Report for 2004TX157B: Development of Smoke Tracer Instrumentation for Groundwater Recharge Investigations in the Edwards Aquifer Region

- Other Publications:
  - Manuscript: Taucer, Philip I., Munster, Clyde L., Wilcox, Bradford P., Dept of Biological and Agricultural Engineering, Texas A&M University, College Station, TX 77843, Professor, Dept of Rangeland Ecology and Management, Texas A&M University, College Station, TX 77843.

Report Follows

SMOKE TRACER SYSTEM DESIGN

DEVELOPMENT OF SMOKE TRACER INSTRUMENTATION FOR GROUNDWATER RECHARGE INVESTIGATIONS IN THE EDWARDS AQUIFER REGION

Prepared by:
Philip Taucer
Dept. of Biological and Agricultural Engineering
Texas A&M University
College Station, TX 77843-2117

Phone: 979-845-7640

Development of Smoke Tracer Instrumentation for Groundwater Recharge Investigations in the Edwards Aquifer Region

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Correspondence: Philip I. Taucer, Dept of Biological and Agricultural Engineering, Texas A&M University, College Station, TX 77843.

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SMOKE TRACER SYSTEM DESIGN

INTRODUCTION

I. Project Objectives: The current project focuses on the development of instrumentation for investigations of brush control impacts on shallow subsurface flow paths in the Edwards Aquifer region. Current research at the Honey Creek State Natural Area and the Camp Bullis training area north of San Antonio, Texas has demonstrated that applied rainfall on large plot areas moves predominantly through discrete conduits and fractures in the subsurface layers. For the Honey Creek site, lateral subsurface flow is observed directly through a trench located at the downhill end of the project plot. While the subsurface flow outlets are easily identified by their discharge into the trench, the contributing zones on the plot surface that feed these outlets and the degree of interconnection between conduits remains unknown. While two dye tracer tests have been carried out in an attempt to address these questions, dyes present a number of limitations. Dyes reveal only the general area of surface inlets and cannot pinpoint exact inlet locations; additionally, they tend to persist in the soil, limiting their effectiveness for multiple tests. However, it may be possible to locate discrete inlets by using a gaseous tracer traveling from an outlet location to the plot surface to identify inlet points. As such, the objectives of this study are: (1) to develop a small, portable, non-invasive portable injection system that uses smoke as a tracer for fractured geologic material (2) determine locations of flow path inlets for the project plot, (3) identify flow path interconnections for the plot, and (4) assess the feasibility of using smoke as a tracer in the Edwards Aquifer region.

II. Use of Smoke as a Tracer: Smoke has been successfully used as a medium to trace air movement in a broad range of fields. It is an especially common tool for testing ventilation systems for domestic, industrial, and agricultural facilities, as well as for locating leaks in piping and other closed-conduit flow systems. In some situations with favorable soil conditions, buried conduits for wastewater/storm water movement can be tested in isolated sections using concentrated smoke at high airflow rates. However, natural geologic formations display a much greater deal of physical complexity than artificial conduit systems and as such must be examined from a different perspective. The size of natural preferential flow paths may span orders of magnitude, ranging from hairline fractures and root-associated soil macropores to large caverns. Even in situations where the potential range in flow path size is known, it is difficult to determine the degree of flow path interconnection with nondestructive techniques. Although smoke has seen only limited use in natural geologic studies, early work by Sasaki et al (2000) indicate the potential for smoke to be used in fractured rock settings; in their study on fracture distributions and persistence, the researchers noted visible smoke travel through fractures ranging in size from approximately one millimeter to over one meter in width, with distance of movement in some cases reaching 100 m and with travel time of approximately 25 minutes. However, the location used for the Sasaki et al study consisted primarily of fractured rock with little or no soil cover. The karst landscapes of the Edwards Aquifer region are considerably more complex, with highly heterogeneous limestone formations overlaid by soils with various textures and depths as well as complex vegetation patterns. As such, one cannot assume that the results of the earlier study will be replicated exactly in different settings, even over a relatively small distance.

III. <u>Conceptual Design Review</u>: Although the research team has developed several different tracer system designs during the course of the project, all of the different systems have conformed to the conceptual design presented in the project proposal. Primary components of the system include an airflow source, smoke generation/containment chamber, a conveyance line network, an injection port, and an adjustable compression member. The injection port is placed over a fracture or conduit outlet and sealed against the rock face using some form of airtight, compressible material. Compression is provided by a hydraulic jack and transmitted to the injection head through a beam. Airflow from the blower unit moves through the conveyance lines to the generation/containment chamber where smoke enters the air stream. The smoke-laden air then travels through the conveyance line to the injection port, where it will enter the fracture outlet. All components are small and modular, simplifying assembly and disassembly in enclosed spaces.

SITE FOCUS

The smoke tracer project has focused primarily on outlets contributing to an artificial trench at the project plot in the Honey Creek State Natural Area. However, additional brush control study sites are located over caves, which allow monitoring of deep subsurface flow rather than shallow flow. If the smoke tracer concept can be adequately demonstrated at Honey Creek, it is likely that the tracer project will shift focus to more cave-based applications.

CONSTRAINTS

I. <u>Physical/Implementation</u>: As stated in the objectives, the design must be small, portable, and non-invasive. It must be able to perform under a variety of conditions and in any orientation. Additionally, it must be capable of forming an airtight seal against irregular surfaces.

II. <u>Environmental</u>: Although initial application and testing for the project are focused on exposed rock face in an artificial trench, future project stages may expand the scope of the study to incorporate testing in natural cave formations. Due to the importance of such features to aquifer recharge and the fragile nature of cave ecosystems, the study requires significant environmental consideration. Any injected smoke or particulate tracer should not reduce surface or groundwater quality or flow properties in any way, nor should it harm cave dwelling species or surface vegetation. Additionally, in accordance with standard caving practices, the equipment should not damage cave formations.

III. <u>Safety</u>: Although the study uses non-toxic smoke cartridges, any source of fine particulate matter can act as an irritant, especially in enclosed situations. To insure the safety of researchers, system components must be inspected for air tightness in the field prior to testing. Additionally, all entrances to the project trench or caves must remain clear to allow free movement of personnel out of enclosed spaces. For a more detailed list of project constraints see Appendix A.

I. Method: While the basic concepts of air conveyance are easily applied in a well-understood setting such as a ducting network, applying these concepts to field conditions presents a considerable challenge. In a natural and complex geologic setting such as the Honey Creek project site, where the hydraulic properties of individual flow paths remain largely unknown, equipment specifications cannot rely on idealized equations or standard equipment. As such, the smoke tracer project makes use of an iterative design method. While trial and error testing exhibits little technical sophistication in of itself and requires considerable time, it is the only method of translating the conceptual design into a functional system. To date there have been four major design iterations for the project, with minor variations on the iterations developed during laboratory testing. The research team is currently considering a fifth major design using somewhat larger components and a more powerful blower than earlier systems.

II. Evaluation Procedure: Each design iteration was evaluated under laboratory conditions before consideration for field testing. Several criteria were applied in a set order to determine the feasibility of each design.

a. *Implementation*: After the individual components of each design were constructed, the design was evaluated on ease of assembly and transport. All designs passed this criterion easily, with only minor modifications for transport (addition of handles and similar changes). Modifications for assembly were made primarily to conveyance line connections on the smoke generation / containment chamber, which proved to be more difficult than expected.

b. *Smoke Conveyance and Sealing*: All design iterations were also tested on the basis of smoke conveyance and sealing under nonrestrictive flow conditions; the injection port remained uncovered during testing to minimize flow resistance to internal friction and turbulence losses. Small cartridges were loaded into each design to test system smoke production. Tests resulting in little or no smoke production indicated high smoke particle deposition losses within the apparatus or "pooling" of smoke in isolated pockets. Modifications were made where necessary to prevent smoke loss. The small cartridges also allowed the research team to locate and seal any leaks in the generation chambers and at conveyance line connections.

c. *Media Column*: Designs which performed well in previous testing underwent porous media column testing as well. Note that selection for this testing stage was somewhat subjective, with those designs capable of conveying smoke but producing low airflow rejected for further testing. For this stage, designs were tested for the ability to convey smoke through a highly resistive column filled with various media used to simulate geologic profiles similar to those to be encountered under field testing conditions. Lower layers of the testing column consisted of a coarse medium (stone of two to five centimeter diameter) overlaid with finer rock and coarse soils. Designs capable of forcing smoke through the column were judged acceptable for further testing under field conditions.

I. <u>Prototype Design</u>: The prototype smoke tracer equipment utilized a very basic design, with air moving directly from its source to a simple smoke generation box and then through a conveyance line to the injection apparatus. For illustrations of this design, as well as other iterations, see Appendix B.

a. *Airflow*: The prototype design utilized a Toro Model 51591 Super Blower Vac industrial-grade leaf blower as an airflow source. Alternative sources were considered in terms of peak flow rate, pressure generation, size, weight, and cost; the selected device represented the most favorable combination of the described properties. Although flow rate and pressure generation play an important role in determining system performance, size and weight considerations played a major role in component selection due to the need for easily-portable components for use in remote locations (and possibly under space-limiting conditions). The 3.3 kg leaf blower unit produces a maximum conveyance velocity of 96 m/s and maximum volumetric flow rate of 0.13 m^3/s. The current draw listed for the enclosed motor is given as 12.0 amps (Toro 2005).

b. *Power Supply*: Power for the prototype unit was supplied by a Generac Model SV 2400 portable generator system with a rated power output of 2400 watts at 120 VAC. Maximum current draw for the generator is listed as 20 amps, which is adequate for the leaf blower apparatus described above. Total mass of the generator system is 37.2 kg (Generac 2005); although this component outweighs other system components, it remains light enough for transport over rough terrain by no more than two people.

c. *Containment*: The initial design made use of a simple chamber for introduction and containment of smoke. The prototype chamber consisted of a wood-framed plywood box with outer dimensions of 27 cm x 28 cm x 64 cm. Inlet and outlet ports were located on opposite ends of the box with ports centered on the ends. Smoke cartridges were loaded into the box through a 10.2 cm (4") threaded PVC sewer cleanout port mounted on the top face of the box.

d. *Conveyance*: Conveyance of smoke-laden air from the containment unit to the injection apparatus utilized a 7.6 meter section of 5.08 cm diameter swimming pool hose. The thick, smooth-sided hose offers significant material strength and minimal resistance to airflow, although limited flexibility and increased weight increase the difficulty of implementation in the field. However, testing of alternative materials (including portable irrigation hose and lightweight laundry water discharge hose) indicated poor durability and high resistance to airflow.

e. *Injection*: The injection apparatus used for the prototype design is similar to that described in the first quarterly project update, with the body of the injector consisting of two parallel metal plates with a canister connected to the top plate and a pipe leading from the conveyance system to a hole in the upper plate, centered within the ring formed by the injection canister.

f. *Seal*: The primary seal for the prototype design consisted of a two-centimeter layer of closed-cell foam pipe wrap ringing the end of the injection canister. Under field conditions a layer of urethane foam was applied at the injection head/trench wall interface as a secondary seal to cover small cracks not sealed by the closed-cell foam.

g. *Smoke Source*: The initial tracer system design used small, colored-smoke cartridges (of the type commonly used on model airplanes) as a smoke source. The cartridges selected were Regin HVAC Model RC 104 cartridges, with a listed smoke production of 34 m^3 and a burn time of approximately three minutes (Regin HVAC 2005). Testing carried out by the project crew indicated that the cartridges typically exhibit a shorter true burn time of roughly 2 minutes and 15 seconds, with the cartridge orientation and rate of ambient airflow having little effect on burn time. In spite of this shortcoming, the cartridges were retained for use in the project due to their small size and relatively low price.

h. *Variations*: The research team constructed several variations on the prototype design before settling on the unit described above. The earliest configuration used a hinged lid on the smoke generation chamber rather than a round port for candle loading. While the lid allowed the use of smoke cartridges of various sizes, it did not seal easily and resulted in smoke loss. In another variation, a valved tee was connected to the round loading port on the top of the chamber, enabling cartridges to be loaded without venting air from the chamber. However, this design was abandoned due to problems with smoke deposition in the tee.

i. *Laboratory Testing*: The prototype design operated well under laboratory conditions, with only minor modifications required to the initial configuration. The most significant problem with the prototype design was that of sealing, with the smoke generation chamber displaying a significant number of leaks during early testing. The unit also performed well during media column testing, with several locations of smoke emergence from the top of the media column. Note that for this design a large diameter column with coarse media was used; a taller, narrower column with a more realistic media profile was developed to test later designs.

II. Combined Blower and Containment System: The second major design utilized a combined blower and containment system approach in order to circumvent the sealing problems encountered for the prototype design. By placing the airflow source within the smoke generation and containment chamber, air was drawn into the box rather than forced through by the blower. As such, any leaks in the box allowed fresh air to enter the box rather than permitting smoke to escape.

a. *Airflow*: For the combined blower and containment system, a new blower unit was installed within the smoke containment and generation chamber, with the blower outlet located at the chamber outlet. The blower selected was a Jabsco Model 34744-0000 flange mounted blower. The 2.3 kg blower unit produces a maximum volumetric flow rate of approximately 0.05 m^3/s, roughly a third of that produced by the leaf blower. The current draw listed for the attached motor is given as 0.75 amps (Jabsco 2000).

b. *Power Supply*: The second design used a permanent laboratory power supply during the testing process. Because the blower did not include any integrated speed control, power for the unit was routed through a dimmer assembly, allowing flow rates to be adjusted smoothly between a no-flow condition and full power.

c. *Containment*: The smoke generation and containment unit for the second design was very similar to that used in the prototype, with the chamber body consisting of a wood framed plywood box with dimensions 29 cm x 30.5 cm x 91 cm. The inlet and outlet openings were placed in the same manner as the openings for the prototype chamber. The flange mounting plate on the blower attached to the inside of the chamber, centered about the outlet connection. Rather than installing a loading port in the box, the research team replaced the plywood box top with a 29 cm x 91 cm sheet of clear polycarbonate; because the combination blower and containment system required no sealing, the top was simply placed on top but not fastened. This allowed the project team to observe movement of smoke through the chamber; once smoke depletion was observed, the lid was slid aside by several inches, a new cartridge was added to the chamber, and the lid was replaced.

d. *Other Components*: For this design, no changes were made to the conveyance system or the injection apparatus. No new seal materials were tested during this stage.

e. *Laboratory Testing*: This design performed poorly in laboratory testing. While the system did convey smoke to the injection apparatus under unrestrictive conditions, the ability of the blower to handle resistance to flow was minimal and flow rates were much lower than expected. Although this system clearly failed to perform in a satisfactory manner, its complete lack of smoke leakage indicated benefits of combining the blower and containment components.

III. Modified Combined System: The third major design iteration developed directly from the second design and could be considered a variation of this earlier design. However, because a completely new containment system was built and several variations were made on the new equipment, it is described here as a separate design.

a. *Airflow*: The modified combined system returned to the leaf blower used in the first design as its airflow source. While the actual blower mechanism did not require modification, the project team had to remove the unit's handle and inlet guard so that it would fit into a smoke chamber of similar dimensions as the previous box.

b. *Power Supply*: The modified combined system also used a permanent laboratory supply for testing. Although the blower unit included a two-position speed selection switch, including the blower in the box rendered the switch inaccessible. As such, the power supply for this design was also routed through a dimmer assembly for speed control.

c. *Containment*: The containment unit for this design was similar to that used in the earlier combined system, consisting of a 28 cm x 32 cm x 91 cm wood framed plywood box with inlet and outlet ports on opposite ends and an upper surface consisting of polycarbonate sheeting. Because the leaf blower did not have a built-in mounting plate, a wooden frame was constructed inside the containment unit to hold the blower in place and elevate the blower inlet above the floor of the chamber.

d. *Other Components*: For this design, no changes were made to the conveyance system or the injection apparatus. The project team did test a new material during this stage. Various thicknesses of fiberglass insulation were tested as potential seals due to the high compressibility of the material, but the highly porous nature of the insulation proved to be a very poor seal for surfaces of high relief.

e. *Variations*: The design team attempted to several variations on this unit with regard to the cartridge loading procedure. Several different loading tees were installed at the inlet of the smoke chamber to allow for more rapid loading of cartridges; however, all of the tee configurations tested severely limited airflow and resulted in significant smoke loss due to deposition on internal surfaces.

f. *Laboratory Testing*: The modified combined system performed quite well in most aspects of the laboratory testing process. Smoke production and airflow were comparable to that produced by the prototype, while the internal blower system eliminated the smoke leakage which had caused problems with the first design. The modified combined system also offered considerable ease of implementation, reducing total size and the overall number of components for transport and assembly. Unfortunately, the enclosed design did not permit for proper cooling of the blower and prevented the unit from operating continuously for more than ten minutes without a severe drop in performance.

IV. <u>Side Chamber System</u>: The fourth major design concept constructed for the project departed from the directly in-line component approach of earlier designs, although it is essentially a modification of the side canister configuration (in-line chamber configuration D) presented in the first project report. These changes were made to facilitate more rapid changing of smoke cartridges while improving containment during reloading. Details of the design are presented below.

a. *Airflow*: The side chamber system utilized the same leaf blower apparatus as the first and third designs. An open wooden frame elevated the blower approximately three feet from the ground, reducing unnecessary flow resistance at the blower inlet.

b. *Power Supply*: The research team used a permanent power supply for laboratory testing, while field testing utilized the same generator apparatus as the prototype. For both laboratory and field experimentation, power was routed through the dimmer assembly built for the modified blower/containment system. However, lower speed settings were only used for minor troubleshooting; all testing was carried out at the maximum speed setting.

c. *Containment*: As stated earlier, the side chamber system departed from the in-line chamber approach used in other iterations. The main body of the containment unit consisted of a 7.6 cm diameter (3") pipe with inlet and outlet connections at opposite ends. Two vertical loading chambers connected to the bottom of the main pipe through tees located along the main line. Smoke cartridges could be inserted into the loading chambers through an access port at the chamber bottom; when not in use, the ports were sealed with a threaded cap. A viewing window mounted in the main line near the outlet enabled the project crew to monitor smoke movement and determine when to load a new cartridge.

d. *Injection*: For the side chamber system, the injection apparatus used in earlier designs was retained but underwent minor modification. The injection canister was removed from the front plate of the injection apparatus to provide a greater surface area for sealing against the rock face.

e. *Seal*: Due to the long curing time of the urethane sealant used for prototype testing and the poor performance of closed-cell foam and fibrous insulation, the design team chose a malleable modeling clay as a sealant material. This clay provided an easily-removable, reusable seal which performed well in both laboratory and field testing. Additionally, implementation time for the clay seal was far less than for the urethane foam.

f. *Smoke Source*: Due to the need to increase smoke density and to decrease the frequency of reloading, the project team chose to abandon the smaller Model RC 104 smoke cartridges in favor of a large cartridge with a longer burn time. The new cartridge selected was the Model S107 cartridge, with approximate smoke yield of 510m^3 and a burn time of roughly eight minutes. Results of field testing by the project crew indicate positive performance by these cartridges, with high smoke yields and burn times up to 10 minutes.

g. *Variations*: The initial configuration for the side chamber system utilized a more complex vertical loading chamber arrangement. The loading chambers were initially much longer, with valves for each chamber to allow loading without venting smoke-laden air. However, preliminary testing showed that the longer chambers trapped all of the smoke. As such, the vertical chambers were shortened until smoke trapping was reduced to an acceptable level.

h. *Laboratory Testing*: The side chamber system performed extremely well during laboratory testing, producing as much smoke as the prototype system while offering a much better loading mechanism and the ability to monitor airflow through the system. During media column testing, the system conveyed smoke through a column consisting of 60 cm of coarse stone, 30 cm of coarse gravel, 30 cm of wet sand, and 5 cm of cedar leaf litter.

I. <u>Initial Test</u>: For the initial test, the prototype system was assembled in the trench with only the generator remaining outside of the trench. The injection apparatus was centered around flow outlet A_1 on the trench face and pressed into place using a wooden beam and a bottle jack braced against the opposite wall of the trench. Urethane foam was applied around the contact of the injection head and the trench face and allowed to dry, after which the system was switched on and the seal was tested using small smoke cartridges. Additional urethane foam was applied to leak locations and the testing process was repeated until all leaks were sealed. The system was then switched on and loaded with smoke cartridges; the system was run for approximately seven minutes before being shut down due to smoke buildup in the trench from smoke emergence from flow outlets on the trench face.

II. <u>Second Test</u>: For the second test, the side chamber system was assembled in the trench with the generator remaining on the outside of the trench. A clay ring of two inches in thickness was built up around location A_1 and the injection apparatus was pressed against the trench face in the same manner as for the first test. The system was switched on and the seal was tested using small smoke cartridges. Additional clay was used to seal all leaks. After all leaks were eliminated, the system was loaded with the RC104 cartridges used with the prototype and allowed to run for ten minutes, during which smoke emergence from other flow outlets in the trench face was monitored. All locations producing smoke were then covered with clay and the system was restarted using large S107 cartridges. The system continued to operate for 20 minutes, after which the side chamber system failed due to warping caused by the heat generated by the large smoke cartridges. The side chamber unit was quickly replaced with the prototype chamber and the test was restarted using the large cartridges. Total test time using the prototype chamber was 20 minutes. See Appendix C for images of field testing and results.

I. Flow Path Interconnection:

a. *Results*: For the first test, smoke injected into location A_1 was observed emerging from locations A_2, A_3, and A_5 in Region A and locations B_2 and B_3 in Region B (see Appendix D). Response time was inversely proportional to distance from the injection point, with nearby A_2 and A_3 responding within 20 seconds, A_5 responding in approximately two minutes, and B_2/B_3 responding after five minutes. Outlet size appeared to play a subordinate role in outlet smoke production as compared to injection to proximity. Although the largest outlet (A_5) produced the greatest amount of smoke, the B_2/B_3 conduits produced far less smoke than the much smaller fractures in Region A.

Results from the second test differed somewhat from those generated in the initial field test. For the second test, smoke emerged from the same three locations in Region A, with near-simultaneous emergence of smoke from outlets A_2 and A_3 and later emergence from A_5. Response times were much slower than for the first test, with smoke emerging from A_2 and A_3 after approximately thirty seconds and from A_5 after five minutes. Overall smoke production/density was also reduced; while A_2 and A_3 were almost unchanged in smoke production, the A_5 outlet, which dominated flow for the first test, produced only faint traces of smoke. No smoke was observed from any location in Region B.

b. *Discussion*: Give the results of the flow path interconnection tests, it is quite clear that some of the preferential flow paths which contribute lateral subsurface water flow to the trench are interconnected. This possibility had been considered likely in the past. Data from earlier dye tracer studies at the plot indicate several locations in Regions A and B which connect to similar plot surface locations; locations A_1, A_2, A_3, B_1, B_2, and B_3 all transmit water from both the forward portion of the plot and the area around the tree in the center of the plot. Several locations also displayed similarly-timed responses to rainfall application, suggesting that the flow networks had some degree of interconnection. However, the emergence of smoke from outlets in the trench face proves at least some degree of interconnection exists. Although this information is of interest to the major research projects at Honey Creek, one must note that while hydraulic interconnection has been demonstrated, air and water are very different fluids with significant differences in behavior. While water will tend to flow downward from the plot surface, the more readily apparent buoyancy effects of the warm, smoke-laden air may allow it to rise into void spaces not normally accessed by water.

While both tests demonstrated physical connection of subsurface flow paths, the differences in response times and locations also require consideration. The simplest explanation would be that the system used for the second test was itself inefficient in conveying air and smoke through the system. However, this seems unlikely since laboratory testing showed that the second system could rapidly convey smoke through a highly restrictive media column. Given the size of the smoke producing outlets and the rapid rate of water movement through the subsurface during rainfall, it is probable that these conduits themselves are less restrictive than the media column. Because antecedent moisture conditions were higher for the second test, it is possible that some portions of conduits were filled or nearly filled with water in a ponded condition, reducing the size and number of flow paths available for air movement.

Recent observations of the trench under field conditions suggest that failure of smoke to appear from the B_2/B_3 area may represent an actual change in conduit structure rather than simply water ponding. While this area once produced the majority of the flow into the trench for simulated rainfall events, for recent events it has produced little flow, while flow from A_1 has increased dramatically. Alteration of the flow paths contributing to B_2/B_3, possibly from sediment clogging or soil pocket collapse, may explain the lack of movement of both smoke and water through these outlets.

II. Inlet Locations: Smoke emergence was not detected at any location on the plot surface for either test. Because airflow was maintained through the tracer units during testing, there are three possible explanations for the lack of smoke emergence which must be considered:

a. *Smoke Loss*: The first is that air may have in fact moved from the injection point through subsurface flow paths to the plot surface but without retaining a detectable concentration of smoke particles. A number of factors could prevent the suspended particles from reaching the surface. If the transit time of the air through the conduits was greater than the suspension time of the smoke particles, the particles may have settled out of the air stream. Smoke particles may also have adhered to the sides of the conduits and soil macropores without settling.

b. *Simulation Time*: Simulation time may have been insufficient for the injected smoke to reach the surface. If the simulation duration was less than the time required for air from the blower to move to the plot surface, no smoke would be observed.

c. *Alternate Paths*: Smoke-laden air may have traveled through flow paths to a location other than the plot surface. As with any fluid, the amount of air that flows through particular pathways is proportional to resistance to flow; the majority of the air will flow through the pathways that offer the least resistance. If the injected air encountered a less restrictive flow path before reaching the plot surface, it would take the easier path and little or no air would reach the surface inside the plot. This is essentially what happened during the first field test, when the least restrictive paths led back to the trench face rather than to the plot surface. This scenario seems quite likely for the second test as well, given the highly complex nature of the subsurface flow paths.

EVALUATION AND FUTURE WORK

Given the results of field testing at the Honey Creek project site, the research team has evaluated the feasibility of small, portable smoke tracer equipment as a tool for geologic research in the Edwards Aquifer region. While the equipment performed quite well in determining flow path interconnections and coordinated well with dye tracer testing results and field observations, it failed to reveal the surface flow inlets of the plot. Although the prototype and side chamber systems were physically capable of forcing smoke through restrictive media, complex field conditions and an unpredictable moisture regime seemed to limit applicability in complex, highly fractured settings. Since the equipment did achieve some of the objectives set forth and follows a precedent set by a larger scale study, the project team intends to continue the project but will likely shift the focus to even more discrete flow paths in a less fractured setting. It is also likely that future work will utilize the more powerful blower system currently in development by the project team.

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APPENDIX A

PROJECT CONSTRAINTS

PHYSICAL/PERFORMANCE CONSTRAINTS

-Adjustable from 1.5 ft to 6 ft in height

-Device performance independent of orientation (horizontal, vertical, angled)

-Lightweight components

-Easy assembly/disassembly in confined spaces

-Capable of forming an airtight seal against uneven surfaces (up to 2-inch differences in relief).

-Equipped for regulation/monitoring of air flow, pressure, possible smoke content

-Conveys air against resistance to flow caused by narrow flow path

-Power supply and blower can be located far from injector

-Injection ports are a modular component

-Unit contains fine adjustment to compensate for minor irregularities in rock surface

-All structural components designed for durability

ENVIRONMENTAL CONSTRAINTS

-No harm caused to cave formations or surface

-No permanent staining of rock surfaces

-Surface/groundwater quality is not impacted by smoke residue

-Cave dwelling species and surface plants are not harmed

-Natural water flow properties cannot be changed

SAFETY CONSTRAINTS

-Smoke source fully contained

-No smoke released into cave volume

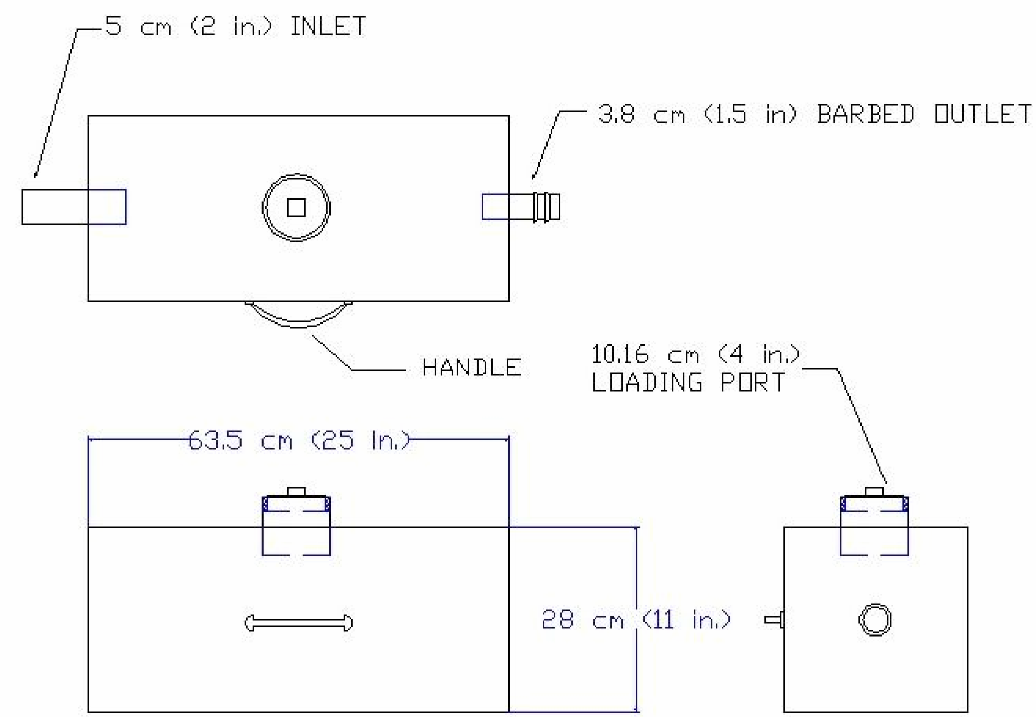
-Unit is capable of rapid shutoff

-Cave access is not blocked

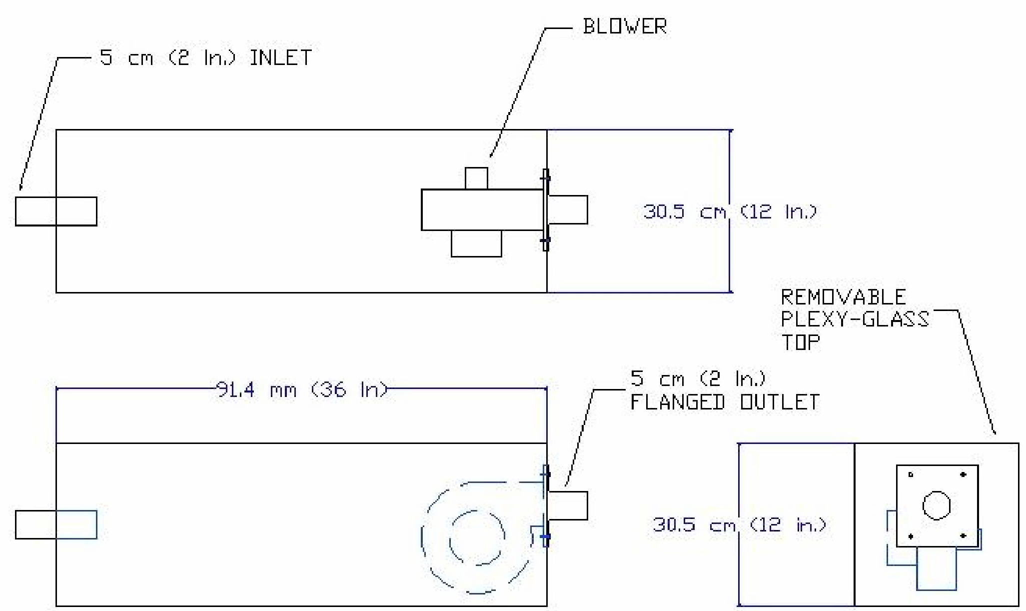
APPENDIX B

DESIGN DRAWINGS

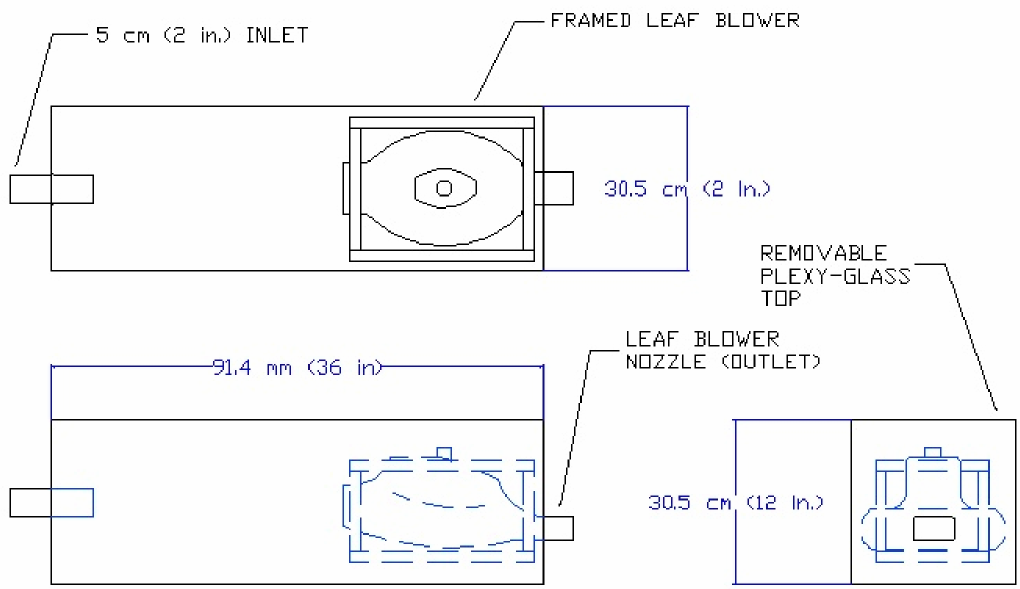
I. Prototype Design



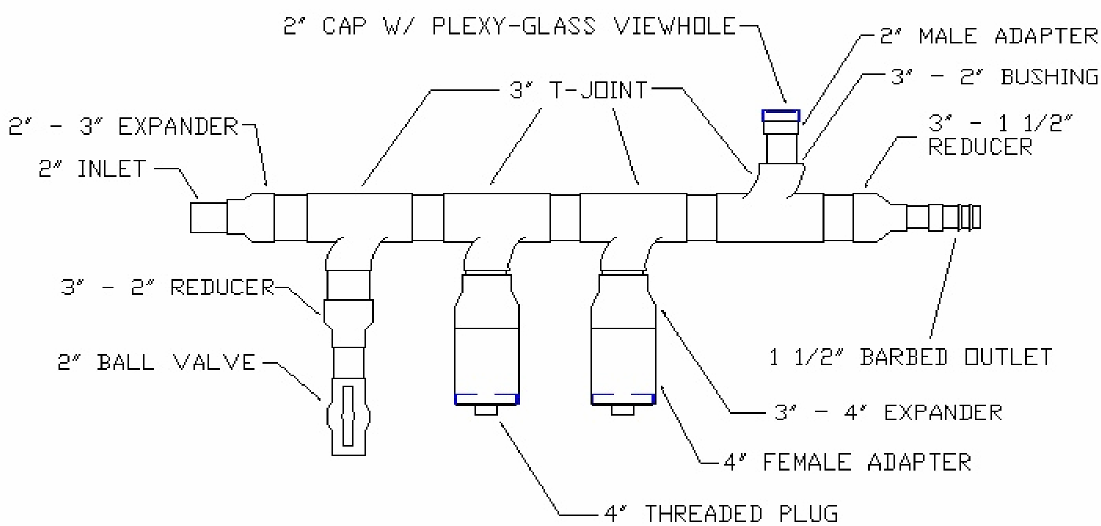
II. Combined System



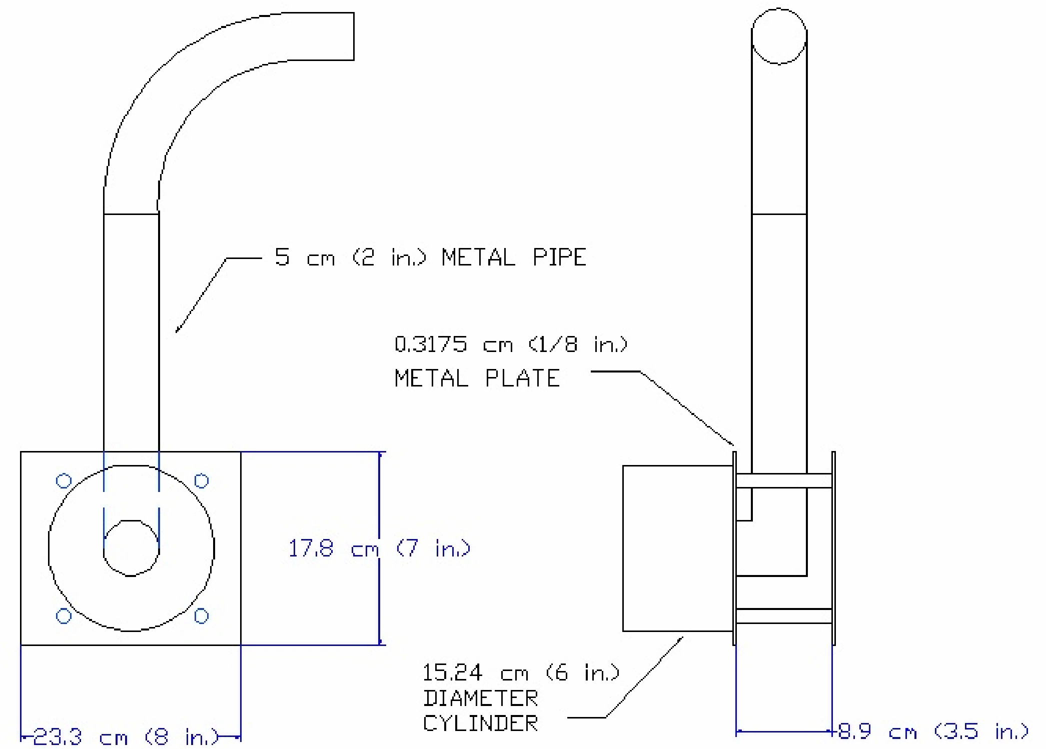
III. Modified Combined System



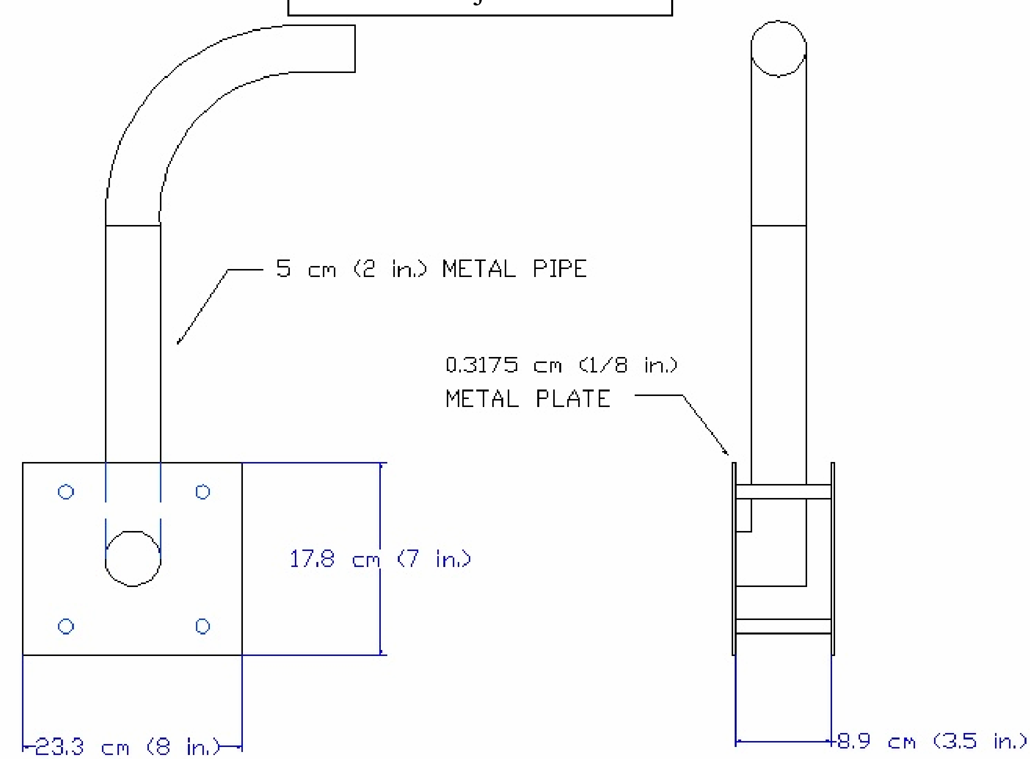
IV. Side Chamber System



Original Injection Head



Modified Injection Head



APPENDIX C

FIELD TESTING

Injector apparatus in the trench

Injector apparatus in the trench

Close view of injector

Sealant application

Jack apparatus

Smoke chamber after test

Smoke emergence from A5

Smoke emergence from A3

Another view of A3

Region A

Smoke emergence from B2/B3

Another view of B2


Side chamber system in trench


Cartridge loading


Trench evacuation

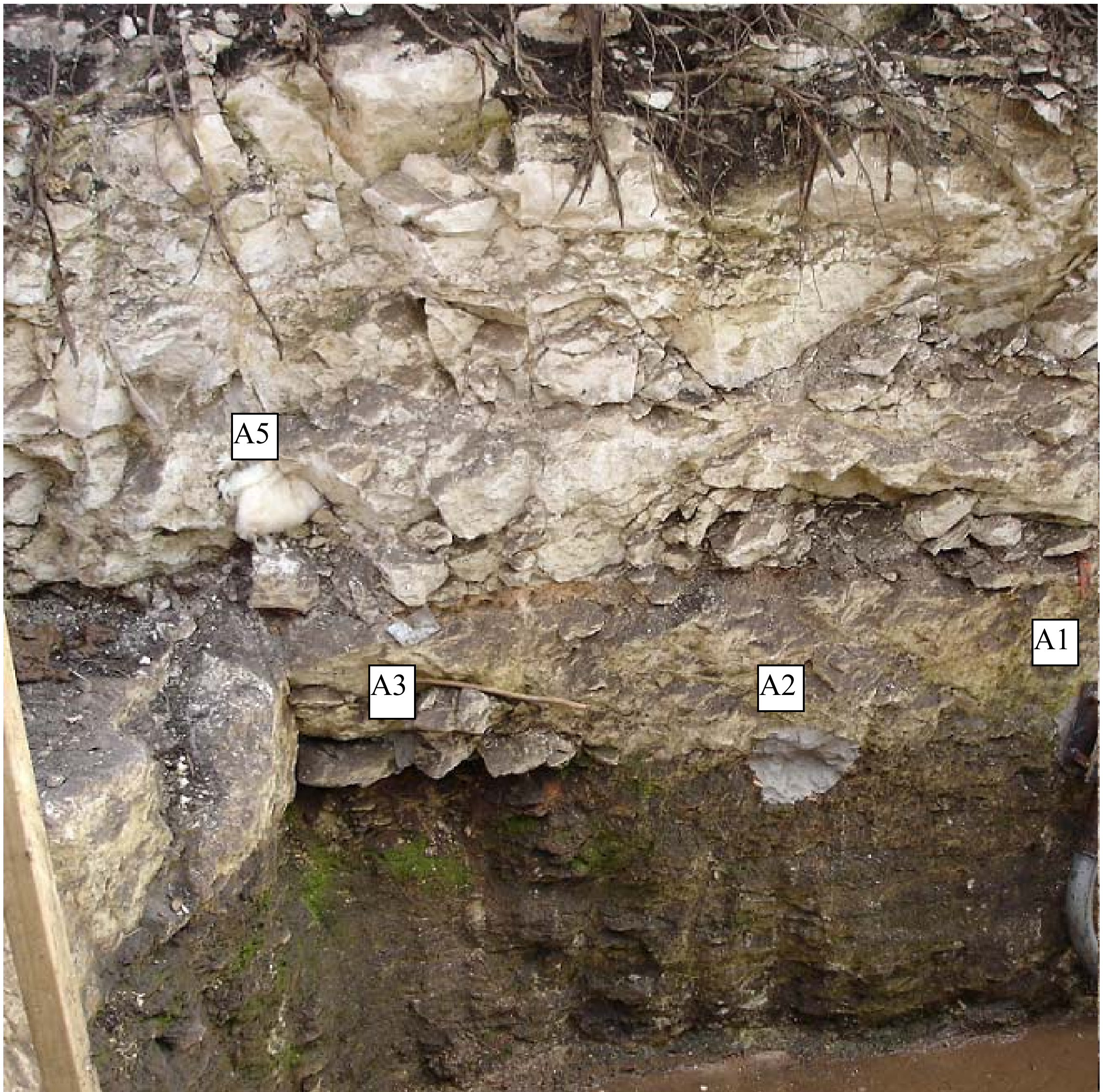

Clay sealing ring


Seal and injection head


Seal functioning after test

APPENDIX D

OUTLET LOCATIONS



Smoke Injection and Emergence Locations (Note: Region A only)