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Propane earth materials drying techniques and technologies

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Propane earth materials drying techniques and technologies

by

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MASTER OF SCIENCE

Major: Civil Engineering

Program of Study Committee:

Christopher Williams, Major Professor

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Iowa State University

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Chapter 1. Introduction

During times of wet weather, surface soils become wet or saturated through infiltration and adsorption of water to clay minerals. The excess water in soils weakens the soils and hinders their ability to be compacted. Thus, construction sites become unworkable. The excessive water in soil delays the earthwork portion of a construction project as present day construction equipment cannot operate in such conditions. To satisfy construction plans and specifications, the foundation soils must meet certain levels of compaction and be close to optimum moisture content. For soil that is too wet of optimum, a drying technique is necessary to reduce the water content of the soil. Whether the drying technique is to wait for the sun and air or to incorporate existing technologies is a decision based on schedules and economics.

The application of subbase drying has great benefits to the earthwork portion on the construction of commercial, industrial and residential buildings, and transportation projects. Although a number of soil drying methods exist, the transportation industry, specifically state departments of transportation and their contractors, would save valuable time and money if a propane based device existed that could expedite the drying of soil and decrease delays in the construction schedule.

The preparation of the soil material in the subgrade is a very important phase in road construction and contributes to pavement performance. “The top six inches of subgrade should be scarified and compacted to the desirable density near the optimum moisture content” (Huang, 2004) where pavement is to be placed. Having the ability to better control the moisture content of the subbase and subgrade materials would be of great value to transportation agencies and construction companies in terms of economics and time efficiency.

This project examined the technical and economic feasibility of using propane as a heating source to assist in drying wet subgrade, subbase and base earth materials in building foundation construction and transportation earthwork projects. A laboratory-based technical feasibility analysis was developed along with conceptual development of field equipment for a combined soil scarifier and propane heater. Additionally, the economic feasibility of propane-assisted drying of subgrade, subbase and base materials was evaluated.

This report examines:

- The need for soil drying on construction projects
- Background of present day drying techniques
- Feasibility of using propane to dry soil
- Types of soil that would benefit from a propane drying device
- Design and development of a propane fueled laboratory scale soil drying device
- Implementation of the laboratory soil drying device
- Statistical analysis of laboratory data
- Practicality and economic feasibility of a propane fueled field scale soil drying device

Chapter 2. Background & Literature Review

For as long as people have been building on natural soils, water has always been the largest obstacle in terms of constructability and time efficiency. To the present, the most common method to dry an area of soil is simply to wait, relying on nature to dry to the soil out. Unfortunately, this usually means waiting for many days. Such time can be costly to everyone involved in the project: the owner, contractor and the laborers. On major highway projects, contractors are contractually obligated to perform their duties in an allotted amount of time. Delays due to weather, flooding and other unforeseen events may cause the project to become off schedule and create undue hardship for these controlling parties. In most cases, delays caused by weather can be negotiated successfully but still present a burden on the schedule and thus the owner/agency. On most construction projects, time constraints preclude relying on nature.

Case Example

An example of such a problem occurred on the construction of the Honey Creek Resort in southern Iowa during the summer of 2008. Located within state park boundaries, wastewater lagoons were required two miles from the resort and the environmentally protected lake. Construction of the wastewater lagoons was performed entirely by a large earthwork contractor. The project fell weeks and months behind schedule because the soil was too wet to achieve the required moisture and compaction specifications of the Iowa Department of Natural Resources (DNR). The soil on site was suitable for lagoons but there was an increase in the average rainfall during the spring and summer of 2008 in Iowa causing the high plastic clay to absorb enough water to become unworkable and unable to achieve compaction even with modern day construction equipment.

Due to the environmental protections surrounding the state park, chemical stabilization was not an option so the only technique available to the contractor and DNR was to wait for the sun and air to dry the soil. Daily density and moisture checks, performed by a third party testing agency, were repeatedly failing specification. Three to four days would have to pass in the hot July sun before the soil was dry enough to use a sheepsfoot roller for compaction. The problem was there were not many three to four consecutive day periods without rain that summer.

The project ended up being delayed for months by the wet soil so the DNR had to ultimately change the specification to permit a higher range in moisture contents and compaction densities that would ensure the opening of the resort would not be delayed. Deviation from the original specification produced lagoons with soil that is less dense than the norm for this type of application and allows the wastewater to permeate through the soil and into the ground water. Had there been a soil drying device available to the contractor and DNR, deviation from the specification would have been avoided, and a higher quality finished project would have been the reality.

Chapter 3. Soil Water Density Relationships

All soils have a soil water density relationship, in which the dry density of the soil changes as the water content of the soil changes. This relationship is also dependent on the amount of compaction energy input to the soil. A key concept of this relationship is that of the optimum water content, which is the water content when the soil is at its maximum density. To achieve good compaction and a stable foundation the water content has to be close to the optimum level, usually plus or minus two percent. Figure 1 (FWHA, 2007) shows an example of the maximum densities and optimum moisture contents of several common gravels, sands and clays.

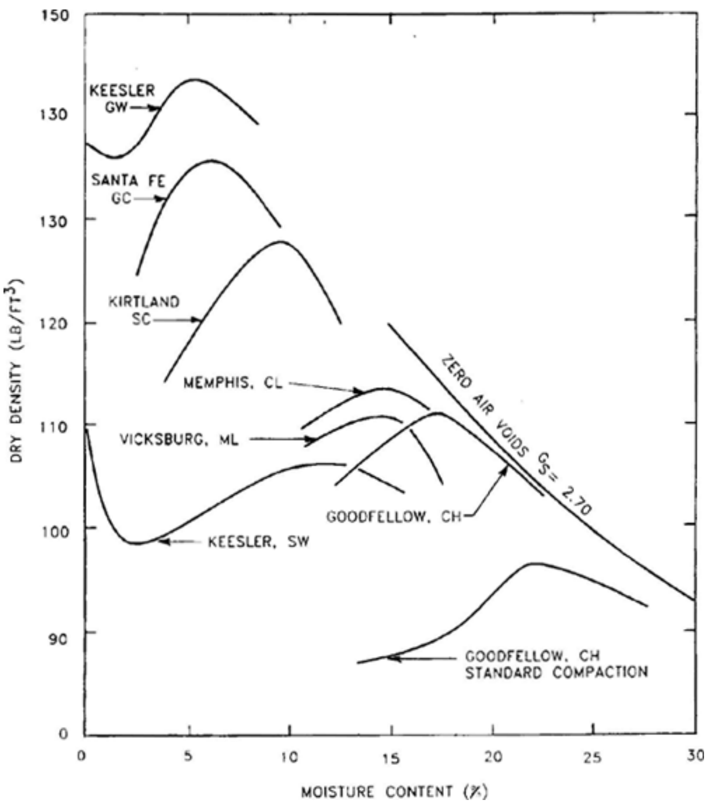

Figure 1. Example of Moisture Content and Density Curves (FWHA 2007)

The addition of water to soil that is being compacted softens the soil because the lubricated particles slide along each other and into a denser state (Das 2002). The dry unit weight increases during compaction when the moisture content is increased. After the initial addition of water and the accompanying increase in dry unit weight, there is an amount of water that, when added to the soil, decreases the dry unit weight. The peak density occurs at the optimum water content. This can be found by running a standard Proctor test (ASTM Standard D698) (ASTM 2007) which involves the preparation of several soil samples at varying moisture contents and compacting the same volume with identical mechanical energy. The samples are then weighed, moisture contents determined and a graphical curve created to determine the maximum density and optimal moisture content. Equation 1 shows the relationship of dry unit weight and moisture content.

$$\gamma_d = \gamma / (1 + \omega(\%) / 100) \qquad \textbf{Eqn. 1}$$

The theoretical maximum dry unit weight occurs when there are no air voids and the sample has a degree of saturation of 100%. This is represented by the zero air void curve in Figure 1. The proctor curve cannot go above this curve, because it would signify over 100% moisture, so the maximum dry unit weight and optimum moisture content are found at the peak of the proctor curve. For the example in Figure 9 the maximum dry unit weight is 103 pounds per cubic foot and the optimum moisture content is 18%.

Every state Department of Transportation has specifications for the compaction of subgrade and subbase materials. The Iowa DOT specification (Section 2109) for the compaction of a natural subgrade material requires that the soil is not 6% drier than optimum and have a dry unit weight that is 95% of maximum density (Iowa DOT, 2009). For a soil aggregate subbase material the Iowa DOT specification (Section 2110) requires only a visual inspection for moisture and a dry unit weight of at least 95% of maximum density as determined by Materials Lab Test Method No. Iowa 103 (similar to the standard Proctor test). The specifications for the placement of a granular subbase requires that the material is uniformly moist prior to and during compaction (Section 2111). The compaction requirements for a granular subbase material must be passed over a maximum of three times by a steel drum or pneumatic roller.

The Iowa Statewide Urban Design and Specifications (SUDAS) set standards for uniformity in urban planning and design. The section on compaction of embankments in the SUDAS manual states that the moisture content of the embankment material must be determined to ensure there is no excess moisture to allow for satisfactory compaction (Iowa SUDAS, 2009). This section in SUDAS also states that “delays from the ordering of moistening or drying will be at the Contractor’s expense”.

Wet Soils

In clayey soils when there is excess water above optimum it is impossible to reach the desired density and the excess water has to be removed (Rossiter, 2007). Free draining granular soils have optimum moisture contents that are unrelated to their density. Clayey soils with a plasticity index of up to 30 are ideal for this experiment because of their ability to absorb and hold water for a prolonged period of time. The fat clay soils are the most troublesome in the field causing lengthy time delays when there has been extended periods of rain or other moisture causing weather events.

Compaction Control

Compaction control is often the most important factor in controlling the behavior of earthwork projects. Compaction is the removal of air from the soil by mechanical energy. Loose soils must be compacted to increase their density, strength, bearing capacity, shearing resistance, deformation resistance, and stability. Generally, mechanical compacting equipment, such as a sheepsfoot roller, is used to compact clay soils, and vibrating plates are used to compact sands.

Acceptable compaction cannot be achieved until the water content is close to the optimum level. The soil to be used for a building foundation or for a subbase for a roadway must have close to optimum water content or compaction will be unsatisfactory. It is almost impossible to achieve acceptable compaction if a soil exhibits a water content that is 4% above optimum. Compacting a soil that is one or two percent below optimum can achieve the desired results but more mechanical effort is required compared to a soil that is one or two percent above optimum.

Some beneficial effects of a well compacted soil result in thinner pavement sections being required for road projects and steeper side slopes for embankments. By reducing air voids and displacing water, compaction will reduce the tendency of a clayey soil to fill with water resulting in higher shearing strengths.

Chemical Soil Stabilizers

Current construction practices for drying soil that has a water content above the optimum level include the addition of fly ash, lime, Portland cement and the commonly used method, sun and air (Rossiter 2004). Tillers and scarifiers may also be used to incorporate soil stabilizers or on their own to mix and air dry the soil. Even with today's technologies for drying soil, there exists a need for a drying device that minimizes chemical and environmental changes to the soil in an economic and timely fashion.

Projects that incorporate fly ash or lime generally are on a strict schedule and have a greater budget at their disposal. Some commercial, industrial and road projects will opt for the sun and air-drying method if time permits because it requires no expenditures except in lost time. Contractors are able to estimate the costs associated with purchasing lime or fly ash versus any penalty for project completion and make their decision based on economics. Only when the contractor and/or owner know the economic feasibility will a method for soil drying be determined.

The methods for drying subbase material that include the addition of soil stabilizers such as fly ash, lime and Portland cement are costly, time consuming and sometimes even impractical. Table 1 shows a cost comparison of commonly used chemically stabilizers and soil replacement (Beeghly 2003). The area of soil that requires drying and/or stabilization is calculated and the required percentage of stabilizer is determined by the level of moisture in the soil and strength requirements. Five to ten percent soil stabilizers are most common to construction projects in the United States. As can be seen from Table 1, avoiding soil replacement is advisable because it is the least economical. Sun and air drying have no cost except where schedule conflicts and penalties exist. Besides soil replacement, there is not an option for drying soil where chemical stabilizers are not permitted and schedule is important. The times of incorporating the soil treatments are assumed to be equal. The current rate in Iowa for drying soil with one bulldozer and a trailing disk is $155 per hour (Construct 2010).

Table 1. Cost Comparison of Common Soil Stabilizers and Drying Techniques (Beeghly 2003)

Soil Treatment	% of Soil Volume	US$/ft^3
Portland Cement	6	0.30
Lime	6	0.24
Fly Ash	6	0.03
Lime & Fly Ash	3 & 6	0.15
Undercutting / Backfilling	NA	2.60
Sun & Air	NA	0.00*

* Does not consider schedule penalties and lost work by contractor.

The United States Environmental Protection Agency has recently proposed regulation of coal combustion waste, including fly ash (AGC, 2010). If fly ash becomes classified as a hazardous waste, it will increase in cost and be eliminated from some projects because additional environmental assessments will become necessary.

Plasticity index is a measure of how much water a soil can absorb before becoming liquefied. The higher the plasticity index the more plastic and weak the soil is. Lime’s chemical reaction with the soil can cause a reduction in the plasticity index. Soils with a plasticity index of over 25 need additional stabilizing methods to ensure a workable foundation (National Lime Association, 2004).

The addition of lime or Portland cement causes permanent stabilization of soil that may be undesirable for some applications such as environmentally sensitive areas or where drainage is important. A good soil for lime use is a soil that has over 25% passing a number 200 sieve and a plasticity index of over 10. Portland cement is a good choice for soil stabilization where the plasticity index is below 20 (Beeghly 2003).

The previously discussed methods of the addition of chemical stabilizers and tilling are both well practiced in the construction industry but there exists a need for a more speedy, less expensive and eco-friendly alternative to alter moisture content for optimum compaction. While mechanical compaction alone may be satisfactory for soils near optimum moisture content, soils with excessive moisture need evaporation through a drying process. The drying practices today that involve tilling and scarifying still require sun and air drying with lengthy time delays.

Propane to Dry Soils

The two required mechanisms for evaporation of excess moisture are a source of heat energy for vaporization and a transportation component such as wind (Penman 1948). In the natural environment, this is accomplished by sunlight and air but is dependent on lengthy time intervals. To expedite the drying process a device that concentrates both heat and air to the desired location would be beneficial. The most practical way to combine heat and wind in the laboratory and/or field, with propane being the fuel source, is a forced air heater capable of producing adequate heat energy (BTU's) to reduce moisture content in the soil closer to optimum level.

The need for a reliable soil drying technique exists and would be well received in the earthwork construction market. All soil types could benefit from a drier device, but fine grained soils, with greater than 20% passing the number 200 sieve, would have the highest benefit in terms of drying times. The incorporation of a drying device that has minimal impact to the environment, using a propane fuel, could provide agencies and contractors with an eco-friendly alternative to ensure timely project delivery.

The use of a forced heated air system would eliminate the need for chemical additives and decrease the environmental impact on the soil. Propane is safe, non-toxic and eco-friendly and causes no contamination if accidentally spilled into the air, soil or water. In the liquid state, propane can cause burning and freezing because of the low temperature of -44F degrees. Propane usually exists in its liquid form when the pressures are very high, such as in storage tanks. Application of heat from propane to soil does not contaminate or chemically modify the soil. This could be a great advantage in suggesting alternatives for soil drying to the ever increasing sustainability movement.

Other environmental benefits of using propane versus chemical stabilizers include the fact that it will not damage underwater ecosystems. This can be of value when a project is near a wetland, water table or some other type of sensitive water boundary. Propane does not contaminate drinking water if it were to be spilled onto the soil and is not considered an air pollutant. Even propane vapor is harmless if inhaled by living organisms.

Propane is also a very safe fuel with accidents being extremely rare. In the five years between 2000 and 2004 the 9.4 million homes that used propane for heating reported only 1390 fires and 23 deaths (Propane 101, 2010). Propane's characteristics of a clean burning and safe fuel make it an ideal choice for the application of soil drying.

Figure 2 shows the different energy contents of seven popular fuels (LPG =liquid propane gas). Liquid propane gas is third in energy content behind gasoline and diesel but the byproduct of propane contains significantly less carbon dioxide (CO_2). The production of propane, however, is accomplished only through the refining of oil and natural gas. Whatever environmental advantages that can be touted with propane must be limited to its non-toxic effect on people, plants, animals, air, soil and water.

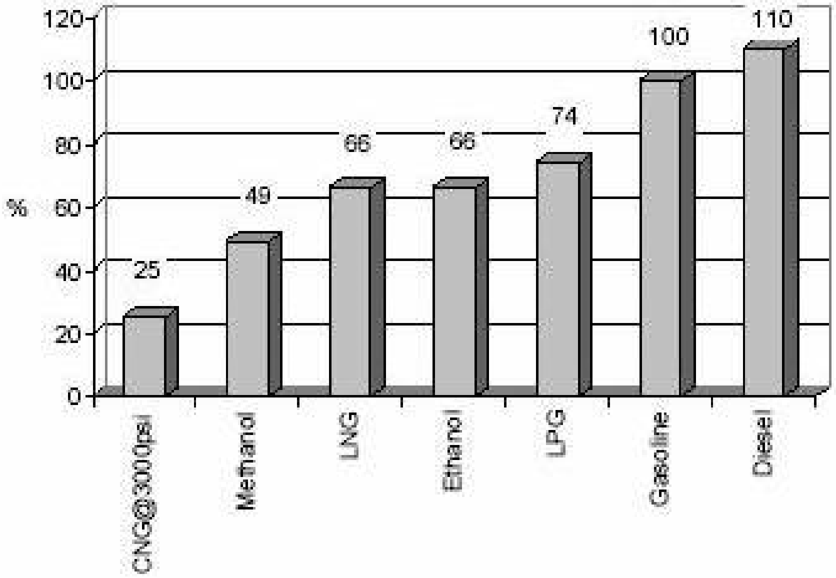

Figure 2. Comparison of energy content of selected fuels.

(Alternate Fuels Technologies, Inc, 2010)

Propane in its liquid or gas state is not a greenhouse gas. However, after combustion in vehicles or machinery, propane byproducts contain a significant, but comparatively small, amount of carbon dioxide (CO_2). Carbon dioxide is the most abundant greenhouse gas accounting for 99% of the total emissions from propane combustion. While greenhouse gases have been proven to be the "unequivocal" cause of the rise in average global temperature, there are still no regulations in the United States to control CO_2 (PERC, 2010). Such regulations are currently being discussed on Capitol Hill in Washington so attention to this issue is important when considering the development of any new device that may have future restrictions. Today, there still exist tax credits for purchasing propane fueled machinery, an attractive alternative when choosing new fleet vehicles and certain types of construction equipment. Figure 3 shows the level of carbon dioxide emission per million BTU's. Propane is second only to natural gas in CO_2 emissions but natural gas has only about half of the BTU's per cubic foot (1030 BTU/ft^3 for natural gas versus 2490 BTU/ft^3 for propane).

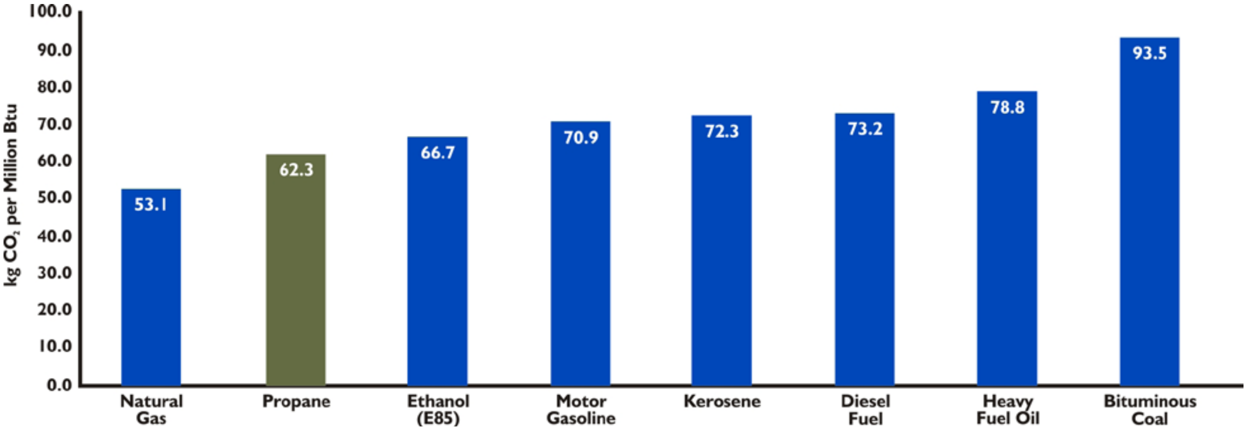

Figure 3. End use CO_2 emissions for various fuels (PERC, 2010)

Propane represents 2% of the U.S. energy market but only 1% of the greenhouse gas total. While natural gas emits less carbon dioxide into the atmosphere than propane after combustion, as a gas it is 25 times more stable in the atmosphere than carbon dioxide (PERC, 2010). Propane gas disperses quickly and does not react with the atmosphere. When all factors are considered, propane is the cleanest choice for a fuel and will be a major consideration for the development of new construction machinery.

Chapter 4. Conceptual Development and Design of the Propane Soil Drier

The construction technique for drying soil investigated in this study is the use of a forced air heat system to physically alter the water content of soil that is above optimum. This can be accomplished with a multitude of fuels but propane was chosen because of its high heat energy and its low impact on the environment. At present, the choice of propane fuel for soil drying is a wise one because there are tax breaks for propane fueled equipment and the byproducts of propane combustion (mainly CO_2) are not yet regulated. In the United States, proposed government regulation of greenhouse gases could cause propane to lose some of the tax benefits it now has as a clean fuel. Propane is a good choice for soil drying because the CO_2 byproduct of combustion is not harmful to humans, machinery or to soil when in direct contact. Indoor propane consumption is already considered an acceptable practice established with the use of warehouse forklifts.

Soil drying in the laboratory is a straight forward process and methods have been well established. Laboratory drying of soil usually involves the distribution of the sample over a large area to allow air drying over a period of days, use of a soil drying oven and/or microwave drying following ASTM Standard D2216 (ASTM, 2005). The size of a soil drying oven can vary between the sizes of a small household oven or a walk-in heated room. In any case, the standard drying temperature for drying soil is 110 degrees Celsius. Microwave drying yields the quickest results but the samples are small, usually 100 grams or less, and the results often vary from the more reliable air and oven drying method.

Using the established practices and methods, a plan for a mobile laboratory soil drying device was developed. The established practices of drying soil, including disk drying and chemical stabilization, were considered for the field equipment used. It was essential that the laboratory device could be logically scaled up into a field sized device and be compatible with existing field equipment. The main concept was to have a motor driven device that could transport a propane forced air heater over a three inch thick by one foot wide soil sample. Originally it was thought that the propane source would be transported as well but it was determined that a lighter, less expensive motor could be used if the propane tank was not on the device and an appropriate length of hose attached.

The size of the propane heater was selected on the dimensions of the planned soil samples, temperature requirements, cost, and advice from the local metal fabricator. It was determined that soil sample over which the device would operate would be about one foot wide and of varying depths. Length of the soil sample was not a concern because the device was to be motor driven and capable of traveling any distance the laboratory dimensions would allow. The size of the heater selected was determined from the dimensions of the proposed soil samples. To operate the 75,000 - 125,000 BTU unit that was selected it was necessary to use a forty pound propane tank because the propane requirement of the heater would freeze the regulator on a smaller tank. Once the heater and device dimensions were known, a motor was selected that could handle the load and velocity requirements.

The PRO-SD was constructed with A36 mild steel plates, bars, and rods. A36 mild steel is a standard carbon steel without advanced alloying and is readily welded by nearly all welding processes. The welding process used for the PRO-SD was shielded metal arc welding (SMAW, or stick welding). The main body of the device is composed of quarter-inch thick steel plates. Figure 4 shows the left side of the drying device.

Figure 4: PRO-SD Laboratory Scale Propane Soil Drying Device

Steel (A36) wheels, with one being chain driven by a variable speed electric motor, were selected because of their low maintenance, resistance to heat and the ability to retain their original material properties. Steel wheel bushings were used for the same reason as well as the relatively thick 5/8 inch width chain. The steel wheels are six inches in diameter and the wheelbase (center of front axle to center of rear axle) is 34.75 inches. The dryable width (distance between the inside of two wheels on the same axle) is 14.5 inches and the total width is 16 inches. The maximum clearance is 2.75 inches and the overall height to the top of the exhaust port is 23 inches. Figure 5 shows the top view dimensions of the laboratory scale drying device.

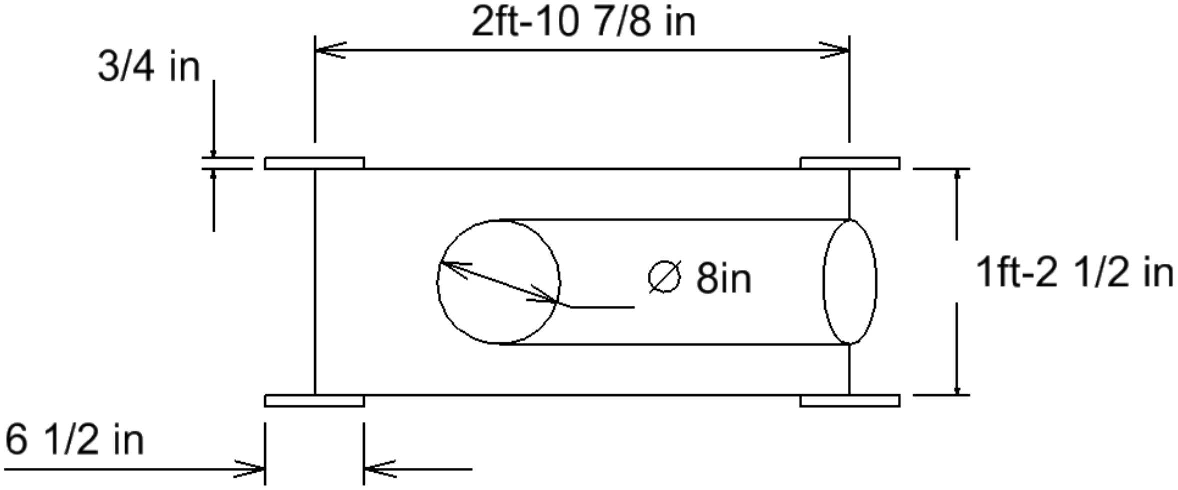

Figure 5. Top view and dimensions of the lab scale device.

The motor that was selected for the PRO-SD was an electric Dayton© Right Angle AC/DC Gearmotor with reversible and variable speed. The weight of the propane heater and steel frame required a motor with enough power to drive the device with an AC power supply because of the laboratory conditions prohibiting gasoline powered engines. The variable speed motor can seen from the left side and rear of the device as in Figures 6 and 7. The black switch on the lower left of the control box is the on/off power switch and the red switch above is the directional switch, with up being for forward travel, the middle for neutral, and the lower switch position is for reverse travel.

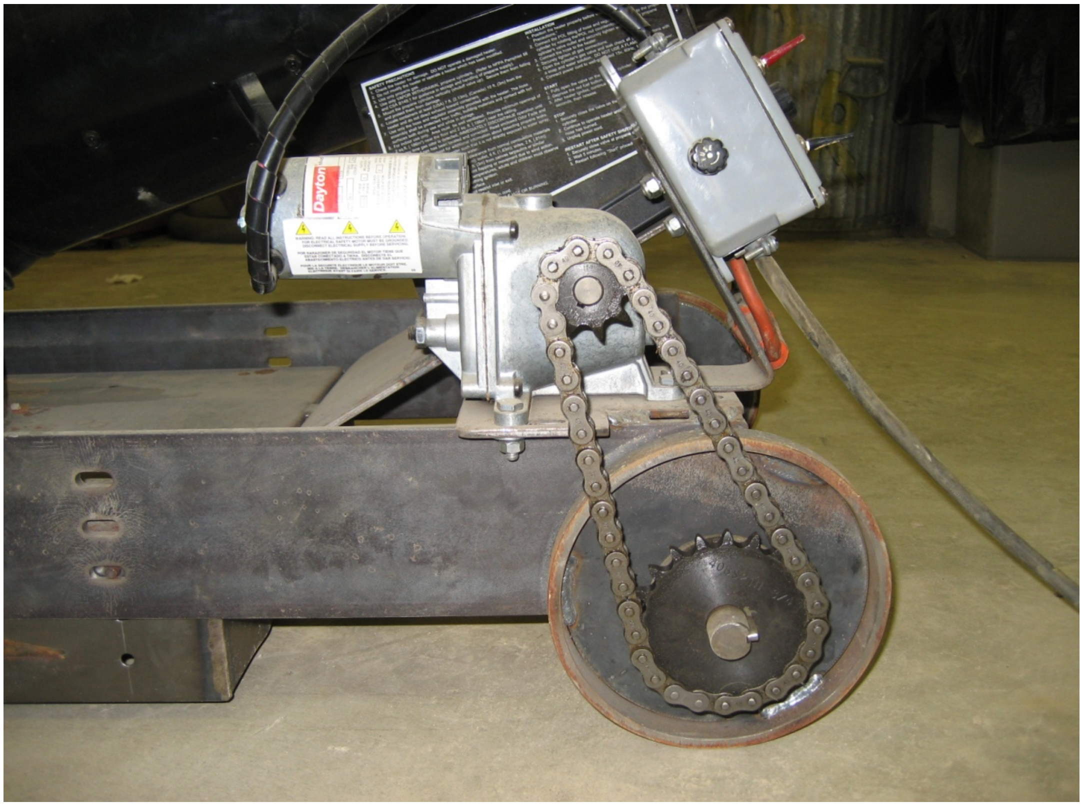

Figure 6. PRO-SD side view of the electric motor and drive chain.

Figure 7. Rear view of the PRO-SD

The device travels over a soil bed, driven by an electric motor, that has a moisture content wet of optimum and the attached tilling equipment mixes the soil as the combusted propane heats the soil and evaporates the excess moisture. Moisture contents were taken periodically and determined using ASTM Standard D2216 (ASTM, 2005). The propane consumption was monitored on a laboratory scale. Determination of propane consumption and moisture content deviation with volume can assist in the economic feasibility of a field scale device. Once it is determined the amount of propane used to dry a soil closer to optimum, the data can be extrapolated to determine the economics of drying field sized areas.

The idea for the attached tilling equipment came after some initial testing. The attached tilling equipment was added to better simulate field conditions and equipment. A mixing apparatus is essential for the proper disbursement of heat throughout the soil sample. Several types of mixing devices were conceived in the design phase of the laboratory device including several variations of discs and tines but the star shaped tines tilling attachment was ultimately selected because of its simplicity, durability and compatibility with our project. The mechanical tilling device on the front of the machine is not motor driven and is on the end of pivoting arms and a tray used to carry weights that enable the tines to turn and penetrate the soil while the electric chain drive motor propels the device.

The attached mechanical tilling equipment came from a standard hardware store garden tool and was modified to fit this machine. The metal tray on the pivoting arms of the tiller was designed to carry weights to assist in vertical downward force to facilitate uniform penetration and turning of the soil. The attached non motorized tiller and support tray were added on a subsequent return to the metal fabricator.

This attached tiller proved insufficient to penetrate and turn the soil adequately because the electric motor lacked sufficient power to both drive the device and overcome the forces experienced when the tines were deep in high moisture content soil. Additionally, since the attached tilling equipment was not motor driven and only turned with the same velocity as the device, the rotational velocity of the tines were insufficient to adequately mix the soil.

Adjustments were made by mixing the soil with a handheld manual operated standard garden tiller between passes and moisture content measurements.

Delivery of the device was taken in April of 2009 with agreement to return to the metal fabricator as needed for changes experienced during laboratory testing. The device was returned to the fabricator in the early summer of 2009 to implement a design change to add a second motor that would drive the tillers to achieve a more appropriate speed for mixing. This effort ultimately turned out to be costly and inefficient because additional motors would require an entire redesign of the device to facilitate the added weight and power requirements. A standard hand held manual garden tiller was used to mix the soil because it provided an economical and functional solution to our mixing requirements. The machine was delivered back to the laboratory unaltered. A standard hand held manual garden tiller was used to mix the soil because it provided an economical and functional solution to our mixing requirements.

Chapter 5. Experimental Plan for Soil Testing

The main requirement for water to evaporate from soil is a source of heat, thus, the first step of the drying process involves application of heat to the soil. The application of heat was done in a timed manner which was dependent on the speed setting on the motor. A speed setting of 6 on the control panel equates to 4 feet per minute which is equivalent to 1 minute and 15 seconds per 5 foot pass. Secondly, the soil was mixed for a fixed amount of time, using either the mechanical or manual (hand) tiller. Next, either more heat was applied or the sample of soil was measured for water content change over the last heat cycle. For all soil types and equipment, the water content was measured at different time intervals to determine the most efficient use of propane, mixing and time.

The primary experimental factors to be considered in this study are: soil type, mixing method, heat level, soil elevation (thickness), and samples for water content measurement. Considering different soils take varying amounts of propane heat and time to dry, an experimental plan with the above factors was developed and is shown in Table 2. Following the initial trials with the laboratory device, the research team selected three soils for testing with three different types of tilling systems (no tilling, mechanical tine tilling, and manual tine tilling), two different soil elevations (1.5 and 4 inch think soil beds), two different heat levels (high and low) and five moisture content measurements. The three soils for testing were a high plasticity clay, a medium plasticity clay, and a fine-grained sand. Considering the factors, a full factorial design would consist of the following: three soils, three tilling systems, two soil elevations, two heat levels and five moisture measurements. This would result in 180 test runs with the laboratory device and thus a partial factorial was pursued.

Table 2. Experimental Plan

		Tilling					
		None		**Mechanical Tines**		**Manual Tines**	
	Elevation	1.5”	4”	1.5”	4”	1.5”	4”
Soil Type	**Fat clay**	XX	XX	XX	XX	XX	XX
	Lean clay	XX	XX	XX	XX	XX	XX
	Sand	XX	XX	XX	XX	XX	XX

“X” represents different heat levels with 5 moisture measurements each.

Initial shakedown testing was on the high plasticity clay with one speed and twenty passes, with the moisture content of the soil being measured after each four passes. Based upon the results of these tests, a more focused partial factorial was done for the concrete sand and Iowa loess. In this manner the results of the high plastic clay were used to project the anticipated outcomes of the concrete sand and Iowa loess, thus not as many tests were conducted.

The highly plastic clay underwent duplicate tests to determine the most efficient use of the propane fuel and to observe any deviations in moisture content change with repeated methods. This data is located in the analysis section of this report and the detailed data is located in the appendix. The repeated tests using the highly plastic clay were consistent and showed minimal deviation proving that machine operation and soil volume are reliable variables.

Chapter 6. Soil Testing

Three field samples, each representing the soils identified for the study, underwent standard soils characterization including the determination of moisture-density curve and Atterberg limits.

Uniform, mostly homogeneous soils were required to test the device and acquire accurate data. It is known that high plastic clays with liquid limits above 50 are the most problematic to become dry and take the most time to become dry under normal conditions. A high plastic clay was selected as the primary type of soil to test because it would demonstrate the ability of the drying device in relation to real world situations. With the help of a private engineering firm, a relatively homogeneous soil sample that would meet the specifications of high plastic clay. The sample originated from a construction project in Dallas County, Iowa.

Three 20 gallon barrels of the light brown clay were delivered to the laboratory and allowed to dry to minimum moisture content to allow for better control of water levels. Along with the highly plastic clay, the two other types of soil were selected to develop differences and correlations within the collected data. The additional two types of soil selected were concrete sand and western Iowa loess for their different engineering properties and their varying ability to dry during heat application.

ASTM laboratory tests were used to determine the water content, grain size, plasticity, density and specific gravity for the newly acquired clay material. Table 2 details the soil properties of the high plastic clay, concrete sand and the Iowa Loess. Figure 8 shows the moisture-density curve for determination of the optimum moisture content for the highly plastic clay. The types of properties demonstrated made the plastic clay the perfect candidate to test a drying device because of its high fine content and its high liquid limit.

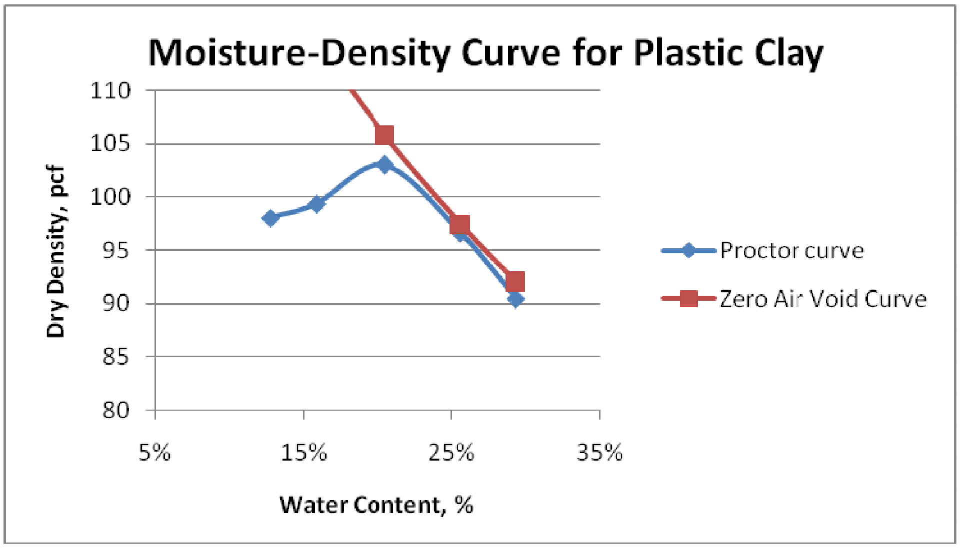

Figure 8. Standard Proctor compaction test results for the plastic clay.

Table 3. Engineering properties of the clay, sand and Iowa loess.

	Plastic Clay	Concrete Sand	Iowa Loess
Maximum Dry Density (pcf)	103.0	109.1	106.6
Optimum Moisture Content (%)	20.5	7.2	16.2
Liquid Limit	50	NA	40
Plastic Limit	24	NA	20
% Passing No. 200 Sieve (%)	72.0	0.0	83.2
Specific Gravity	2.61	2.60	2.67

The grain size distributions of the three soils are shown in Figure 9. For the clay material, 72 percent of the material passed the number 200 sieve (0.074 mm), the defining boundary of a fine material. Some of the engineering properties of the concrete sand and loess material were already documented in the teams' previous research projects and class assignments because they are in regular supply in the Iowa State geotechnical laboratory, these properties are also listed in Table 2.

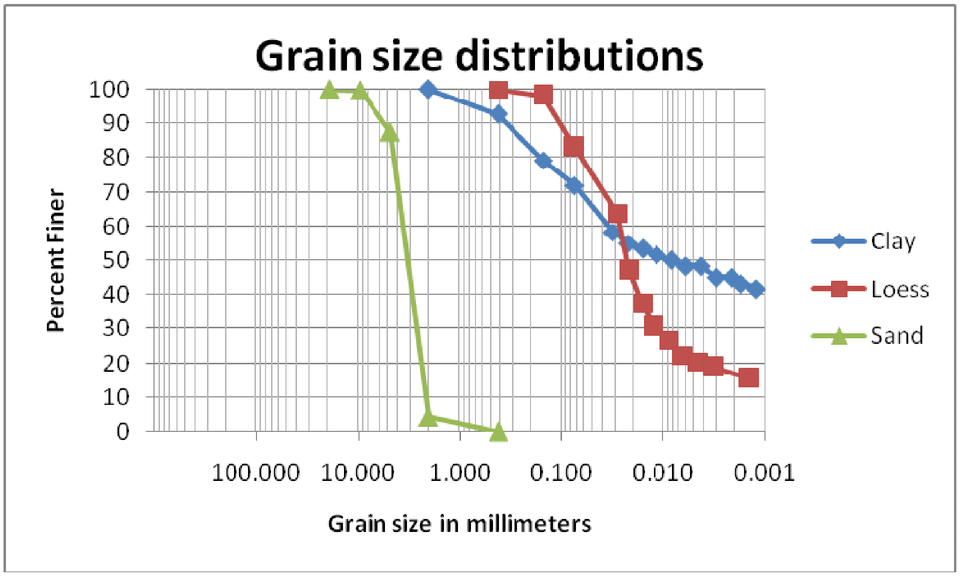

Figure 9. Grain size distributions for the three soil types.

The western Iowa loess material is considered to have low to medium plasticity and was expected to lose moisture at a faster rate than the highly plastic clay. The concrete sand is non plastic and lost moisture the quickest when the propane heat was applied. With three distinct soils, the rate of moisture loss when a measurable amount of propane heat is applied was expected to be clear and distinguishable.

Chapter 7. Implementation of Lab Scale Device

The drying tests in the laboratory can be split into main and sub-categories, with the main category being soil type and the sub-categories consisting of the variable device settings and soil depths. Three soil types, two heights, one motor speed, two heat levels, and three types of tilling were used. The soil was prepared both to saturation levels of moisture and to levels four percent above optimum, the usual maximum moisture content allowed in construction specifications.

The method of device operation became evident after some initial testing as it was an evolving process. For instance, the single speed setting became the most logical choice because it was the slowest speed that allowed enough torque for movement but where the velocity of the device was not too high to maintain control and uniform drying of the soil sample.

The testing of the device was conducted on a concrete floor to ensure efficient operation. A soil test strip of five feet long, one foot wide, and one and a half inches thick makes optimum use of the device dimensions, soil volume and available laboratory space. Each sample to be tested of each soil type was weighed at its current moisture content and water added until the saturation point was reached.

The one and a half inch thick layers required the preparation of approximately 35, 56 and 38 pounds of soil for the high plastic clay, concrete sand and Iowa loess respectively. The four-inch thick layers required the preparation of approximately 75, 90 and 79 pounds of soil for the highly plastic clay, concrete sand and Iowa loess respectively. Operation of the PRO-SD over the four inch soil height is shown in figure 10.

During later trials, target moisture contents of four and eight percent above optimum were used on the high plastic clay to simulate real world conditions. Saturated soil in the laboratory is a good medium because a larger range of data can be collected on the rate of propane consumption and moisture content change. In the field, however, it would be unadvisable to operate most kinds of earthmoving equipment in fully saturated soil conditions. Soils with moisture contents between four and eight percent would be the most likely candidates for a drying device. As discussed earlier, soils above four percent optimum moisture content will not meet specifications for moisture and density control. Soils above eight percent optimum moisture content would be too wet for the most common earthmoving equipment to operate effectively.

Figure 10. PRO-SD in operation over a 4 inch depth soil sample.

For the high plastic clay and Iowa loess the amount of water added varied between four and nine liters depending on the water content during preparation. The concrete sand required less additional water because of its porous nature and it's comparatively low optimum water content. The amount of water added to the concrete sand varied between two and five liters. Preparation of all the soil samples involved the weighing of soil, addition of the required water, hand mixing to ensure uniform moisture distribution throughout the samples and a mellow time of at least 16 hours under conditions where minimal evaporation occurs. The mellow time was determined from the soil preparation section of the ASTM Standard Compaction Test (ASTM D-698). This was accomplished by covering the mixed and wetted sample with common plastic wrap and, on the day the sample was to be tested, adding one percent moisture by weight to account for evaporation losses.

To begin the tests the propane tank was weighed, the soil was wetted to a target of 30% moisture (approximately 10% above the optimum moisture content), the heat setting on low, and the speed setting on 6 out of 10 (approximately four feet per minute). During initial trials It was determined by observation that the low heat setting was more efficient because on a higher setting there was too much heat loss towards the outside of the device. An increase in room temperature was observed by the laboratory researchers.

Use and Monitoring of Propane in the Laboratory

The use of propane in the laboratory is used with the latest safety techniques available. The amounts and time of the propane use was recorded accurately in the lab in order to convert it for the larger scale field application. The propane cylinders were weighed before and after each test to determine the amount of fuel spent. An accurate time piece was used to record the time of each test. The times of the tests varied in order to determine the most efficient use of propane for drying soil to near optimum water content. Figure 11 shows the PRO-SD in operation with the 40 pound propane tank on the scale.

Figure 11. PRO-SD in operation.

Mixing of the Soil in the Test Strips During Drying

A device that would both mix and heat the soil in the laboratory was considered but deemed too cost prohibitive for this study. The motors required and the attachments on the device to meet the requirements of both drying and mixing the soil involve a more complex design and a higher budget. It will be more practical to heat and mix the soil in separate steps and monitoring their reactions carefully. When the results of the laboratory tests are evident it will be advantageous to develop the field equipment from this data, combining the best heating and mixing equipment. Typically the soil will be heated by the propane for a timed period, and then mixed with hand tools. The process can be repeated multiple times until desired results are achieved.

The notion to discontinue use zero tilling and the mechanical tilling implement became evident when they performed unsatisfactorily. The use of no tilling was ruled out of the experiment at an early stage, when the results showed a crusting effect on the top layer and near zero moisture change on the bottom of the soil bed.

Chapter 8. Testing and Results

The device is equipped with a reversible, variable speed motor. After a single pass the motor was switched to the reverse position to allow another pass. Moisture contents were taken at the beginning of the test and originally after every four passes. Subsequent tests revealed that taking moisture contents every eight passes would produce longer uninterrupted heating cycles and therefore greater moisture content change. Table 4 shows the water content change per pass of the clay material in early trials.

Table 4. Water change in early trials.

Test	# of Passes	Initial MC (%)	MC Change (%)	MC Change per Pass (%)
1	20	29.2	9.2	0.46
2	20	31.0	12.5	0.63
3	24	32.1	13.6	0.57

All three tests managed to dry the soil drier than the optimum moisture content. This data suggested that a more efficient tilling system, i.e. discs, should be implemented to optimize the mixing of the soil while the heat is applied.

Mechanical Tilling at 1.5 Inch Depth

The first tests producing valuable data were performed on a 1.5 inch deep, five foot long, and one foot wide soil bed on a concrete floor slab. The mechanical tiller was used during these tests but proved ineffective as discussed previously. The heat setting was on low, which is 75,000 BTU's and the speed on setting six (four feet per minute).

As shown in Figure 12, the clay sample lost water at an erratic rate. The high plastic clay did not lose moisture at a near constant rate like the concrete sand and Iowa loess. This can be attributed to high plastic clay’s tendency of slow moisture migration. On the first passes the clay would lose moisture and, during the few minutes to take water content measurements, the moisture in the clay would migrate to the air voids within the soil. This can also be attributed to the tendency of the mechanical tiller that slowly penetrates the soil instead of quickly turning it. Uneven heat distribution because of the ineffective mechanical tilling could have caused pockets of high and low water content. The clay in the tests is the same material and multiple tests are shown to provide consistency.

Figure 12 also shows the results of the less plastic loess material. The loess material clearly dries at a more consistent rate, which can be attributed to its medium plasticity and lower fines content. The sand test result in Figure 12 also dries at a stable rate, although more quickly at first then evening out. This can be attributed to the zero plasticity of the sand and its porous nature. The void ratio of the sand allows for more heat to migrate through the sample even without much assistance from the tiller.

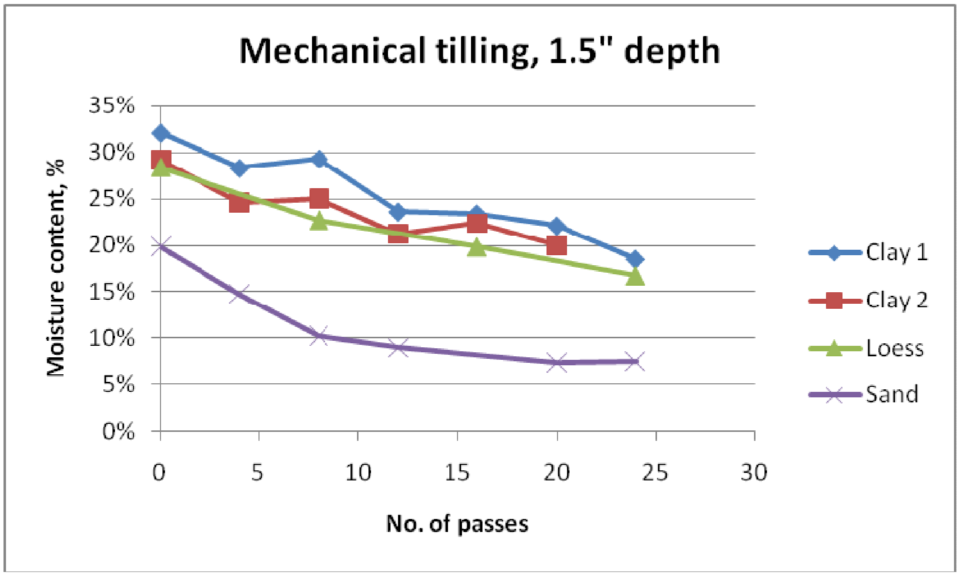

Figure 12. Initial testing using mechanical tilling.

Figure 13 shows the tests during operation over a one and a half inch soil depth and mechanical tilling. The specially designed tray to hold weights was helpful in applying the necessary downward force but the low spinning speed of the tines is what deemed the mechanical tiller ineffective.

Figure 13. PRO-SD in operation over a 1.5 inch soil depth and mechanical tilling.

Manual Tilling at 1.5 Inch Depth

To better distribute the propane heat throughout the soil a more effective method of tilling was essential. Implementation of a motorized tiller to more efficiently transmit the heat energy to the soil was considered, but was ultimately a too expensive and time consuming option. A simple hand held garden tiller was used and proved to be effective in turning the soil and allowing for more efficient use of propane.

Figure 14 summarizes the data collected using the manual tiller, a 1.5 inch depth, a low heat setting and velocity of four feet per minute. The manual tiller was used every two passes starting after four passes. It was necessary to delay tilling until the fourth pass because the tiller could not sufficiently turn the soil in its near saturated state.

From Figure 14 it can be clearly seen that the rate of moisture loss from the soil was at an almost constant rate for each of the three soil types. The two data series for the clay are from the same material prepared at slightly different moisture contents and are shown for assurance.

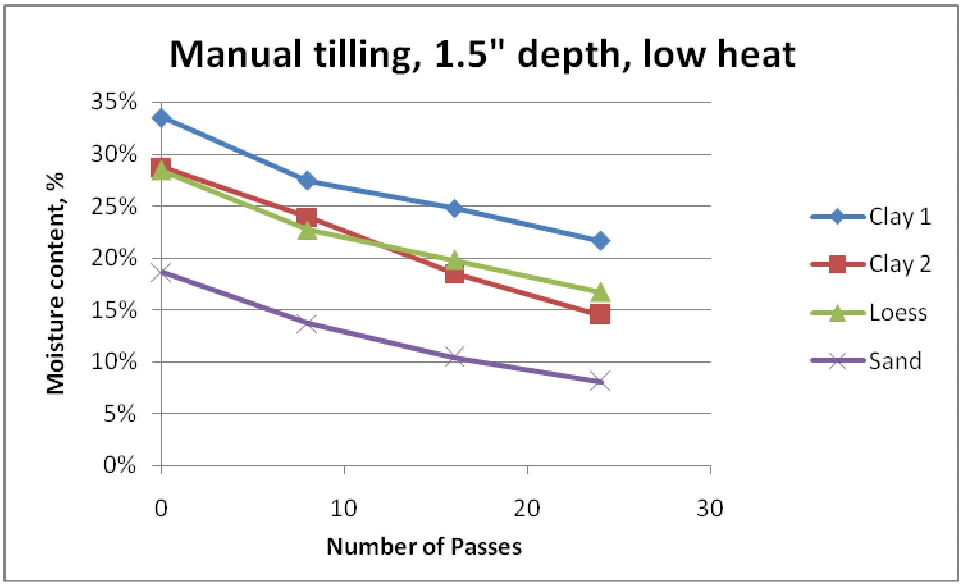

Figure 14. Manual tilling test data at 1.5" depth.

Four Inch Soil Depth and Variable Heat

To get a better idea on how a field device would work where the soil depths are much greater, it was necessary to have higher lifts in the laboratory. Attempts to make a rail style platform on which the drying device would travel proved to be insufficient due to the weight of the device and cost. Subsequently six foot long, four by four inch steel beams were acquired and proved to be a satisfactory platform on which the device could operate. Figure 15 illustrates the use of the steel beams to achieve a four-inch soil depth and the manual tiller.

Figure 15. 4 inch depth clay soil bed with manual tiller.

The test data for the clay in four inch lifts comparing high (125,000 BTU) and low (75,000 BTU) energy inputs are summarized in Figure 16. It can be seen that the application of higher heat energy will more expeditiously rid the soil of its excess moisture than the low heat output. The results from the high heat output would be desired in the field because of the more efficient use of time. These tests were conducted using the manual tilling method.

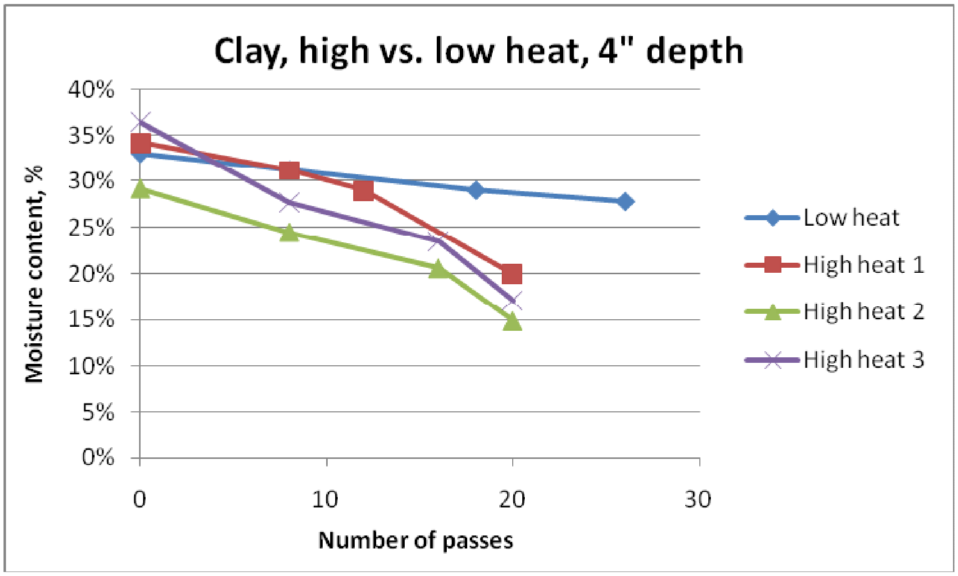

Figure 16. High and low heat with a 4-inch deep soil sample.

Loess and Concrete Sand Behavior at Four Inch Depth

The loess and sand materials were subject to the same patterns of testing as the clay. The results of averaged test data are shown in Figure 17. The results are similar to the shallower depth, low heat tests in the sense that they show a consistent rate of change in moisture content. Figure 16 also shows that the loess and sand materials are less sensitive to heat and depth changes than the clay material. These tests were conducted using the manual tilling method.

At the high heat setting and four inch depth the loess and sand material had an average water content change of 0.6% and 0.25% per pass respectively.

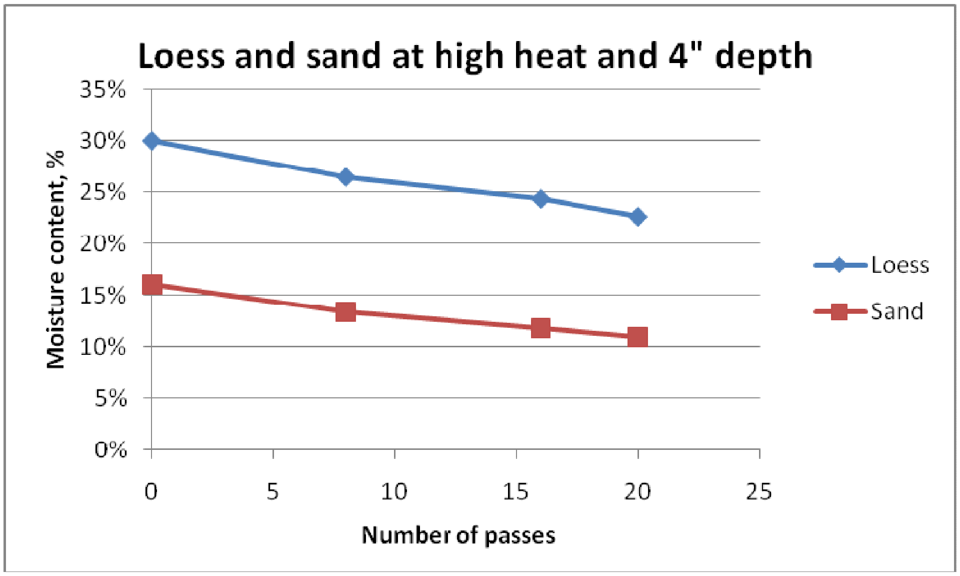

Figure 17. Loess and sand at high heat and 4 inch depth.

Clay at Four Inch Soil Depth, High Heat and Varying Moisture Contents

The tests and data collected up to this time were primarily focused on clay that was at or near its saturation point. While this may be good to demonstrate the device's capabilities, saturated conditions are not what would be expected in the field. Typically, moisture levels above four percent of optimum moisture content will fall outside the range of construction specifications. This being known, it would be beneficial to collect data with the lab scale device at levels above the four percent level. These tests were conducted using the manual tilling method.

Ninety pounds of clay material were prepared to target water contents of 26% and 28%, 6% and 8% above optimum, respectively. The water content decreased an average 0.35% per pass when prepared at these levels. These tests of the targeted water content below saturation exhibited the lowest water content change per pass.

The clay material, when wetted to target amounts of six and eight percent above optimum, reacted in similar fashion, that is, the initial application of heat caused and immediate change in moisture content. Subsequent heating application did not have as much of a drying affect as the material approached its optimum moisture content of 20.5%. Figure 18 shows the graphic relation of the moisture content change for the clay material prepared at the targeted levels of moisture content below saturation.

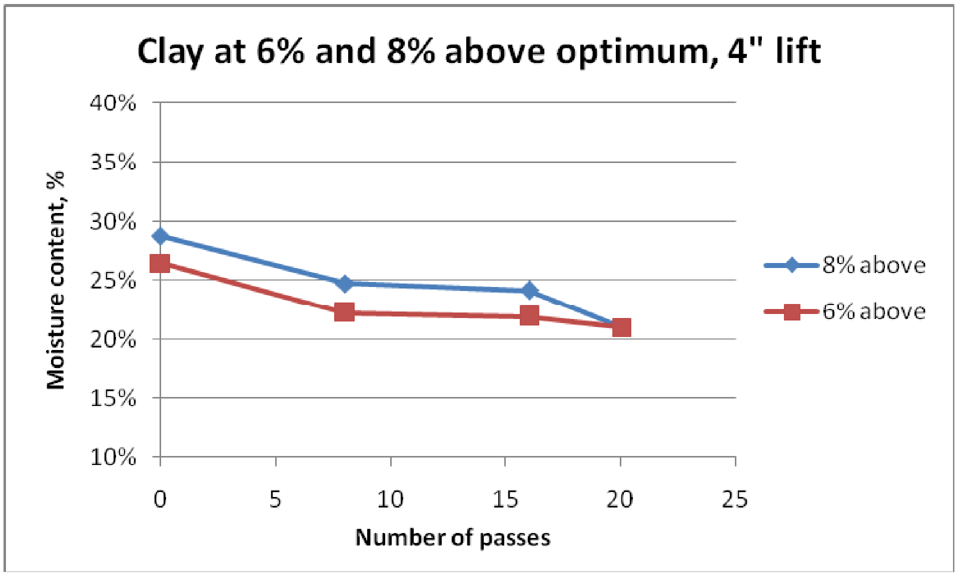

Figure 18. Drying behavior of clay material at targeted moisture contents.

Chapter 9. Propane Consumption

Propane consumption was constantly monitored and recorded during all testing. Knowing the soils weight, moisture content change and fuel spent, it would be easy to determine, through scaling, the amount of fuel required in a field sized area. This is not the case, however, because the heat energy that escapes through the front, back and sides of the lab scale device is lost to the atmosphere, wherein a field scale device the heat energy would simply be absorbed by the additional soil outside of the direct path. Of course some heat would be lost to the atmosphere in the field scale device as well, but those losses are not comparable to those exhibited in the laboratory.

The amount of propane consumption and resulting moisture change in the clay material became more erratic with an increase in soil mass and depth. Table 5 shows the average propane consumption and standard deviation for the clay at the two depths. The results show that at shallower depths there is less efficient use of the propane heat, most likely caused by the atmosphere loss characteristics. At the deeper depth the propane is more efficiently converted into drying heat simply because there is more volume in which it can be absorbed. The higher standard deviation in the deeper depth should be attributed to the volume as well, that is it is more difficult to achieve even heat distribution throughout the entire larger sample.

Table 5. Propane consumption in varying clay depths.

Clay Depth	Moisture Content Change per Pound of Propane	Standard Deviation
1.5”	5.4%	0.7%
4.0”	8.4%	3.9%

The propane consumption, as it relates to moisture change, of the loess and sand materials were unaffected by varying heights, volumes or heat levels. This is most likely caused by the high void ratio in the sand and the medium plasticity of the loess which allows for more even distribution of the heat energy. The standard deviations for moisture content change per pound of propane in both the loess and sand materials were less than 1% for all tests.

The rate of propane consumption slows as the tank becomes less full with drying effects remaining constant. This can be attributed to the higher flow rate of a full tank. The drying effects (the amount of propane to change moisture) remaining constant suggests that all of the fuel is not being burned with the forced air heater when the tank is closer to being full.

It took less propane to change the water content of the clay 4% than a similar change in the sand or loess material. This suggests that the clay material is more reactive with the heat energy because of its less porous properties which trap and hold the heat within. Table 6 summarizes these findings.

Table 6. Propane consumption to dry soil 4 %.

Soil Type	Clay		Loess	Sand
Layer Thickness (in)	1.5	4	4	4
Propane (lbs)	0.76	0.61	0.70	1.10

Propane Economy

To fill the 40 pound propane tank we had to purchase propane at the non-bulk rate, which was $0.62 per pound compared to $0.27 per pound for bulk. These prices were current as of fall 2009. Table 7 summarizes the cost to dry each soil 4%. The results show that there is a more efficient use of propane with depth, except in the case of concrete sand, showing that the lab scale device is burning fuel too quickly for shallow depths, even at its lowest heat setting.

Table 7. Propane Cost to Dry One Cubic Foot of Each Soil by 4%.

	Soil Type					
	Clay		**Loess**		**Sand**	
Layer Thickness (in)	1.5	4	1.5	4	1.5	4
Non Bulk Cost (US $)	0.76	0.23	0.74	0.26	0.83	0.41
Bulk Cost (US$)	0.12	0.10	0.12	0.11	0.13	0.18

Chapter 10. Analysis

From the results of the manual tilling at the 1.5 inch depth it is clear that the soil dries with more consistency than with the mechanical tiller. This is shown in Figures 12 and 13. The non-linear relationship of the data collected during the mechanical tilling tests illustrates that ineffective tilling will allow for moisture migration and some higher water contents even after additional passes with the PRO-SD. This reinforces the idea that the soil needs to be mixed thoroughly to dry evenly and for efficient use of the propane. Mixing the soil manually instead of mechanically allowed for better distribution of the heat energy and better drying results. While the water content changes per pass stay relatively consistent no matter what kind of mixing technique is used, the more predictable and constant rate changes come from the manually mixed tests.

Development of a relationship of fuel consumption with low and high heat settings reveals that propane consumption is unaffected by the heat setting on the propane heater. The reason for this may be inefficient mechanics in the device itself or the tendency for a full tank of propane to release fuel at a higher rate than one that is not full. The higher heat setting did provide a consistently faster drying technique when used on the high plastic clay but not with the loess nor sand materials.

At deeper depths it becomes evident that uniform and consistent moisture loss is less likely. Thorough mixing and a high heat setting will provide beneficial drying to the clay soil but these benefits decrease with depth. However, more of the propane heat is absorbed by the clay material at deeper depths, it is the drying rates that become more inconsistent because of the larger volumes involved.

Adding propane heat to the clay material at levels approaching the saturation level (approximately 30% moisture content) dissipated moisture at a much faster rate than when the clay material was prepared at levels slightly above optimum. In field applications it would be difficult to have machinery dry nearly saturated soil. The tracks and tires on modern earthwork equipment can get clogged with saturated soils making operation difficult. So the expectations should be to expect less dramatic changes in moisture content as the material approaches its optimum level.

The evidence collected from the data supports the theory that more of the propane heat is used to alter the moisture content as the depth of the sample increases. The moisture content change of 5.4% (per pound of propane) for the 1.5-inch depth versus 8.4% for the 4-inch depth is significant it that it demonstrates the potential for propane heating in large volumes of high plastic materials. This is of great importance because it leads to the major point of this study which is the feasibility of a field propane drying device.

Statistical Analysis

A statistical analysis of all the data collected during the propane drying of the soil was conducted using the statistics computer software program JMP (SAS Institute 2010). The six independent treatments entered into the program included soil depth, soil type, tiller type, heat level, device height, and number of passes. The dependent factor being analyzed is the moisture content change. A statistical analysis will determine which treatments are most likely to cause a significant effect on the change in moisture content.

Initial statistical analysis produced a correlation matrix of the independent variables as seen in Appendix B, Figure B1 and Table B1. The table of multivariate correlations revealed which of the independent variables were closely related in order to eliminate some of the independent variable to produce a more accurate statistical model. Where values are near 1 and -1 in Table B1, the variables are correlated and one can be omitted from further statistical analysis. Machine height is closely correlated to soil depth and heat level so the latter two independent variable were eliminated. Pounds of propane consumed are correlated to the number of passes so the latter was eliminated from further statistical analysis. The multivariate correlation model coupled with a regression analysis reveals which of the independent variables are most significant to the change in moisture content.

Determining which of the independent variables were of highest significance required the construction of an original model that included all of the variables. The first model showed that the heat level and soil depth had p-values greater than 0.05 (95% level of significance) and therefore had to be eliminated. A second model that would more accurately define the most significant independent variables was then developed. The second model determined that both the tiller and number of passes were statistically unlikely to cause a change in water content so they both were eliminated. The final set of independent variables that determined the final model included machine height, soil type and pounds of propane used. Therefore the change in moisture content is a function of the machine height, soil type and pounds of propane consumed.

Moisture Content = f(Machine Height, Soil Type, Pounds of Propane Used) Eqn. 2

The following Tables 8 and 9 contain the relevant data obtained from the final model of the statistical analysis. A more detailed statistical analysis of all the models can be found in Appendix B. The level of significance used in the analysis was $\alpha = 0.05$.

Table 8. Analysis of Variance

Source	DF	F Ratio
Model	3	62.09
Error	58	**Prob > F**
C. Total	61	<0.0001*

Table 9. Parameter Estimates

Term	t Ratio	Prob>|t|
Soil Type	2.38	0.0204*
Machine Height	-2.18	0.0334*
Lbs of Propane	9.57	<0.0001*

The prediction equation (EQ. 3) associating the change in water content to the soil type, machine height and pounds of propane was also determined during the statistical analysis. The soil type and machine height are class variables meaning that they were not numerical values. The numerical values of -1, 0 and 1 were assigned to the different class variables as shown in Table 10. The developed prediction equation is summarized below.

$$\textbf{\% Moisture Change =}$$

$$\textbf{0.77 * Soil Type – 0.89 * Machine Height + 5.42 * Pounds of Propane} \qquad \textbf{Eqn. 3}$$

Table 10. Numerical substitutes for the class variables.

Soil Type	Machine Height
Loess -1	Low -1
Sand 0	Med 0
Clay 1	High 1

The statistical data demonstrates that the soil type, machine height and pounds of propane used are statistically significant and most influence the change in moisture content. It makes sense that the more propane that is consumed the greater the change in water content would occur. The fact that the p-value for pounds of propane is below 0.0001 indicates that it is the most significant variable and its effect is the greatest on the change in moisture content as indicated by its coefficient of 9.57. It is also intuitive that machine height and soil type would have a statistically significant effect on the change in moisture content. When the machine height is high it allows the heat energy of the propane to escape to the outside before it has the opportunity to affect the moistened soil. It is also predictable that soil type would have a significant effect on the change in moisture content and is confirmed by the statistical analysis.

Chapter 11. Limitations of Lab Scale Device

The purpose of the development of a lab scale device was to collect data relating to propane consumption and change in moisture content for determining the economic feasibility of a field scale device. Throughout the laboratory testing phase of the device limitations were discovered that would not be present in real-world conditions. The five most significant limitations were the loss of heat energy towards the outside of the device, the low humidity and constant temperature of the laboratory, the preparation of a uniform soil with a constant moisture content, the device’s steel wheels, and the thorough manual tilling that was utilized in some of the test runs.

The primary limitation is the loss of heat energy toward the outside of the device that would otherwise be absorbed in the surrounding soil in the field. The dimensions of the soil bed that was prepared for testing in the laboratory was specifically designed to match the width of the machine and the area in which the propane heat was directed. It is impossible to measure the percentage of propane that was used for drying the soil and the amount that was lost to the surrounding concrete floor and open space. In the field, the percentage of heat energy used towards drying the soil versus loss to the environment would surely be higher than in the laboratory.

The laboratory where the testing of the device took place was in a temperature controlled environment with moisture content in the air essentially zero. The temperature of the room was a constant 72 degrees Fahrenheit, plus or minus four degrees. The environment in which the lab scale device was tested can not be replicated in the field because of the variation of weather patterns. Wind in the laboratory is also non-existent and does not simulate field conditions. Additional wind could be beneficial in the drying of soil in close proximity to a heat source to evaporate excess moisture.

The three soils used in the experiment (highly plastic clay, Iowa loess, concrete sand) were homogenous in nature. The soil samples to be tested were prepared to a uniform moisture content following applicable ASTM standards (ASTM D-698). The engineering properties of the soils tested in the laboratory were determined and documented. Soil conditions in the field are not homogeneous, do not contain uniform moisture contents throughout and the engineering properties can vary greatly over small areas. Determining soil properties in the field requires extensive testing to ensure that all types of soils in the project area are included.

The PRO-SD's steel wheels ran on the flat concrete floor surface for the one and a half inch soil height and on four inch high flat steel beams for the four inch soil height. This ensured constant velocity of the device and even distribution of the propane heat energy over the length of the soil sample. Field conditions would require wheels, tires and/or tracks that could operate on a variety of different surfaces. Steel wheels would not operate efficiently on a soil surface, if at all.

The tilling methods used between and during the passes of the PRO-SD were designed to mix the soil evenly for uniform water content throughout the sample. The attached tiller on the PRO-SD lacked sufficient force to adequately turn the soil. Tilling equipment used on today's construction projects contain substantial weight where penetration of the soil is usually not an issue. The method of manual tilling in the laboratory the soil sample could be more efficient of what could be expected in the field. Depending on the choice and method of tilling, the laboratory and field results may vary greatly.

Chapter 12. Conceptual Design of Field Device

The requirement of a field scale device would be that it would have to possess a chassis capable of supporting several of tons of equipment including forced air heaters, propane fuel tanks, tilling equipment and wheels or tracks for operation on varying soil conditions, especially wet of optimum. This could be accomplished with a dedicated motor driven unit or, more simply, a tow behind device. Figure 19 shows the current method for soil drying using disks. This unit also has the potential capacity to support the required equipment for propane soil drying.

Figure 19. Disking method for soil drying. Propane forced air heaters could be added onto the trailer to reduce drying times (Blahut 2010).

A field scale device to achieve drying of wet of optimum soil would be required to achieve an effective depth of 8 to 12 inches. Additionally, a self contained motor driven device would be costly and complex so a trailer type device should be used. There is generally a larger selection of tillage equipment in the farming equipment industry so it is there that a suitable device could likely be found.

The trailing tiller would be pulled by typical earthwork construction equipment such as a loader or a dozer. A sheepsfoot roller should not be used to tow the tiller because this would cause premature compaction of the soil. Compaction equipment should be use only after the soil is dried sufficiently to allow appropriate water content levels to be reached, usually at less than four percent above optimum water content.

The tilling trailer should have an adequately exposed and strengthened frame to support the attachment of heavy duty propane heaters and their fuel source. Alternately the fuel source could be supported by the pulling equipment and the appropriate hose attached. Figure 19 shows the current method of using discs to dry soil with a trailer that may be suitable to carry the extra load of attached forced air heaters.

The 125,000 BTU propane heater that is being implemented in the laboratory provides moderate heat energy to dry soil sample of up to four inches. Figuring field soil depths of 8 to 12 inches would mean a substantial increase in heat energy would be required. 400,000 and 1,000,000 BTU propane heaters are readily available and would satisfy the requirements for these depths. Using a pair of the high output or four of the lower output heaters or some combination of the two would provide sufficient heat energy. A reasonable starting point would be to obtain one each of the 1,000,000 and 400,000 BTU propane heaters to be welded onto the trailing tiller. Field testing would determine if the heat supplied is sufficient or if additional heaters would be required.

The heaters would have to be fastened or welded on horizontally to satisfy safety requirements recommended by the manufacturer. A duct type system as on the laboratory device would be constructed to channel the forced heated air towards the tines and soil. The tilling equipment may require additional welding of a platform to accommodate the propane heater and its fuel.

Figures 20 and 21 show readily available tilling equipment that, with modifications, would be suitable to transport large propane heaters and their fuel. Consultation with purveyors of farm equipment and earthwork contractors would prove beneficial in the development of a field scale device. The development a specialized device of this type is possible and needs to be explored.

Construction and testing of a field device would eliminate the limitations that were encountered during the testing of the lab scale device. The limitations of the laboratory that would be eliminated are the constant climate conditions, heat energy loss, uniform soil conditions, no grip steel wheels and manual tilling.

Figure 20. Five Foot Wide Field Tiller for Soil Drying

Figure 21. Trailing Disks for Soil Drying

Chapter 13. Conclusions and Recommendations

The use of propane as a fuel to dry soils in the laboratory proved the concept that propane is a compatible fuel source for this type of application. The test results showed varying degrees of success in drying three different types of soils. Tests on varying depths of soils show that the drying efficiency improves with depth. The testing and data collected demonstrate that propane is a suitable drying technique for drying earth materials.

The specific results and findings of the study are:

1. A laboratory prototype propane drying device was designed, constructed and implemented to dry earth materials.
2. The test results demonstrated, at a laboratory scale, the viability of using propone to dry soils from a very wet condition to a condition suitable for proper compaction of the materials.
3. Statistical analysis of the test data demonstrates that propane consumption is the most significant variable effecting drying of the soils. Other statistically significant variables include the soil type and machine height.

The amount of propane consumption in the laboratory tests should not be scaled to estimate field scale values because of the nature in which the heat is applied. The laboratory test sample consists of a single strip of soil, on which the lab scale device travels over, with no soil to the outsides. The heat loss to the outside atmosphere is significant but could not be accurately measured. In a field scale device there would be less loss to the atmosphere, deeper depths and higher volumes of soil permitting more absorption and efficient use of the propane heat. Also, the heat that was lost to the atmosphere and concrete floor would be easily absorbed by additional material that would be present in the field. The presence of a propane pressure regulator on a field scale device would ensure even consumption of propane and allow for consistent measurement of water content change with propane consumption. Various field tilling methods (tilling, disking, and tines) should be explored to determine the best method and compatibility propane.

With the propane soil drying concept proven in the laboratory, the ultimate benefits and economical aspects of using propane as a soil drying fuel need to be explored in the field to determine its true potential. Thus it is recommended that a field scale device be designed, constructed and subjected to field trials to determine the field viability of propane soil drying. This report provides conceptual guidance for development of a field device. Limitations encountered in the laboratory scale testing can be overcome in field scale testing, thus better proving the benefits of propane for soil drying.

Table 11 summarizes the findings of this report. Non-bulk propane was used for the laboratory testing and bulk propane would be used for field testing.

Table 11. Propane Usage to Dry One Cubic Foot of Soil 4%

Soil Type	Clay		Loess		Sand	
Layer Thickness (in)	1.5	4	1.5	4	1.5	4
Propane (lbs)	1.22	0.36	1.19	0.42	1.33	0.66
Non-Bulk Cost (US$)	$0.76	$0.23	$0.74	$0.26	$0.83	$0.41
Bulk Cost (US$)	$0.12	$0.10	$0.12	$0.11	$0.13	$0.18

A field scale device is recommended to prove the concept that propane will dry a variety of soils. A field scale propane soil drying device would provide valuable data that could not be achieved in the laboratory because of limitations relating to laboratory environment, soil conditions, device characteristics, and tilling options. A field scale device would provide a more accurate economic feasibility study because propane would be consumed at the less expensive bulk rate.

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Appendix A: PRO-SD Laboratory Data

PROPANE DRYING TESTS WITH MOISTURE CONTENT MEASUREMENTS

ID (Group, Round, Sample)	Soil Type	Heat Level	Soil Thickness, in	Device Height	Tiller Type	Passes This Round	Passes Cumulative	MC %	MC % Change This Round[ab]	MC % Change Total	Propane, lbs	Propane, lbs This Round[c]	Propane, lbs Total
1.0a (Initial)	Clay	Low	1.5	High	None	0	0	32.6	0.0	0.0	70.60	0.00	0.00
1.0b (Initial)	Clay	Low	1.5	High	None	0	0	31.6	0.0	0.0	70.60	0.00	0.00
1.1a	Clay	Low	1.5	High	None	4	4	27.4	4.7	4.7	70.20	0.40	0.40
1.1b	Clay	Low	1.5	High	None	4	4	29.2	2.9	2.9	70.20	0.40	0.40
1.2a	Clay	Low	1.5	High	None	4	8	29.6	-1.3	2.5	69.80	0.40	0.80
1.2b	Clay	Low	1.5	High	None	4	8	29.0	-0.7	3.1	69.80	0.40	0.80
1.3a	Clay	Low	1.5	High	None	4	12	24.9	4.4	7.2	69.40	0.40	1.20
1.3b	Clay	Low	1.5	High	None	4	12	22.3	7.0	9.8	69.40	0.40	1.20
1.4a	Clay	Low	1.5	High	None	4	16	22.8	0.8	9.3	69.10	0.30	1.50
1.4b	Clay	Low	1.5	High	None	4	16	23.9	-0.3	8.2	69.10	0.30	1.50
1.5a	Clay	Low	1.5	High	None	4	20	21.5	1.9	10.6	68.70	0.40	1.90
1.5b	Clay	Low	1.5	High	None	4	20	22.6	0.8	9.5	68.70	0.40	1.90
1.6a	Clay	Low	1.5	High	None	4	24	21.8	0.3	10.3	68.30	0.40	2.30
1.6b	Clay	Low	1.5	High	None	4	24	15.1	7.0	17.0	68.30	0.40	2.30
2.0a (Initial)	Clay	Low	1.5	Med	Mech	0	0	29.2	0.0	0.0	68.40	0.00	0.00
2.0b (Initial)	Clay	Low	1.5	Med	Mech	0	0	29.2	0.0	0.0	68.40	0.00	0.00
2.1a	Clay	Low	1.5	Med	Mech	4	4	24.9	4.3	4.3	68.00	0.40	0.40
2.1b	Clay	Low	1.5	Med	Mech	4	4	24.3	4.9	4.9	68.00	0.40	0.40
2.2a	Clay	Low	1.5	Med	Mech	4	8	25.9	-1.3	3.3	67.60	0.40	0.80
2.2b	Clay	Low	1.5	Med	Mech	4	8	24.0	0.6	5.2	67.60	0.40	0.80
2.3a	Clay	Low	1.5	Med	Mech	4	12	19.4	5.6	9.8	67.20	0.40	1.20
2.3b	Clay	Low	1.5	Med	Mech	4	12	23.0	2.0	6.2	67.20	0.40	1.20
2.4a	Clay	Low	1.5	Med	Mech	4	16	22.7	-1.5	6.5	66.80	0.40	1.60
2.4b	Clay	Low	1.5	Med	Mech	4	16	22.1	-0.9	7.1	66.80	0.40	1.60
2.5a	Clay	Low	1.5	Med	Mech	4	20	20.6	1.8	8.6	66.50	0.30	1.90
2.5b	Clay	Low	1.5	Med	Mech	4	20	19.3	3.1	9.9	66.50	0.30	1.90
3.0a (Initial)	Clay	Low	1.5	Med	Mech	0	0	31.0	0.0	0.0	66.60	0.00	0.00
3.0b (Initial)	Clay	Low	1.5	Med	Mech	0	0	31.0	0.0	0.0	66.60	0.00	0.00
3.1a	Clay	Low	1.5	Med	Mech	4	4	26.4	4.6	4.6	66.20	0.40	0.40
3.1b	Clay	Low	1.5	Med	Mech	4	4	30.5	0.5	0.5	66.20	0.40	0.40
3.2a	Clay	Low	1.5	Med	Mech	8	12	8.3	20.2	22.7	65.40	0.80	1.20
3.2b	Clay	Low	1.5	Med	Mech	8	12	28.7	-0.3	2.3	65.40	0.80	1.20
3.3a	Clay	Low	1.5	Med	Mech	8	20	16.6	1.9	14.4	64.70	0.70	1.90
3.3b	Clay	Low	1.5	Med	Mech	8	20	29.0	-10.5	2.0	64.70	0.70	1.90

PROPANE DRYING TESTS WITH MOISTURE CONTENT MEASUREMENTS

ID Group, Round, Sample	Soil Type	Heat Level	Soil Thickness, in	Device Height	Tiller Type	Passes This Round	Passes Cumulative	MC %	MC % Change This Round[ab]	MC % Change Total	Propane, lbs	Propane, lbs This Round[c]	Propane, lbs Total
4.0a (Initial)	Sand	Low	1.5	Med	None	0	0	19.9	0.0	0.0	64.90	0.00	0.00
4.0b (Initial)	Sand	Low	1.5	Med	None	0	0	19.9	0.0	0.0	64.90	0.00	0.00
4.1a	Sand	Low	1.5	Med	None	4	4	13.6	6.3	6.3	64.50	0.40	0.40
4.1b	Sand	Low	1.5	Med	None	4	4	15.9	4.0	4.0	64.50	0.40	0.40
4.2a	Sand	Low	1.5	Med	None	4	8	9.3	5.5	10.6	64.10	0.40	0.80
4.2b	Sand	Low	1.5	Med	None	4	8	11.3	3.5	8.6	64.10	0.40	0.80
4.3a	Sand	Low	1.5	Med	None	4	12	7.0	3.3	12.9	63.70	0.40	1.20
4.3b	Sand	Low	1.5	Med	None	4	12	11.1	-0.8	8.8	63.70	0.40	1.20
4.4a	Sand	Low	1.5	Med	None	8	20	4.0	5.1	15.9	62.90	0.80	2.00
4.4b	Sand	Low	1.5	Med	None	8	20	10.8	-1.8	9.1	62.90	0.80	2.00
4.5a	Sand	Low	1.5	Med	None	4	24	4.4	3.0	15.5	62.50	0.40	2.40
4.5b	Sand	Low	1.5	Med	None	4	24	10.7	-3.3	9.2	62.50	0.40	2.40
5.0a (Initial)	Loess	Low	1.5	Med	Mech	0	0	28.4	0.0	0.0	62.60	0.00	0.00
5.0b (Initial)	Loess	Low	1.5	Med	Mech	0	0	28.4	0.0	0.0	62.60	0.00	0.00
5.1a	Loess	Low	1.5	Med	Mech	8	8	20.2	8.2	8.2	61.90	0.70	0.70
5.1b	Loess	Low	1.5	Med	Mech	8	8	25.1	3.3	3.3	61.90	0.70	0.70
5.2a	Loess	Low	1.5	Med	Mech	8	16	16.2	6.5	12.2	61.10	0.80	1.50
5.2b	Loess	Low	1.5	Med	Mech	8	16	23.5	-0.9	4.9	61.10	0.80	1.50
5.3a	Loess	Low	1.5	Med	Mech	8	24	13.4	6.5	15.0	60.30	0.80	2.30
5.3b	Loess	Low	1.5	Med	Mech	8	24	20.1	-0.3	8.3	60.30	0.80	2.30
6.0a (Initial)	Clay	Low	1.5	Med	Man	0	0	28.7	0.0	0.0	60.40	0.00	0.00
6.0b (Initial)	Clay	Low	1.5	Med	Man	0	0	28.7	0.0	0.0	60.40	0.00	0.00
6.1a	Clay	Low	1.5	Med	Man	8	8	23.4	5.3	5.3	59.70	0.70	0.70
6.1b	Clay	Low	1.5	Med	Man	8	8	24.4	4.3	4.3	59.70	0.70	0.70
6.2a	Clay	Low	1.5	Med	Man	8	16	17.4	6.5	11.3	58.85	0.85	1.55
6.2b	Clay	Low	1.5	Med	Man	8	16	19.6	4.3	9.1	58.85	0.85	1.55
6.3a	Clay	Low	1.5	Med	Man	8	24	13.7	4.8	15.0	58.05	0.80	2.35
6.3b	Clay	Low	1.5	Med	Man	8	24	14.8	3.7	13.9	58.05	0.80	2.35
6.3c	Clay	Low	1.5	Med	Man	8	24	15.0	3.5	13.7	58.05	0.80	2.35

PROPANE DRYING TESTS WITH MOISTURE CONTENT MEASUREMENTS

ID Group, Round, Sample	Soil Type	Heat Level	Soil Thickness, in	Device Height	Tiller Type	Passes This Round	Passes Cumulative	MC %	MC % Change This Round[ab]	MC % Change Total	Propane, lbs	Propane, lbs This Round[c]	Propane, lbs Total
7.0a (Initial)	Clay	Low	1.5	Med	Man	0	0	33.5	0.0	0.0	58.05	0.00	0.00
7.0b (Initial)	Clay	Low	1.5	Med	Man	0	0	33.5	0.0	0.0	58.05	0.00	0.00
7.1a	Clay	Low	1.5	Med	Man	8	8	26.0	7.5	7.5	57.35	0.70	0.70
7.1b	Clay	Low	1.5	Med	Man	8	8	28.8	4.7	4.7	57.35	0.70	0.70
7.2a	Clay	Low	1.5	Med	Man	8	16	23.8	3.6	9.7	56.65	0.70	1.40
7.2b	Clay	Low	1.5	Med	Man	8	16	25.8	1.6	7.7	56.65	0.70	1.40
7.3a	Clay	Low	1.5	Med	Man	8	24	22.3	2.5	11.2	55.90	0.75	2.15
7.3b	Clay	Low	1.5	Med	Man	8	24	20.9	3.9	12.6	55.90	0.75	2.15
7.4a	Clay	Low	1.5	Med	Man	8	32	18.4	3.2	15.1	55.15	0.75	2.90
7.4b	Clay	Low	1.5	Med	Man	8	32	16.5	5.1	17.0	55.15	0.75	2.90
8.0a (Initial)	Sand	Low	1.5	Med	Man	0	0	18.7	0.0	0.0	55.05	0.00	0.00
8.0b (Initial)	Sand	Low	1.5	Med	Man	0	0	18.5	0.0	0.0	55.05	0.00	0.00
8.1a	Sand	Low	1.5	Med	Man	8	8	13.5	5.1	5.1	54.30	0.75	0.75
8.1b	Sand	Low	1.5	Med	Man	8	8	13.9	4.7	4.7	54.30	0.75	0.75
8.2a	Sand	Low	1.5	Med	Man	8	16	10.1	3.6	8.5	53.55	0.75	1.50
8.2b	Sand	Low	1.5	Med	Man	8	16	10.6	3.1	8.0	53.55	0.75	1.50
8.3a	Sand	Low	1.5	Med	Man	8	24	7.9	2.5	10.7	52.75	0.80	2.30
8.3b	Sand	Low	1.5	Med	Man	8	24	8.4	2.0	10.2	52.75	0.80	2.30
9.0a (Initial)	Loess	Low	1.5	Med	Man	0	0	31.9	0.0	0.0	52.70	0.00	0.00
9.0b (Initial)	Loess	Low	1.5	Med	Man	0	0	31.7	0.0	0.0	52.70	0.00	0.00
9.1a	Loess	Low	1.5	Med	Man	8	8	28.8	3.0	3.0	52.10	0.60	0.60
9.1b	Loess	Low	1.5	Med	Man	8	8	28.3	3.5	3.5	52.10	0.60	0.60
9.2a	Loess	Low	1.5	Med	Man	8	16	26.1	2.5	5.7	51.35	0.75	1.35
9.2b	Loess	Low	1.5	Med	Man	8	16	26.4	2.2	5.4	51.35	0.75	1.35
9.3a	Loess	Low	1.5	Med	Man	8	24	19.4	6.9	12.4	50.55	0.80	2.15
9.3b	Loess	Low	1.5	Med	Man	8	24	19.8	6.5	12.0	50.55	0.80	2.15
10.0a (Initial)	Clay	Low	4.0	Med	Man	0	0	33.0	0.0	0.0	50.50	0.00	0.00
10.0b (Initial)	Clay	Low	4.0	Med	Man	0	0	33.0	0.0	0.0	50.50	0.00	0.00
10.1a	Clay	Low	4.0	Med	Man	8	8	30.0	3.0	3.0	50.15	0.35	0.35
10.1b	Clay	Low	4.0	Med	Man	8	8	32.3	0.7	0.7	50.15	0.35	0.35
10.2a	Clay	Low	4.0	Med	Man	10	18	25.0	6.2	8.0	49.75	0.40	0.75
10.2b	Clay	Low	4.0	Med	Man	10	18	33.1	-2.0	-0.1	49.75	0.40	0.75
10.3a	Clay	Low	4.0	Med	Man	8	26	24.5	4.6	8.5	49.40	0.35	1.10
10.3b	Clay	Low	4.0	Med	Man	8	26	33.5	-4.5	-0.5	49.40	0.35	1.10

PROPANE DRYING TESTS WITH MOISTURE CONTENT MEASUREMENTS													
ID (Group, Round, Sample)	Soil Type	Heat Level	Soil Thickness, in	Device Height	Tiller Type	Passes This Round	Passes Cumulative	MC %	MC % Change This Round[ab]	MC % Change Total	Propane, lbs	Propane, lbs This Round[c]	Propane, lbs Total
11.0a (Initial)	Clay	High	4.0	Low	Man	0	0	34.2	0.0	0.0	49.40	0.00	0.00
11.0b (Initial)	Clay	High	4.0	Low	Man	0	0	34.2	0.0	0.0	49.40	0.00	0.00
11.1a	Clay	High	4.0	Low	Man	8	8	31.3	2.9	2.9	48.85	0.55	0.55
11.1b	Clay	High	4.0	Low	Man	8	8	31.2	3.0	3.0	48.85	0.55	0.55
11.2a	Clay	High	4.0	Low	Man	4	12	27.2	4.1	7.0	48.60	0.25	0.80
11.2b	Clay	High	4.0	Low	Man	4	12	30.7	0.6	3.5	48.60	0.25	0.80
11.3a	Clay	High	4.0	Low	Man	8	20	10.4	18.6	23.8	47.85	0.75	1.55
11.3b	Clay	High	4.0	Low	Man	8	20	29.3	-0.4	4.9	47.85	0.75	1.55
12.0a (Initial)	Clay	High	4.0	Low	Man	0	0	29.2	0.0	0.0	47.85	0.00	0.00
12.0b (Initial)	Clay	High	4.0	Low	Man	0	0	29.2	0.0	0.0	47.85	0.00	0.00
12.1a	Clay	High	4.0	Low	Man	8	8	22.0	7.2	7.2	47.30	0.55	0.55
12.1b	Clay	High	4.0	Low	Man	8	8	27.0	2.2	2.2	47.30	0.55	0.55
12.2a	Clay	High	4.0	Low	Man	8	16	18.1	6.4	11.1	46.80	0.50	1.05
12.2b	Clay	High	4.0	Low	Man	8	16	23.1	1.4	6.1	46.80	0.50	1.05
12.3a	Clay	High	4.0	Low	Man	4	20	8.1	12.5	21.1	46.55	0.25	1.30
12.3b	Clay	High	4.0	Low	Man	4	20	21.7	-1.1	7.5	46.55	0.25	1.30
13.0a (Initial)	Clay	High	4.0	Low	Man	0	0	36.5	0.0	0.0	46.50	0.00	0.00
13.0b (Initial)	Clay	High	4.0	Low	Man	0	0	36.5	0.0	0.0	46.50	0.00	0.00
13.1a	Clay	High	4.0	Low	Man	8	8	21.2	15.3	15.3	45.95	0.55	0.55
13.1b	Clay	High	4.0	Low	Man	8	8	34.2	2.3	2.3	45.95	0.55	0.55
13.2a	Clay	High	4.0	Low	Man	8	16	18.2	9.5	18.3	45.40	0.55	1.10
13.2b	Clay	High	4.0	Low	Man	8	16	28.8	-1.1	7.7	45.40	0.55	1.10
13.3a	Clay	High	4.0	Low	Man	4	20	13.0	10.5	23.5	45.10	0.30	1.40
13.3b	Clay	High	4.0	Low	Man	4	20	21.0	2.5	15.5	45.10	0.30	1.40
14.0a (Initial)	Sand	High	4.0	Low	Man	0	0	16.2	0.0	0.0	45.10	0.00	0.00
14.0b (Initial)	Sand	High	4.0	Low	Man	0	0	15.9	0.0	0.0	45.10	0.00	0.00
14.1a	Sand	High	4.0	Low	Man	8	8	11.4	4.7	4.7	44.55	0.55	0.55
14.1b	Sand	High	4.0	Low	Man	8	8	15.4	0.7	0.7	44.55	0.55	0.55
14.2a	Sand	High	4.0	Low	Man	8	16	8.5	4.9	7.6	44.00	0.55	1.10
14.2b	Sand	High	4.0	Low	Man	8	16	15.1	-1.7	1.0	44.00	0.55	1.10
14.3a	Sand	High	4.0	Low	Man	4	20	7.5	4.3	8.6	43.70	0.30	1.40
14.3b	Sand	High	4.0	Low	Man	4	20	14.4	-2.6	1.7	43.70	0.30	1.40

PROPANE DRYING TESTS WITH MOISTURE CONTENT MEASUREMENTS

ID (Group, Round, Sample)	Soil Type	Heat Level	Soil Thickness, in	Device Height	Tiller Type	Passes This Round	Passes Cumulative	MC %	MC % Change This Round[ab]	MC % Change Total	Propane, lbs	Propane, lbs This Round[c]	Propane, lbs Total
15.0a (Initial)	Loess	High	4.0	Low	Man	0	0	30.6	0.0	0.0	43.70	0.00	0.00
15.0b (Initial)	Loess	High	4.0	Low	Man	0	0	28.4	0.0	0.0	43.70	0.00	0.00
15.1a	Loess	High	4.0	Low	Man	8	8	24.2	5.3	5.3	43.20	0.50	0.50
15.1b	Loess	High	4.0	Low	Man	8	8	28.9	0.6	0.6	43.20	0.50	0.50
15.2a	Loess	High	4.0	Low	Man	8	16	22.3	4.3	7.2	42.70	0.50	1.00
15.2b	Loess	High	4.0	Low	Man	8	16	26.4	0.1	3.1	42.70	0.50	1.00
15.3a	Loess	High	4.0	Low	Man	4	20	18.4	6.0	11.1	42.50	0.20	1.20
15.3b	Loess	High	4.0	Low	Man	4	20	26.9	-2.6	2.6	42.50	0.20	1.20
16.0a (Initial)	Clay	High	4.0	Low	Man	0	0	37.7	0.0	0.0	42.45	0.00	0.00
16.0b (Initial)	Clay	High	4.0	Low	Man	0	0	35.3	0.0	0.0	42.45	0.00	0.00
16.1a	Clay	High	4.0	Low	Man	8	8	25.3	11.2	11.2	41.95	0.50	0.50
16.1b	Clay	High	4.0	Low	Man	8	8	32.7	3.8	3.8	41.95	0.50	0.50
16.2a	Clay	High	4.0	Low	Man	8	16	21.2	7.8	15.3	41.50	0.45	0.95
16.2b	Clay	High	4.0	Low	Man	8	16	31.9	-2.9	4.6	41.50	0.45	0.95
16.3a	Clay	High	4.0	Low	Man	4	20	16.6	10.0	19.9	41.25	0.25	1.20
16.3b	Clay	High	4.0	Low	Man	4	20	31.2	-4.7	5.3	41.25	0.25	1.20
17.0a (Initial)	Clay	High	4.0	Low	Man	0	0	26.5	0.0	0.0	41.20	0.00	0.00
17.0b (Initial)	Clay	High	4.0	Low	Man	0	0	26.3	0.0	0.0	41.20	0.00	0.00
17.1a	Clay	High	4.0	Low	Man	8	8	17.4	9.0	9.0	40.65	0.55	0.55
17.1b	Clay	High	4.0	Low	Man	8	8	27.0	-0.6	-0.6	40.65	0.55	0.55
17.2a	Clay	High	4.0	Low	Man	8	16	18.5	3.7	7.9	40.10	0.55	1.10
17.2b	Clay	High	4.0	Low	Man	8	16	25.2	-3.0	1.2	40.10	0.55	1.10
17.3a	Clay	High	4.0	Low	Man	4	20	18.7	3.2	7.7	39.80	0.30	1.40
17.3b	Clay	High	4.0	Low	Man	4	20	23.4	-1.6	3.0	39.80	0.30	1.40
18.0a (Initial)	Clay	High	4.0	Low	Man	0	0	28.7	0.0	0.0	39.80	0.00	0.00
18.0b (Initial)	Clay	High	4.0	Low	Man	0	0	28.8	0.0	0.0	39.80	0.00	0.00
18.1a	Clay	High	4.0	Low	Man	8	8	24.3	4.5	4.5	39.30	0.50	0.50
18.1b	Clay	High	4.0	Low	Man	8	8	25.0	3.8	3.8	39.30	0.50	0.50
18.2a	Clay	High	4.0	Low	Man	8	16	21.4	3.3	7.4	38.80	0.50	1.00
18.2b	Clay	High	4.0	Low	Man	8	16	26.8	-2.2	2.0	38.80	0.50	1.00
18.3a	Clay	High	4.0	Low	Man	4	20	18.0	6.1	10.8	38.50	0.30	1.30
18.3b	Clay	High	4.0	Low	Man	4	20	24.0	0.1	4.8	38.50	0.30	1.30

a - Negative values indicate an increase in moisture content

b - Percent moisture content change per round and cumulative are calculated using the average of the two values from the previous round.

c - Propane used per round and cumulative are calculated using the average of the two values from the previous round.

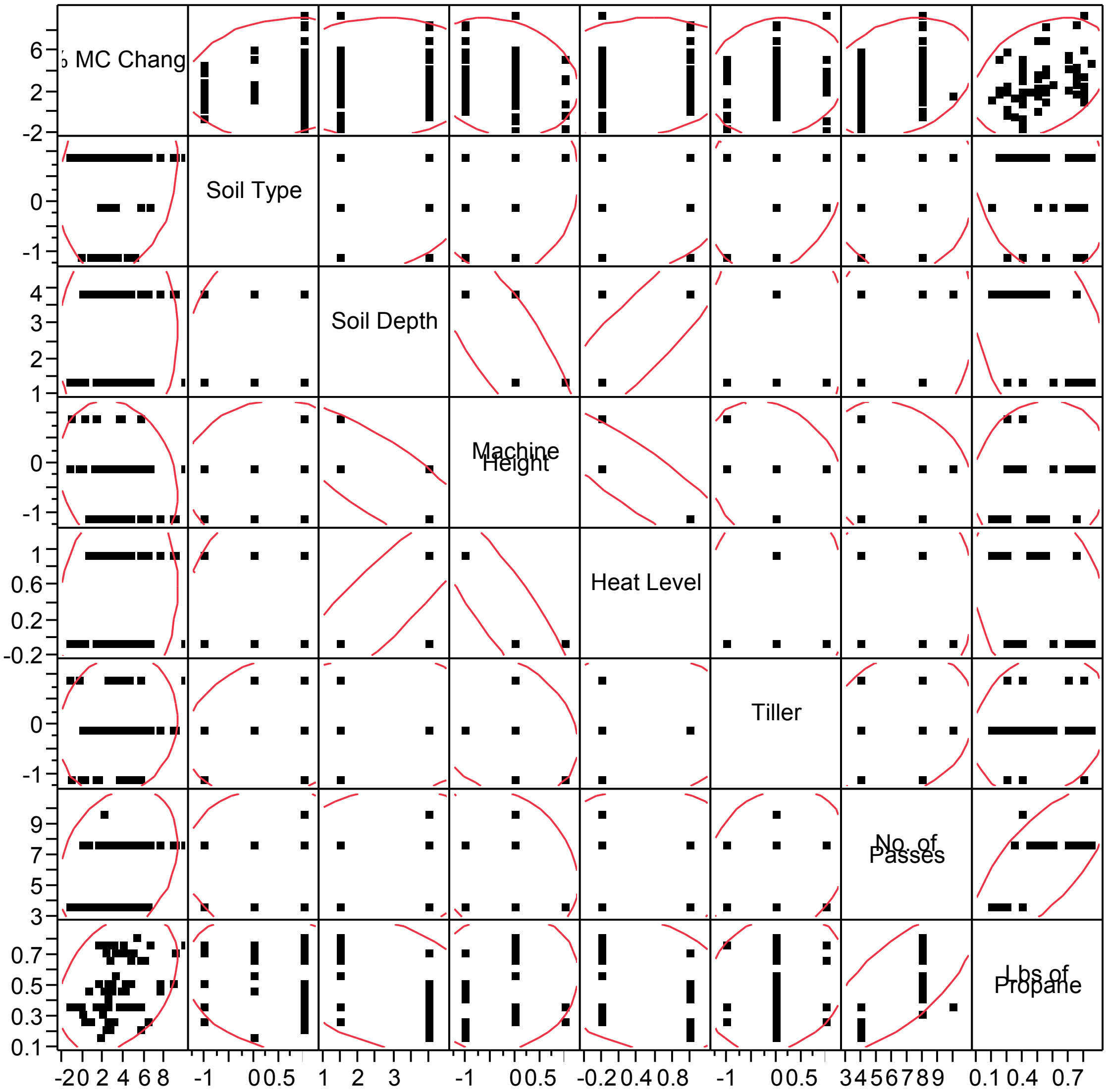
Appendix B: Statistical Data Using JMP

Multivariate Correlations

	% MC Change	Soil Type	Soil Depth	Machine Height	Heat Level	Tiller	No. of Passes	Lbs of Propane
% MC Change	1.0000	0.1775	0.0616	-0.1932	0.1525	0.1288	0.2808	0.3618
Soil Type	0.1775	1.0000	0.1994	-0.0049	0.1373	0.2322	-0.0396	-0.2040
Soil Depth	0.0616	0.1994	1.0000	-0.8318	0.9038	0.0249	0.1919	-0.3925
Machine Height	-0.1932	-0.0049	-0.8318	1.0000	-0.8924	-0.2766	-0.2547	0.1262
Heat Level	0.1525	0.1373	0.9038	-0.8924	1.0000	0.0225	0.0838	-0.3147
Tiller	0.1288	0.2322	0.0249	-0.2766	0.0225	1.0000	0.2024	0.1876
No. of Passes	0.2808	-0.0396	0.1919	-0.2547	0.0838	0.2024	1.0000	0.7314
Lbs of Propane	0.3618	-0.2040	-0.3925	0.1262	-0.3147	0.1876	0.7314	1.0000

The correlations are estimated by REML method.

Scatterplot Matrix



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	804.98	268.33	62.09
Error	58	250.64	4.321	**Prob > F**
C. Total	61	1055.63		<0.0001*

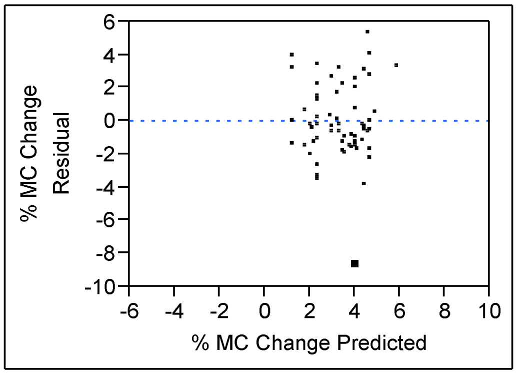
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Soil Type	0.770	0.323	2.38	0.0204*
Machine Height	-0.889	0.408	-2.18	0.0334*
Lbs of Propane	5.420	0.566	9.57	<0.0001*

Prediction Equation

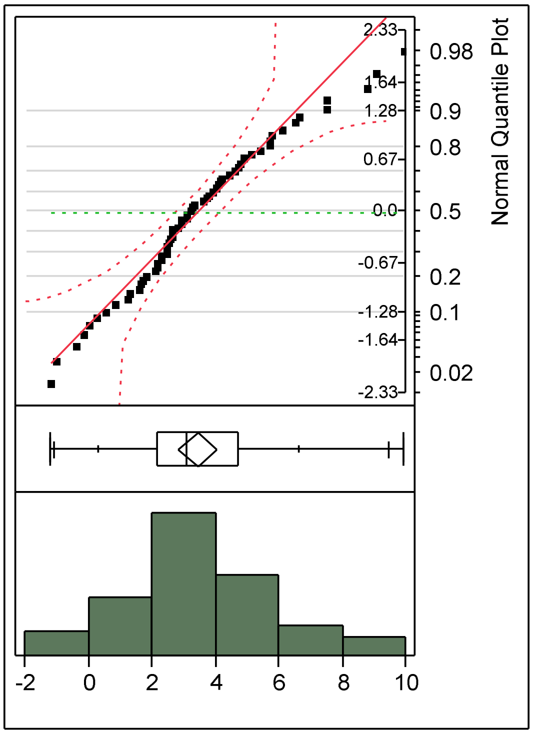
$$\% \mathit{Moistuire\ Change} = 0.77 * \mathit{Soil\ Type} - 0.89 * \mathit{Machine\ Height} + 5.42 * \mathit{Pounds\ of\ Propane}$$

Residual by Predicted Plot

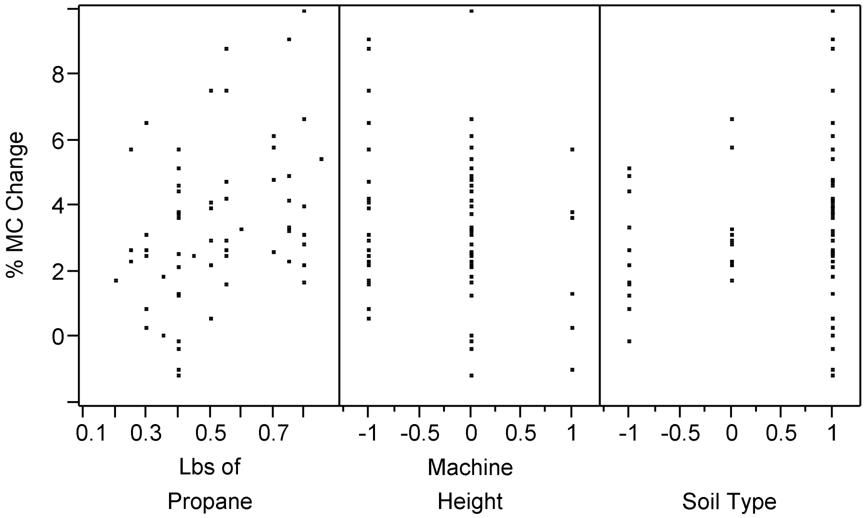


Distributions

% MC Change



Scatterplot Matrix of Residuals



Statistical Model – Run 1

Response % MC Change

Summary of Fit

Root Mean Square Error	2.08596
Mean of Response	3.431967
Observations (or Sum Wgts)	61

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	820.6612	117.237	26.9435
Error	54	234.9663	4.351	**Prob > F**
C. Total	61	1055.6275		<.0001*

Tested against reduced model: Y=0

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	23	80.70429	3.50888	0.7051
Pure Error	31	154.26204	4.97619	**Prob > F**
Total Error	54	234.96633		0.8052
				Max RSq
				0.8539

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Soil Type	1.0024442	0.426047	2.35	0.0223*
Soil Depth	0.0516109	0.518009	0.10	0.9210
Machine Height	-1.3757	1.325034	-1.04	0.3038
Heat Level	0.0811907	2.057025	0.04	0.9687
Tiller	-0.490292	0.641053	-0.76	0.4477
No. of Passes	-0.423461	0.32849	-1.29	0.2029
Lbs of Propane	9.84624	2.890378	3.41	0.0012*

Statistical Model – Run 2

Response % MC Change

Summary of Fit

Root Mean Square Error	2.048931
Mean of Response	3.431967
Observations (or Sum Wgts)	61

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	820.5328	164.107	39.0905
Error	56	235.0947	4.198	**Prob > F**
C. Total	61	1055.6275		<.0001*

Tested against reduced model: Y=0

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	25	80.83265	3.23331	0.6498
Pure Error	31	154.26204	4.97619	**Prob > F**
Total Error	56	235.09469		0.8638
				Max RSq
				0.8539

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Soil Type	1.0400424	0.347962	2.99	0.0042*
Machine Height	-1.512654	0.517087	-2.93	0.0050*
Tiller	-0.549219	0.483654	-1.14	0.2610
No. of Passes	-0.398498	0.22268	-1.79	0.0789
Lbs of Propane	9.7220214	2.495029	3.90	0.0003*

Statistical Model – Run 3

Response % MC Change

Summary of Fit

Root Mean Square Error	2.078807
Mean of Response	3.431967
Observations (or Sum Wgts)	61

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	804.9840	268.328	62.0923
Error	58	250.6435	4.321	**Prob > F**
C. Total	61	1055.6275		<.0001*

Tested against reduced model: Y=0

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	23	69.35823	3.01558	0.5822
Pure Error	35	181.28529	5.17958	**Prob > F**
Total Error	58	250.64352		0.9120
				Max RSq
				0.8283

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Soil Type	0.7703065	0.323104	2.38	0.0204*
Machine Height	-0.889002	0.408043	-2.18	0.0334*
Lbs of Propane	5.4197861	0.566233	9.57	<.0001*