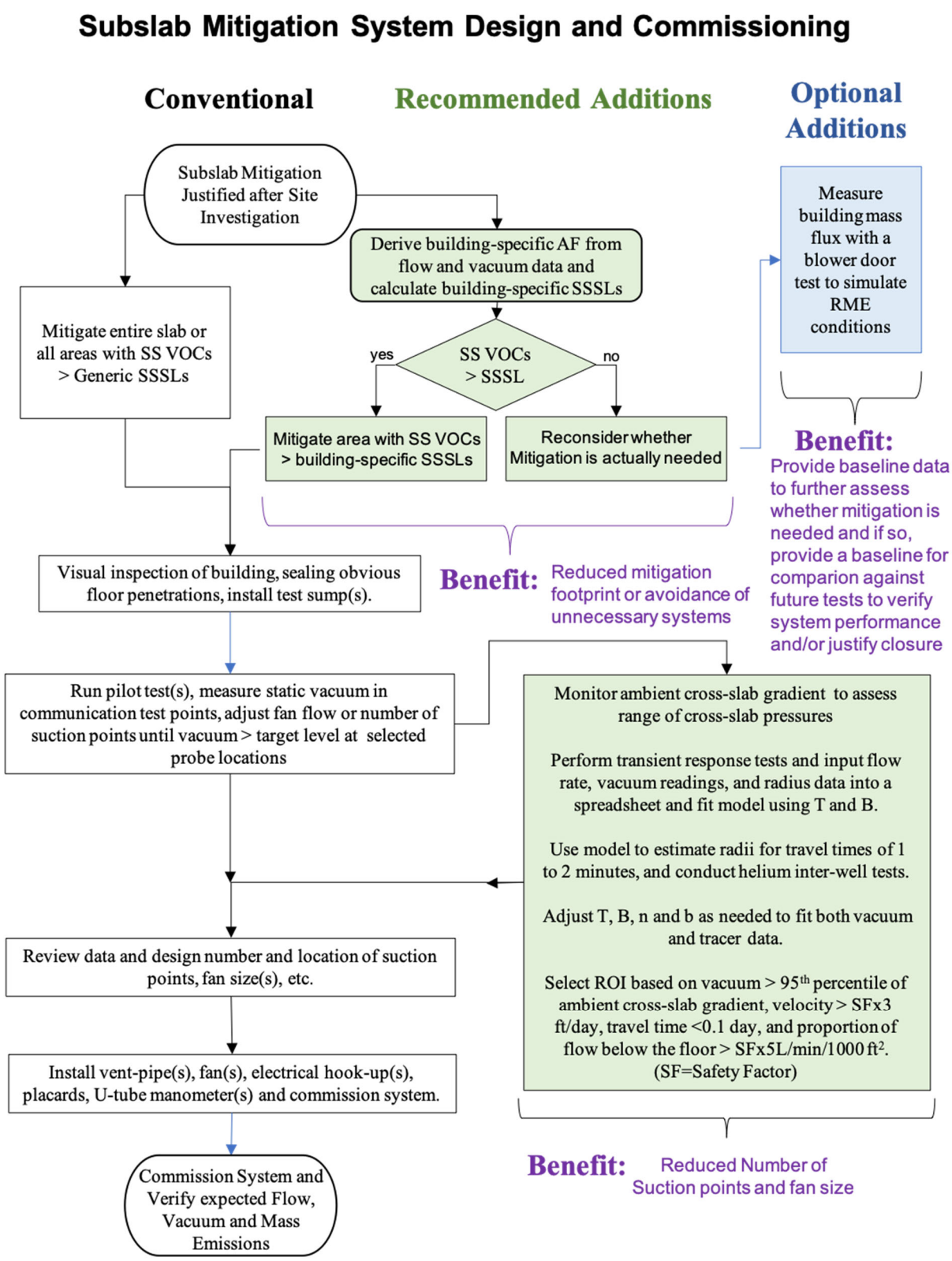


Figure TG1a: Summary of Logic Flow and Lines of Evidence for Mitigation System Design and Commissioning. The left side summarizes conventional standard practice, the additional lines of evidence developed in this research are outlined in the middle (recommended) and right (optional) columns.

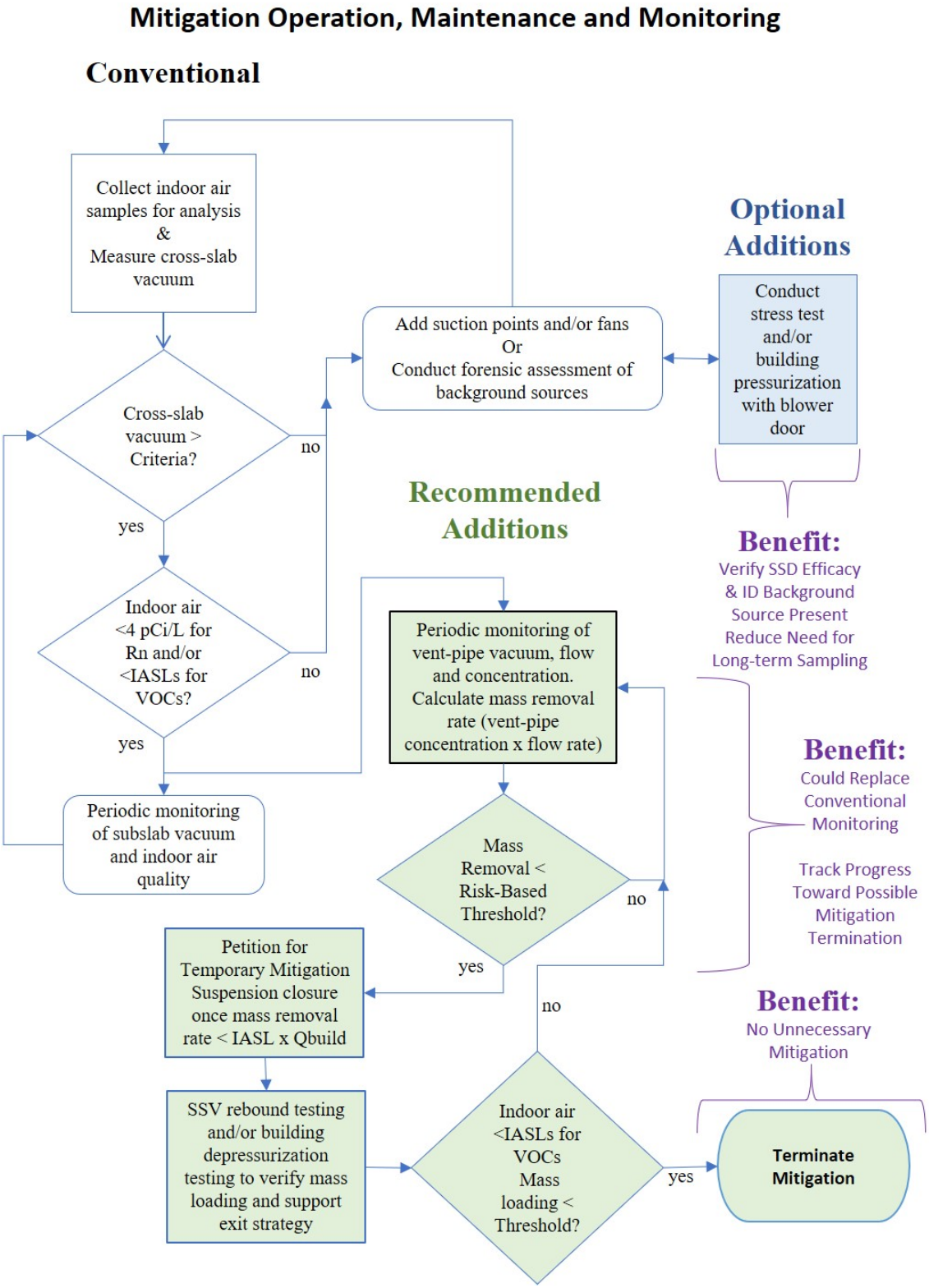


Figure TG1g: Summary of Logic Flow and Lines of Evidence for Mitigation System Operation, Monitoring and Maintenance. The left side summarizes conventional standard practice, the additional lines of evidence developed in this research are outlined in the middle (recommended) and right (optional) columns.