RESEARCH AND DEVELOPMENT OF EFFECTIVE SUSPENDED SOLIDS REMOVAL FROM STORMWATER RUNOFF IN COLLECTION SYSTEMS USING IN-LINE LAMELLA PLATE SEPARATORS

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ABSTRACT

Many of the problem pollutants are particulate-bound in storm water runoff. Test results indicated the following: (a) soil disturbance increased the TSS and turbidity in the runoff; and (b) correlations were observed between TSS and particulate runoff concentrations of chromium, copper, and zinc, indicating that solids removal may reduce total metals concentrations. The first concern when investigating innovative treatment methods is determining the needed level of stormwater control. Specific treatment goals usually specify about 80% reductions in suspended solids concentrations. In most stormwaters, this would require the removal of most particulates greater than about 10 μm in diameter, which is about 1% of the 1 mm size to prevent sewerage deposition problems.

Numerous manufacturers have developed proprietary devices to treat stormwater runoff. These devices have been designed to treat one or more of the common stormwater pollutants – solids, metals, oil and grease, nutrients and bacteria. The ability of inclined cells (lamella plates) to provide excellent treatment of stormwater for a variety of pollutants was demonstrated by Pitt et al. (1999) in the report on the multi-chambered treatment train (MCTT) at the University of Alabama at Birmingham.

Terre Hill Concrete Products is sponsoring a research project at Penn State Harrisburg. One of the pertinent questions to be answered during this research is:

> At the planned flow rates, what is the removal efficiency for suspended solids, particles less than 50 microns, and particles less than 10 microns? How is the influent flow rate dependent on the influent solids concentration and particle size distribution?

Prior research has shown that combining treatment technologies provides the best overall treatment efficiencies. The Hydrodynamic Separator, named "TERRE KLEEN™", has been designed to efficiently guide the storm water flow through the unit and enhance the gravitational settling of the entrained particles in such a way that flow patterns are virtually in the opposite direction of the pull of gravity. Inclined plate cell technology offers five to ten fold increase in efficiency compared to conventional settling and swirl settling technology because of the increased area of settling and reduced depth of settling. A high repetition of plates can lead to a basin size reduction to 10%-20% of conventional settling area requirements. The primary separation of solids will take place in a receiving chamber where oils and

large debris float or sink. A baffle wall and optional screen separate the inclined plate cells located in the secondary chamber. It is important to note that the bottom of the inclined plate cells is at an elevation that resembles a water condition where turbulence is the main cause in particle suspension. Those particles will settle as the water flows upward at an incline in the settling cell.

The data from the MCTT testing by Pitt et al. (Dr. Clark was a member of that research team) indicates that inclined-cell settling has the potential to effectively remove solids and the associated pollutants. Many current technologies uses design flow rates of 100 gallons per square foot of projected settling area. The inclined cell technology of the TERRE KLEEN™ (and being tested by Penn State Harrisburg) is anticipated to meet and exceed these requirements with cost savings and finer particle removals can be achieved with a minor increase in equipment cost.

OVERVIEW OF THE STORMWATER RUNOFF POLLUTION PROBLEM AND OF THE RECEIVING WATER IMPACTS

During the first 18 years of the Clean Water Act (CWA), regulatory efforts aimed at pollution control focused almost entirely on point source, end-of-pipe, wastewater discharges. However, during this same period, widespread water quality monitoring programs and special studies conducted by state and federal agencies and other institutions implicated nonpoint sources (NPS) as a major pollutant category, affecting most degraded waters around the country. In February 1987, amendments to the federal CWA were passed by Congress and required states (Sections 101 and 319) to assess NPS pollution and develop management programs on a watershed-specific basis. The EPA published the Phase 1 stormwater discharge regulations for the CWA in the Federal Register on November 16, 1990. The regulations confirm stormwater as a point source that must be regulated through permits issued under the National Pollutant Discharge Elimination System (NPDES). The Phase 2 regulations were enacted in October 1999, requiring municipalities of 10,000 and greater to comply with stormwater control guidelines. Permitting under Phase 2 began in 2003.

The EPA reported that only 57% of the rivers and streams in the U.S. fully support their beneficial uses. A wide variety of pollutants and sources are the cause of impaired uses, but runoff from urban and agricultural sources dominate. Even in non-industrialized urban areas, metallic and organic contamination of local streams can be high. Unfortunately, bacteria concentrations, especially near outfalls during and soon after rains, are always very high in these small streams, although the health risks are poorly understood. Children, and others, playing in and near the streams therefore are exposed to potentially hazardous conditions. In addition, inner city residents sometimes rely on close-by urban waterways for fishing opportunities, both for recreation and to supplement food supplies. Sediment/suspended solids, by itself, also impair many beneficial uses of waterways due to the smothering of fish habitat and by blocking light from penetrating deep into the water column, thus changing the character of the stream. TMDLs in many areas of the country have been written for sediment. Patwardhan and Kreutzberger (2002) linked sediment loads to biotic integrity for developing clean sediment TMDLs.

<u>Runoff Pollutant Sources</u>. A number of studies have linked specific pollutants in stormwater runoff with sources. Runoff from paved parking and storage areas, and especially gas station areas, has been observed to be contaminated with concentrations of many critical pollutants. These paved areas are usually found to contribute most of the pollutant loadings of toxicants to stormwater outfalls. Polycyclic aromatic hydrocarbons (PAHs), the most commonly detected toxic organic compounds found in urban runoff, along with heavy metals, are mostly associated with automobile use, especially during the starting of vehicles.

Clark (2000) and Pitt, *et al*. (1995) reviewed the literature on stormwater pollutant sources and effects and also measured pollutants and sample toxicity from a variety of urban source categories of an impervious and pervious nature. The highest concentrations of synthetic organics were in roof runoff, urban creeks and combined sewer overflows (CSOs). Zinc was highest from roof runoff (galvanized gutters). Nickel was highest in runoff from parking areas. Vehicle service areas produced the highest cadmium and lead concentrations, while copper was highest in urban creeks (Pitt, *et al*. 1995). Most metals in stormwater runoff originate from streets and parking areas. Other metal sources include wood preservatives, algaecides, metal corrosion, road salt, batteries, paint, and industrial electroplating waste. One large survey (EPA 1983) found only 13 organics occurring in at least 10% of the samples. The most common were 1,3-dichlorobenzene and fluoranthene (23% of the samples). These 13 compounds were similar to those reported in most areas. The most common organic toxicants found have been from automobile usage (polycyclic aromatic hydrocarbons, PAHs), combustion of wood and coal (PAHs), industrial and home use solvents (halogenated aliphatics and other volatiles), wood preservatives (PAHs, creosote, pentachlorophenol), and a variety of agricultural, municipal, highway, and pesticides.

<u>Particulate-bound pollutants</u>. Many of the problem pollutants are particulate-bound in stormwater runoff, indicating that sediment removal could provide significant water-quality improvements. Furumai et al. (2002) studied the dynamic behavior of suspended pollutants and particle size distribution in highway runoff. Particle-bound heavy metals (Zn, Pb, and Cu) accounted for more significant pollutant loads than soluble fractions. Their content decreased with increasing total SS concentration in runoff samples. Caltrans monitored fifteen highway construction sites in order to assess the runoff quality (Kayhanian et al., 2001). The results indicated the following: (a) soil disturbance increased the TSS and turbidity in the runoff; and (b) correlations were observed between TSS and particulate runoff concentrations of chromium, copper, and zinc, indicating that solids removal may reduce total metals concentrations.

The fate and transport of metallic pollutants through a watershed were related to the characteristics of the solid particles to which they are bound (Magnuson et al., 2001). The particles most often associated with metal pollution were found to have nominal diameters of < 50 µm. Sansalone et al. (2001) showed that urban storm water levels of Zn, Cu, Cd, Pb, Cr, and Ni were significantly above ambient background levels, and for many urban and transportation land uses, often exceed surface water discharge criteria for both dissolved and particulate-bound fractions. The authors advocated a multiple-unit-operation approach to stormwater treatment.

Mosley and Peake (2001) characterized urban runoff from a catchment in Dunedin, New Zealand during base flows and storm flows from five rainfall events. Fe and Pb were found to be predominantly particle-associated (>0.4 µm) with concentrations increasing significantly at the beginning of storm run-off. In contrast, the majority of Cu and Zn was found in the <0.4 µm fraction prior to rain but a significant proportion was present in the > 0.4 µm fraction during the initial period of storm flows. Buffleben et al. (2001) monitored four storms in the watershed. The watershed is developed mostly with residential, commercial and light industrial land uses. They found that the suspended solids phase primarily transported the mass for five of the six metals studied: cadmium, chromium, copper, lead, and nickel. Arsenic was found primarily in the aqueous phase.

Previously-Developed Stormwater Treatment Devices

Many of the problem pollutants are particulate-bound in stormwater runoff, indicating that sediment control may be very effective in mitigating receiving-water impacts from stormwater. Caltrans monitored fifteen highway construction sites in order to assess the runoff quality (Kayhanian et al., 2001). The results indicated the following: (a) soil disturbance increased the TSS and turbidity in the runoff; and (b) correlations were observed between TSS and particulate runoff concentrations of chromium, copper, and zinc, indicating that solids removal may reduce total metals concentrations.

The first concern when investigating innovative treatment methods is determining the needed level of stormwater control. This determination has a great affect on the cost of the stormwater management program and needs to be carefully made. Problems that need to be reduced range from sewerage maintenance issues to protecting many receiving water uses. This treatment objective can be easily achieved using a number of cost-effective source area and inlet treatment practices. In contrast, much greater levels of stormwater control are likely needed to prevent excessive receiving water degradation. Specific treatment goals usually specify about 80% reductions in suspended solids concentrations. In most stormwaters, this would require the removal of most particulates greater than about 10 μm in diameter, which is about 1% of the 1 mm size to prevent sewerage deposition problems.

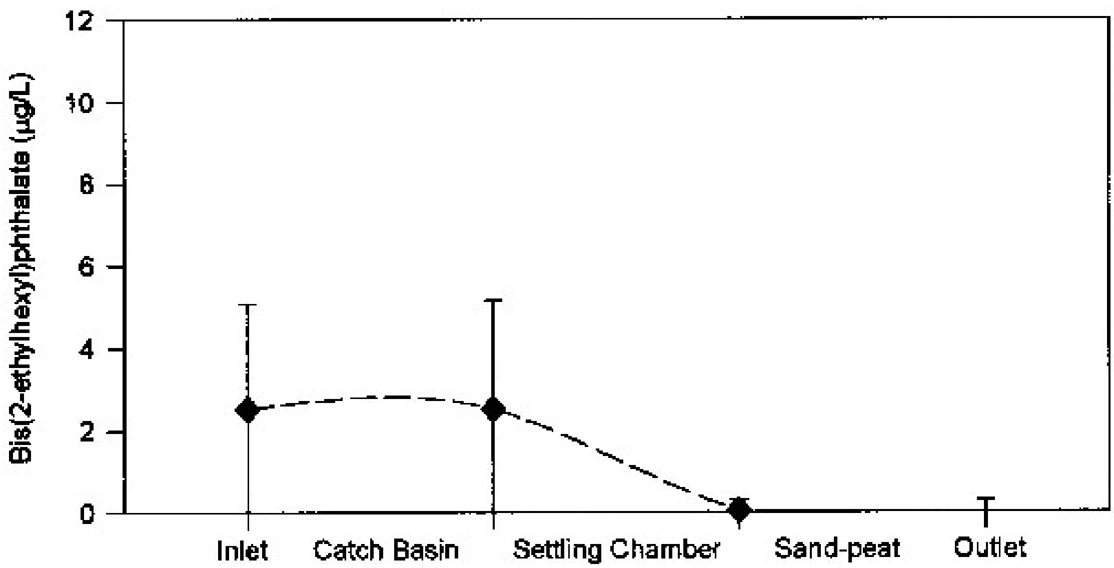
Obviously, the selection of a treatment goal must be done with great care. The Engineering Foundation/ASCE, Snowmass, CO conference held in 2001 included many presentations describing receiving water impacts associated with stormwater discharges (ASCE/Urbonas 2002). Similarly, Pitt (1996) summarized numerous issues concerning potential groundwater impacts associated with sub-surface stormwater disposal. These references illustrate the magnitudes and variations of typical problems that can be caused by untreated stormwater. Specific control programs will therefore need to be unique for a specific area due to these variations. Many conventional urban runoff control practices are available at the sources where the sediment is generated and at inputs to sewerage systems. These include infiltration devices (such as subsurface infiltration trenches, surface percolation areas, and porous pavements), grass drainage swales, grass filters, detention basins, street cleaning, and catchbasin cleaning. Other practices include those specialized for construction sites, such as site mulching and the use of filter fencing. Another important practice is the elimination of inappropriate discharges to sewerage through cross-connections. Outfall controls most commonly include wet detention ponds.

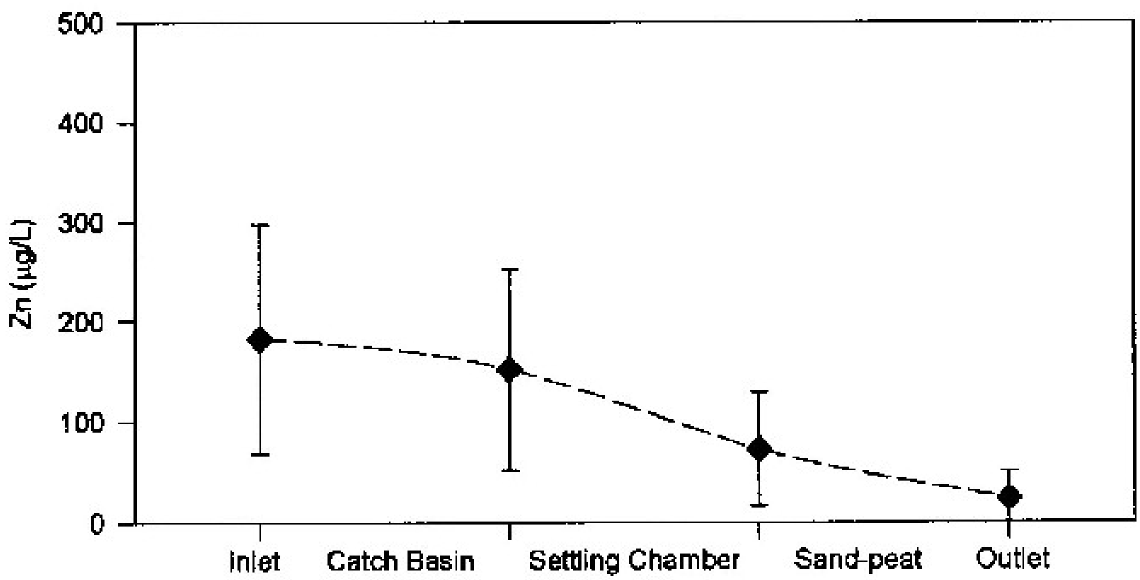
Components of a comprehensive urban runoff control program typically include structural devices such as detention ponds, grass swales, infiltration trenches, and other physical devices. The goal of this upcoming research project is to add additional tools to these other technologies for use in "ultra-urban" critical source areas. The target area for use of this particular device includes areas such as vehicle service facilities, parking areas, paved storage areas, and fueling stations. In prior studies and during the first phase of this research project, these areas were found to have some of the highest concentrations of toxicants compared to all source areas (Pitt, *et al*. 1995). Inclined-cell separators in an inlet device are especially suited for these locations as they can be contained in a subterranean unit directly consuming no land surface area. Space is extremely limited for these typically small areas and these critical source areas are therefore left with few alternatives.

The most common treatment devices for stormwater runoff from ultra-urban areas are small prefabricated separators intended to remove oils and solids from runoff. These separators are rarely specifically designed and sized for stormwater discharges, but usually consist of modified grease and oil separators. The solids are intended to settle within these separators, by free fall and the lighter oily fraction by counter-current or cross-current corrugated lamellar separation. Many of these separators have been sold for use along highways. These have been found to be greatly under-sized for the actual flows expected and they are not designed to be easily cleaned. In addition, the basic designs assume free floating oils that are relatively rare in stormwater. The major issue in this paper is the use of inclined cells to settle solids instead of floating oils.

INCLINED-PLATE UNITS FOR SOLIDS REMOVAL IN STORMWATER

The ability of inclined plates/cells to provide excellent treatment of stormwater for a variety of pollutants was demonstrated by Pitt et al. (1999) in the report on the multi-chambered treatment train (MCTT). The MCTT was designed to combine the benefits of a sump pre-settling chamber, lamella plates/inclined cells and a polishing filter. Typical results for the plate settlers are shown in Figure 1 for a representative organic compound (bis 2-ethylhexyl phthalate) and a representative metallic compound (zinc), as well as for total suspended solids. As the results show, statistically significant removals occur in the settling chamber. In fact, the polishing filter had very little polishing to do in the device. The stormwater runoff during these tests was typical of urban runoff. The site was a maintenance yard at the University of Alabama at Birmingham. Zinc is considered one of the more difficult metals to remove because it is typically not as well sorbed to the sediments. Therefore, to find a 45 – 50% removal of zinc indicated that removal of other metals would be significantly better because they are more closely associated with the suspended solids in runoff. A device that can remove TSS to acceptable levels is likely to have excellent removals associated with it for other pollutants of interest.





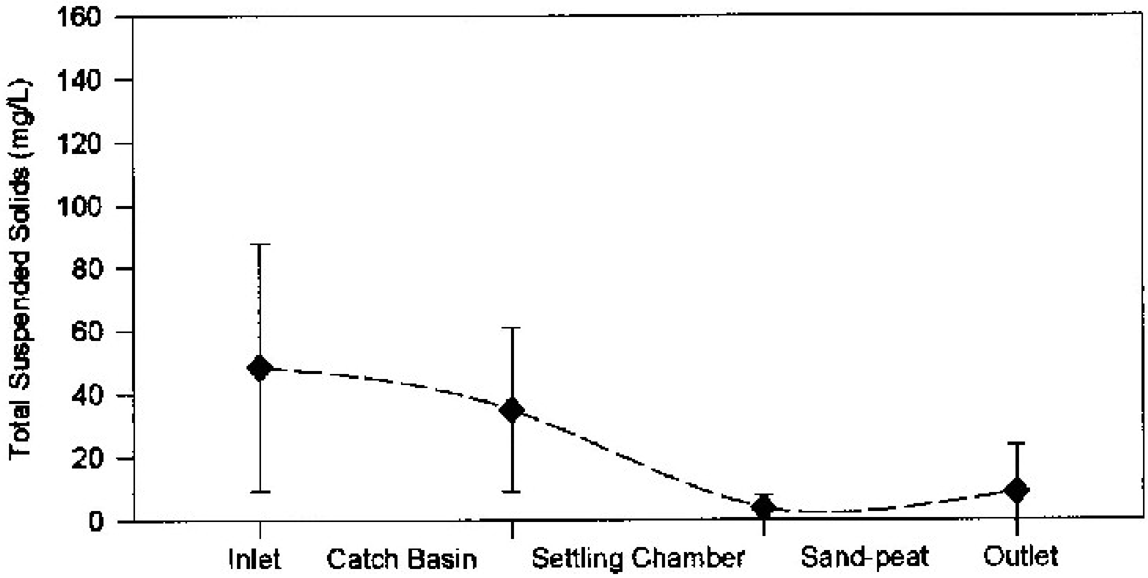


Figure 1. Removal efficiencies for the MCTT (Pitt et al. 1999).

The inclined cell settling chamber mimics the completely mixed settling column bench-scale tests previously conducted by Pitt, *et al*. (1995) and uses a hydraulic loading rate (depth to time ratio) for removal estimates. This loading rate is equivalent to the conventional surface overflow rate (SOR), or upflow velocity, for continuous-flow systems, or the ratio of water depth to detention time for batch systems. Compared to conventional detention devices, the retention of the settled material is enhanced through the use of inclined tube settlers which prevent scouring velocities from re-suspending previously settled particles. Inclined tubes (or plate settlers) increase solids removal by reducing the distance particles travel to the chamber floor and by reducing scour potential (Davis, *et al.*1989). The main settling chamber operates much like a settling tank, but with the tube settlers increasing the effective surface area of the tank. The increase in performance is based on inclined cells that overlap each other. Each cell forms the ceiling of the next cell, etc. The projected area of each base forms the settling surface of each cell. However, the horizontal distance between each plate is a fraction of the horizontal projection of the cell base. Hence, the efficiency in settling surface is obtained by this cell-packing arrangement. If the plates are relatively flat and close together, the increase in performance is greater than if the plates are steeper and wider apart. The effective increase is usually about 3 to 5 fold, and in the drinking water industry where this technology has been studied and optimized, the increase has been about 10 fold. The drinking water industry uses these to save on plant space, increase settling of the floc from the treated water, and ultimately to increase the filter run life.

<u>TERRE KLEEN device using inclined cell settlers</u>. The size of the particle removed is the essential element in minimizing the pollution potential of stormwater solids and the pollutants that are associated with them before the runoff is discharged back into the environment. Second, knowledge of the flow rate that a treatment device can handle to provide a given level of treatment is crucial. Effective treatment devices are capable of handling high and varied flow rates, all of which will be location- and storm-dependent. Third, in order for a device to be of interest in stormwater treatment, the land area that is required for the device should be minimized. In many cases, the urban areas that contribute the most pollution are the ones where land area to install an above-ground device is at a premium. A schematic of the TERRE KLEEN device is shown in Figure 2, and Figure 3 presents two pictures of the device model (the first picture of the complete model showing the behavior of the device – noting the large sediment

storage area below the plates to trap sediment between storms and the depth which will prevent resuspension of trapped particles; the second picture of the device from the side – again noting the amount of sediment trapped both in the sump area and in the sediment storage area).

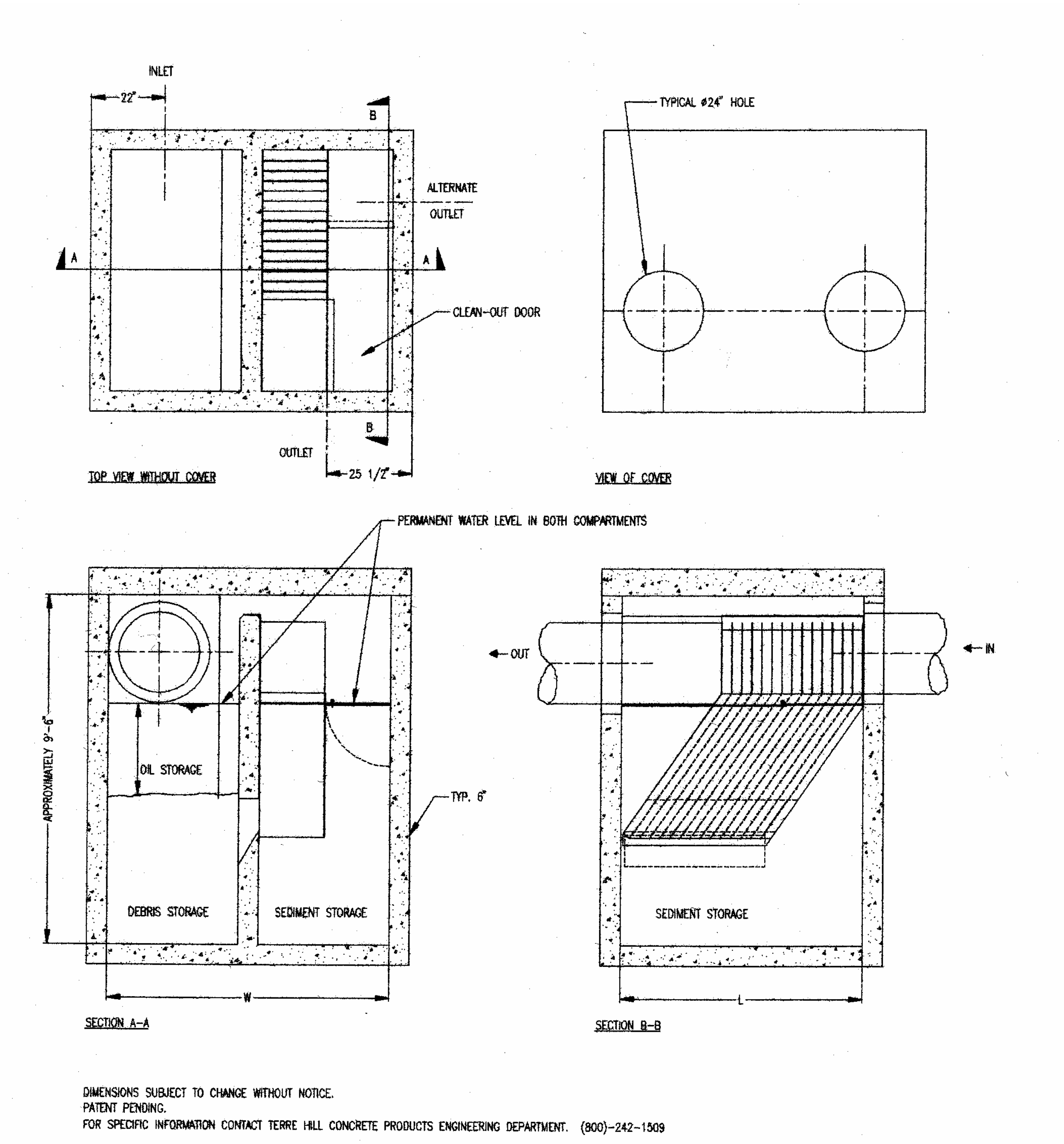


Figure 2. Schematic of the TERRE KLEEN device (patent pending)

Figure 3. Photographs of the model of the TERRE KLEEN device. Sediment storage provided in both the catch basin for larger particles, trash and other debris, and below the inclined cell settlers for sediment removed by the inclined cells.

The TERRE KLEEN device assembles debris and oil trap, baffle, screen, and inclined cells into a self-contained unit. The inclined cell technology is based on the new art taught in patent 3,706,384. It has been shown, through the research of Drs. Clark, Pitt and others, that a single treatment device which combines several treatment technologies into a single device is more effective than the use of a single technology for runoff treatment. The conceptual design of the unit provides for underground installation as an in-line treatment device. It may be applied at critical source areas or larger units may be installed in a storm sewer main to provide treatment for larger flows. Installation can be performed using conventional construction techniques and units can be designed to provide specific removal efficiencies based on the characteristics of both the typical flow and solids concentration to be treated.

The TERRE KLEEN device also addresses the third concern of being space-effective. This device is designed to be installed in-line in the storm sewer system. It is also designed to be installed below-ground. The ability to install the device below ground allows for the complete use of the above-ground space, and it will make it easier for the device to be retro-fitted into an already-existing storm sewer system.

The concern that has been raised about below-ground devices is the required maintenance interval and the ease of maintenance. This device has been designed to have storage space for sediment that is deep enough to prevent resuspension of captured material. This storage space also will allow for sufficient storage that frequent clean out will not be required. Part of the testing program will be to evaluate the size of the sediment storage. The device has been designed though to allow for easy access to all chambers for clean-out when it is required.

When reviewing this device from the life-cycle analysis perspective, this device should have an overall positive effect on the environment, i.e., the benefits of the device will well outweigh the environmental impact of manufacturing. Municipalities and developers are currently purchasing catchbasins as part of their infrastructure development and rehabilitation. In addition, many municipalities are going to be required to install a stormwater treatment in or at the exit of their collection system. This device has the benefit of being a minimal retrofit to an already-existing system. The ability to remove 80% of the solids (the goal of the regulations and of the TERRE KLEEN device), as described previously, will greatly benefit the environment by protecting habitat, by preventing the entry of particulate-sorbed pollutants into the receiving water where they may contact recreational water users, and by reducing the cost of creating clean drinking water.

The TERRE KLEEN models were developed to match current available technology but at a lower cost. It will remove the trash and other debris that enter the manhole in the catchbasin section of the device. At 100 gpm/ft^2 (of flow at the design storm), it will remove all particles 500 μm and larger and will remove a measurable fraction of particles smaller than 500 μm. The promise of this technology is the ability to compress the settling into an area approximately ten times smaller than a traditional detention basin. In addition, since most storms are smaller than the design storm, the anticipated removal efficiency overall is expected to increase because the flowrates into the device will be smaller than the design loading rate.

Although the inclined cell settling technology is proven to work and is used to treat potable water worldwide, this new application in stormwater treatment will offer efficient removal in a small footprint. It is also a feasible technology for retrofit applications. Testing of the device is planned for at Penn State Harrisburg. The testing protocols will follow the requirements for a device to be tested and performance-verified under the US EPA ETV Program for Wet-Weather Flow Treatment Technologies.

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