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College of Engineering
Box 41023
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16. Abstract:

Phase III of Research Project 0-1860 was initiated with the primary objective of evaluating the feasibility of using SOVIT technology for slope stabilization purposes. Accordingly, two sites in the Dallas metropolitan area were selected and limited scale, trial vitrification projects performed at each site. These trial projects demonstrated the viability of using SOVIT technology for slope stabilization purposes. At the same time, however, the experience from the trial projects showed that several modifications to the current portable SOVIT system were necessary before it could be used in a full-scale slope stabilization project. These modifications include: (a) providing the arc melter head and the CGAM electrodes with independent mobility so that electrodes can be easily aligned over a pre-drilled borehole, (b) attaching a hand held gasoline powered auger to the arc melter frame, and (c) re-design of the Power Conditioning System (PCU) to make it more suitable for extreme temperature conditions found in the field. The modification of the PCU was also completed as a part of Phase III research effort.

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SUBGRADE REPAIR AND STABILIZATION USING IN-SITU VITRIFICATION – PHASE III: FINAL REPORT

By

Edgar A. O'Hair, P.W. Jayawickrama,
James C. Dickens & M. Shabbir Hossain

Research Report Number 0-1860-3

Research Project 0-1860

Research Project Title: Subgrade Repair and Stabilization Using In-Situ Vitrification

Conducted for
Texas Department of Transportation

By the

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and
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November 2001

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The members of the TxDOT Project 0-1860 research team wish to express their gratitude to each person, who assisted us during the planning, execution of the research, and completion of the written report. We appreciate your generosity and willingness to help us with this work.

Special thanks go to our TxDOT Project Director, George Dozier, and to the members of the Project Monitoring Committee. Also, we wish to thank Carl Utley, P.E., District Engineer, Lubbock District, for his generous support through all phases of this project and to Bennie McCormack, Assistant District Maintenance Manager, for coordinating the work on behalf of TxDOT Dallas District.

IMPLEMENTATION STATEMENT

At this point in time, experimental work has not been completed to validate the inferences made in this report.

Prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

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There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

Engineering Disclaimer

Not intended for construction, bidding, or permit purposes. The engineer in charge of the research study was Phillip T. Nash, P.E., Texas 66985.

Trade Names and Manufacturers' Names

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate

(Revised September 1993)

TABLE OF CONTENTS

LIST OF FIGURES

TABLE

IN-SITU VITRIFICATION FOR SLOPE STABILIZATION

1. Background

This report documents the work accomplished and the results obtained from the third and final phase of TxDOT Research Project 0-1860: Subgrade Repair and Stabilization using In-situ Vitrification. Two other phases have already been completed in this project. The following is a brief overview of the objectives and the scope of these two previous phases.

Phase I work involved the demonstration of the potential of using Concentric Graphite Arc Melter (CGAM) vitrification technology for soil stabilization purposes. Accordingly, seven soil types that are representative of subgrade soils commonly found in Texas were selected for the Phase I study. Large samples of each soil type were obtained and placed in 55-gallon drums. In some samples, the initial water content and density were varied so that the influence of these variables on the effectiveness of stabilization could be determined. Using the CGAM equipment available at Montec Associates' research laboratories in Butte, Montana, a total of 10 soil samples were vitrified. Once vitrification of all soil samples was complete, the vitrified products were shipped back to Texas Tech University for further evaluation. Texas Tech University test program included characterization of each vitrification product with respect to strength, stiffness, density, porosity and resistance to moisture attack. The test results showed that vitrification had been successfully achieved in all soils, initial water contents and densities. The results further revealed that the strength, stiffness and other mechanical properties of the vitrified soils varied significantly. On the average the strengths were similar to that of Portland cement concrete while the modulii of elasticity were lower. Both the strength and stiffness showed close correlation with the density and porosity of the vitrified product. In other words, the strength and stiffness increased with increasing density and decreasing porosity. Complete documentation of Phase I research activities and the findings can be found in TxDOT Research Report No. TX/99/1860-1 (*1*).

Phase II was primarily concerned with the development of a mobile, trailer mounted soil vitrification (SOVIT) system and its demonstration in the field. The two major components of the mobile SOVIT system are: Concentric Graphite Arc Melter (CGAM), and Power Conditioning Unit (PCU). Montec Associates accomplished the design and manufacture of a CGAM unit, suitable for mounting on a trailer. A photograph of this device is shown in Figure 1. Unlike the original laboratory CGAM that uses commercial 3-phase power, the field CGAM is operated by a trailer mounted electric generator. Figure 2 shows the 125kW, 460VAC portable power generator used for this purpose. The AC power produced by this generator must then be converted to DC before it can be used by the CGAM. The PCU shown in Figure 3 accomplished this AC-DC conversion, and further conditioning of the power supply. This PCU was designed and manufactured by Texas Tech University especially for this

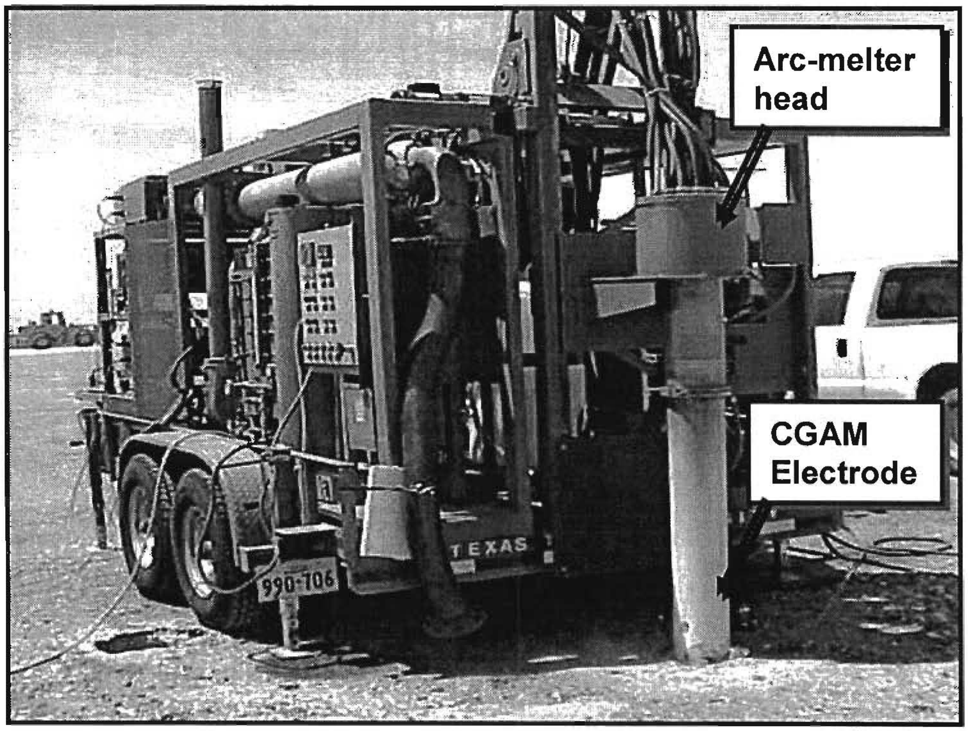

Figure 1. Mobile, Trailer-Mounted SOVIT System

Figure 2. Electric Power Generator Used with SOVIT

Figure 3. Power Conditioning Unit

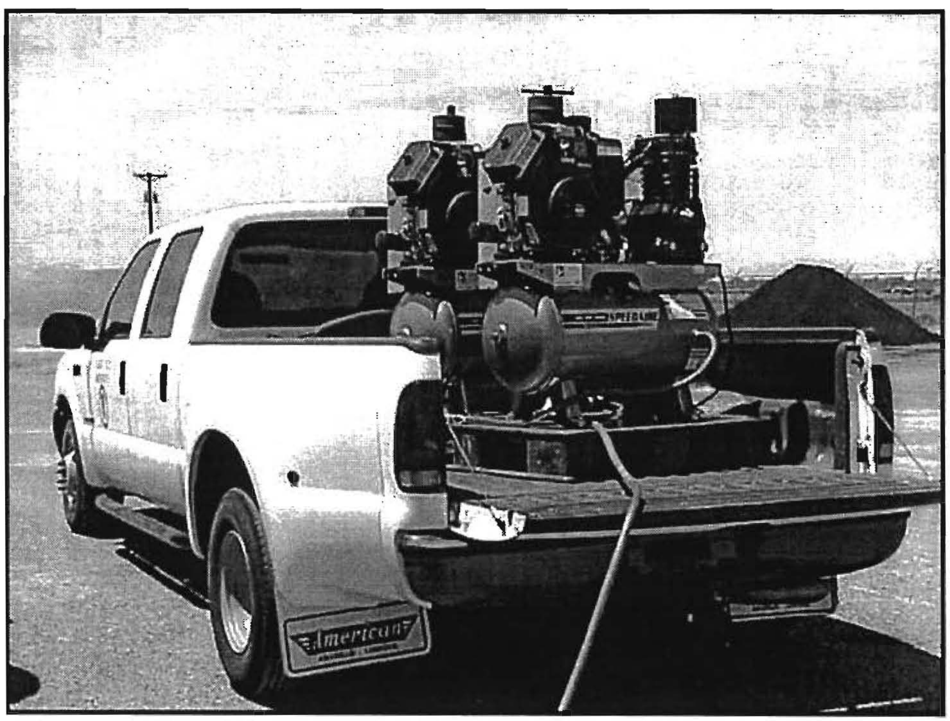

Figure 4. Air Compressor

project. The CGAM also requires a continuous supply of air during its operation. Figure 4 shows the air compressor that was used for this purpose. Once the development of the mobile SOVIT system and the PCU was complete, it was necessary to test the equipment in a field setting. Therefore, Phase II research also included two field trials of the equipment. The first of these was conducted on Texas Tech campus. The second was conducted at the TxDOT maintenance facility in Dimmitt, Texas. In both of these field trials, the SOVIT equipment was used for roadbed stabilization purposes. The results from these field trials indicated that the effect of vitrification and strength increase was very localized. Based on this evaluation, it was concluded that a better application for the vitrification technology would be to stabilize soil slopes using the SOVIT equipment. Research work completed under Phase II of this project is documented in a companion report (*2*).

2. Objectives and the Scope of Phase III Research

The primary objective of the third and final phase of this research was to evaluate the feasibility of using SOVIT technology for slope stabilization purposes. As a first step towards achieving this objective, two sites were selected in the Dallas metropolitan area. Each site was fully characterized in terms of site topography and soil conditions. Subsequently, limited scale soil vitrification experiments were conducted at each site. The observations and experience from these trial projects are documented in this report. This information was then evaluated to determine the future potential use of SOVIT technology for soil stabilization purposes.

3. Site Selection

Because of the abundance of medium to high plastic clays, embankment slope failures are a common problem in the Dallas area. Because of this and the convenient distance from Lubbock, where Texas Tech University is located, the Dallas district was selected for conducting Phase III trial projects. The criteria for selection of the two specific locations for trial vitrification project sites included the following:

- The topography and soil conditions at the selected sites must be typical of those sites where slope failure is common

- There must be easy access to the base of the slope so that the truck, the trailer that carried the SOVIT system, the generator, and the air compressor can be brought to the project site without much difficulty.

- There must be adequate working room near the base of the slope so that vitrification could be conducted without need for traffic control.

- The project sites must be within a convenient distance from a secure area where the equipment could be stored at the end of each day's work.

The selection of project sites that best met the above criteria was accomplished with assistance from Mr. George Dozier, research project director and Mr. Bennie McCormack, Maintenance Manager, Dallas. After visiting and evaluating a number of candidate sites, two sites were selected for vitrification trial projects. In this report, the two project sites are identified as: Motley Drive Site and Galloway Avenue Site. The locations of these two sites are shown in Figure 5. As seen in the map, both of these sites are located in Mesquite, Texas on Interstate Highway –30.

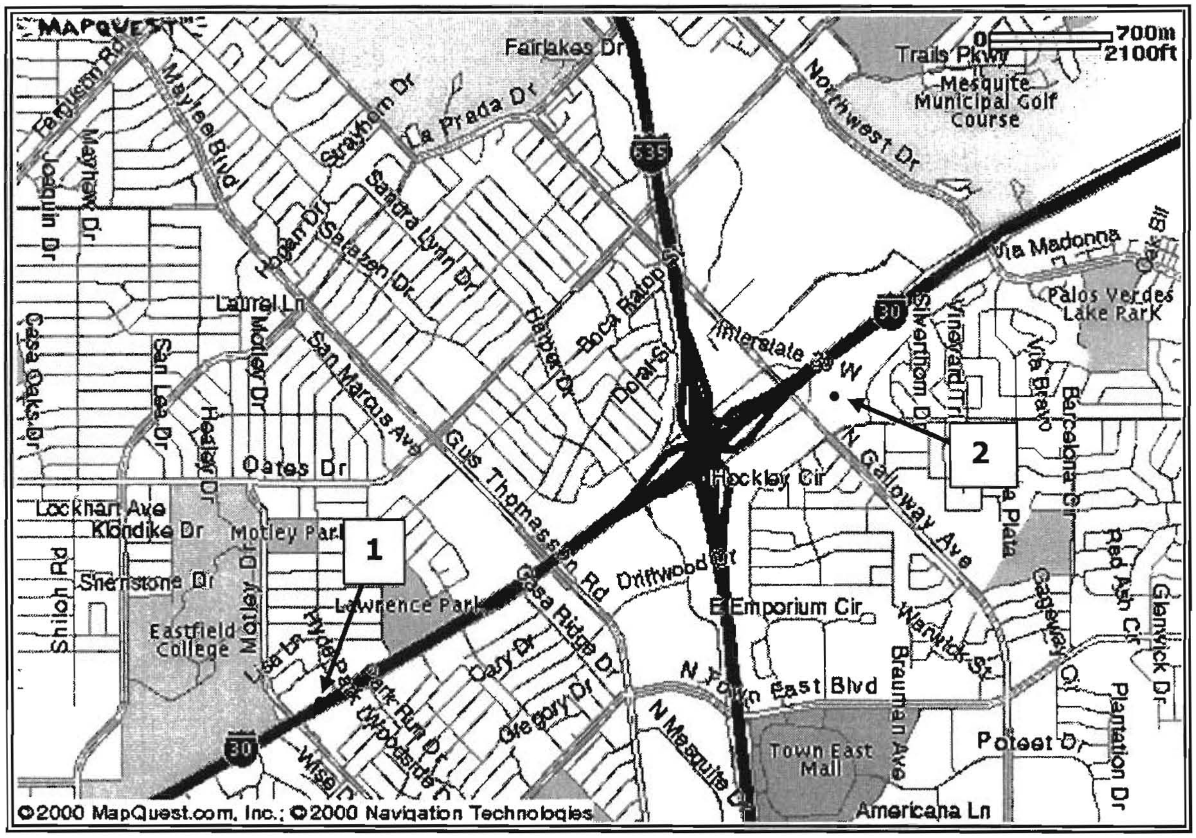

Figure 5. Map Showing Locations of Two Project Sites; (1) Motley Drive Site, (2) Galloway Avenue Site

4. Site Description

Motley Drive Site:

Motley drive site is located at the Motley Drive overpass over Interstate Highway-30. The trial vitrification project took place on the northeast side of the approach embankment. This embankment has had recurrent problems due to slope failure, typically after heavy rain. One such failure had occurred and the failed slope repaired shortly before the vitrification demonstrations were conducted at the site. At the time trail vitrification projects were conducted, there was no established vegetation on the slope. There was no direct access to the site from I-30 or Motley Drive. Nearby side streets and an alley way provided access to the site. Figure 6 shows a photograph of the Motley Drive site.

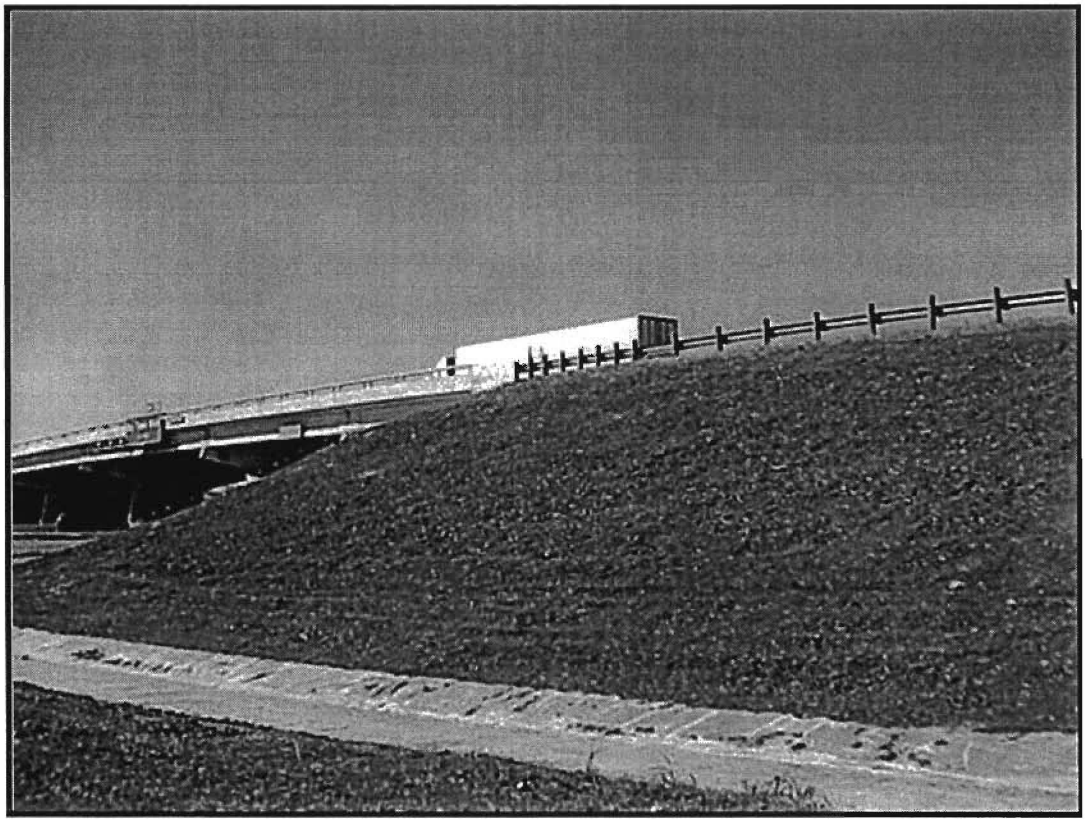

Figure 6. Motley Drive Site in Mesquite, Texas

Galloway Avenue Site:

Galloway Avenue site is located at the Galloway avenue overpass over Interstate Highway-30. The location selected for vitrification was on the southeast side of the approach embankment. This embankment had been constructed recently and had not experienced slope failure problems since its initial construction. There was good grass cover on the slope surface. Figure.7 shows a photograph of the Galloway Avenue site that was taken at the time of the initial site visit.

Figure 7. Galloway Avenue Site in Mesquite, Texas

5. Site Characterization

Site characterization involved two primary tasks: (1) topographic survey of the site, (2) drilling, sampling of the embankment soil and its characterization through laboratory testing.

(a) Topographic Survey

Topographic survey of each project site was conducted by the TxDOT, Dallas district personnel at the researchers' request. Contour plots showing the surface topography at each site were developed based on the data collected. Figure 8 and Figure 9 show the contour plots for Motley Drive and Galloway Avenue sites, respectively.

The approximate locations of the vitrification holes are also shown on the contour maps.

(b) Soil Characterization

Soil samples representative of the treatment zone were recovered from each project site by drilling and sampling with thin-wall Shelby tubes. Mr. Amir (Al) Aramoon, P.E., district materials engineer coordinated this effort on behalf of the TxDOT, Dallas district.

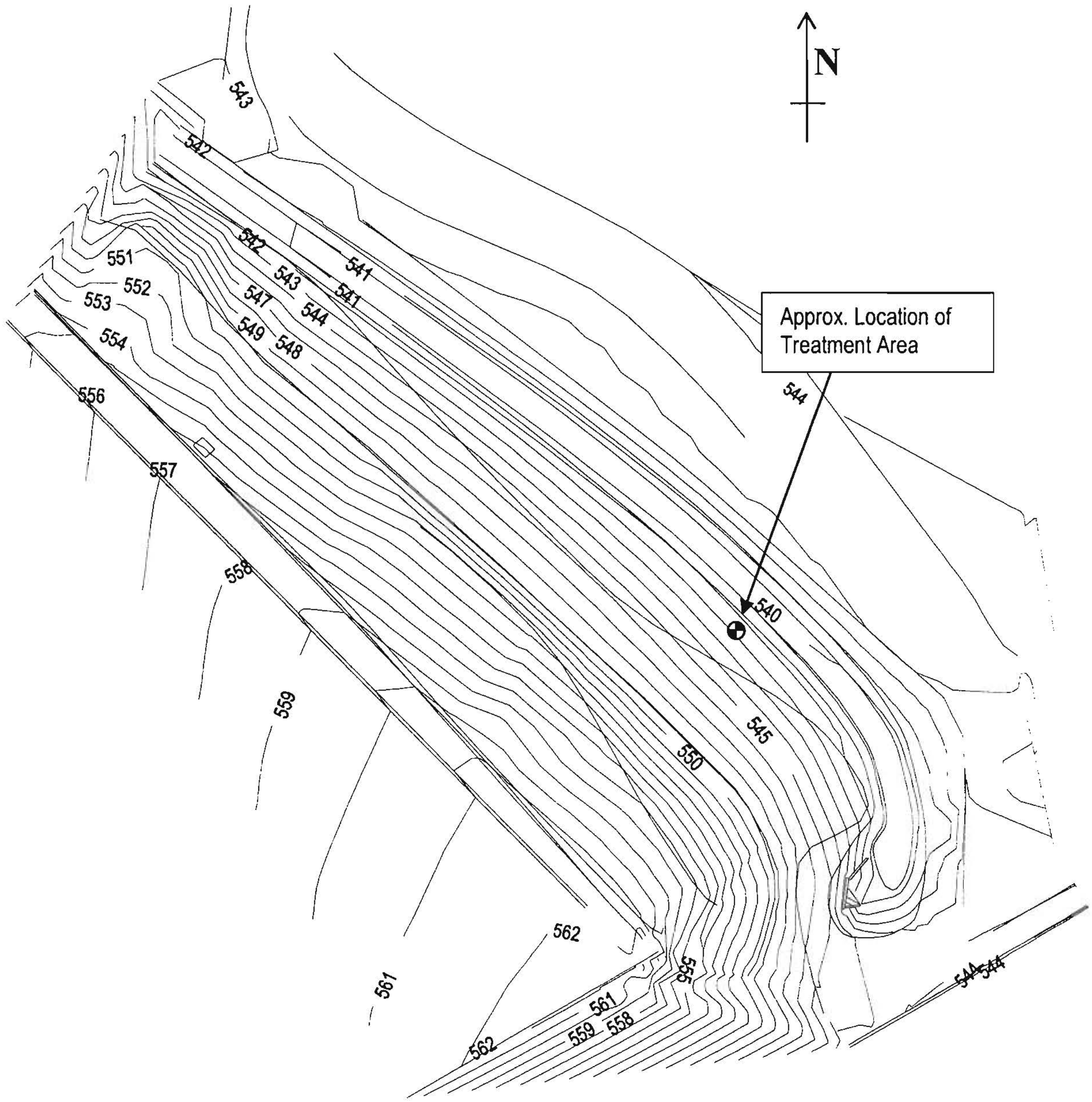

Figure 8. Site Topography at Motley Drive Site

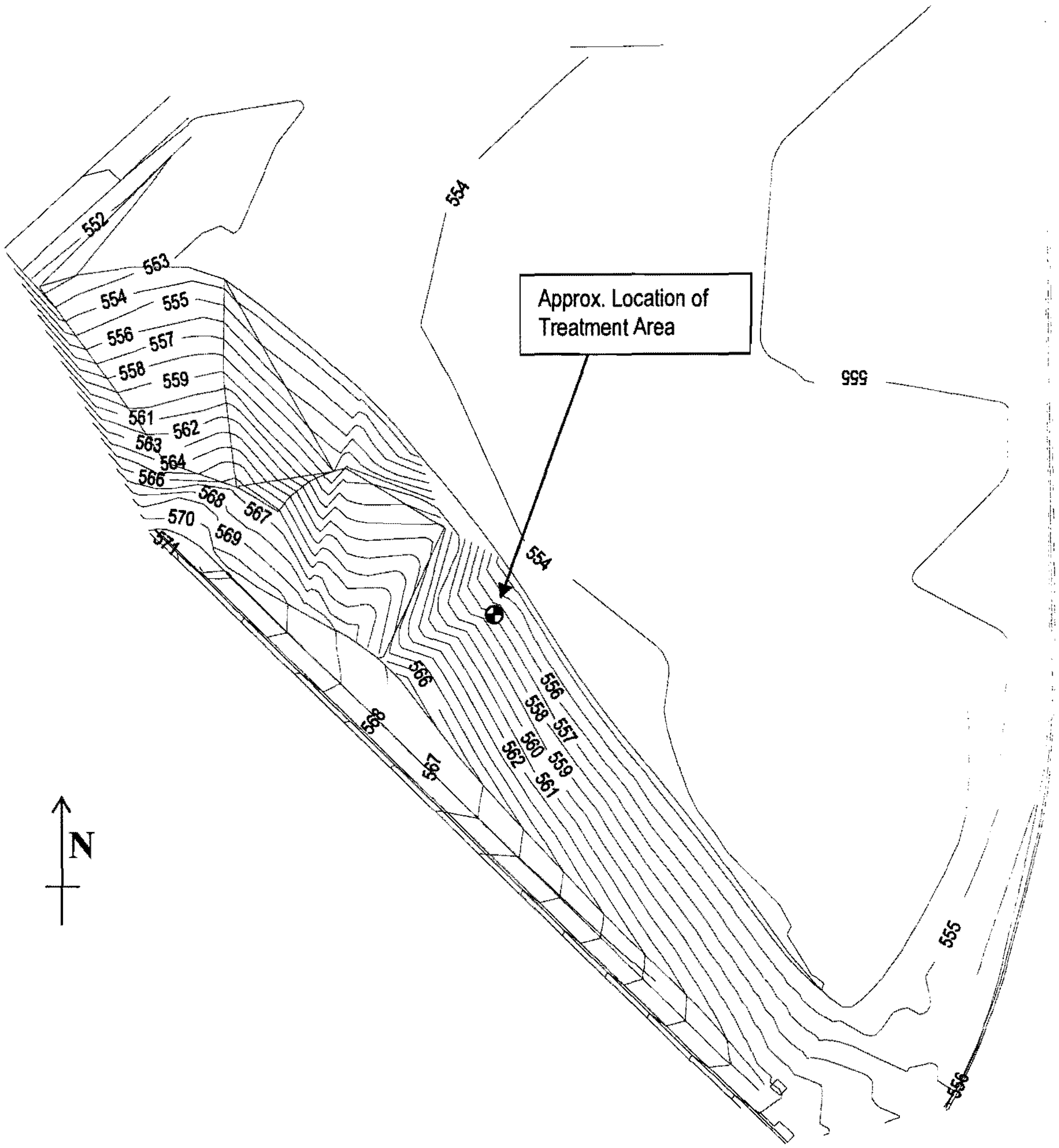

Figure 9. Site Topography at Galloway Avenue Site

The soil samples were then shipped to Texas Tech University Civil Engineering Department where necessary geotechnical characterization tests were performed. The geotechnical characterization of soil samples recovered from project sites included the following tests and procedures:

- Natural water content
- Percent fines (i.e. percent passing ASTM No. 200 sieve)
- Atterberg Limits tests
- USCS Classification
- AASHTO Classification

The results from soil characterization tests are summarized in Table 1 below.

Table 1. Results from Soil Characterization Tests

Test Parameter	Test Designation	Motley Drive Soil	Galloway Avenue Soil
Natural Water Content	ASTM D2216	30.0	33.3
Percent Passing No. 200	ASTM D1140	96.4	86.5
Atterberg Limits	ASTM D4318		
Liquid Limit		64.0	77.5
Plastic Limit		23.5	28.2
Plasticity Index		40.5	49.3
USCS Classification	ASTM D 2487	CH	CH
AASHTO Classification	AASHTO-M145	A-7-6 (43)	A-7-6 (52)

According to the results from soil characterization tests, the soil found at both locations were inorganic clays of high plasticity. Both of these soils classified as CH according to USCS procedure and as A-7-6 according to AASHTO procedure.

6. Site Preparation

Mr. Bennie McCormack, Maintenance Manager. TxDOT Dallas District Office coordinated and supervised the necessary site preparation work.

The intent of these trial vitrification projects was not to perform a full-scale stabilization of the entire slope at each site. Instead, the objective was to stabilize a small section of the slope so that the feasibility of using in-situ vitrification technology for slope stabilization purposes could be evaluated. Accordingly, the plan for these limited-scale slope stabilization projects was to complete 3 vitrification holes along the length of the slope at each site. The columns of vitrified material, placed near the toe of the slope, will provide additional resistance and hence increase the factor of safety against shear failure. Figure 10 on the next page illustrates this slope stabilization mechanism.

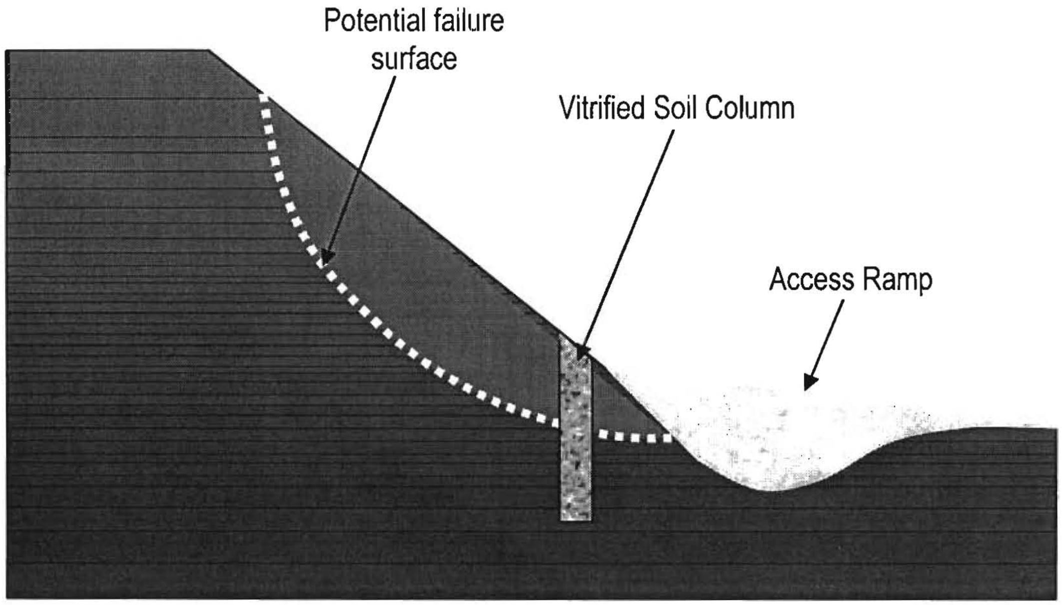

Figure 10. Use of In-situ Soil Vitrification for Slope Stabilization

At each site, an area near the base of the slope was selected for vitrification so that, once installed, the vitrified soil columns will intercept the most likely failure slope. Next, three boreholes, each 10in (250mm) diameter and approximately 3.0ft (1.0m) in depth were drilled using a soil auger. The boreholes were drilled so that the line of boreholes is parallel to the slope. Figure 11 below shows the soil auger in operation at the Motley drive site.

Figure 11. Drilling Boreholes at Motley Drive Site

As seen in Figures 10 and 11, the optimum locations for vitrification holes were not at the same elevation as the base of the slope but approximately 3-5ft (1.0 -1.5m) above that elevation. The mobile SOVIT system that was originally developed for roadbed soil stabilization purposes did not have capability to reach and perform vitrification on a slope. To overcome this problem, a temporary access ramp was built by a TxDOT crew by hauling in earth from a nearby borrow source. Once stabilization was complete, this ramp was removed. Figure 10 illustrates the use of an access ramp.

7. Field Operation of SOVIT System

The SOVIT system was taken to Dallas for slope stabilization demonstrations with only two AC to DC power electronic modules. As can be seen in Figure 3, the SOVIT is designed to have three modules, each capable of producing 400A DC in steady state operation. Thus, for the demonstrations, 800A was the maximum available current. At this level it took longer to melt each hole; the solidified soil was not uniform and was porous.

We only had two modules because the US distributor for the foreign made the integrated gate bipolar transistors (IGBT's), the major component of the module, could not fill our order. The distributor had received the order three months prior to this time. We have never been able to receive IGBT's in a timely manner; because of their high cost, (over $2,000 each) we could not "stock" these parts.

The first demonstration was on the northeast slope of Motley Drive overpass of I-30. With significant support from Mr. Bennie McCormack and personnel, and equipment from the Dallas District Office, we were able to position the SOVIT trailer such that it was horizontal and could vitrify vertical holes on the slope.

The modules are cooled by ambient air blown through each module. By mid day we noted that the exhaust air from both modules was at the maximum allowable operating temperature for the IGBT'S and other electronic components. As a result we lowered the current to a little over 700A. The ambient temperature that afternoon was only in the 80's. We recognized that two module operations at the lower current level would produce marginal results. At the end of the day either because of over heating, too high a current, or a combination of the two, one of the modules burned out.

Each evening the SOVIT and generator was moved and stored in the Districts' equipment yard. The last morning at the Motley Drive overpass site, we moved the demonstration to the Galloway Avenue site. This is the site that was set-up so that interested TxDOT personnel could observe the operation of the SOVIT. With only one module, we were limited to 300+ Amps for maximum output. Even at this low current we were able to melt soil although the product produced was very porous and nonhomogeneous. After all observers left, we maintained 350A current but increased the output voltage by raising the arc melter further above the melt surface. The voltage is a function of the arc melter position in or above the molten soil. The total power from the module is the product of the voltage and current. By raising the arc melter we increased voltage from 80V to 200V, while the current remained at 350A. During this process we did not closely monitor the exhaust air temperature (this required placing a thermometer in the air stream). As a result of high temperatures, too much power or both, the last module burned out.

Thus, the demonstrations in Dallas were terminated.

Major lessons learned during this phase of the project were:

- The concentric graphite Arc Melter can be manufactured into a portable system and operated in the field.
- The present IGBT is too expensive.
- Due to the possible variation in ambient temperature, air-cooling of the modules is not recommended.
- Better current control of the IGBT output is needed.
- Higher power generator (~ 160kW) is desired.
- The trailer mounted SOVIT and the need for an articulated auger reveal that an individual SOVIT, generator, and auger systems (which can confirm the technology concept) are not suitable for a practical field operating system.

8. Limitations of the Existing SOVIT System

Most of the limitations of the existing SOVIT systems are alluded to in the last section. There are two classes of limitations that need to be mentioned in this section. The first class is caused by the change in the application of subgrade soil vitrification technology to slope stabilization. The second addresses the limitations, which with modifications to the SOVIT, the slope stabilization implementation program can proceed at a reasonable cost and period of time.

In order to accomplish the implementation program, we do not propose that any major changes be made to the SOVIT system. We do, however, recognize that the existing system would be inadequate for a cost effective application of the technology to slope stabilization. A better designed system would include a 1 to 2 ton truck mounted system that would have the three major subsystems: generator, articulated auger, and a SOVIT with an arc melter that could work off the same articulating system of the auger.

The implementation program can be performed without such a piece of equipment; however, it will require on-site support such as the support provided in Dallas. The operational field costs of a final SOVIT system will have to be estimated from the results obtained.

The present SOVIT can be modified and adapted such that slope stabilization vitrification operations are more reliable and simpler. The first and most important modification is to obtain better and cheaper IGBT's. The AC to DC modules with this new IGBT needs to be water-cooled. We need to have spare modules on hand in the event of failure in the field. Next, the arc melter head can only be moved back and froth; there is no left-right motion capability. Thus, it is very difficult to back the trailer over the augured hole.

For slope stabilization, we do not believe that a large powerful auger is absolutely necessary, in most cases. However, for roadbed repair it maybe necessary to have a more powerful auger system. Thus, we feel that it may be possible to mechanically mount a two person auger on the rear of the trailer such that the larger truck mounted auger used in Dallas during this phase would not be required.

9. Modification of the SOVIT System

Upon return to Texas Tech after the Dallas demonstrations, the focus of work was to improve the PCU, of which the AC to DC modules are the major subsystem. A new, to the market, and much cheaper IGBT (~ $200) was identified. We ordered six of them and received them within a couple of weeks. These new IGBTs allow us to mount them on water-cooled support structures, thus we have solved both our expensive component and cooling problems. With these new IGBTs we also modified and reduced the number of elements in the AC to DC modules. The upgraded circuit provides higher repetition rate of the IGBT and higher speed for sampling and control of the output.

These "new" modules have been tested using a constant dummy load. In addition to the modules' modifications, we have also reduced the size of the isolation transformer (between the generator and modules), and reduced the size of the output inductors from the modules.

The modified modules need only be operated at 200A each. With the six circuits (two in each module) we can produce the designed 1200A output by operating the IGBTs at only one third of their maximum rated output.

A patent has been submitted on this new module design. A brief technical description and circuit design is provided.

As mentioned above, the entire PCU was redesigned to achieve a lower overall cost and increase reliability. With the knowledge gained from phase two and phase three operations, it became apparent that the loop bandwidth of the current control system had to be increased greatly. In the previous system, the output of the current transducer was averaged over several cycles; thus we were controlling the average discharge current. This is a common control topology for many current mode supplies. In the case of the SOVIT arc plasma, however, the dynamics of the load changes very rapidly (10's of micro-seconds). This rapid change would cause the peak current in the IGBT's to exceed their rating, even though the average current was well below their maximum rating.

To account for these fast dynamic swings, a new control loop was designed. The new control system monitors the instantaneous current in each inductor and controls the peak current rather than the average current. In this new configuration, each IGBT buck circuit has its own pulse with modulation (PWM) and feedback controller. There are a total of 6 buck circuits and each has a peak current rating of 500A. For thermal management and reliability reasons, we have de-rated each module to 250A.

A master clock supplies a synchronization pulse via a fiber optic cable to each module. By synchronizing IGBT switching of each module, greater loop stability is achieved with lower radiated electromagnetic interference (EMI). In the event of a loss of the master clock signal, each module will continue to operate, but with reduced performance and high radiated EMI.

A microprocessor based master controller is connected to the module via fiber optics that sets the individual module current set point and monitors the module status (errors, base plate temperature, etc.). The master controller also monitors the output voltage and average discharge current and calculates the SOVIT input power. In the event that the input power exceeds a specified set point (125kW generator maximum), the controller will override the user set point and reduce the current set point until power falls below the maximum specified. This safety feature reduces peak stresses on the generator and isolation transformer during transient operation. Figure 12 is a photo of one IGBT buck module.

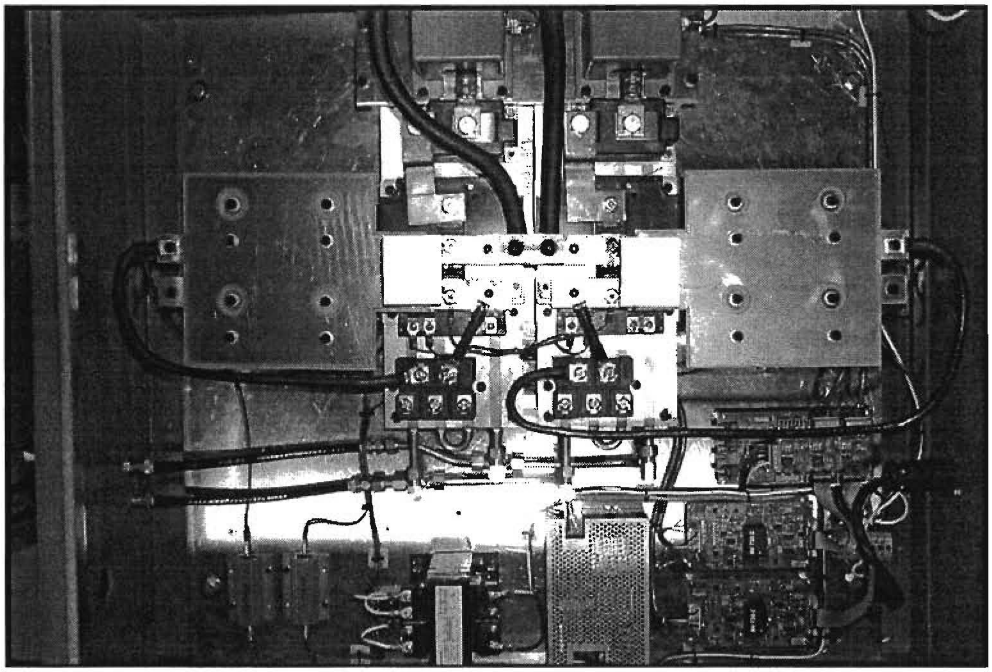

Figure 12. Modified PCU Module

Two adaptations to the SOVIT are planned for the first couple of months during the implementation program. Both of these are to facilitate slope stabilization operations. The first is to add left and right motion (4 inches each way) to the arc melter so that backing of the trailer need not be as accurate as before. The second is to attach a hand held gasoline powered auger to the arc melter frame. This small auger can be moved in and out of position for boring a hole in the ground for the arc melter.

10. Conclusions

As stated previously, the primary objective of Phase III research was to evaluate the feasibility of using SOVIT technology for slope stabilization purposes. Accordingly, two sites were selected in the Dallas metropolitan area and limited scale soil vitrification experiments performed at each site. These trial projects demonstrated the viability of using SOVIT technology for slope stabilization purposes. At the same time, however, a number of limitations in the SOVIT equipment in slope stabilization applications became apparent.

The SOVIT equipment that was used in these trial projects was originally developed for the purpose of roadbed soil stabilization and therefore, was not ideally suited for work in rough, uneven terrain. The experience from the trial projects showed that it was important for arc melter head and electrodes to have independent mobility. In other words, the operator must be able to move the CGAM electrodes and have them properly aligned with the predrilled auger holes without having to move the truck or the trailer. In a future, commercial prototype of this equipment, this may be achieved by using an articulating system from which the auger and the arc melter head may be operated. Although the implementation of such a system is beyond the scope of this research project, it will be very necessary to provide the arc melter head and the CGAM electrodes in the current SOVIT system with some independent mobility. The present system has sufficient front-and-back mobility. It will be desirable to provide it with some independent left-right mobility as well. Therefore, it is recommended that two adaptations to the SOVIT be made during the first couple of months of the implementation project. The first is to add left and right motion (4 inches each way) to the arc melter. The second is to attach a hand held gasoline powered auger to the arc melter frame. This small auger can be moved in and out of position for boring a hole in the ground for the arc melter.

Another limitation found in the current design of the SOVIT system is its inability to access to the upper reaches of the slope. Therefore, if the need to stabilize upper reaches of the slope arises during the implementation phase, the current SOVIT equipment will need to be provided with a ramp or platform so that SOVIT will have necessary access. A commercial prototype with an articulated system to operate the arc melter head will obviously not have this limitation.

Finally, the trial slope stabilization projects conducted in Dallas revealed that re-design of the PCU was necessary to make it more suitable for extreme temperature conditions found in the field. The necessary modification of the PCU was accomplished by replacing the old, foreign made IGBTs with a newer, more robust IGBT. The new IGBT allows the use of a water-cooled support structure and, therefore, is expected to operate better under high temperature conditions.

11. References

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