NEW METHODS FOR DESIGN AND PERFORMANCE MONITORING OF SUB-SLAB VENTING SYSTEMS FOR VOCS AND RADON

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ABSTRACT

This paper summarizes recent research funded by the U.S. Department of Defense Environmental Security Technology Certification Program (ESTCP) intended to improve the cost-effectiveness of systems to protect building occupants from subsurface radon gas and volatile organic compound (VOC) vapors. Standard practice for sub-slab depressurization (SSD) uses a fan or blower to create a measurable vacuum below the building and has not changed in a few decades. ASTM E-2121-13 specifies a minimum target vacuum of 6 to 9 Pascals (Pa) everywhere below the building floor slab, but this can be difficult to measure compared to baseline fluctuations (a signal-to-noise challenge). A key variable that is not usually measured is the permeability of the material below the floor. If granular fill is below the floor (as specified in most building codes), high flow velocities can be generated with small pressure gradients, which can protect occupants via sub-slab ventilation (SSV). Alternatively, if the floor is well sealed, the venting system may be able to capture all of the available mass of VOCs or radon at a modest flow rate, in which case mass flux might be the most important metric. Using vacuum as the only performance metric will often result in an over-designed system that is not energy efficient because it draws an excessive amount of conditioned indoor air across the floor slab for discharge above the rooftop and requires excessive electricity to power fans or blowers. Research was conducted at a 64,000 ft² (5,950 m²) commercial building with an existing SSD system comprised of 27 suction points connected to 9 fans to demonstrate and validate new methods and criteria for system optimization and monitoring, including transient and steady-state pneumatic testing and mathematical modeling using the Hantush-Jacob model, sub-slab tracer testing, building depressurization testing, trichloroethene (TCE) mass flux monitoring, and confirmatory indoor air sampling and analysis. The results of this study demonstrate that the number of SSD extraction points can be reduced substantially and still maintain health-protective indoor air quality.

Keywords: Vapor Intrusion Mitigation system Design & Optimization

1. INTRODUCTION

Subsurface vapor intrusion into indoor air has been a widely-recognized public health concern for radon for several decades and VOCs for about 25 years. For structures where mitigation is needed to reduce concentrations or achieve regulatory approvals, active sub-slab venting (SSV) or sub-slab depressurization (SSD) systems are the most common mitigation technologies.

Conventional SSV/SSD mitigation systems for radon and VOCs are based on a decades-old technology and policy (e.g., ASTM E-2121-12), which specifies a minimum target vacuum of 6 to 9 pascals (Pa) everywhere below the building floor slab. The reason this level of vacuum is specified is to enable a typical radon contractor to quickly and easily verify an induced vacuum relative to the natural fluctuations in the pressure differential across the floor slab of a building from wind gusts, occupants’ activities, exhaust appliance operation, thermal convection (e.g., the “stack effect”), and heating, ventilating and air conditioning (HVAC) operations (see Figure 1). The ASTM vacuum criterion of 6 to 9 Pa can draw excessive flow, causing increased energy usage, which is recognized by many...
practitioners (see Moorman 2009, for example), but no alternative design process or performance specifications have been published to replace the current standards.

Concrete floor slabs are commonly poured on top of a layer of compacted granular fill, which is relatively permeable. A concrete floor is not usually impermeable because expansion joints, stress fractures and utility penetrations leak to varying degrees. The performance of a SSV or SSD system depends on the relative permeability of the floor and sub-floor, the number of fans and the power of suction applied by each fan. If the sub-floor is highly permeable, the system can ventilate below the floor with very modest vacuum levels. Alternatively, if the floor is not very permeable, the system can capture the available mass flux of VOCs or radon with lower flow rates. Vacuum measurement may be fast and simple, but it is not the ideal performance metric because of baseline fluctuations and instrument sensitivity limitations. This research is designed to better understand the relative permeabilities of the floor and sub-floor and the mass removal rate in order to develop an energy efficient design.

In residential buildings, a vacuum of 6 to 9 Pa can often be achieved with a single fan drawing about $100/yr of electricity, so there is little incentive for optimization. However, in larger buildings (typical of National Defense facilities), the power draw for multiple fans or large blower operation alone can cost >$10,000/yr for a single building. The installation of a system designed to meet the current ASTM performance criteria also requires significant disruption to operations in an active building for installation and balancing. Furthermore, operation of SSV/SSD systems typically draws large volumes of conditioned (heated or cooled, humidified or dehumidified, and filtered) building air through the floor slab, resulting in substantial additional energy losses (Moorman 2009, Turk and Hughes 2009).

2. NEW DESIGN

The new technology described here is basically an adaptation of standard practice for designing groundwater extraction systems, which is being deployed in an analogous mode for containment of vapors below a building. In both cases, the analysis depends on the mathematics of fluid flow through porous media (Bear, 1979). Gas and water have different density and viscosity, but otherwise both fluids flow in response to pressure gradients and permeabilities in similar ways and are both amenable to mathematical modeling. Groundwater extraction systems are generally designed and optimized using a process that includes: 1) conducting pumping tests to assess the hydraulic properties of the aquifer(s), 2) mathematical modeling of capture zones to devise a pumping scheme (number of wells, locations and flow rates) to provide containment without excessive pumping that would draw a lot of water from outside the region of contamination, and 3) performance monitoring to verify and optimize the design. The same methods can be applied to soil vapor extraction system design (Thrupp et al., 1996) and sub-slab venting system design (McAlary et al., 2010, 2011). However, the gas-phase pumping tests are much faster (usually on the order of minutes instead of days) and the cost of waste disposal is dramatically lower or zero.
Pneumatic testing for SSD/SSV systems usually includes measuring steady-state vacuum at different distances from the suction points, plotting the data on a semi-logarithmic graph of vacuum versus log distance and fitting a straight line to the data. The point where the line intersects a vacuum level of 6 to 9 pascals is usually taken as the radius of influence (ROI) of the suction point. This research also includes collection of transient vacuum response data (vacuum vs time) in response to cyclic operation of an extraction fan. The fluctuations in vacuum that plague the conventional steady-state measurements do not affect the transient measurements, because data loggers and pressure transducers are able to collect hundreds of measurements in a few minutes or less, and at that scale of measurement, the response from the cyclic operation of the fan or blower is very easy to resolve against natural pressure fluctuations. The transient response is analyzed using the mathematical model of Hantush and Jacob (1955), which was developed for groundwater pumping test analysis, but is equally applicable to analyzing gas extraction tests as long as the density and viscosity of the fluid are considered in the analysis (Bear, 1979). For the proposed application, the conceptual model (Figure 2) is modified such that the leaky aquitard is the floor slab and the aquifer is the sub-floor soil or granular fill.

![Conceptual Model for the Hantush-Jacob (1955) Leaky Aquifer Solution](image)

**Figure 2:** Conceptual Model for the Hantush-Jacob (1955) Leaky Aquifer Solution (Bear, 1979).

Fitting the Hantush-Jacob model to the transient vacuum response data provides the transmissivity ($T$) of gas flow through materials beneath the floor slab and the vertical leakance ($B$) of air flow into the subsurface (i.e. across the slab). The leakage factor ($B$) is defined as follows:

$$B = \frac{\sqrt{Tb'}}{K'}$$

[1]

where:
- $T$ = transmissivity of the zone of extraction ($L^2/T$),
- $b'$ = thickness of the semi-confining zone ($L$),
- $K'$ = vertical pneumatic conductivity of the semi-confining zone ($L/T$).

An approximation of the leaky aquifer solution for steady-state flow conditions is a useful tool for estimating the subsurface pressure drawdown (i.e. vacuum) as a function of distance from an SVE well (Bear, 1979):

$$S(r) = \frac{Q_w}{2\pi T} K_o(r/B)$$

[2]

where:
- $B$ = the leakage factor as defined above (Equation 1), and
- $S(r)$ = vacuum in feet of air column as a function of radial distance,
- $r$ = radial distance from the extraction point ($L$),
- $Q_w$ = discharge from the extraction point ($L^3/T$),
- $T$ = transmissivity of the zone of extraction ($L^2/T$),
- $K_o$ = modified Bessel Function of the second kind of order zero of $(r/B)$ (dimensionless)
Equation 2 can be used to calculate the profile of steady-state vacuum versus radial distance using the T and B values derived from the Hantush-Jacob Model analysis of the transient vacuum response data. There are two sets of data (vacuum vs time at a given distance and vacuum vs distance for a given time), and iterative fitting of the model to both sets of data provides a unique solution for the values of T and B.

The proportion of gas withdrawn from the subsurface \( (Q(r)) \) as a function of the radius from which the vapors were drawn can be calculated using equation 3.

\[
\frac{Q(r)}{Q_w} = \frac{r}{B} K_1 \left( \frac{r}{B} \right)
\]

where \( r, B, \) and \( Q_w \) are as defined above, and

- \( Q(r) = \) flow from the subsurface at distance \( r \) from extraction well \( (L^3/T) \), and
- \( K_1 = \) modified Bessel Function of the second kind of order one of \( (r/B) \) (dimensionless).

Equation 3 can be used to evaluate the influence of leakage as a function of distance from the point of suction. For example, at a radial distance of two times the leakage factor \( (2B) \), 75% of the air flow through the system originates as leakage of indoor air across the floor slab within this distance, and 25% of the extracted gas originates from the subsurface beyond this distance. This can be used to calculate the sub-floor ventilation rate at various radial distances from the suction point.

Helium tracer testing can also be performed to provide additional assurance of the distance from which vapors travelled below the floor slab during the HVS test. This can be compared to velocities calculated using Darcy’s Law, the sub-floor transmissivity and Equation 2 as a supplemental line of evidence for calibrating the Hantush Jacob model to the building-specific sub-floor conditions.

The optimal SSV system design will capture all or nearly all of the available mass of VOCs or radon over a given time period. **Figure 3** shows the expected trend conceptually. If the flow rate of the system is low, the rate of mass removal will also be low. As the total flow of sub-slab gas extracted by the system increases, the rate of mass removal will also increase, but this cannot continue indefinitely, it will be limited by the rate at which VOC vapors migrate to the region being flushed by the SSV system or the rate at which radon gas is produced below the floor. Once all the available mass flux is captured from the area of concern beneath a building, any additional flow simply withdraws more air from either downward flow of indoor air from the building, or lateral flow of outdoor air from beside the exterior walls. If there are essentially no VOCs in the indoor and outdoor air, the mass flow rate will stabilize. Excessive pumping is not optimal because of the energy costs associated with running oversized fans and the energy loss associated with conditioned air that is drawn across the floor slab.

**Figure 3:** Expected trend of mass flux extracted by sub-slab venting (SSV) system versus total system flow rate (after McAlary et al., 2011)
3. SITE DESCRIPTION

Building 205 at the former Raritan Arsenal in Edison, New Jersey is a single-story brick building with a concrete slab floor on grade. The building use is predominantly office space and the building is surrounded by a parking lot with a small landscaped lawn area. Indoor air and sub-slab sampling and analysis showed indoor air concentrations of tetrachloroethene (PCE) ranging from non-detect at 0.2 to 18.99 micrograms per cubic meter (µg/m^3), while the TCE concentrations ranged from non-detect at 0.2 to 3.87 µg/m^3. The soil gas concentrations for PCE ranged from non-detect at 0.2 to 160 µg/m^3, while the TCE concentrations ranged from non-detect at 0.21 to 2,800 µg/m^3. The maximum concentrations were above screening levels established by the New Jersey Department of Environmental Protection (NJDEP), so a sub-slab depressurization system was installed consisting of nine identical components each of which includes three (3) vent pipes with 3” piping leading through a ceiling mounted header pipe to a rooftop blower (Figure 4). As a result, there are a total of 27 extraction points and nine HS-2000 high suction fans (HSF). The fans operate between 5 and 8 inches of water vacuum (in-H2O) and provide between 26 and 73 standard cubic feet per minute (scfm) of flow per fan totaling about 490 scfm for the combined system. This achieved target levels of vacuum below the floor.

![Figure 4: Building layout showing locations of 9 fans, each connected to three suction points through a header](image)

Limited information is available on building footer construction, however the building appears to be constructed with a perimeter footing and interior columns supported on separate individual footers spaced at approximately 20 foot centers. The building has three air zones services by separate heating, ventilating and air conditioning (HVAC) units shown on Figure 4 as green (about 29,000 square feet), blue (about 24,000 square feet), and yellow areas (about 11,000 square feet).

4. BASELINE TESTING

Baseline testing consisted of measurement of the flow rate from each of the 9 vent fans and deployment of Waterloo Membrane Samplers (WMS) in each of the vent-pipes for about one month followed by analysis by Eurofins/Air Toxics of Folsom, California to measure the long-term average VOC vapor concentrations. Radon concentrations were measured with a Durridge RAD-7 over 30 minutes at each fan exhaust (see Table 1). TCE was the dominant VOC detected in the samples from the vent pipes. The TCE concentrations in the effluent from Fans 1 through 4 were all within a factor of 2 (49 to 100 µg/m^3) and concentrations for Fans 5 through 9 were about an order of magnitude lower (average about 4 µg/m^3), which is only slightly above the IASL of 3 µg/m^3). The mass flux (MF) of TCE extracted by each venting fan was calculated as the product of the volumetric flow rates and concentrations. These data show the TCE distribution is primarily beneath the left side of the building as shown on Figure 4. The mass flux values can be divided by the volume of the building (assuming average 15 ft ceilings) and the 10th percentile air exchange rate for a commercial building (0.6 air changes per hour) to provide a conservative estimate.
of the indoor air concentration that might have been expected in the absence of a venting system, which showed a value of 2.0 µg/m³ for the left side of the building and about an order of magnitude lower for the right side (Table 1). The risk-based screening level for TCE in a commercial building is 3 µg/m³, so this indicated the potential risk is low, but there may be temporal fluctuations, so there is justification for continued operation in some capacity. By similar logic, the indoor air radon concentrations would be expected to be 147 Bq/m³ and 260 Bq/m³ for the left and right sides of the building, which are slightly above the level recommended for mitigation of 148 Bq/m³. Note that if the building air exchange rate is closer to the average of 1.5 exchanges per hour for commercial buildings, the indoor air concentrations in the absence of a venting system would be 2.5 times lower than the values calculated here.

Table 1: Concentrations, Flow Rates, Mass Flux and Potential Indoor Air Concentrations

<table>
<thead>
<tr>
<th>Fan #</th>
<th>HSF-1</th>
<th>HSF-2</th>
<th>HSF-3</th>
<th>HSF-4</th>
<th>HSF-5</th>
<th>HSF-6</th>
<th>HSF-7</th>
<th>HSF-8</th>
<th>HSF-9</th>
</tr>
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<tbody>
<tr>
<td>Radon (becquerels/m³)</td>
<td>5300</td>
<td>8100</td>
<td>5000</td>
<td>4000</td>
<td>970</td>
<td>3000</td>
<td>4500</td>
<td>3700</td>
<td>3900</td>
</tr>
<tr>
<td>TCE (µg/m³)</td>
<td>100</td>
<td>58</td>
<td>100</td>
<td>49</td>
<td>9.3</td>
<td>3.4</td>
<td>2</td>
<td>3.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Flow rate (scfm)</td>
<td>30</td>
<td>27</td>
<td>30</td>
<td>46</td>
<td>64</td>
<td>72</td>
<td>72</td>
<td>73</td>
<td>73</td>
</tr>
<tr>
<td>TCE Mass Flux (g/day)</td>
<td>0.12</td>
<td>0.063</td>
<td>0.12</td>
<td>0.091</td>
<td>0.024</td>
<td>0.010</td>
<td>0.006</td>
<td>0.010</td>
<td>0.004</td>
</tr>
<tr>
<td>Region flux (g/day)</td>
<td>0.42</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>10th %-ile Qbuild (m³/d)</td>
<td>210,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>170,000</td>
<td></td>
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<tr>
<td>CI potential (µg/m³)</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.18</td>
</tr>
</tbody>
</table>

5. PNEUMATIC TESTING

5.1 Specific Capacity Testing

Specific capacity is defined as the ratio of the flow divided by the applied vacuum (scfm per in. H₂O) and this value is directly proportional to the permeability of the sub-surface materials. The flow rate in each vent-pipe was monitored using a Dwyer 471 thermal anemometer and the vacuum was monitored using a U-tube manometer previously installed at each vent pipe. The results showed a range of values spanning a factor of 30, with a distribution shown in Figure 5.

Figure 5: Specific capacity distribution below the floor, showing 30x range of variation in sub-floor permeability

5.2 Transient Pneumatic Response Testing

Transient vacuum response testing was conducted using every other Fan (e.g., 1, 3, 5, 7 and 9) to provide pneumatic data across the footprint of the building. Each fan was turned off long enough for the vacuum to dissipate and turned on again until vacuum was re-established. Transient tests occur quickly (usually under 5 minutes) making them fast
and economical. On this site the vacuum dissipated slowly due to the sub-surface materials and since this was research based project the tests were run longer to ensure stabilization. However, even during these tests the majority of the test was completed in 15 minutes. Transient vacuum data was collected at newly installed sub-slab probes located at radial distances of about three feet from the central suction point and 20 ft from the central suction point (midway to one of the perimeter suction points). Data logging micromanometers were used to record vacuum measurements at 1-second intervals. An example data set is shown in Figure 6. The response was slower than observed at most buildings, indicating the supply of air to the subsurface is restricted. This is a qualitative indication that the floor slab is not very permeable. Quantitative analysis of the data is shown in Figure 7, which yielded a transmissivity of 95.5 ft²/day and a B value of 21 ft. Note how closely the data on Figure 7 matches the blue line (the fit is nearly perfect). This indicates that the assumptions inherent in the Hantush Jacob model are reasonable for this building.

![Figure 6: Vacuum versus time for a probe located 3 feet from a suction point showing transient response to the nearest fan being turned off for about 25 minutes and then turned on again (other fans remained running)](image)

![Figure 7: Curve fitting of transient response data to the Hantush Jacob (1955) Model](image)
5.3 Vacuum versus Radial Distance

A range of T and B values were calculated from each fan and set of probes and used with equation 2 to calculate a profile of vacuum versus radial distance. Steady-state vacuum levels were also measured at surrounding probes. Comparison between the measured and modeled vacuum profiles was used to verify the T and B values. Figure 7 shows that the range of measured values fall within the range of calculated values over a range from less than 1 pascal to 2000 pascals and a distance over 200 feet. This indicates a radius of influence that may extend far beyond the value that would usually be set based on a 6 to 9 pascal criteria.

![Graph showing vacuum versus radial distance](image)

**Figure 8:** Vacuum versus radial distance from the suction points calculated using equation 2 and measured at sub-slab probes.

6. HELIUM TRACER TESTING

Two types of helium tracer testing were performed to assess the velocity of gas flow below the floor: inter-well test and a helium flood. The inter-well tests were performed by injecting about 10L of helium over about a minute into a sub-slab probe while operating a single fan. Helium concentrations were monitored at the closest vent pipe by installing a small port in the vent pipe and extracting gas using a small pump. This slip stream sample of air was monitored continuously with a portable helium meter to determine the time lag between the midpoint of the helium injection and the moment of maximum helium concentration at the vent-pipe, which was taken as the average travel time for sub-slab gas between the point of injection and extraction. An example data set for the inter-well test is shown on **Figure 9**, where the radial distance was 6 feet, and the flow rate in the vent-pipe was 28 scfm. The entire test happens quickly, lasting approximately 10 minutes making the inter-well test fast and economical. The inter-well also strengthens the mathematical model by providing another line of independent calibration shown on **Figure 10**.
The helium flood was performed by shutting off all the fans and blowing air into fan HSF-03 using a ShopVac on the roof top. A bleed air valve on the ShopVac was adjusted until the pressure in each vent pipe was equal in magnitude to the normal operating vacuum, which resulted in approximately 75 scfm of air flow. A continuous stream of helium was added to achieve an influent helium concentration of about 2% v/v for about 90 minutes. The helium concentration was measured at several sub-slab probes at various distances from the injection pipes. The time needed for the helium concentrations to reach one half of the injection concentration was taken as the average travel time.

**Figure 10** shows the results of measured sub-slab gas flow velocities from the helium tracer tests and a range of values calculated from the Hantush-Jacob model analysis. Three of the five measured values corresponded very well with the calculated range. Two of the measured values were faster than the calculated range, which may indicate the presence of a localized preferential flow path (shrinkage gap below the floor, granular fill around a footer, etc.). This indicates a potential opportunity to use this research to identify preferential pathways below floors, although this was not the focus of this research.
7. INTERPRETATION

The vent-pipe monitoring indicated that the majority of the TCE mass removal was achieved by fans 1 through 4, and that fans to the right of the building could probably be turned off because the concentration of TCE in the fan exhausts were barely above the indoor air screening level. The initial mass flux calculations indicated that indoor air quality would likely be acceptable even without a venting system, unless the air exchange rate was very low. Furthermore, the pneumatic analysis indicated that a single fan (#3) could achieve a radius of influence that encompasses the area of elevated TCE vapors and the helium flood test indicated that Fan #3 alone could ventilate the sub-slab region of elevated TCE vapors with an exchange rate of about 1 per day (extrapolation of the dashed blue line on Figure 9). Therefore, the operation of Fan #3 alone was considered sufficient to be protective.

8. SYSTEM MODIFICATIONS AND PERFORMANCE MONITORING

All 9 fans were turned off on a Friday night in August 2015 to allow the system to stabilize. Then, Fan #3 alone was turned on. The flow rate and TCE concentrations in the discharge from Fan #3 was measured after 10, 100, 1,000, and 17,500 minutes of operation, to assess whether there was any substantial change in the rate of mass removal over time. The TCE mass removal rates were 0.47, 0.46, 0.45 and 0.43 g/day, respectively, which is similar to the total system mass removal rate recorded with all 9 fans running (Table 1). Indoor air concentrations of TCE at nine locations collected two months after the system modification were all less than 0.21 µg/m³.

Radon monitoring with only Fan #3 running indicated a slight increase in indoor air concentrations in the green zone (right side of Figure 1), although the concentrations remained below the radon mitigation level. As a precaution, Fan #8 was returned to service, and subsequent testing indicated a small decrease in the indoor air radon. Therefore, although indoor air concentrations never exceeded the mitigation standard, Fan #8 is also recommended for continued operation as part of the optimized system. The average indoor air radon concentration from 9 samples collected via electret over 30 days were 60, 74 and 66 Bq/m³ with all 9 fans, fan 3 alone and fan 3 and 8 together, respectively. These are all well below the mitigation standard of 148 Bq/m³.

There are three costs associated with the mitigation system; energy loss due to exhausting conditioned air, electrical cost to run the system and maintenance costs to replace worn out fans. Based on calculations of total flow rate versus flow rate of conditioned air lost, energy costs can be reduced by $2,700 per year or about $80,000 over a 30-year operation. By operating two fans rather than nine, operating costs can be reduced by $3,120 per year or $94,000 over a 30-year operation. Service costs would be reduced by $53,000 over a 30-year operation, due to fewer fans needing replaced. Total savings amount to about $7,600 per year or about $230,000 over a 30-year operating period. Additional capital saving could have been realized if the design process described in this article was used prior to the initial SSD system design and installation.

9. CONCLUSIONS

The conventional radon mitigation system design approach resulted in 27 suction points and 9 high suction fans to achieve a clearly measurable vacuum below the 64,000 ft² building footprint; whereas, two fans and six suction points provides more than adequate mitigation with a fair margin of protectiveness. The floor slab at Building 205 appears to have a very low permeability based on the length of time required for vacuum to dissipate when fans are turned off. This enables each suction point to achieve a large radius of influence because the radius of influence keeps expanding until the amount of air leaking down across the slab is equal to the amount of air withdrawn by the vent-pipe. The cost savings associated with the reduction of operating fans incorporates the decreased volume of conditioned air being drawn down through the slab, the electrical cost of having fewer fans running and the reduced cost of replacing worn out fans. There is approximately a $7,600 per year cost savings associated with this building. Research is ongoing to assess whether a subset of the tests performed in this research would be sufficient for routine practical applications, but it is clear that a better understanding of subsurface conditions is readily achievable with current technologies compared to the radon mitigation system design standards that were developed decades ago. Some of these tests are fast and economical and are therefore valuable even if used as a supplemental line of evidence.

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REFERENCES


