Validation Testing of Flameless Thermal Oxidation For the Destruction of Particulate Matter from Mining Vehicles

A Proposal Submitted to:

DEEP
(Diesel Emissions Evaluations Program)

Submitted by:

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Executive Summary

Thermatrix (TMX) is requesting support from the diesel emission evaluation program (DEEP) to conduct validation tests of its flameless thermal oxidation (FTO) process for the destruction of diesel PM from mining vehicles. The TMX technology offers very high destruction efficiency and is commercially available for the treatment of industrial organic vapors. The FTO process also has been shown to destroy diesel smoke very effectively, but to date, no independent data using approved measurement procedures are available that demonstrate and quantify the technology's ability to destroy diesel PM.

TMX will provide, at its own expense, the prototype test unit and all its own direct and indirect expenses related to the proposed program. The DEEP support will cover costs for the testing services provided by the University of Minnesota (UMinn), as described herein. The work is expected to require five to six weeks for the completion of all tasks, including engine and FTO setup, testing at three mode points of the untreated engine, and the engine FTO combination at two operating temperatures. Results will include gaseous emissions (HC, CO, NO, NO_2, SO_2), particulate mass, particulate composition (soluble, fixed, sulfate) and particle size distribution. The project deliverables will be a final report from UMinn and a report from TMX on its interpretation of the test results.

The program will be carried out on a Time & Materials – Not To Exceed basis. The DEEP share of the program will not exceed $******* (US). TMX may elect to continue the work and incur testing costs beyond the not-to-exceed level at its own expense, should that prove to be a prudent course of action.

Purpose and Objectives

Emissions from diesel engines make up the dominant fraction of sub-2.5 micron particulate matter (PM) found in underground mines. Recently, the American Conference of Governmental Industrial Hygienists proposed that the Threshold Limit Value (TLV) for diesel particulate matter be set to 0.15 mg/m^3, down from 1.5 mg/m^3, which is the current standard. The Mine Safety and Health Administration (MSHA) is expected to set limits on PM exposure which would be enforced beginning in March 1999. These developments show that a solution to the problem of particulate emissions from diesel engines will soon be needed.

The objective of the proposed program is to test and validate the performance of a prototype TMX aftertreatment system for the reduction of PM, CO, HC, and NOx emissions from a laboratory diesel engine under static conditions, representative of underground mining applications.

If the results are promising from this primary phase, TMX desires to extend the program with DEEP to include two additional phases. The second phase would validate the prototype device under automatic control over an approved transient engine test cycle. The third phase would install and test a prototype device on an "in-service" mining vehicle to evaluate its durability. Details of these phases would be developed after completion of the validation exercises. Rough cost estimates are included herein.

Background

Because they are extremely rugged, long lived, and have the highest energy efficiency of any prime mover, diesel engines are the preferred power source for a number of transportation and industrial applications. Diesel engines are also high emitters of particulate matter. Although recent advances in engine and fuel injector technology have greatly reduced the amount of mass emitted as PM, studies have shown that the number of ultra-fine particles has actually increased. Further, the long life of diesel engines has slowed the turnover to newer technologies, thus creating a need for a retrofit technology for the reduction of PM emissions.

Competition. One approach to reducing particulate matter from diesel engines is to use alternative fuels such as bio-diesel, however the use of alternative fuels is costly and can affect engine life and performance. Further, the use of alternative fuels presents difficulties from the perspective of the infrastructure required for fuel delivery, storage, and transportation.

Another approach to reducing PM emissions from diesel engines is the use of particulate traps or filters. While these devices are shown to be effective in trapping particulate matter, numerous difficulties (e.g. engine performance degradation, the potential for plugging, and trap durability) have been experienced.

Other technologies are being developed to reduce NOx (e.g. SCR, SNCR, plasmas) from diesel exhaust, but none are commercially available and none achieve significant PM reduction.

Prior Results. Flameless thermal oxidation (FTO) is a proprietary Thermatrix (TMX) process that has been employed successfully in a wide range of industrial applications for the efficient, non-catalytic oxidation of volatile organic compounds[1]. In its core business (industrial VOC control), TMX guarantees its FTO process to give a Destruction Efficiency (DE) of at least 99.99%. In over seventy commercial installations (most of which were sold to blue-chip clients such as Dow, Monsanto, Chevron, Mobil, Georgia Pacific, etc.), TMX has always met its performance guarantee. TMX has received 12 U.S. and numerous international patents for its FTO processes and apparatuses.

Recently, this field proven technology has been applied to PM reduction in diesel engines. For approximately the last eighteen months, TMX has been conducting evaluation tests on the technology as applied to diesel exhaust. Based on test results from five bench and prototype FTO systems (see Table 1), TMX has concluded that the FTO technology can be applied successfully to diesel exhaust, and has initiated a prototype demonstration and design phase for this line of business. In early 1998, Thermatrix created a wholly-owned subsidiary, Thermatrix Diesel Systems, to focus internal resources on this new business endeavor.

Some data from the evaluation phase are presented in Figure 1 and Figure 2. In these tests, gaseous emissions were quantified using calibrated, continuous analyzers (HC = flame ionization, CO = infrared, NOx = chemiluminescence), and smoke levels were quantified based on filter reflectance readings from a semi-automated AVL smoke meter.

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[1]DeCicco, S.G. and Martin, R.J. ; (1997); "Flameless Thermal Oxidation"; ***Standard Handbook of Hazardous Waste Treatment and Disposal-2nd Edition***; H.M. Freeman, editor; Section 8.7; New York: McGraw Hill.

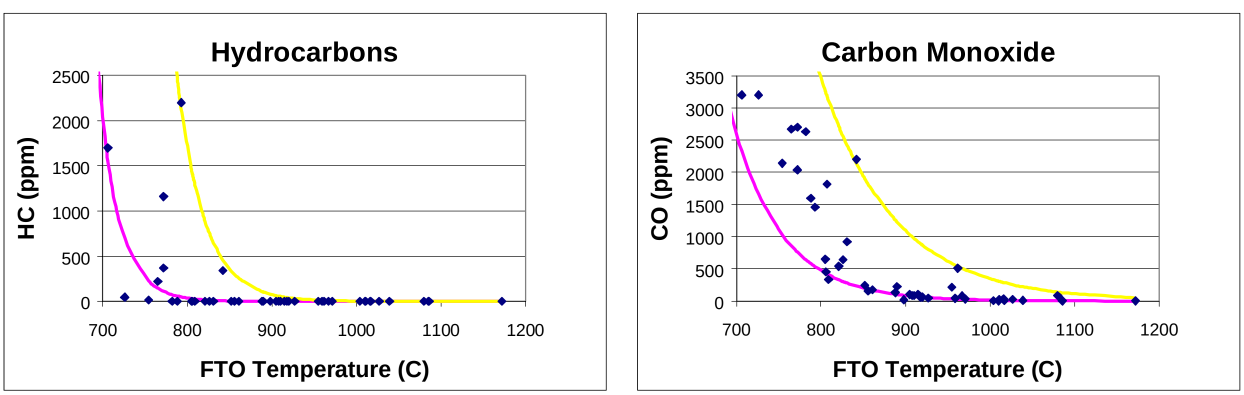
Table 1 : Recent Evaluation and Development Tests

Style	Date	Flow (scfm)	Conclusions
ES	1997	5	• 70% to 97% reduction of smoke • Temperature dependency shown (850-1000ºC)
H	1997	150	• Successful Heliox trial on diesel exhaust • Heat recovery ~50% • Preheating options tested • Low pressure drop verified
H	1998	500	• Heliox scale-up • High DE on industrial stream • Heat recovery ~80% • Automatic control verified
GR	1998	600	• Characterization of smoke, NOx, ΔP on 12-liter diesel • HC, CO non-detect above ~1000ºC • Smoke reduction to 99%, depends on T, τ, O_2. • Smoke non- or barely-detectable above ~1000ºC • Some NOx reduction (5% to 20%) • Heat recovery 40% to 80% • Device size reduced 95% from industrial version
GS	1997	3000	• Injection of diesel fuel proven ➢ Flameless operation ➢ High destruction ➢ FTO temperature control (850 to 1050ºC) with liquid fuel

As seen in Figure 1, when operated above 900-1000ºC, the FTO device destroys HC and CO to essentially non-detectable levels, which is consistent with industrial applications of the FTO process. This benefit should allow for the elimination of oxidation catalysts now used on some mining vehicles for control of odors and carbon monoxide.

Figure 1: Diesel emissions with FTO vs temperature: (a) HC; (b) CO

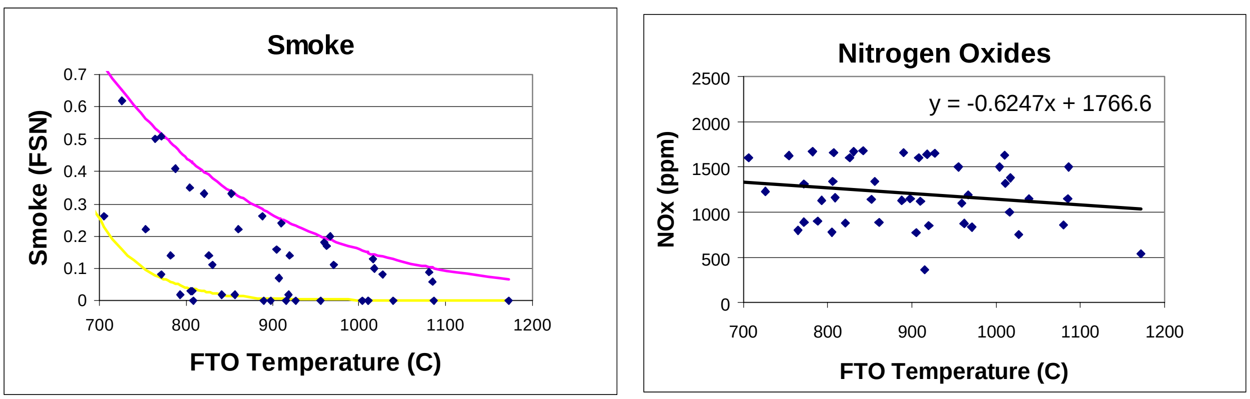
(a) **(b)**



As seen in Figure 2(a), very high PM destruction efficiencies were observed. Smoke was not detectable for many runs and did not exceed the detection limit by more than a factor of three under all conditions where FTO temperature exceeded 1000ºC. In fact, the observed DE appears to be significantly higher than that predicted by a numerical model TMX has developed for PM destruction, which is based on particle size distributions and kinetic data for soot oxidation reported in the literature[2]. This difference may be due to differences in gas composition with respect to the literature, differences in particle size distribution in the actual engine, or the presence of the matrix itself, which alters particle heat transfer, chemistry, and fluid dynamics. The magnitude of destruction observed in these tests revealed that, unlike catalysts, the FTO was able to oxidize both the soluble organic fraction (SOF) and the elemental carbon concurrently.

Figure 2: Diesel emissions with FTO vs temperature: (a) smoke, (b) NOx

(a) **(b)**



Some NOx reduction was also observed during the trials, as evidenced in Figure 2(b) by the declining slope of the least-squares NOx versus FTO temperature plot. We believe this effect is attributable to a phenomenon called "lean reburning", wherein the supplementary fuel added reacts with both the NOx and O_2 in the exhaust stream, reducing them in proportion to their concentration.

TMX has also performed theoretical analyses that indicate that the FTO would likely produce lower SO_3 levels and smaller numbers of fine particles. This is in contrast to some oxidation catalysts that augment both the sulfate fraction and the number of fine particles.

Process Description. The fundamental basis of the FTO process is to heat the PM in the exhaust stream to the temperature at which oxidation will take place. The proprietary FTO technology makes use of a non-catalytic, porous inert matrix, which creates a high temperature environment that can deliver energy efficiently to the solid PM via visible and infrared radiation, in addition to convection and conduction. The matrix operates effectively at temperatures of at least 850ºC, and the PM destruction rate increases with temperature.

Because the porous inert medium is non-catalytic, problems normally associated with catalysts such as deactivation or poisoning are avoided. Unlike a catalyst, the performance of the matrix

[2] Haynes, B.S., and Wagner, H.Gg.; (1981); "Soot Formation"; **Prog. Energy Combust. Sci.; 7**; 229.

does not degrade over time. Furthermore, the matrix material can be selected from among those that are resistant to overheating, thermal shock, and mechanical impact, which are all imperatives for treatment devices in mining vehicles. Thermatrix has broad experience in the use of many metallic and ceramic materials in its industrial systems that operate at very high temperatures (>1000ºC) and with very corrosive gases, including SO_2, HCl, and HF.

The energy required to carry out the thermal oxidation reactions is minimized through the internal recuperation of heat and utilization of the chemical energy inherent to the organic emissions themselves. Thermatrix sells industrial systems that achieve 70-80% heat recovery effectiveness, many of which operate without any supplementary fuel. The process relies on the use of radiatively-coupled fins to enhance the recovery of heat. A desired level of heat recovery can be a design criterion for specific applications.

For many heavy-duty vehicles, an FTO treatment device is approximately the same size as the vehicle's standard muffler/silencer. The oxidizer is expected to provide sound attenuation equal to or better than the performance of a standard muffler.

DEEP and TMX. In January 1998, TMX received a call from Dr. Jozef Stachulak of INCO Ltd., who had become aware of TMX through our website and recent press releases. Dr. Stachulak was seeking more information about the FTO process, which he recognized as being potentially applicable to mining vehicle emissions. After conducting some additional research and receiving substantial encouragement from Dr. Stachulak, TMX believes that the FTO technology may be a very good solution to the treatment of diesel PM from mining vehicles. Indeed, since that time, TMX and DEEP committee members have held several discussions to explore how a FTO device might undergo validation testing for DEEP without delay.

Based on these discussions, we have concluded that the best approach for proceeding forward is for TMX to provide a prototype FTO treatment device for testing at the University of Minnesota Center for Diesel Research, where validated measurements of PM destruction can be obtained. We seek support from DEEP committee members to offset the costs of these tests, which are considerably more expensive than the smoke measurements we have previously obtained. The scope, schedule, and cost of the proposed work is described below.

Description of Work Scope

The destruction efficiency and overall performance of the system will be tested on a Caterpillar model 3306 DITA JWAC engine. This engine is a 6-cylinder direct injection turbocharged diesel engine with jacket- water aftercooling and is now used in Elphinstone R1300 LHD load-haul-dump vehicles in underground hard-rock mines worldwide. The engine’s airflow ranges from 118 to 585 scfm; its exhaust temperature ranges from 126 to 515 ºC; its emissions range from 1 to 18 g/hr (PM); 27 to 460 g/hr (NOx); and 22 to 196 g/hr (CO).

The parameters to be measured include all regulated emissions (PM, CO, HC, NO, NO_2, SO_2), pressure drop, energy consumption, and operating parameters such as flows and temperatures. A limited number of PM size distribution and PM composition measurements will be taken during some of the tests. The testing will be conducted in accord with the MSHA-adapted, steady-state, off-highway engine test cycle (ISO-8178), using a subset of three of the eight standard operating modes. Tests will be conducted for three conditions: (A) No FTO; (B) FTO at 950ºC; and (C) FTO at 1050ºC. These tests are outlined in Table 2.

If, during the very early stages of the test program, PM results are as encouraging as the earlier smoke tests indicate, a change in course may be proposed, wherein the remainder of the characterization tests would be truncated, in favor of a full 8-mode test conducted according to ISO-8178-4. Results from a full 8-mode test, which can be used for comparison to other technologies and reported in the literature, would be more desirable to obtain, if the prototype meets performance targets. This change in course would be enacted only after consultation between DEEP, TMX and UMinn. The "modified" test program is itemized in Table 4.

Table 2: Matrix of test conditions

No.	Condition	Mode	Tests (replicates in parentheses)
1	Baseline Engine (No FTO)	Mode B-8 (or Mode C1-7) Intermediate speed; 50% load	• (3) Performance data[3] • (3) Gases[4] • (3) PM-mass[5] • (2) Particle size distribution[6] • (2) Particle composition[7]
2	"	Mode B-6 (or Mode C1-5) Intermediate speed; 100% load	"
3	"	Mode B-1 (or Mode C1-1) Rated speed; 100% load	"
4	FTO #1 (950 ºC)	Mode B-8 (or Mode C1-7) Intermediate speed; 50% load	"
5	"	Mode B-6 (or Mode C1-5) Intermediate speed; 100% load	"
6	"	Mode B-1 (or Mode C1-1) Rated speed; 100% load	"
7	FTO #2 (1050 ºC)	Mode B-8 (or Mode C1-7) Intermediate speed; 50% load	"
8	"	Mode B-6 (or Mode C1-5) Intermediate speed; 100% load	"
9	"	Mode B-1 (or Mode C1-1) Rated speed; 100% load	"

In order to gauge the efficacy of the TMX unit, its performance will be compared to a series of target specifications that are consistent with DEEP expectations. These are given in Table 3. If the proposed engine test stand results are favorable, TMX may propose one or two additional phases of testing: (a) dynamic tests conducted on an engine stand according to an approved transient cycle; and (b) installation of a prototype device on an operating mining vehicle to study performance and durability.

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[3]Performance data includes engine speed, engine load, engine air flow, engine fuel flow, engine exhaust temperature, engine exhaust pressure, FTO operating temperature, FTO exit temperature, FTO fuel flow, FTO ΔP

[4]Gas measurements include HC, CO, NO, NO_2, O_2, CO_2

[5]PM-mass is measured in accordance with ISO-8178 using dilution tunnel sampling

[6]Particle size distribution is determined with a Scanning Mobility Particle Sensor (SMPS) technique

[7]Particle composition is the proportion of soluble, insoluble, and sulfate fractions in the particulate mass

Table 3: Target Performance Specifications

Criterion	Target
Exhaust Particulate Mass	<0.02 $g_{DPM(TC)}$/kWh (weighted average of 8178-4-C1 cycle)
Capital Cost	<$100(US)/kW
Device Heat Recovery	>80% (~$60(US)/kWy extra fuel)
Back Pressure	<200 mbar (at mode C1-1)
Maintenance Service Interval	>500 h
Life	> 5000 h

Cost and Schedule

The proposed work will commence in September or October of 1998, depending on the availability of the test stand at UMinn and on the completion of the prior test work TMX has committed to with the proposed prototype. The estimated duration of the proposed program, including commissioning, testing, de-commissioning, and reporting is 6 weeks. A proposed schedule is given in Figure 3.

Table 4: Modified matrix of test conditions

No.	Condition	Mode	Tests (replicates in parentheses)
1	Baseline Engine (No FTO)	ISO-8178-4 Modes C1-1 to C1-8	• (3) Performance data • (3) Gases • (3) PM-mass • (2) Particle size distribution • (2) Particle composition
2	FTO #1 or #2 (to be determined)	ISO-8178-4 Modes C1-1 to C1-8	“

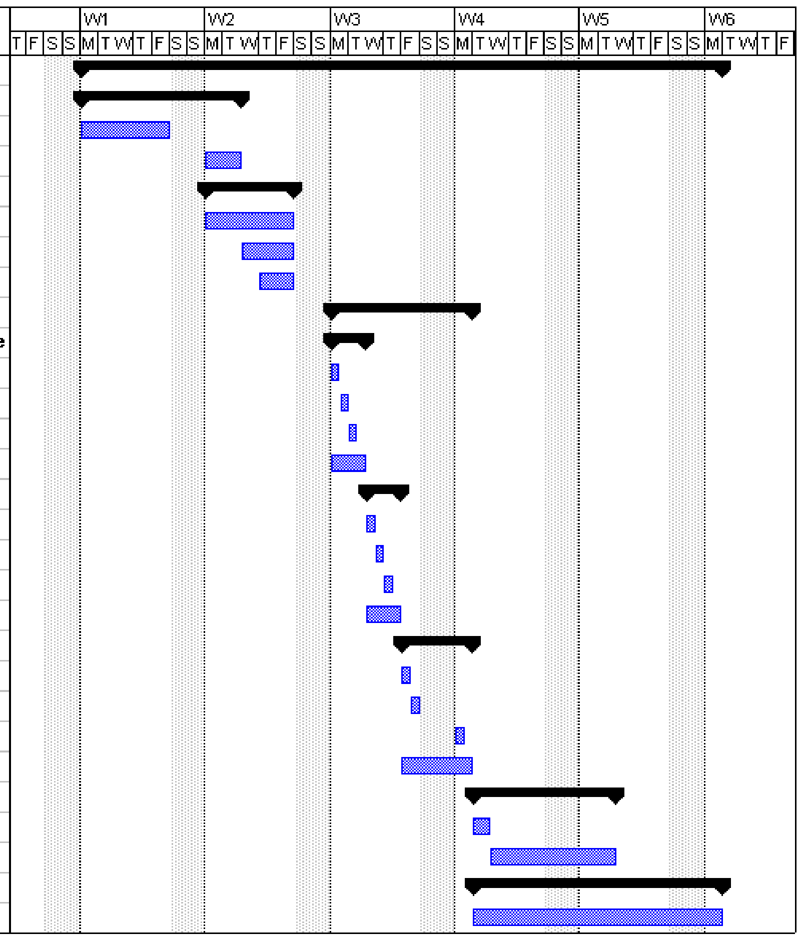
Thermatrix will provide the prototype and all of its own labor and expenses to the program (estimated cost US$*******). With this proposal, we are soliciting DEEP to cover the costs associated with the UMinn testing effort, on a time and materials basis, with a not-to-exceed limit of US$*******. Copies of the preliminary quotation (10 June 1998) and the revised second quotation (24 June 1998) from R. W. Waytulonis of UMinn are attached as Appendix 1. The scope of work identified in the 24 June revised quotation as “Case Description 4” corresponds to the scope of work described in this proposal.

Costs for the two potential follow-on testing efforts have not been estimated in detail as yet. TMX would most likely seek DEEP funding to defray the sampling and analysis costs associated with each of these efforts, and would contribute its own costs for labor, equipment, etc. as with the current effort.

It is reasonable to assume that the cost of follow-on phase (a) Dynamic Testing would be of the same order as the current testing program (~US$*******) because the program would be of approximately the same duration (~4 to 6 weeks). The scope of work for follow-on phase (b) Durability Testing is less clear, but most likely would involve a considerably longer duration (~6 months or more) to get good data on durability of the FTO materials and design. It is possible that the bulk of the sampling/analysis expense could be focused on the "initial" performance (just after installation) and the "final" performance (after the durability tests were complete), thereby minimizing the on-site time and cost of the sampling crew. The total cost for this level of testing might therefore be approximately double the cost of the current program (~US$*******), not accounting for any costs associated with the actual retrofit of the mining vehicle, which possibly could be borne by the host mining company.

Figure 3: Proposed Schedule

ID	WBS	Task Name
1	**1**	**Validation Testing**
2	**1.1**	**TMX Preparation**
3	1.1.1	Prepare Oxidizer
4	1.1.2	Ship Oxidizer
5	**1.2**	**UMinn Preparation**
6	1.2.1	Install Engine
7	1.2.2	Install FTO
8	1.2.3	Prepare SMPS
9	**1.3**	**Testing**
10	**1.3.1**	**Baseline Engine (no FTO) Te**
11	1.3.1.1	Mode 1
12	1.3.1.2	Mode 2
13	1.3.1.3	Mode 3
14	1.3.1.4	SMPS
15	**1.3.2**	**Condition #1 with FTO**
16	1.3.2.1	Mode 1
17	1.3.2.2	Mode 2
18	1.3.2.3	Mode 3
19	1.3.2.4	SMPS
20	**1.3.3**	**Condition #2 with FTO**
21	1.3.3.1	Mode 1
22	1.3.3.2	Mode 2
23	1.3.3.3	Mode 3
24	1.3.3.4	SMPS
25	**1.4**	**Decommissioning**
26	1.4.1	Disconnect Oxidizer
27	1.4.2	Ship Oxidizer
28	**1.5**	**Reporting**
29	1.5.1	Final Report



Personnel

UMinn personnel entitled "Engineer/Scientist" and "Technician/Machinist" are identified as contributors in their 10 June 1998 proposal, but names of these individuals were not provided.

The TMX personnel assigned to this program are Dr. Richard Martin and Mr. William Binder, with support from Mr. John Delk. Brief resumes are given below for these individuals.

Dr. Richard J. Martin-. is Director of Technology for Thermatrix' Emerging Business Group. He reviews product improvement activities for the company's core business lines and provides technical management for the company's intellectual capital resources. Dr. Martin is a seasoned combustion specialist with expertise in the design, development and testing of various technologies. He is recognized internationally as a leader in the commercialization of porous inert media combustion systems. Previously, Dr. Martin has conducted studies on the combustion chemistry of nitrogen compounds, the high temperature chemistry of metal silicates, and the combustion of coal. He is a member of ASME, ACS, AIChE and ASM and has published numerous articles in the fields of combustion and environmental technology. Dr. Martin regularly lectures for the University of California and serves on the Executive Committee of the Western States Section of the Combustion Institute. Dr. Martin received his Ph.D. in mechanical engineering from the University of California, Berkeley and his MS and BS degrees from Stanford University. Dr. Martin will be Program Manager for the proposed work and will be responsible for its successful execution.

Mr. William D. Binder – is Project Manager for Thermatrix in its Emerging Business Group where he manages technology and resources related to the development of new products. He is currently the lead technical manager for diesel technologies at Thermatrix. Bill Binder also has extensive experience in air regulations, permitting and compliance. Before joining Thermatrix, Mr. Binder was a Project Manager for an engineering and environmental consulting firm. Mr. Binder is a registered professional engineer in California and Texas and has a Bachelor of Science in chemical engineering and a Bachelor of Arts in English from the University of Texas at Austin. Mr. Binder will be Assistant Program Manager for the proposed work and will be responsible for Thermatrix' technical content.

Mr. John C. Delk – is Executive Vice President of Thermatrix and General Manager of its Diesel Systems division. He is charged with leading the new Thermatrix product from concept to full commercialization, and will oversee the development of partnerships, joint ventures and/or licensing arrangements instrumental to the commercial exploitation of the product. Mr. Delk's background includes 25 years of management experience, culminating in successful P&L responsibility for a $250 million division of a tier one automotive component supplier, whose customers included major automobile manufacturers in North America, South America, Europe and Asia. Mr. Delk holds a MBA degree in management from Xavier University and a BS in industrial engineering from General Motors Institute.

References

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Stilger, J.D., Martin, R.J. and Holst, M.R.; (1994); U.S. Patent No. 5,320,518; "Method and Apparatus for Recuperative Heating of Reactants in a Reaction Matrix"; Assigned to Thermatrix Inc., Jun. 14, 1994.

Martin, R.J., Stilger, J.D. and Holst, M.R.; (1992); U.S. Patent No. 5,165,884; "Method and Apparatus for Controlled Reaction in a Reaction Matrix"; Assigned to Thermatrix Inc., Nov. 24, 1992.

Appendix 1: Copies of UMinn Quotations