A REPORT ON THE DEVELOPMENT OF AN EMISSION PARTICULATE TRAP SYSTEM FOR DIESEL BUS ENGINES

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DEVELOPMENT OF EMISSION PARTICULATE TRAP SYSTEM FOR DIESEL BUS ENGINES

PROJECT OVERVIEW

This report presents a summary of the research project undertaken during the period 2/91 through 3/93 under a contract from the Michigan Department of Transportation (MDOT) and the Jackson Transportation Authority (JTA) for development of a particulate trap system by Converter Technology Inc. (CTI). Following the project inception (i.e., determination of CTI as the contract agency) in December 1989, the following tasks were performed between 2/91 and 3/93.

1) **Project Preliminaries and Establishment of Base-Line Data**

   Project preliminaries regarding the design and mounting of the trap, considering the vehicle exhaust system, drive train, location of trap, and ancillary details were resolved between the JTA and CTI officials (see Appendix-I: JTA final report, page 1).

   The MSU staff advised on project coordination and provided details on the research design. One aspect of the research plan was the analysis of the JTA fleet maintenance reports, and fuel and oil consumption records to establish baseline data. A typical bus from the fleet was to be fitted with a trap, and used in revenue service by JTA. The performance of the bus equipped with the enhanced trap system was to be evaluated by comparing the test vehicle data against the baseline data and extended performance data from the rest of the fleet.

For this purpose, JTA furnished initial data for the period 12/88-11/90 on fleet maintenance and fuel and oil consumption for their buses with 6.2L engines. This information was analyzed to determine the average fuel and oil consumption for each unit and the fleet average.

2) **Prototype Enhancement and Additions**

All the major physical work on the trap enhancement and additions was performed by CTI after consulting with JTA, MDOT and MSU. Various issues related to project implementation were resolved. These included: i) procurement of interfaces to get electronic readings from the existing mechanical engine; ii) protection of the trap from road hazards; iii) installation of an additional thermocouple to record the temperature at the floor of the passenger compartment of the bus during operation and regeneration; and iv) upgrading of bus fuel tank sensors (see Appendix-I: JTA final report, pages 2-4).

3) **Off-Vehicle Testing and Debugging**

The performance and efficiency of the trap were tested in the laboratory prior to installation on the test vehicle. The MSU staff advised on data requirements and reporting criteria. The data output from the trap was to be incorporated into the fleet maintenance software for optimum usage. The salient feature was the performance of dynamometer testing relating to particulate collection efficiency and the resultant engine exhaust back pressure (see Appendix-I: JTA final report, page 5-6).

4) **On-Vehicle Testing**

In August 1991, the prototype was installed on the test coach for pre-operational testing. Important design changes were made to provide adequate air-flow to avoid malfunctioning of the opacity meter due to excessive heat and soot. Improvements were also made to ensure durability of the regeneration coils coating against vibrations (see Appendix-I: JTA final report, page 7). Arrangements were finalized for revenue service to accomplish the operational testing of the trap and pre-converter.

In September 1991, the test vehicle with the trap was run in revenue service for a total of 482 miles. After this, the trap was removed for a tear-down inspection and re-installation with a standard exhaust for additional base line data. The tear-down inspection covered various mechanical components, wire mesh and alumina coating and the electronic systems.

5) **Emission Data Acquisition.**

After several trial runs and modifications to the trap, its mounting structure and the data acquisition system, the project was ready for final emission data acquisition. Unfortunately, due to overheating of the trap, the testing operations in revenue service were discontinued for the safety of passengers (see Appendix-I: JTA final report, page 10). The research plan was modified such that JTA leased CTI a bus equipped with a 6.2L engine for field testing of the trap. CTI continued with the development and testing of the trap including a noise test performed at the Walker Manufacturing proving grounds (for the details on the results of testing, see Appendix-I and II: JTA and CTI final reports, pages 15 and 9 respectively).

PRESENT STATUS

Research, development and testing on the particulate trap has been completed by CTI. Their internal measurements indicate that the trap successfully removed the particulate matter from the exhaust, and the regeneration process performed as designed. The JTA is satisfied with the results and has requested funding to install these traps on the buses in its fleet. There was no independent emission test performed by EPA or an EPA approved laboratory as originally planned. Thus, we do not have quantitative data on the suspended particulate matter to compare with alternative technologies nor to compare with national standards. These tasks should be conducted to complete the original test objectives.

SUMMARY

The Jackson Transportation Authority, in an attempt to meet the future emission standards set for diesel engines (as promulgated by the 1990 Clean Air Act), supported the development of a particulate trap system for diesel bus engines by a local firm, Converter Technology Inc. This demonstration project was partially funded by the Michigan Department of Transportation (total project completion cost of

$187,089 was borne by CTI and MDOT in a proportion of $109,339 and $76,750 respectively). The role of Michigan State University was to advise on project coordination and research design, and to provide technical assistance as necessary.

In developing the trap, a series of reliability problems were solved by sequential enhancements based on experience gained from off-vehicle and on-vehicle tests. These problems were not all related to the trap technology but also included modifications to the mounting devices, exhaust system and software necessary for data acquisition. The overall performance of the final product was evaluated by CTI based on readings from the opacity meter. These results appear to show excellent performance, with readings near zero.

The efforts of JTA to utilize local resources and technical expertise to improve its fleet performance to meet emission standards are laudable. The conduct of this demonstration project has helped identify several problems that are likely to be encountered in installing a particulate trap system. It is hoped that with the continued pursuits of CTI in developing their product and meeting the EPA approved laboratory tests, the commercial production of the trap will be possible.

APPENDICIES

1. Jackson Transportation Authority
   Final report

2. Converter Technology, Inc.
   Final report

April 27, 1993

NARRATIVE REPORT

for Jackson Transportation Authority

MDOT Contract No. 90-1355

09-11-90/03-31-93

After execution of the contract by MDOT and the City of Jackson Transportation Authority (JTA) in early September, various concerns by MDOT technical staff resulted in all work put into temporary hold. The temporary hold continued to delay the project as MDOT Management and Budget staff requested additional contract language be entered into the third party contract between JTA and Converter Technology Incorporated (CTI). The delays continued until late January when JTA was verbally advised that the project could continue. The actual contract approval was received February 14, 1991. In spite of these excessive delays beyond their control, JTA and CTI anticipate timely completion of the project tasks.

TASK I - COLLECTION OF DATA FROM THE BUS:

September, 1990/February, 1991

JTA and CTI staff met at JTA maintenance facility to review the designated vehicle. In attendance were; Garrett Erb, JTA Administrative Director, Stan Deneka, JTA Maintenance Director, William Vaughn, JTA Senior Mechanic, Ray Kammel, CTI President, William Williams, CTI Mechanical Technician.

The designated vehicle currently runs dual exhaust from the manifold back to the exhaust tail pipes. The method and location to cross-over into one single exhaust was discussed and determined. JTA staff agreed to do the actual exhaust work. CTI was to see if GM would provide the cross-over piping section.

The location of the trap was determined to be in the third quarter, right side of the vehicle (facing forward). This area provides enough room to work with the converter/trap, as well as provide for reasonably straight exhaust work into and out of the trap.

The mechanical aspects of the engine and drive train were heavily discussed. CTI has only worked with a 6.2 electronic engine provided by GM. CTI staff were certain of the availability of equipment from GM which would allow for the necessary electronic controls to be installed on this engine as required for the trap to work. CTI was to establish the equipment needs and request those items from GM. Additional equipment needs would be discussed as necessary.

JTA staff consulted with MSU staff to establish the various coordination efforts to be made. JTA staff forwarded all 6.2 liter bus data to MSU engineering staff for evaluation and base-line data establishment.

JTA staff established billing forms for utilization by CTI in billing JTA for CTI costs. JTA staff reviewed the necessary progress report format and other contract requirements with CTI.

CTI and JTA staff further reviewed the progress to date and determined future direction. JTA staff generated billing documents.

July, 1991

JTA and CTI staff established parameters for the installation of the trap, Mobile Data Acquisition System (MDAS) power and cable routing for the test vehicle. JTA staff identified restrictions/guidelines based upon operator and safety requirements.

August, 1991

Trap, pre-converter and opacity meter locations finalized. Thermocouple locations determined.

September, 1991

No further work was performed in this task in September, 1991 as this task is complete for JTA.

TASK II - PROTOTYPE ENHANCEMENT AND ADDITIONS:

September, 1990/February, 1991

While JTA staff have no formal work on this task, staff did perform the following to keep up-to-date on the progress of the project.

JTA staff discussed pre-converter aspects of the unit with CTI staff. Review of the intended goals versus the exiting and future emission regulations took place.

Discussions regarding methods to ensure trap and pre-converter reliability due to the nature and the condition of Jackson County roads took place. JTA and CTI staff are investigating various methods to ensure the trap is not damaged by conditions beyond normal road hazards. CTI is working on various means to enhance vibration isolation and rigidity of the trap.

JTA staff performed budget analysis by task and prepared billing to MDOT.

NARRATIVE REPORT
(continued)

March, 1991

CTI and JTA staff discussed additional interfaces to be procured in order to get electronic readings from the JTA mechanical engine.

The impulses are necessary in order that the various components of the trap receive necessary data for operation. In addition, the electronically generated information is required to perform the various comparisons, data collection and analysis necessary to the project.

JTA and CTI discussed the various testing equipment necessary to collect the necessary data. JTA staff performed billing analysis and review of CTI billing and invoices; prepared billings to MDOT.

April, 1991

JTA and CTI staff reviewed the I/O Plexor and the required interfaces for this equipment to provide all of the required data from the engine, trap and pre-converter to the computer. The necessity for some spare components and subsystems was agreed to.

In addition, JTA staff performed billing analysis on the CTI billings and vendor invoices; prepared JTA billings to MDOT;

May, 1991

JTA and CTI staff discussed catalyst work. JTA staff viewed the containment devices.

June, 1991

JTA staff met to review catalyst achievements to date. Discussion was held regarding the ability of the wire mesh to maintain shape and integrity under road conditions.

July, 1991

JTA and CTI staff reviewed the positioning of the trap on the test vehicle, establishing exhaust modifications to fit the trap and standard mufflers as interchangeable modules.

August, 1991

JTA/CTI staff installed thermocouple for temperature disclosure above trap to bottom of vehicle. Thermocouple were placed on the opacity meter box and exhaust pipe close to manifold in position where pre-converters will be installed to determine temperatures at these locations. JTA staff installed new fuel tank sensor to stabilize the reading of actual fuel usage. The previous float type sensor gave wide ranges of fuel level depending on acceleration, deceleration, up and down-hill travel. The new sensor is designed to eliminate the majority of this fluctuation.

September, 1991

Limited work was performed. Some final material billings were charged to this line item for electrical wiring. Essentially, this task is complete.

October, 1991

CTI determined from "on-the-road" testing that various components of the trap required additional strength or temperature resistance enhancement, as well as vibration dampening over-all. Do to this, modification to the trap supports, trap housing, all butterfly components and wire mesh and containment supports were addressed.

November, 1991

JTA did not perform any functions in this task during November.

December, 1991

JTA did not perform any functions as this task is complete for JTA.

TASK III - TESTING AND DEBUGGING:

April, 1991

JTA staff developed recommended procedures for the testing of the trap system. The potential testing sites were discussed with MDOT staff and CTI. JTA and CTI staff discussed the various component testing on heating element and wire mesh assembly. JTA staff discussed with MSU the specific data which it desires to have monitored. It was determined that the UMTA AFI reporting criteria would be utilized as the same data is pertinent to both the CTI and AFI projects. JTA staff discussed the report format and issued request to the fleet maintenance software package developer to establish these report criteria and format in a formal report within their software package that JTA would be able to request at any time. The software developer is in the process of providing the report format under the established UMTA criteria. JTA staff reviewed billings and invoices from CTI.

May, 1991

JTA/CTI discussed regeneration work. JTA issued purchase order to vendor for UMTA/DOT report format. JTA reviewed UMTA report criteria with software vender so vendor could begin programming of data base and report parameters. JTA reviewed software query format and received training on optimum usage of the software for the data collection needs of AFI and Trap projects. JTA staff reviewed CTI billings and compiled monthly report.

June, 1991

JTA staff viewed a test of the prototype and discussed operation of the system as regards the positioning of trap and exhaust under the vehicle for best wiring and component protection.

JTA reviewed UMTA report generating software with the software vendor regarding format and informational input. JTA reviewed vendor billings and generated monthly report.

July, 1991

JTA staff reviewed test results on regeneration materials utilized in the trap.

JTA staff reviewed CTI billing documents, corrected and generated billing to MDOT.

August, 1991

JTA staff reviewed tests results on trap regeneration, opacity meter readings, computer generated data of vehicle revenue service operation. Changes were made to software to indicate "real-time" instead of numbers of seconds of operation.

September, 1991

Jta and CTI staff coordinated closely to perform both revenue service and dyno testing of the trap and its effect on the vehicle approximately every 100 miles. The driver was questioned daily regarding any noted degradation of power curve, noise level or other normal operating characteristics of the vehicle. None were noted by the driver.

JTA's Maintenance Director monitored and worked with CTI staff to ensure vehicle integrity as regards wiring, electronic readings, fuel sensor. JTA staff assisted CTI in the modification of the opacity meter containment box.

October, 1991

CTI performed dynamometer testing relating to trap collection efficiency and the resultant back-pressure.

NARRATIVE REPORT
(continued)

November, 1991

JTA performed no work on this task during November

December, 1991

JTA performed no work on this task during December

TASK IV - INSTALLATION ON THE BUS:

JTA performed no work on this task @ February 28, 1991.
JTA performed no work on this task in March, 1991.
JTA performed no work on this task in April, 1991.
JTA performed no work on this task in May, 1991.

June, 1991

JTA and CTI staff conferred on the installation of data collection device on vehicle. It is anticipated that the data collection system will be installed on the bus mid-July to gather baseline data and calibration information.

July, 1991

JTA staff built new exhaust piping for both the trap and standard muffler system in order to make these items interchangeable for trap and baseline emission testing. JTA modified the exhaust tail-pipe to accommodate the MDAS smoke opacity meter.

JTA staff assisted CTI staff in electronic conversion of the mechanical 6.2 liter engine. Several problems dealing with the conversion from mechanical to electronic output devices were successfully dealt with.

August, 1991

JTA/CTI staff installed prototype on the coach for pre-operational testing. Excessive heat and soot were trapped within the stainless steel box housing the opacity meter. Changes were made in the design of the box and tail pipe installation and a blower was installed to provide adequate air flow to keep the opacity meter functioning. Testing was done to verify that this additional air flow did not affect the opacity readings.

MDOT raised the issue of the trap durability due to vibrations on the road. A meeting was held to discuss the best method to test the trap and components. It was determined that MDOT's concern was on the ability of the wire-mesh/alumina to hold up to the vibrations after regeneration temperature. A decision was made to subject a wire-mesh/alumina sample which had been regenerated several time to vibration testing. MDOT is to see if it can provide the hardware to determine the frequency and amplitude during this vehicle's revenue service. This operating "envelope" would then be utilized to perform vibration testing. Aeroquip Corporation in Jackson was contacted by JTA staff to see if they would consider performing vibration testing. Aeroquip has expressed an interest in doing the testing. Aeroquip can perform single axis testing; multiple axis testing could be achieved by turning the sample and re-running the test.

In addition, actual revenue service and regeneration of the trap will provide additional testing of the trap, pre-converter and MDAS components. Actual revenue service with the trap will begin on or about September 20, 1991.

September, 1991

The prototype trap was installed on the vehicle and the vehicle run in revenue service to a total of 482 miles. The vehicle was closely monitored on a daily basis by both JTA mechanics/administrative staff and CTI. Daily testing for trap soot loading, back-pressure, opacity of exhaust.

The trap was removed from the vehicle at 482 miles in order to tear the trap down and visually inspect the various mechanical components, wire mesh and alumina and electronics. The standard exhaust was put back on the vehicle to allow for continued data acquisition under normal operating conditions for additional base-line data.

December, 1991

JTA did no work on this task in December. JTA's direct labor is completed for this portion of the project.

TASK V - DATA ACQUISITION:

JTA performed no work on this task @ February 28, 1991.
JTA performed no work on this task in March, 1991.
JTA performed no work on this task in April, 1991.
JTA performed no work on this task in May, 1991.
JTA performed no work on this task in June, 1991.

July, 1991

JTA staff assisted in wiring for data acquisition and controls for the MDAS.

JTA worked with CTI in establishing the reporting output which MDOT, CTI, JTA and UMTA desire to review. Discussion regarding the ability to easily understand the various information took place. Final report formats and how these will be generated will be finalized in August, 1991.

JTA discussed the calibration of the various signals with Dr. Taylor of MSU. It was determined that MSU staff would not monitor the calibration performed by CTI/JTA staff. Dr. Taylor believed that the actual emission testing completed at an emission laboratory as well as the standard data which JTA maintenance software program compiles would determine whether the information collected by the MDAS system are valid.

August, 1991

The Mobile Data Acquisition Systems (MDAS) was operated during August. Problems were found with the ability to operate the "on-board" computer via the 12 volt vehicle system. Surges and "brown-outs" were noted as the vehicle electrical systems were operated,

(turned on and off, lift usage, etc.) Several changes were made in the interface between the vehicle electrical system and the MDAS components. The installation of an additional back-up battery and one-directional diodes appear to have corrected the major "boot-up" problems of the computer.

As noted in **TASK II** above, the original "float-type" fuel sensor allowed for wide variations in the actual fuel in the vehicle's tank. A new sensor was ordered and will be installed in September to correct this problem.

The Opacity meter operated for a short time, then excessive heat within the meter's protective box, along with soot entrapment, caused failure of the meter as identified in **TASK IV**. Design changes were made to provide a continuous exhaust pipe through the

opacity box and a hole drilled through the pipe for the Meter's sensing light. A blower draws air from the vehicle passenger compartment and blows into the opacity meter box. Air escape vents were made to the box to eliminate pressure build-up which would be created by the blower and might have affected the meter readings. These modifications were tested and have eliminated smoke and heat build-up within the box, allowing the opacity meter to function continuously during revenue service.

The actual trap, pre-converter and MDAS system will be fully integrated and operational during mid to late September and the actual revenue service operation, Dyno back-pressure testing, full trap loading, regeneration and data acquisition will be started at that time.

JTA staff verified CTI billing figures. JTA calculated its expense for the combined billing to MDOT and compiled current narrative.

September, 1991

JTA discussed vibration testing with Tom Parrish, Testing Director of Aeroquip Engineering Laboratory in Jackson, Michigan to determine the ability to test the trap or wire-mesh sample in a meaningful way which would allow for some "real-time" calculation of failure. Mr. Parrish stated that Aeroquip does much vibration testing for both government and private industry materials. While some have a known operating environment, the ability to perform "accelerated" vibration and rationalize or extrapolate that data into a "real-time" standard is virtually impossible. Mr. Parrish advised that vibration testing may determine at what frequency and amplitude an item or material may fail. However, unless the tests revolve around a known envelope of operation, the test is virtually meaningless.

Mr. Parrish advised that Aeroquip would be happy to perform a test which they utilize for air brakes. This test would cover 40-250 hertz @ 8.5 G's. He believed that this test would more then exceed anything the trap would be subjected to on the vehicle. He also advised that a one time "shock" test could be performed. Testing from 600 cycles per minute to one million could be performed, although he doubted that any useful data could be generated. If JTA/CTI want to test the trap until it fails, he suggested running it on the bus until that does happen. He stated that in reality, this is how much of the "proof of the pudding" is determined. He noted that some of the components of existing commercial and military aircraft do not have known durability regarding total operational life. Many components have "estimated" life values based upon known elements and are rated for service at half of that value. CTI and JTA submitted a potential vibration and durability testing schedule to MDOT.

MDOT staff were at JTA's facility to discuss the parameters of such testing. MDOT staff were to coordinate their paperwork in Lansing to see if the accelerometer testing could be done on the trap during vehicle revenue service. This would provide the necessary "operating envelope" information required to perform some meaningful vibration testing. As of this date, no further word from MDOT as to this possibility.

The trap was installed for actual revenue service and run over the period of September 20th through 26th. The accompanying test report from CTI provides insight into the information received during this period of time.

JTA staff noted with pleasure an absence of "visible" smoke while the vehicle was running with the trap regardless of acceleration, deceleration, up and down hill. The driver noted no changes in the overall performance of the vehicle. Fuel measurements are inconclusive in determining whether there has been a fuel penalty as the period of time offers to little variance to make conclusive statement regarding any penalty. Due to the low back pressures noted during Dyno testing, it is anticipated that such penalty will be minimal.

The accompanying reports are from both CTI and JTA. CTI's report covers the on-the-road-data for pressure drop and calculated collection efficiency. The JTA report covers basic information regarding fuel and oil use for the vehicle for July, August and September, 1991.

October, 1991

CTI made upgrades to the Mobile Data Acquisition System (MDAS) to automate the smoke meter zeroing and identify malfunctions of any systems or the computer itself. Problems were encountered where the "real time" from the computer clock was lost. However, data continued to be collected. Work will be done in November to solve this problem which appears to be related to voltage fluctuation of the vehicle.

JTA staff reviewed the software modification from Computerized Fleet Analysis to determine whether all UMTA required information was included in the newly generated report. Some modification was deemed necessary and the information passed on to CFA for additional work.

JTA staff reviewed and corrected CTI billings, generated monthly billing and narrative for MDOT, cut check for CTI.

November, 1991

JTA installed new exhaust system to accommodate the bellows and additional thermocouple. Out of memory problems were isolated and corrected.

JTA verified CTI billings and generated monthly narrative and billing to MDOT. Attended meetings with MDOT, CTI staff.

December, 1991

JTA placed the bus back in service the morning of December 12, 1991. The driver drove for to an out county area and when he stopped at the client home, he noted smoke from underneath the vehicle. The vehicle was towed back to JTA.

NARRATIVE REPORT
(continued)

It was determined that the trap had achieved natural regeneration do to the improvements made in maintaining exhaust manifold temperatures to the wire mesh of the trap.

However, the control system device, the butterfly valve actuator, failed to cycle this valve. This allowed internal trap temperatures to exceed 1000 degrees Centigrade, and exhaust temperatures out of the trap to exceed 690 degrees C. This high temperature was located near a heater hose which JTA had failed to protect. The foam around this hose caught fire and charred the hose. In addition, two electrical wires running from the trap had plastic hose around them to protect from rubbing against the vehicle. This plastic hose also was not protected and it melted. The electrical wires insulation also became charred.

Upon checking the software recording devices, it was determined that the temperature halo-sensor had called for the actuator to be closed at 600 degrees C. However, the vacuum line which ran from the engine to the actuator had a small leak. There was not enough vacuum to actuate the valve. This allowed the regeneration to continue without oxygen flow control and therefore, no method to keep the temperature at the 600 +/- degree C. The regeneration ran unchecked through its total burn of available particulate.

This "natural" regeneration was a by-product of changes made to the trap and wrapping of the pipes from the exhaust manifolds to the trap intake. This was done in an attempt to maintain much of the 500 to 600 degrees C from the manifold to the trap. It was calculated by CTI that if the temperature would be in the area of 450 degree C that "natural" regeneration could be achieved by the catalyst on the wire mesh. "Natural" regeneration would be of significant value as it would allow for lower temperatures due to reduced amount of soot collection as compared to "forced" regeneration of a trap was fully loaded with soot. This reduced temperature would greatly enhance the life of the wire mesh and catalyst.

In addition, "natural" regeneration on the road would eliminate the difficulties of regenerating each vehicle in the garage when traps required regeneration. In addition, exhaust is not by-passed around the trap wire-mesh during "natural" regeneration as it is during "forced" regeneration. This would indicate that little or no particulate would actually be discharged into the atmosphere during "natural" regeneration. Due to the substantially smaller amounts of particulate to be burned, the length of a "natural" regeneration will be substantially less then that of a trap loaded with 200 to 300 grams of soot.

An additional by-product of "natural" regeneration should be the down sizing of the trap. The trap currently is projected to collect

250 to 300 grams of soot before requiring regeneration. "Natural" regeneration at 20 to 40 grams of soot should require less quantity the wire mesh which is a major contributor of the size of the trap.

This size differential will require some consideration and calculation depending upon the volume of exhaust a particular engine may generate and the exhaust temperatures generated. If the 450-500 degree C temperature cannot be reached, the natural regeneration would not happen and the trap would require "forced" regeneration at its facility. Systems would not want to do forced regeneration every night so the trap loading ability would have to be necessarily higher. It should be noted however, that the 6.2 liter engine produces lower exhaust temperatures then the larger engines in medium to heavy duty buses. It is anticipated that the temperatures for "natural" regeneration should be easier to achieve in the rear engine large bus due to higher engine exhaust and less pipe distance to the trap.

The uncontrolled "natural" regeneration pointed out some note-worthy items. First, "natural" regeneration is possible. Second, the method to operate the butterfly valve to control the high regeneration temperatures was dependant upon the vehicle. Due to the possibility of leaks, or idling, the vacuum from the vehicle could not be guaranteed. Hence the failure on the JTA bus. Such an important safety feature must be self-contained and not dependant upon the vehicle systems. This pointed to electric control. If the power fails, a battery back-up could maintain the functionality of the actuator. If the total vehicle system has failed, the engine will not be running; no exhaust would be generated and likewise, no oxygen would be forced into the trap. Regeneration would burn itself out quickly from lack of oxygen. CTI has developed this alternative from conversations with JTA.

Another item of interest is that the trap contained the extremely high temperatures in excess of 1000 degrees C. This is an important item, as it demonstrates the durability and safety aspects of the trap design.

Another result of this uncontrolled regeneration and the high temperature resulted in JTA determining that it could not place this on a vehicle in revenue service. Safety of passengers of the utmost concern. JTA and MDOT have agreed to lease CTI one of its 6.2 liter diesel 1985 Carpenters for a minimum of one year. This vehicle was scheduled to be sold at public auction. It will be utilized by CTI to perform any required testing of the trap. JTA will assist in mechanical work as necessary as well as data collection and reporting to MDOT. CTI will be required to maintain insurance costs, maintenance and fuel costs of the vehicle.

NARRATIVE REPORT
(continued)

January, 1992

JTA reviewed the status report and compiled billing during January, 1992. All other work was done by CTI and essentially all cost was absorbed by CTI. The different bus was leased to CTI and they have made necessary changes to put the trap and pre-converter on this vehicle and make modifications as necessary to continue the project.

February, 1992

JTA staff met with CTI and reviewed progress on the different bus. CTI identified that the collection efficiency of the trap had dropped due to the efficiency of the pre-converters in oxidizing CO and other volatile organic fractions. This, combined with the high temperatures carried from the exhaust manifold to the trap, has made the soot consistency "dryer", which has reduced the collection efficiency to 70%. To counter this, CTI has provided a double-walled exhaust from the manifold to the trap. Air is circulated between the walls, cooling the exhaust temperature, allowing for collection efficiency to increase to the 95% +/- range. Once trap loading is sufficient, the air circulation is eliminated and the higher exhaust temperature initiates natural regeneration.

CTI is testing this environment via both dyno and on-road testing. CTI has again absorbed the majority of the costs for these changes and is planning for emission testing in April, 1992.

March, 1992

JTA staff met several times with CTI at CTI and reviewed the new catalysts with CTI staff. The newest catalysts, which was developed with CTI funds, allows for "natural" regeneration at lower exhaust temperatures then previous designs. CTI reviewed information gathered during dyno and on-the-road tests performed with the new catalysts. The results are positive in nature and indicate better control of the regeneration temperatures.

The CTI heat exchanger (reduction method) requires improvement to maintain exhaust temperature below 320 degrees C at the trap intake to prevent premature natural regeneration. As a "green" or new trap is less efficient in collection of particulate, it is desirable to control regeneration until exhaust back-pressure indicates that the desired level of particulate has been accumulated. Frequent natural regeneration would keep the trap "green" or clean and reduce the collection efficiency beyond what is desired.

JTA staff reviewed the CTI billing and compiled the billing to MDOT.

NARRATIVE REPORT
(continued)

April, 1992

JTA staff met with CTI to review progress to date. JTA staff offered suggestions regarding the heat exchanger design to improve the ability to reduce the exhaust temperature. This is difficult as the exchange is hot gas-to metal exhaust-to outside air. CTI is working on the revised exchanger and it is expected to be completed during May, 1992.

JTA staff discussed the various testing which CTI has performed on-the-road. CTI showed the computer results of the testing and the natural regeneration pattern. Discussion regarding the rise of temperature from 600 degrees C to 850 degrees C was discussed. CTI is modifying the software to "anticipate" the rise and shut the butterfly valve earlier to keep the regeneration temperature around 600 degrees C. While the trap and its components have shown no adverse effects from the higher temperature, it is desirable to keep the temperature closer to the 600 degrees C area. This may also be achieved by capturing less soot/particulate, however this would decrease the overall efficiency of the trap.

JTA staff were able to view the actual components inside of the trap while it was torn down for review. There has been a great deal of simplification in the design to ensure operability. In spite of this, the trap is obviously of better design and components then when the project first started.

JTA staff discussed the project close-out and the fact that the vehicle and trap must be tested. CTI is hoping to have emission testing performed in late May, 1992, or possible June. This is dependant upon the revised heat exchanger working to expectations.

May, 1992

JTA met with CTI staff to review the work on the heat exchanger. CTI also discussed the lubrizol fuel additive which has shown the ability to reduce the "lite-off" point of particulate substantially. Through the combination of the cooling effect produced by the heat exchanger which will allow for more complete collection of "wet" volatile organic material, the reduced ignition temperature of the particulate, the trap will be more effective with less temperature involvement. Some delay in road testing by CTI was experienced as the opacity meter was in for repairs by its manufacturer.

JTA reviewed the CTI billings and generated the narrative for May. MDOT billing will be held for one month as CTI's balance is under $20.00 dollars. CTI will also be scheduling noise and emission tests for late June or July. These tests will be included in the monthly report if available, as well as the final report.

June, 1992

JTA discussed current status of trap with CTI. Review of road test information collected by the MDAS indicates that the heat exchanger is working very well in cooling the exhaust temperature from the manifold. Such cooling will enhance collection efficiencies on a green or newly regenerated trap.

Road test data (included) identifies the lower temperature for regeneration as triggered by the computer control system. Once the heat exchanger blower system is shut down, the heat rise is enough to trigger the lubrizol aided regeneration. This naturally fired regeneration, because of reduced ignition temperature, can be identified in the MDAS recorded data. The rapid decline of temperature into the trap via the heat exchanger system is clearly visible.

CTI is requesting formal noise testing at Walker Manufacturing proving grounds for late July. CTI also is requesting the EPA laboratories in Ann Arbor to perform emission testing. CTI's verbal discussions with EPA staff indicate that there is a high probability for these tests to be run.

CTI has also contacted MSU to request their consideration to be observers at either or both tests. JTA will have staff at the noise test. It is questionable whether the EPA will allow JTA or MSU staff to be present during emission testing. If possible, JTA would desire both MSU and MDOT technical staff to view this testing.

CTI has now expended their portion of this grant. CTI has contributed over $109,339 of its own monies due to the several changes of direction and requirements requested by JTA, MDOT Engineers, and CTI's own desire for improvements. While the final test results are not yet received, it should be noted that the test bus has no visible signs of smoke, and greatly reduced exhaust smell. The vehicle is old, dirty, and without enhanced electronic controls. If emission test results indicate reductions of particulate of anything beyond fifty percent (50%), the project will have achieved a major milestone exceeded only by the latest engine technologies of OEM engine manufacturers, and Donaldson Corporation. Those entities have spent literally millions on research and development. CTI, MDOT, and JTA will have achieved a major step towards a clean, cheap retrofit for diesel engines for a limited investment of funding.

July 92/March 93

CTI had noise tests run at the Walker Manufacturing proving grounds in Grass Lake, Michigan during August, 1992. The vehicle was tested with a new standard muffler system, and with the CTI trap system to determine the variation between the OEM and trap noise.

NARRATIVE REPORT
(continued)

The noise testing results indicated a small difference of 3 to 5 dB in peak noise level and a small decrease in low frequency noise with the CTI trap. It was noted that the outer shell of the trap vibrates and generates excessive noise. This needs to be modified to provide greater rigidity which will reduce this noise level.

CTI and JTA staff met with the Environmental Protection Agency staff at the EPA Ann Arbor facility. The EPA staff were provided with a demonstration ride and the ability to view the Mobile Data Acquisition System information while on the road. Design of the trap was discussed and reviewed. Formal emission testing of the trap was discussed. EPA staff suggested a formal letter of request from CTI, JTA and MDOT would be beneficial.

JTA asked MDOT staff if MDOT would participate in a formal request to the EPA for testing. MDOT staff were to discuss and advise if they would do so. No information was heard over the next two month. JTA's Administrative Director again asked MDOT if they would be able to do so. No response was given.

CTI took the vehicle back to the EPA Ann Arbor facility to see if the vehicle would be able to be tested intact. It was determined that the engine and trap system would have to be removed from the bus if testing was approved. Due to the cost and time involved, JTA advised that while they would desire formal testing, limited staff time was available for removal of the engine and trap from the vehicle and set up to run in a test stand environment. As the MDOT contract does not call for formal EPA testing, no funding is available for this, and MDOT had indicated that no additional monies is available.

Mr. Don Crary, EPA Grant Funding, Washington, D.C., came to Jackson with his assistant in November to review the CTI work. The EPA had funded initial and second cycle funding for the trap development. Mr. Crary visited with EPA staff in Ann Arbor to investigate the possibility of some type of emission testing. In January, 1993, he advised CTI that such testing would not be available until CTI had other "independent" testing performed at approved emission testing facility.

CTI discussed the possibility of buying the vehicle which it has been utilizing for this grant. Agreement was reached to sell the vehicle for $800. CTI would continue to utilize the 6.2 liter diesel engine for additional trap enhancements and testing.

SUMMARY

The project concept was established in December, 1989: To determine if the Converter Technology Trap concept was viable in a public transit system environment; to ascertain the practicality and reliability of such a trap for future "retrofit" projects.

At the time the project was originally discussed and formally proposed, the was tremendous concern regarding the ability for public transit fleets to meet proposed EPA emission guidelines. During the course of this project, engine manufacturers have developed engines which meet the 1994 new vehicle standards. Detroit Diesel Corporation has developed rebuild packages for some engines to bring them into compliance with current standards. Testing is on-gong to determine the length of time such rebuilds will maintain the EPA standards.

The ability of OEM's to meet existing EPA emission standards has reduced the feeling of crisis for most public transit systems. However, it should be noted that the EPA emission regulations have stricter guidelines regarding both particulate and NOX in the future. It is anticipated that EPA "Rebuild" regulations will also tighten.

This project with Converter Technology, Inc.(CTI), has demonstrated that the CTI trap can reduce viable smoke and odor. Based upon calculations of particulate generation of the worn 6.2 liter engine utilized in the JTA test vehicle, substantial reduction of particulate emission has been established. The technical aspects of the calculations may be questioned, but the fact that this bus does not generate smoke or odor under full load is impressive. Following this CTI equipped test vehicle down the road is comparable to following one of JTA's large vehicles which is equipped with a $16,000 1993 Detroit Diesel Electronic Controlled 6V92TA engine and a $13,000 Donaldson Company trap system.

The original trap was designed to be manually regenerated at a transit facility. Due to JTA's direction, the trap was modified to achieve "natural" regeneration during revenue service. While a seemingly simple request, this meant that many major modifications were required to the trap and software. This took considerable time, effort and money to achieve. This delayed the actual road testing of the trap by several months and necessary modifications to the originally proposed monitoring program.

The ability to monitor the many aspects of the trap operation was also an added requirement well into the project. The Mobile Data Acquisition System (MDAS) is unique in its ability to monitor exhaust opacity (smoke) during actual operation of the vehicle. Several other areas were determined to be monitored as well, including exhaust temperature at the trap intake and outlet, trap internal temperature, bus RPM, throttle position, speed, distance traveled, and trap loading of particulate (based upon complex calculations). The software work to provide these many readings with the existing mechanical engine was difficult and time consuming. Work continues on the software calculations necessary to provide accurate readings for each

SUMMARY

of these items, as well as several other readings. CTI spent considerable time and effort in development of the MDAS.

The current version of the prototype is dramatically different than the original. The many months of this project has led to many enhancements and refinements of the trap, its software, mounting devices and transmitted engine vibration. The joint expertise of the Jackson Transportation Authority maintenance department and Converter Technologies, Inc. multi-talented staff have greatly improved the reliability and operating cycle of the trap.

The existing trap design is essentially ready to be placed into a production mode pending the ability of CTI to obtain satisfactory financial support. CTI is presently investigating various methods for joint venture capital to begin the long process of establishing a manufacturing environment for this trap. As CTI's final report indicates, final enhancements to the trap shell and other modifications are dependant upon a strict quality control program during the manufacturing process.

Within the CTI joint venture plan is funding for formal emission testing at EPA approved testing facilities. This is a necessary step to ensure that the production model can be certified by the EPA.

It is appropriate to note that JTA has experienced some problems with the Donaldson Company traps. Michigan Detroit Diesel-Allison staff who are trained in service of the Donaldson trap have been to the JTA facility several times for a wide array of problems. These problems have ranged from incorrect warnings of trap regeneration failure to actual non-regeneration of one or both traps on vehicles. In spite of the fact that Donaldson is a very large company with vast resources, the Donaldson trap is still being modified and enhanced well into production, sales, and operation of the traps. Software modifications have been made to such an extent that existing test equipment is not compatible with the latest version of the Donaldson trap.

The overall CTI project therefore, while delayed by both administrative and required enhancement, should be deemed to have achieved its basic goals. The many and various enhancements to the trap and its operating mode have contributed to an improved CTI trap. This trap, if further developed into a manufacturing prototype, will provide an additional choice for public transit systems in the quest for vastly improved emission and clean air for all diesel engines.

FINAL REPORT

Converter Technology Trap System Demonstration Project for Jackson Transportation Authority

MDOT Contract No. G90-1355COM, Project No. A06368

April, 1993

Prepared By:
Converter Technology Inc.
414 N. Jackson St.
Jackson, MI 49201

Prepared For:
Jackson Transportation Authority
&
Mich Department of Transprtation

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Executive Summary

The utilization of diesel engines in the transit industry contributes to a wide range of air pollutants. A number of pollutants associated with the ignition of diesel fuel has been identified as toxic air contaminants. The major pollutant is particulate matter, commonly known as "soot". Soot is a prime contributor to a host of environmental degradations such as objectionable foul odor, health related impacts, poor visibility, and soiling. The diesel engine has been established in the transit industry as the most reliable and cost effective source of power. However, unless the environmental impact of the diesel engine is resolved, the diesel engine is out. The current alternatives are not attractive either, especially in terms of capital and operating expenses.

Converter Technology Inc. (CTI) has been working on developing particulate traps since 1982. Through negotiation with the Jackson Transit Authority (JTA) and the Michigan Department of Transportation (MDOT), CTI proposed a cooperative demonstration project. In turn, JTA furnished a bus equipped with a 6.2L diesel engine. Work on this demonstration project commenced in February, 1991. The project progressed well, however, a few delays were encountered. These were coupled with some reliability problems. (A natural regeneration was encountered without the benefit of a vacuum power source, resulting in the destruction of the wire mesh through excessive heat. The prototype was replaced on another bus that was assigned to CTI, and a design change solved the problem.) Remaining reliability problems encountered on the road were identified , quantified, and resolved in a satisfactory manner.

Currently, CTI is negotiating with established manufacturers to produce the design for which three patents were received. These include Nelson Manufacturing, Walker Manufacturing, The Flexible Corporation, and others. CTI believes that their product offers advantages over the only current trap system on the market, produced by Donaldson. Competition is in pressure drop, fuel penalty (0.1% for CTI vs. 3% for Donaldson), less complex and costly product ($5,000 for CTI vs. $12,000 for Donaldson), and anticipated higher reliability in operation. Furthermore, CTI traps provide sound attenuation comparable to the muffling system on a bus. This feature allows the replacement of the muffler with the trap which is a critical factor in resolving space problems in retrofit applications.

Converter Technology appreciated the opportunity of working with the teams at JTA and MDOT. The project was conducted in a cooperative spirit and it demonstrated how government and small private industry can put their resources together. Although the outcome of this project is not clearly visible, CTI anticipates that the experience gained laid the groundwork for a new and growing high-tech business in the Jackson area.

1. Introduction & Statement of Opportunity

The utilization of diesel engines in transit bus application is common throughout the world. However, diesel engines contribute a wide range of air pollutants associated with the combustion of diesel fuel. These pollutants have been identified as toxic air contaminants. Of major concern is particulate matter, commonly known as "soot." Particulate matter is responsible for a multitude of environmental problems such as objectionable foul odor, poor visibility, and soiling the environment. Many health scientists believe that suspended particulate matters aggravate bronchitis, asthma, cardiovascular disease, influenza, and are regarded as carcinogenic.

The diesel powerplant has been established over the years as the most reliable and effective power source for a host of energy sources, particularly transit buses. Almost all transit buses on the road in the U.S. are powered with diesel engines. Because of the nature of bus operation, being in urban areas and mostly in congested localities, the U.S. EPA targeted the problem of bus emissions. The standards set for bus emissions, as promulgated by the 1990 Clean Air Act, are stricter than those set for other vehicles, such as trucks. Furthermore, bus retrofitting standards are also mandated by the 1990 Clean Air Act and the final rulings are anticipated to be released in 1993 with an effective date in 1995.

Alternative technologies are being demonstrated nationwide. This includes methanol, compressed natural gas, liquified natural gas, ethanol fumigation, and electric buses. These technologies provide both alternative fuels and usually lower emissions. However, the impact of such alternatives is severe, particularly in terms of capital costs, safety issues, and qualified technical personnel capable of working with these new breed of technologies, etc. It is CTI's opinion that the diesel engine will remain the most reliable and economical power source for a long time, provided that the emission problem is resolved satisfactorily.

The opportunity presented here was to demonstrate CTI's particulate trap technology on a small bus operated by the Jackson Transportation Authority. Converter Technology presented the technology to a group from the Jackson Transportation Authority and the Michigan Department of Transportation. As a result, CTI entered into a contract agreement with the Jackson Transportation Authority and work commenced on February 14, 1991.

2. CTI Trap System & Performance Highlights

2.1 Hardware & Operation

CTI trap system hardware is primarily composed of the trap unit which is installed on the exhaust system and a microprocessor which is installed in the same compartment with the electrical and electronic devices. The microprocessor is linked to the trap and the engine electronic through a wiring harness. Electric power to the microprocessor is received from the vehicle's electrical system.

The trap mechanical design is shown on page 7. The exhaust gases entering the trap are guided to the bottom of the composite wire mesh reactor. The frontal surface area of the wire mesh is larger compared to the inlet exhaust pipe cross-sectional area. A ratio of 30:1 is selected. This high ratio assists with two characteristics: 1) It slows down the exhaust gas velocity which contributes to larger particle collection efficiency, and 2) it decreases the pressure drop across the wire mesh by a large factor. As the exhaust gases pass through the wire mesh reactor, a large portion of particulates are collected inside the wire mesh. The cleaned gases leaving the wire mesh exit the trap unit at the outlet.

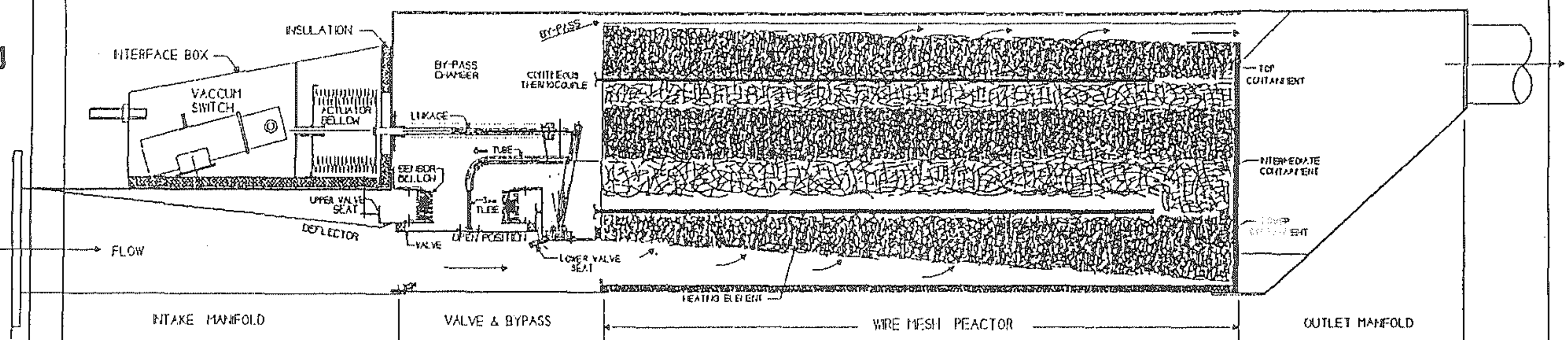
The wire mesh is made of high-temperature resistant stainless steel. This material is shaved into wool of fine and medium qualities. CTI currently purchases this wool from Germany. This wool is bonded with a metallic coating to form a rigid matrix, then is coated with alumina. The alumina (ceramic) coating and the associated calcination processes provide a very high surface area. For each gram of calcined alumina, the surface area is about 100 to 150m^2/gm or 1,000 to 1,500ft^2/gm. Each reactor has close to 6,000 grams of alumina coating. This remarkably-high surface area is the key to achieve good particulate collection efficiencies. The calcined alumina, finally, is coated with a base-metal catalyst. This catalyst is primarily composed of copper salts with added promoters such as vanadium and potassium salts. The catalysts provide a very essential function: lower carbon (soot) ignition temperature from 620°C to 350-400°C range. This unique characteristic is an essential key element to achieve "natural regeneration" during bus operation.

This unique characteristic of the CTI trap system is its ability to achieving natural regeneration on the road. This simplifies hardware design and enhances reliability through the elimination of heating elements or burner systems to regenerate the trap. Briefly, the collected soot on the wire mesh is slowly incinerated in the presence of base-metal catalysts when the exhaust gas temperature reaches or exceeds the reduced soot ignition temperature which, in the presence of the base-metal catalyst, is 350-400°C. Continuous or frequent incineration during bus operation on-the-road usually results in slight temperature rises that are so small they cannot be detected through temperature measurements. This characteristic is very desirable as regeneration is achieved without the high temperature rises that could destroy the reactor.

Of great importance is designing against low-probability events that could take place under certain circumstances that could develop during bus operation. Such a scenario involves the accumulation of significant amount of soot without regeneration, which could lead to a large amount of heat when regeneration takes place.

To guard against this problem, the CTI trap system is equipped with a unique safety system that provides protection against sudden temperature increases during regeneration. The safety system design is simply a "closed-loop feedback" control system. An intriguing device called a "continuous thermocouple" is embedded inside the wire mesh reactor at various zones to continuously measure the temperatures during engine operation. The continuous thermocouple is furnished in a wire form and close to 10 feet is embedded in the wire mesh. The output electrical signal from the continuous thermocouple correlates with the maximum temperature experienced anywhere along the length of the embedded wire. In the event a sudden temperature rise takes place as a result of an inadvertent natural regeneration, the continuous thermocouple will detect the high temperature and forward the signal to the microprocessor for action. The microprocessor logic is set up to act on high temperature (500°C) or rate of increase of temperature (20°C/sec). Both are signals indicating the possibility for a runaway regeneration to take place. When such conditions are received by the microprocessor, it immediately forwards a signal to close the butterfly valve ahead of the wire mesh. When the valve closes, the exhaust gases and the oxygen are bypassed around the wire mesh to the trap outlet. Eliminating the flow of oxygen to the wire mesh provides immediate control of the incineration process by stopping the soot combustion. If the valve is left closed too long, oxygen starvation will lead to quenching of the incineration process which is not desirable either. Therefore, the microprocessor will allow the valve to open when the temperature cools down to 480°C. Incineration of the remaining soot will continue at a slower rate. Should the temperature rise to unsafe limits again, the microprocessor will close the valve again. Such a second command has not been encountered in operation. One valve closing time is sufficient to bring incineration of such natural regeneration under control. Actual valve closing time was found to be in the 4 to 6 minute range.

Further discussions relating to CTI's trap system design features, operation, and performance are presented in References 1 thru 4.



TRAP ASSEMBLY - SIDE VIEW

CONVERTER TECHNOLOGY INC.

2.2 Performance Highlights

A. Particulate Collection Efficiency & Pressure Drop

The Trap system tested on the JTA bus employed base-metal catalysts. These catalysts assisted with achieving natural regeneration during bus operation on the road. As it implies, natural regeneration does not rely on external heating sources such as an electric heater or a fuel burner. As such, there is saving in power consumption and improvement in the fuel penalty. The net fuel penalty, when the trap system replaces the muffler, is due to the increase in back pressure.

Prime performance highlights are: 1) Soot collection efficiency, and 2) the pressure drop or net fuel penalty. Measurements were conducted on the trap system on four successive dates to evaluate trap performance, taking into account the effect of breaking a trap from its new condition (green) to a normal condition. Also, performance data with the muffler installed were measured. The results of measurements taken on CTI's chassis dynamometer are presented in Appendix "A".

The results tabulated in Appendix "A" demonstrates a particulate collection efficiency of 85% when the trap system operates properly. Furthermore, the pressure drop from the trap at 50mph averaged about 13 inches of water compared to 10.3 inches of water from the muffler. The net increase in pressure drop is 2-7 inches of water. This increase in pressure drop has an insignificant effect on the fuel penalty. It is less than 0.1%, and for all practical purposes there is no net fuel penalty when the muffler is replaced with the CTI trap. The current fuel penalty for Donaldson's trap is 3% (Ref. 6).

B. Performance on the Road

Performance characteristics on the road were measured through a Data Acquisition & Control System installed on the bus. Arrangement of the Data Acquisition System is presented in Appendix "C". Typical data collected on the road is included in Appendix "B". It should be noted that such a rigorous data acquisition system was helpful in identifying problems encountered on the road and that, in turn, was helpful in establishing proper diagnosis and action to resolve such problems.

The measurements taken on the road confirmed the performance values measured during lab dyno testing, particularly those of smoke opacity and pressure drop. The data collected during bus operation is extensive in volume and is available on 3 1/2" computer disks that were forwarded to JTA.

C. Noise Attenuation & Testing

The trap system employing wire mesh and having large expansion and contraction of the exhaust flow was anticipated to provide a muffling effect. To determine the degree of muffling effect achieved with the trap system, noise tests were performed on the bus once with the muffler on and another time with the muffler replaced by the trap system. The noise testing was performed at Walker Manufacturing's facilities in Grasslake, Michigan, per the Society of Automotive Engineers' test procedure J366. The results of the measurements are presented in Appendix "D". The test data showed.the trap to have a lower noise level than the muffler below 100 Hertz, and a higher noise level than the muffler above 100 Hertz noise frequencies. Further discussions with Walker's engineers as to the significance of trap noise attenuation vs. the muffler indicated that although both noise characteristics are different, the behavior of the trap and muffler are about the same. Further, it was observed that the outside housing of the trap was very flexible which could render it a source of noise. Stiffening the housing in a manner similar to the way mufflers are constructed will further reduce noise. Such enhancement will take place in the production units during stamping operations through the formation of longitudinal and transverse ribs designed to stiffen the shell.

In summary, CTI trap performances are superior to other trap systems based on published data. A matrix illustrating the competitiveness of CTI traps vs. other exhaust aftertreatment alternatives is shown in Appendix D.

3. Reliability & Durability

Particulate traps are complex devices that can experience high temperatures during regeneration as well as severe shocks and vibrations on the road. This, coupled with the fact that trap systems are new products having a limited history of operation, raises a number of issues about reliability and durability. The issue of trap reliability is of significance in this field that should be addressed and resolved in a satisfactory manner in order for a trap system to gain acceptance by transit companies.

Reliability issues relating to trap systems are addressed. These issues are broadly classified into: 1) Design-related, 2) Quality-related, 3) Shock & Vibration.

3.1 Design-related Issues

There are a few design related issues that were quickly identified during bus operation on the road. The following summarizes each:

Engine Vacuum Reliance on engine vacuum to operate the butterfly valve actuator was determined as an unreliable source for the actuation of the butterfly valve. During bus operation on the road, the need to close the butterfly valve arose due to excessive temperature encountered during a natural regeneration. Although the control system functioned as intended, and a signal was forwarded to activate the actuator by vacuum, no vacuum was available, and the actuator did not respond. The failure of the valve to close resulted in loss of control of the natural regeneration and consequently, control of the regeneration temperature. This resulted in the destruction of the wire mesh due to excessive heat. Upon examining the actuator system, it was found that the vacuum had leaks and that vacuum pressure could fluctuate during bus operation due to other utilization. The conclusion reached was that the vacuum system was deemed unreliable. The design was changed to an electrical actuator, which although more expensive, provides the necessary degree of reliability.

Housing Construction Another issue that was encountered related to the construction of the housing and the intake manifold of the trap. A bolted joint between the two pieces was used at first. After accumulating a few hundred miles, the joint started to leak exhaust gases as a result of vibration and shocks on the road. Although having such a joint was selected for prototype purposes only to facilitate disassembly and inspection, and was not intended to be on the production unit, the bolted joint was deemed unsatisfactory. A welded design replaced the bolted joint, eliminating the leakage problem.

3.2 Quality Related Issues

Quality related issues by far represent the majority of problems encountered during CTI's trap testing. A distinction should be drawn between a prototype and a production unit quality. It is normally expensive to construct a prototype. Implementing quality control measures are even more expensive. As such, reliance was made to focus on having the best workmanship coupled with visual inspection by R.A. Kammel of CTI on the most critical components. This approach was the best alternative, particularly when project costs had to be kept under control. It is believed that most components functioned properly. The critical remaining issues relate to the manufacturing of the composite wire mesh and the associated chemical processes. Although careful measures were taken, no quality control plan could be implemented due to the cost factor. These quality measures will be implemented in the upcoming stage of small-volume manufacturing.

Donaldson experienced similar problems on their trap system which is more complex than CTI's system. As a result, Donaldson implemented a strict quality standards from the military, MIL-STD78JB type reliability program. This program calls for higher standards than those in the automotive industry. Donaldson measures incidences of frequent occurrences and devises action plans to improve/decrease their frequency of occurrence and impact.

A CTI production trap system is anticipated to have at least a compatible degree of reliability as the current Donaldson system, if not better. This is due to the fact that CTI's design is at least 50% less complex than the Donaldson design.

3.3 Shock & Vibration

Shock and vibration are detrimental to reliability of a trap system, particularly the durability aspects. Wire mesh is susceptible to damage should excessive vibration or shock be encountered. As such, it is important to address the issue of vibration and isolate it from the wire mesh to the maximum extent.

Two design features were implemented to isolate vibration from the wire mesh. The first one relates to the wire mesh reactor which was supported completely on an elastic cushion of knitted wires (acting as springs). The second one relates to isolating engine vibration from the trap. This was accomplished by installing bellows in the exhaust pipe between the engine and the trap. Upon examining the vibration issue further through meetings with MDOT personnel, measurements of vibration was taken on the trap during bus operation. The maximum measured vibration on the road was 2 to 3 G's after implementing the above two measures. This value was assessed as low and would not cause any damage or impact the durability of the wire mesh. Further discussion on the vibration plan and measurements are contained in Appendix "D".

4. Economics of CTI's Trap System

It is CTI's belief that the proprietary CTI system is the least complex system on the market. As such, CTI's trap system is less expensive to manufacture in comparison to the Donaldson system or other known systems. Current cost analysis of CTI trap systems for the Detroit Diesel 6V92TA engine or equivalent stand at close to a $5,000 sale price per bus plus $1,000 for installation. A cost analysis of the system compared to Donaldson's trap system as well as other alternative technologies such as methanol and natural gas are summarized on the following page. This evaluation is based on a study by Booz, Allen, & Hamilton for the San Diego Transit Authority (Ref. 5). The conclusion of this study is an obvious one which is known industry wide. Particulate traps are the most cost effective alternative when compared to methanol, compressed natural gas, and liquified natural gas. Further, the CTI trap system is even less expensive than the Donaldson system.

In order to realize commercialization of the CTI trap system, the management initiated contacts and presentations to a number of manufacturers for joint ventures. The outcome of these negotiations, hopefully, will materialize in the near future.

ECONOMICS OF BUS RETROFITTING

COST CATEGORY	DIESEL BASE-LINE	METHANOL	CNG	LNG	CERAMIC TRAPS	CTI'S TRAPS
Capital Cost / Bus	$210,000	$240,000	$255,000	$250,000	$230,000	$216,000
Capital Cost Differential (including fuel facility)	-----	$30,335	$52,110	$41,970	$20,000	$6,000
Fuel Cost Differential (annual)		$4,792	$(258)	$(698)	$475	$95
Annualized Costs	$44,070	$53,891	$51,389	$49,273	$48,676	$45,822
Annualized Costs Differentials	0	$9,821	$7,319	$5,203	$4,609	$1,752
Total Cost / Mile (50,000 m/y)	$ .88	$1.07	$1.03	$ .99	$ .97	$ .91
Cost of Pollution Control dollars / lbs. of particulate	----	$31.78	$23.69	$16.84	$16.58	$6.00

*Cost data are based on a report by Booz, Allen, & Hamilton, April, 1991.

5. Project Cost & Analysis

The data sheet on the next page is the final invoice submitted for this project and it illustrates the total costs encountered and the breakdown by task.

It is evident that the project experienced situations that required more efforts and expenditures than what was originally planned. This was compounded with a special request to address issues such as vibration and administrative problems delaying the project. The total cost at the conclusion of the project was $187,089. MDOT's contribution was $76,750. CTI's contribution was $109,339 instead of $30,970 that was originally planned at the outset of the project.

PAYMENT REQUEST - JTA CONTRACT NO. 90-1967

CONVERTER TECHNOLOGY INC.
414 N. Jackson Street
Jackson, Michigan 49201

Progress Report Number: 17

Date: July 11, 1992

Line Item	Cost This Period	Total Budget	Total Cost To Date	Billing Balance	CTI Contribution This Period	CTI Contribution Cumulative
TASK I:						
CTI Engineering	$0.00	$1,971.00	$2,263.00	$0.00	$0.00	$292.00
CTI Technicians	$0.00	$729.00	$1,161.00	$0.00	$0.00	$432.00
Sub-Total:	$0.00	$2,700.00	$3,424.00	$0.00	$0.00	$724.00
TASK II:						
CTI Engineering	$2,445.50	$3,393.00	$38,327.00	$0.00	$2,445.50	$36,934.00
CTI Technicians	$827.00	$2,007.00	$33,139.13	$0.00	$827.00	$28,132.13
Materials	$376.66	$3,500.00	$5,852.19	$0.00	$376.66	$2,352.19
Sub-Total:	$3,649.16	$8,900.00	$77,318.32	$0.00	$3,649.16	$67,418.32
TASK III:						
CTI Engineering	$2,920.00	$10,208.00	$17,337.50	$0.00	$2,920.00	$7,129.50
CTI Technicians	$334.00	$6,292.00	$14,434.75	$0.00	$334.00	$8,142.75
Dyno Test Time	$0.00	$3,000.00	$3,030.00	$0.00	$0.00	$30.00
Sub-Total:	$3,254.00	$19,500.00	$34,802.25	$0.00	$3,254.00	$15,302.25
TASK IV:						
CTI Engineering	$1,460.00	$6,570.00	$15,956.50	$0.00	$1,460.00	$9,386.50
CTI Technicians	$1,080.00	$2,430.00	$14,334.00	$0.00	$1,080.00	$11,904.00
Sub-Total:	$2,540.00	$9,000.00	$30,290.50	$0.00	$2,540.00	$21,290.50
TASK V:						
CTI Engineering	$2,190.00	$18,925.00	$21,513.00	$0.00	$2,190.00	$2,588.00
CTI Technicians	$810.00	$12,725.00	$13,516.88	$0.00	$791.88	$791.88
Test Equipment	$0.00	$5,000.00	$6,224.68	$0.00	$0.00	$1,224.68
Sub-Total:	$3,000.00	$36,650.00	$41,254.56	$0.00	$2,981.88	$4,604.56
TOTAL COSTS:	$12,443.16	$76,750.00	$187,089.63	$0.00	$12,425.04	$109,339.63

PAYMENT REQUEST: Cost This Period - CTI Contribution
$12,443.16 - $12,425.04 = $18.12

R. A. Kammel

R. A. Kammel, President

Date: July 11, 1992

6. Future Projects

CTI's believes that a particulate trap system sale price should not exceed $5,000, which is in line with EPA guidelines. CTI trap system can compete at prices below $5,000 provided that a large enough volume is manufactured. Financial and manufacturing resources for bus trap system are currently beyond CTI's resources. Therefore CTI is pursuing a joint venture with an established manufacturer having the resources to serve this market segment.

Once CTI finalizes a joint venture agreement, CTI will approach the Michigan Department of Transportation and various Michigan transit authorities. CTI anticipates to finalize a joint venture in 1993. Production trap units will be available towards the end of 1994. This timing will be in-line for the EPA retrofit mandated standards for buses to take place in 1995.

7. Acknowledgement & References

CTI acknowledges the financial assistance contributed by the Michigan Department of Transportation and the cooperation of the Jackson Transportation Authority team. The results and achievements arrived at the conclusion of the project are very valuable to CTI and MDOT. This project is a true cooperative research and development agreement (CRADA) in that both the state government and a private company (CTI) put their resources and finances together. CTI's management believes that these efforts are leading to the creation of a new business in the state of Michigan in the environmental market. Propelling this technology further, CTI stands an excellent chance to market and sell the bus/truck traps nationwide, and thus create an economic base and new jobs in the Jackson area. Through this grant and two other grants received from the EPA, CTI raised $424,000 from private sources in equity investment as of today.

CTI acknowledges the assistance and contribution received from the staff at the Michigan Department of Transportation (MDOT). In particular, special thanks to Mr. Frank DeRose, Administrator, Bus Transit Division, for his leadership and resolving administrative problems encountered in the course of the project, Mr. Russell P. Laverty, Project Manager for his participation in project plans and activities, as well as other members of the staff at UPTRAN in Lansing, Michigan. CTI also acknowledges the assistance and contribution received from the staff at the Jackson Transportation Authority. In particular, special thanks to Gordon L. Szlachetka, General Manager, for his leadership and wise handling of various issues and problems encountered in the course of the project, Garrett W. Erb, Administrative Director, for his total dedication, support, and involvement in the project with an entrepreneurial spirit, and Stanley Denika, Director of Maintenance, and his crews for their assistance and cooperation in installation and consultation on various issues, particularly those relating to maintenance.

The management of CTI also appreciates the contribution of the following personnel:

- Ray Kammel, for his dedication to the overall project in the technical and managerial areas.
- Gary L. Sirois, for dedicated efforts in electronics, mechanical and chemical work.
- Elmer Mueller and Scott Tipner for software development, Data Acquisition System.

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APPENDIX A

Particulate Collection Efficiency Data

TEST REPORT NO. 1
ON-THE-ROAD TEST DATA
FOR
DEO SYSTEM ON JACKSON TRANSIT AUTHORITY
BUS NO. 371

October 9, 1991

1. Testing Period: September 20 to September 26, 1991

2. Total Cumulative Mileage: 482 miles

3. Pressure Drop, Collection Efficiency Data

				Press. Drop, inches of Water				
Date	Cumulative Mileage, Miles	Smoke Opacity %	Soot Collection Efficiency %	Idle	20 mph	30 mph	40 mph	50 mph
9-20	3	0 - 2%	77%	0.5	1.6	3.1	5.8	13
9-23	142	0 - 1%	85%	1.0	2.5	4.2	6.9	11.5
9-24	266	0 - 1%	85%	1.0	2.8	5.0	9.4	13.1
9-26	423	0%	85%	0.7	2.4	4.2	8.0	12.5
9-27	482	0%	27%	0.6	2.6	4.7	10.5	16.5
10-3	Original Muffler	0 - 20%	---	1.0	2.5	3.5	7.5	10.3

Notes:

1) The data presented in this table are generated when the bus is on the chassis dynamometer and the horsepower setting of the power absorption unit is 17 hp at 50 mph. This setting may be increased in the future to a higher horsepower that would be comparable to engine load on the road.

2) Smoke opacity numbers represent the maximum readings registered on the smoke meter at speeds ranging from idle to 50 mph during bus testing on the chassis dynamometer. Separate opacity numbers are recorded every 2 seconds while the bus is on-the-road and are available on computer files.

3) Collection efficiency represents the ratio between collected particulate to the incoming particulates. This efficiency calculation is based on raw exhaust gas data and would be different if a dilution tunnel per EPA's procedures is used. The filters are standard 49 mm teflon coated glass fiber filters, commonly used in the EPA's procedures. Collection time and bus speed are set at 32 seconds and 30 mph when the samples are collected, respectively. One base line sample was collected. A baseline sample will be collected every time an after-the-trap sample is collected. This will be done to accommodate for variations in baseline emission encountered from day to day.

4) Pressure drop data are the difference in pressures measured before and after the trap using a manometer while the bus is on the chassis dynamometer.

5) The initial collection efficiency of a "green trap" of 77% increased to 85% once the trap was loaded and remained essentially constant. Upon discovering a low collection efficiency on September 27, the trap was disassembled. The butterfly valve linkage was broken and that, apparently, allowed the exhaust gases to take the path of least resistance (by-pass) which resulted in the low collection efficiency.

4. Trap Disassembly and Examination

Examination of the trap components after the accumulation of the 482 miles revealed mechanical problems that are, in our judgement, the product of insufficient welds, excessive shock/vibration encountered on the road, and improper support. The interface plane between the intake manifold and trap inlet represents the weakest section in the trap assembly. The lower side of this interface plane, apparently, was subjected to excessive tension that caused a series of mechanical failures radiating from that side. This included break away of two nut tacks, break of 3 weld tacks on an internal deflector plate and break of the weld on the butterfly linkage. Despite these failures, the trap continued to perform and degradation in performance was not easily detected through smoke measurement. It is believed that most of these failures took place after September 26, 1991. Despite all the excessive static and dynamic loadings the trap has undergone, no apparent damage was observed on any part of the wire mesh. The trap was repaired with particular emphasis on reinforcing the welds.

5. Analysis of Data and Conclusions

5.1 The data represents remarkable achievements that are the best, industry-wide, in terms of soot collection/smoke opacity reduction and the associated penalty in terms of pressure drop. Comparing the pressure drop data from the trap to the pressure drop from the muffler, there is virtually no difference. Since the trap is designed and intended to provide muffling effect compatible with the muffler, the replacement of the muffler with the trap would provide, virtually, no impact on the engine performance nor fuel economy. These initial results are consistent with our understanding/assessment of performance characteristics. For comparison purposes, the maximum measured pressure drop on the trap was 16.5 inches of water in comparison to the muffler pressure drop of 10.3 inches of water at 50 mph. When compared to other trap systems, a typical Donaldson Trap having 85% efficiency has a pressure drop upward of 75 inches of water. The pressure drop fluctuation in a Donaldson Trap is very rapid in comparison to the DEO system.

5.2 Pressure drop increase versus mileage accumulation appeared to level off after 200 to 300 miles of driving. It even declined after accumulating additional mileage. Unfortunately, external leakage developed and was observed on September 24, 1991 but was corrected immediately. The leakage continued, however, until the trap was removed on September 27, 1991. Upon disassembling the trap, internal leakage in the butterfly valve was confirmed, also. Both internal and external leakages would contribute to the decline in pressure-drop observed on September 26, 1991. As a result, the measured trap efficiency is not conclusive. However, smoke and collection efficiency measurements confirmed no increase in smoke opacity.

5.3 The stabilization, even decline, in pressure drop as more mileage was accumulated on-the-road was very encouraging results supporting an early system design goal, Natural Regeneration. It appears that some form of natural regeneration has been taking place during bus operation.

The following summarizes our observations supporting the existence of this phenomenon.

5.3.1 Examination of the wire mesh after disassembly revealed the entire mating surface areas were clean of black soot. The greenish wire mesh color could be seen clearly indicating no accumulation of soot in these areas. The soot around the heating element was low to the point that a forced regeneration was not warranted and would be difficult to initiate.

5.3.2 An estimate of particulates emitted from the engine during the 482 miles was made. Although this estimate is preliminary, it is useful to provide basic data. The 1988 engine was certified to 0.60 grams per Hp. hr. which corresponds to about 0.80 to 1.2 grams per mile. For a distance of 482 miles this corresponds to 385 to 580 grams of particulate. Assuming an average collection efficiency of 85%, the particulates trapped inside the unit will be in the 327 to 493 gram range. The wire mesh was heated to 250° C for 2 hours to boil moisture off and the weight was recorded. The wire mesh, then, was heated to 550° C (high enough to burn all soot) for 2 hours and the weight was recorded. The weight loss, presumably that of burned particulate, was 84 grams. The difference 327 - 84 = 243 to 493 - 84 = 409 grams is likely attributed to natural regeneration. A small portion of that particulate (2 to 5%), based on our judgement of the amount of leakage, might have escaped through external leakage. The natural regeneration phenomenon will be scrutinized more and more during the upcoming road tests. This data suggests that 74% to 83% of the soot has been incinerated in "a natural way" on the road. For natural regeneration to be completely effective, 100% regeneration will be required to eliminate the need for forced regeneration. On the other hand, less than 100% will reduce the frequency or the need for forced regeneration. For example, an 80% natural regeneration will extend the mileage between regenerations by a factor of 5 (100/100-80).

5.3.3 Temperature measurements at the inlet to the trap indicated a maximum value of 409° C. Two base-metal catalysts are used in the wire mesh and both had a maximum soot ignition temperature (measured by testing during the EPA Phase II program) of 430° C. Actual incineration (slow rate) starts at a lower temperature. Apparently, some incineration has been taking place slowly. Further, the type of soot collected is termed "wet soot" which might incinerate slowly at temperatures below 400° C.

6. Recommendations and Modifications

Observations and examination of the trap prompted the necessity to take immediate and short-term actions to improve the reliability of trap operation. These are:

6.1 Immediate Modifications

These modifications are being performed for the upcoming installation on the bus:

6.1.1 Provide an elastic support in the vicinity of the weakest plane to relieve static and dynamic bending moment.

6.1.2 Provide reinforcement in the junctions subjected to the excessive movement.

6.1.3 Provide a stronger weld for the deflector.

6.2 Short-Term Modifications

6.2.1 Conduct vibration measurements on the trap on-the-road.

6.2.2 Design a support system adequate for the total support of the deadweight of the trap and spring and dampening action for the reduction of shock and road vibration. This is being done in conjunction with an exhaust system support supplier.

6.2.3 Design and install bellows immediately after the exhaust flange to filter engine mechanical vibration.

6.2.4 Increase the wall thickness of the sheet metal in the failed areas.

6.2.5 Relocate the butterfly valve bellow which is susceptible to loss of function resulting from direct contact with the exhaust gases to the by-pass chamber. This is due to the difference in actual exhaust temperatures measured being higher than those published in an SAE paper by GM for the 6.2 L engine.

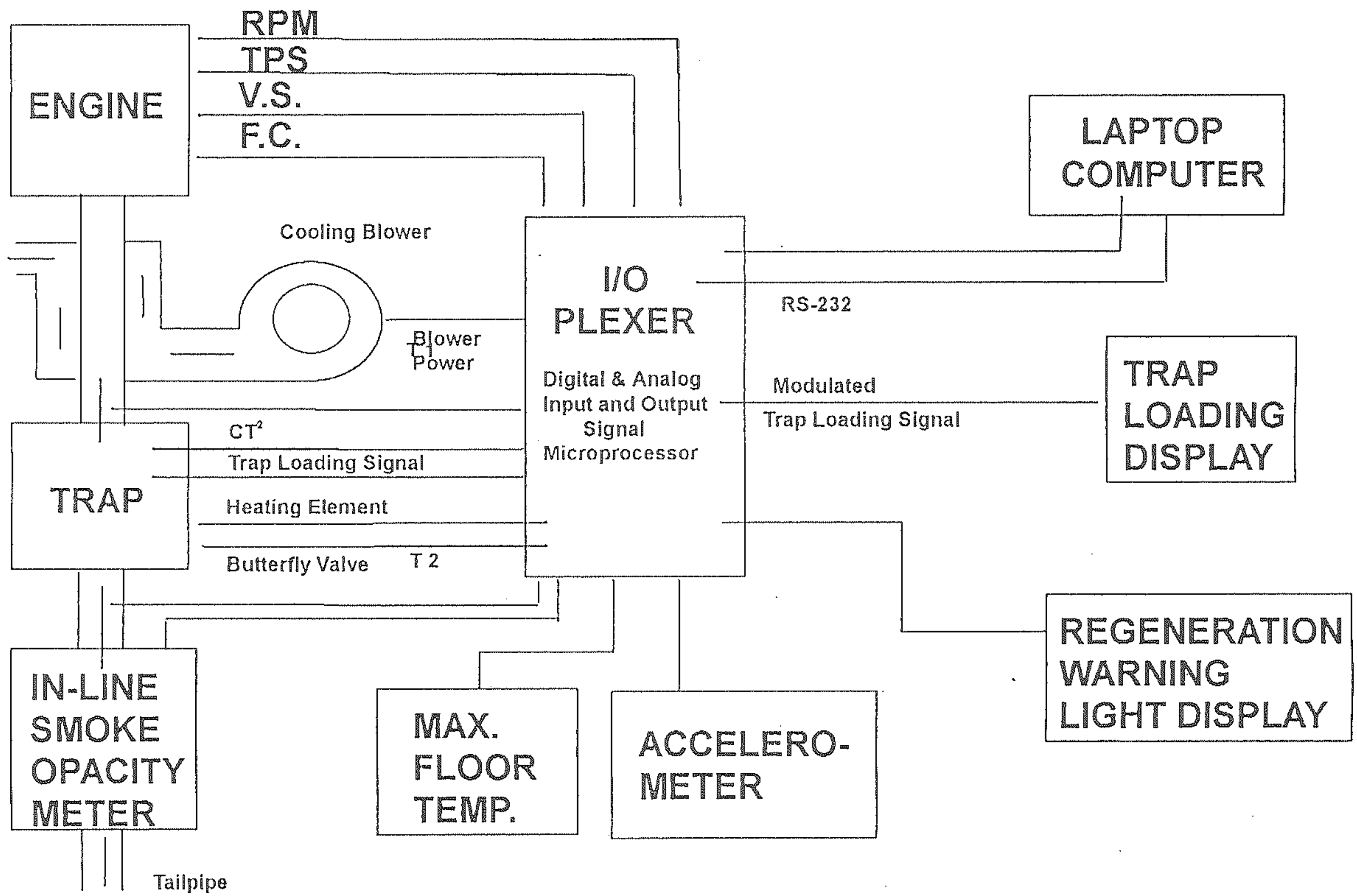
APPENDIX B

Typical Emissions, Engine & Bus Data on the Road

PERFORMANCE HIGHLIGHTS

2. Emission Test Data

Mobile Data Aquisition System



Typical Smoke Readings without the Converter

Bus equiped with GM 6.2L Diesel engine - on the road test data

Plexer, Postprocessing, Program.—2 second intervals.
Base Date: 05/15/92 Base time: 09:20 :08

Time(sec)	ITime	TTime	RPM	TPS	Speed	Smoke	Load	Prss	Dist	1Temp	CTemp	2Temp
09:20:46	00:00	00:00	0	0	0	1	0	48	0.00	12	-1	-1
09:20:48	00:00	00:00	0	8	0	1	0	48	0.00	12	-1	-1
09:20:50	00:00	00:00	0	23	0	1	0	48	0.00	12	-1	-1
09:20:52	00:00	00:00	255	23	0	3	0	48	0.00	11	-1	-1
09:20:54	00:00	00:00	938	14	0	69	0	53	0.00	16	-1	-1
09:20:56	00:00	00:00	900	5	0	56	0	50	0.00	18	-1	-1
09:20:58	00:00	00:00	915	7	0	6	0	50	0.00	18	-1	-1
09:21:00	00:00	00:00	938	7	0	4	0	50	0.00	19	-1	-1
09:21:02	00:00	00:00	930	7	0	4	0	50	0.00	20	-1	-1
09:21:04	00:00	00:00	952	7	0	4	0	50	0.00	20	-1	-1
09:21:06	00:01	00:00	938	7	0	4	0	51	0.00	21	-1	-1
09:21:08	00:01	00:00	938	7	0	3	0	50	0.00	22	-1	-1
09:21:10	00:01	00:00	938	7	0	3	0	50	0.00	22	-1	-1
09:21:12	00:01	00:00	915	6	0	3	0	50	0.00	23	-1	-1
09:21:14	00:01	00:00	810	0	0	3	0	49	0.00	23	-1	-1
09:21:16	00:01	00:00	750	15	0	5	0	50	0.00	23	-1	-1
09:21:18	00:01	00:00	1028	10	0	20	0	50	0.00	27	-1	-1
09:21:20	00:01	00:00	840	8	0	8	0	50	0.00	27	-1	-1
09:21:22	00:01	00:00	832	0	2	6	0	50	0.00	27	-1	-1
09:21:24	00:01	00:00	562	0	2	4	0	49	0.00	27	-1	-1
09:21:26	00:01	00:00	615	18	1	4	0	51	0.00	27	-1	-1
09:21:28	00:01	00:00	1312	36	1	29	0	55	0.01	34	21	-1
09:21:30	00:01	00:00	1440	32	5	14	0	55	0.01	42	42	-1
09:21:32	00:01	00:00	1275	0	5	4	213	49	0.02	43	54	-1
09:21:34	00:01	00:00	578	0	9	2	15	49	0.02	38	50	-1
09:21:36	00:01	00:00	578	0	9	3	0	49	0.02	36	48	-1
09:21:38	00:01	00:00	952	28	6	7	0	54	0.03	38	46	-1

Typical Smoke Readings with the Converter Installed

CTI Converter on a Bus equiped with a GM 6.2L engine - on the road test data

The Maximum CTSQ Temperature Was 385 At 14:14:58
Base Date: 11/02/92 Base time: 14:14 :31

Time(sec)	ITime	TTime	RPM	TPS	Speed	Smoke	Load	Prss	Dist	1Temp	CTemp	2Temp
14:26:45	00:07	00:05	1380	34	36	0	44	13.0	1.92	223	177	132
14:26:47	00:07	00:05	1388	34	36	0	44	13.5	1.94	223	179	134
14:26:49	00:07	00:05	1395	34	37	0	44	13.5	1.96	223	178	136
14:26:51	00:07	00:05	1538	33	37	0	0	14.0	1.98	224	179	137
14:26:53	00:07	00:05	1192	27	38	0	0	11.5	2.00	223	179	138
14:26:55	00:07	00:05	1612	27	38	0	0	10.0	2.03	222	179	138
14:26:57	00:07	00:05	1725	32	40	0	0	13.5	2.05	220	178	140
14:26:59	00:07	00:05	1298	28	40	0	0	14.5	2.07	219	179	142
14:27:01	00:07	00:05	1388	27	40	0	0	12.5	2.09	218	179	143
14:27:03	00:07	00:05	1508	28	40	0	0	9.5	2.11	216	178	143
14:27:05	00:07	00:05	1492	43	38	0	0	14.0	2.13	214	177	144
14:27:07	00:07	00:05	1320	44	38	0	0	15.0	2.16	218	180	144
14:27:09	00:07	00:05	1328	30	39	0	0	14.0	2.18	223	177	148
14:27:11	00:07	00:05	1320	0	39	0	0	4.5	2.20	222	176	146
14:27:13	00:07	00:05	885	0	33	0	0	2.0	2.21	220	176	144
14:27:15	00:07	00:05	712	0	33	0	0	2.0	2.23	219	174	142
14:27:17	00:07	00:05	1162	52	19	3	0	8.0	2.24	220	174	144
14:27:19	00:07	00:05	1852	53	19	4	0	10.0	2.25	226	174	138
14:27:21	00:07	00:05	1838	47	23	1	20	10.5	2.26	234	173	149
14:27:23	00:07	00:05	1680	44	23	0	0	11.5	2.28	242	174	151
14:27:25	00:07	00:05	1575	42	30	0	0	12.0	2.29	250	173	152
14:27:27	00:07	00:05	1635	37	30	0	0	12.0	2.31	255	172	153
14:27:29	00:07	00:05	1718	36	32	0	0	11.5	2.33	257	172	154
14:27:31	00:07	00:05	1470	37	32	0	0	11.5	2.35	257	172	155
14:27:33	00:07	00:05	1508	41	32	0	0	12.0	2.37	257	172	156
14:27:35	00:07	00:05	1545	42	32	0	33	12.0	2.38	257	171	157
14:27:37	00:07	00:05	1515	46	33	0	37	13.0	2.40	258	171	158

Typical Smoke Readings with the Converter Installed

CTI Converter on a Bus equiped with GM 6.2L engine - on the road test data

Base Date: 10/28/92 Base time: 14:25 :16

Time(sec)	ITime	TTime	RPM	TPS	Speed	Smoke	Load	Prss	Dist	1Temp	CTemp	2Temp
14:35:00	00:09	00:00	0	0	0	0	0	0.0	0.00	-1	117	14
14:35:02	00:09	00:00	0	0	0	0	0	0.0	0.00	-1	114	14
14:35:04	00:09	00:00	0	0	0	0	0	0.0	0.00	-1	116	14
14:35:06	00:09	00:00	0	0	0	0	0	0.0	0.00	-1	114	14
14:35:08	00:09	00:00	0	22	0	0	0	0.0	0.00	-1	116	14
14:35:10	00:09	00:00	218	30	0	0	0	0.0	0.00	-1	111	16
14:35:12	00:09	00:00	330	30	0	0	0	2.0	0.00	-1	116	18
14:35:14	00:10	00:00	810	18	0	0	0	1.5	0.00	-1	116	22
14:35:16	00:10	00:00	788	19	0	6	0	1.5	0.00	-1	116	24
14:35:18	00:10	00:00	810	20	0	2	0	1.5	0.00	-1	116	25
14:35:20	00:10	00:00	802	21	0	1	0	1.5	0.00	-1	115	26
14:35:22	00:10	00:00	825	21	0	1	0	1.5	0.00	-1	115	27
14:35:24	00:10	00:00	698	0	0	1	0	1.0	0.00	-1	115	27
14:35:26	00:10	00:00	578	0	0	1	0	1.0	0.00	-1	115	27
14:35:28	00:10	00:00	585	0	0	1	0	1.0	0.00	-1	114	28
14:35:30	00:10	00:00	585	0	0	1	0	1.0	0.00	-1	114	28
14:35:32	00:10	00:00	592	0	0	1	0	1.0	0.00	-1	115	29
14:35:34	00:10	00:00	585	0	0	1	0	1.0	0.00	-1	114	29
14:35:36	00:10	00:00	600	0	0	1	0	1.0	0.00	-1	114	29
14:35:38	00:10	00:00	592	0	0	1	0	1.0	0.00	-1	114	30
14:35:40	00:10	00:00	592	0	0	1	0	1.0	0.00	-1	113	30
14:35:42	00:10	00:00	592	0	0	1	0	1.0	0.00	-1	113	30
14:35:44	00:10	00:00	592	0	0	1	0	1.0	0.00	-1	113	30
14:35:46	00:10	00:00	592	0	0	1	0	1.0	0.00	-1	113	31
14:35:48	00:10	00:00	592	0	0	1	0	1.0	0.00	-1	113	31
14:35:50	00:10	00:00	592	0	0	1	0	1.0	0.00	-1	112	31
14:35:52	00:10	00:00	592	0	0	1	0	1.0	0.00	-1	111	31

Typical Smoke Readings with the Converter Installed

CTI Converter on a Bus equiped with GM 6.2l engine - on the road test data

Base Date: 10/28/92 Base time: 14:25 :16

Time(sec)	ITime	TTime	RPM	TPS	Speed	Smoke	Load	Prss	Dist	1Temp	CTemp	2Temp
14:43:50	00:13	00:05	1290	43	39	0	0	12.5	1.92	-1	284	123
14:43:52	00:13	00:05	1335	42	39	0	0	13.0	1.94	-1	285	124
14:43:54	00:13	00:05	1282	39	41	0	0	13.5	1.97	-1	288	126
14:43:56	00:13	00:05	1252	39	41	0	0	13.5	1.99	-1	289	129
14:43:58	00:13	00:05	1192	38	42	0	0	14.0	2.01	-1	291	130
14:44:00	00:13	00:05	1245	36	42	0	0	14.0	2.04	-1	294	132
14:44:02	00:13	00:05	1245	35	43	0	43	14.0	2.06	-1	295	133
14:44:04	00:13	00:05	1238	34	43	0	43	14.0	2.09	-1	298	136
14:44:06	00:13	00:05	1230	34	43	0	44	14.0	2.11	-1	299	135
14:44:08	00:13	00:05	1245	34	43	0	43	14.0	2.13	-1	301	139
14:44:10	00:13	00:05	1222	32	43	0	45	14.5	2.16	-1	302	141
14:44:12	00:13	00:05	1245	28	43	0	43	14.0	2.18	-1	302	142
14:44:14	00:13	00:05	1192	18	44	0	0	13.5	2.21	-1	304	144
14:44:16	00:13	00:05	1448	0	44	0	0	5.0	2.23	-1	305	140
14:44:18	00:13	00:05	1088	0	42	0	0	3.0	2.25	-1	307	140
14:44:20	00:13	00:05	952	0	42	0	0	2.5	2.27	-1	307	139
14:44:22	00:13	00:05	915	0	40	0	7	2.5	2.30	-1	308	138
14:44:24	00:13	00:05	892	0	40	0	6	2.5	2.32	-1	308	137
14:44:26	00:13	00:05	878	0	38	0	6	2.5	2.34	-1	308	137
14:44:28	00:13	00:05	1200	37	38	1	0	11.5	2.36	-1	307	141
14:44:30	00:13	00:05	1658	33	37	0	0	12.5	2.38	-1	309	146
14:44:32	00:13	00:05	1282	18	37	0	0	10.5	2.40	-1	311	148
14:44:34	00:13	00:05	1418	0	39	0	0	4.5	2.42	-1	311	146
14:44:36	00:13	00:06	1305	36	39	0	0	8.0	2.44	-1	311	146
14:44:38	00:13	00:06	1560	47	38	0	0	13.5	2.47	-1	312	151
14:44:40	00:13	00:06	1380	31	38	0	0	13.0	2.49	-1	313	154
14:44:42	00:13	00:06	1298	10	40	0	0	12.0	2.51	-1	314	156
14:44:44	00:13	00:06	1680	31	40	0	0	9.0	2.53	-1	314	155

Typical Smoke Readings with the Converter Installed

CTI Converter on a Bus equiped with a GM 6.2L engine - on the road test data

Base Date: 10/28/92 Base time: 14:25 :16

Time(sec)	ITime	TTime	RPM	TPS	Speed	Smoke	Load	Prss	Dist	1Temp	CTemp	2Temp
15:12:06	00:27	00:19	1778	39	41	0	0	9.0	8.47	-1	308	211
15:12:08	00:27	00:19	1792	39	41	0	13	9.0	8.49	-1	305	211
15:12:10	00:27	00:19	1748	39	41	0	14	9.0	8.51	-1	302	211
15:12:12	00:27	00:19	1808	39	41	0	0	9.5	8.54	-1	302	211
15:12:14	00:27	00:19	1762	39	42	0	14	9.5	8.56	-1	304	211
15:12:16	00:27	00:19	1732	44	42	0	16	10.0	8.58	-1	304	211
15:12:18	00:27	00:19	1642	44	43	0	0	10.0	8.61	-1	305	212
15:12:20	00:27	00:19	1702	49	43	0	0	10.5	8.63	-1	314	212
15:12:22	00:27	00:19	1560	51	43	0	0	11.0	8.66	-1	310	213
15:12:24	00:27	00:19	1605	50	43	1	0	11.0	8.68	-1	312	213
15:12:26	00:27	00:19	1560	42	45	0	0	10.5	8.71	-1	307	213
15:12:28	00:27	00:19	1575	41	45	0	0	10.5	8.73	-1	315	213
15:12:30	00:27	00:19	1612	36	45	0	0	10.0	8.76	-1	310	214
15:12:32	00:27	00:19	1665	38	45	0	0	10.0	8.78	-1	308	213
15:12:34	00:27	00:19	1732	39	44	0	0	10.0	8.80	-1	307	214
15:12:36	00:27	00:19	1702	45	44	0	16	10.5	8.83	-1	309	214
15:12:38	00:27	00:19	1590	44	44	0	0	10.5	8.85	-1	309	214
15:12:40	00:27	00:19	1568	44	44	0	0	10.5	8.88	-1	313	214
15:12:42	00:27	00:19	1605	44	45	0	0	11.0	8.90	-1	312	215
15:12:44	00:27	00:19	1530	43	45	0	0	11.0	8.93	-1	312	215
15:12:46	00:27	00:19	1515	36	46	0	21	10.5	8.95	-1	313	215
15:12:48	00:27	00:19	1552	36	46	0	20	10.5	8.98	-1	316	215
15:12:50	00:27	00:19	1545	36	47	0	20	10.5	9.01	-1	315	216
15:12:52	00:27	00:19	1582	37	47	0	19	10.5	9.03	-1	314	216
15:12:54	00:27	00:19	1590	37	46	0	19	10.5	9.06	-1	316	216
15:12:56	00:27	00:19	1612	41	46	0	19	10.5	9.08	-1	316	216
15:12:58	00:27	00:19	1560	42	46	0	0	11.0	9.11	-1	319	217

APPENDIX C

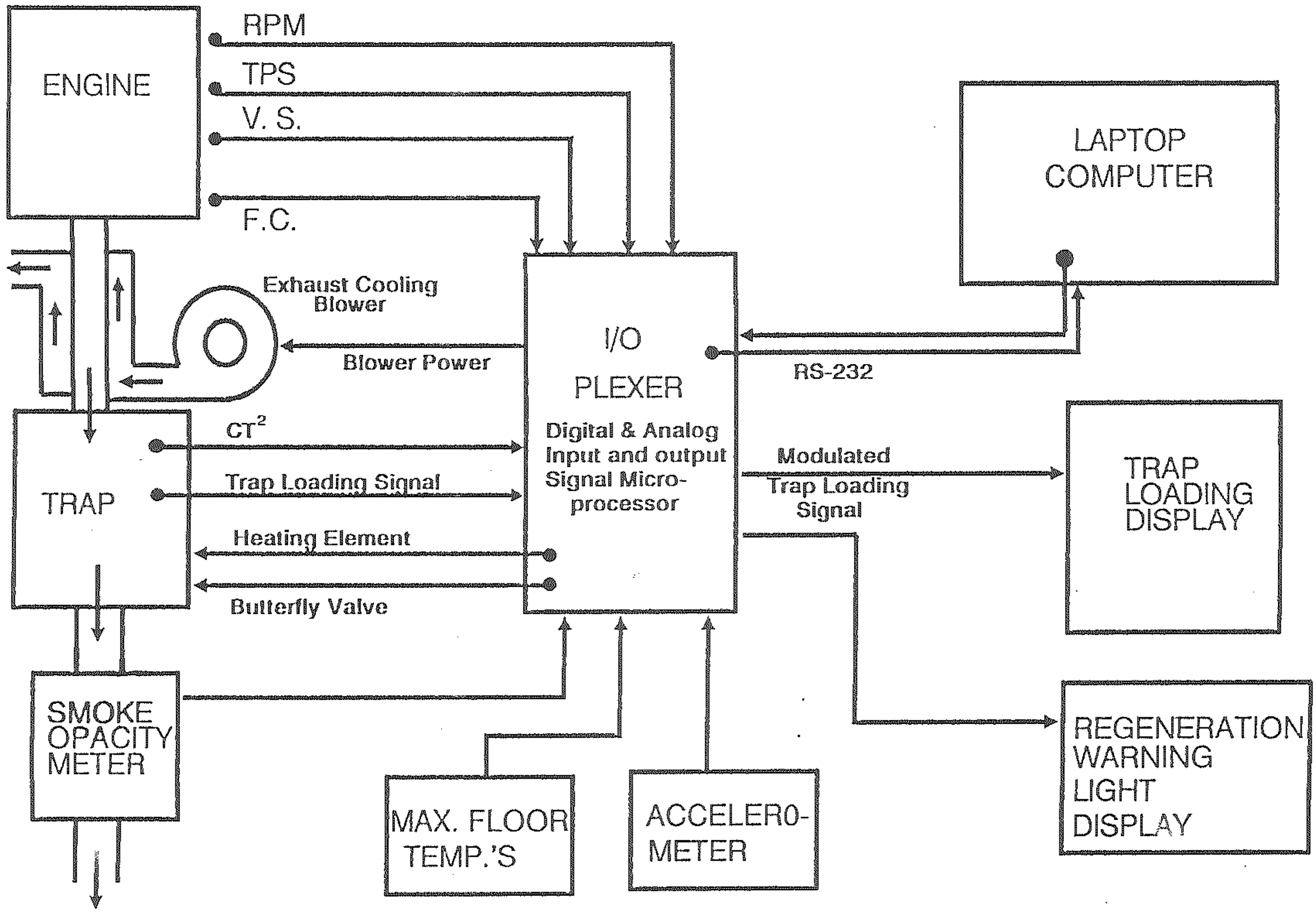
Project Displays on the Bus

PROJECT HIGHLIGHTS

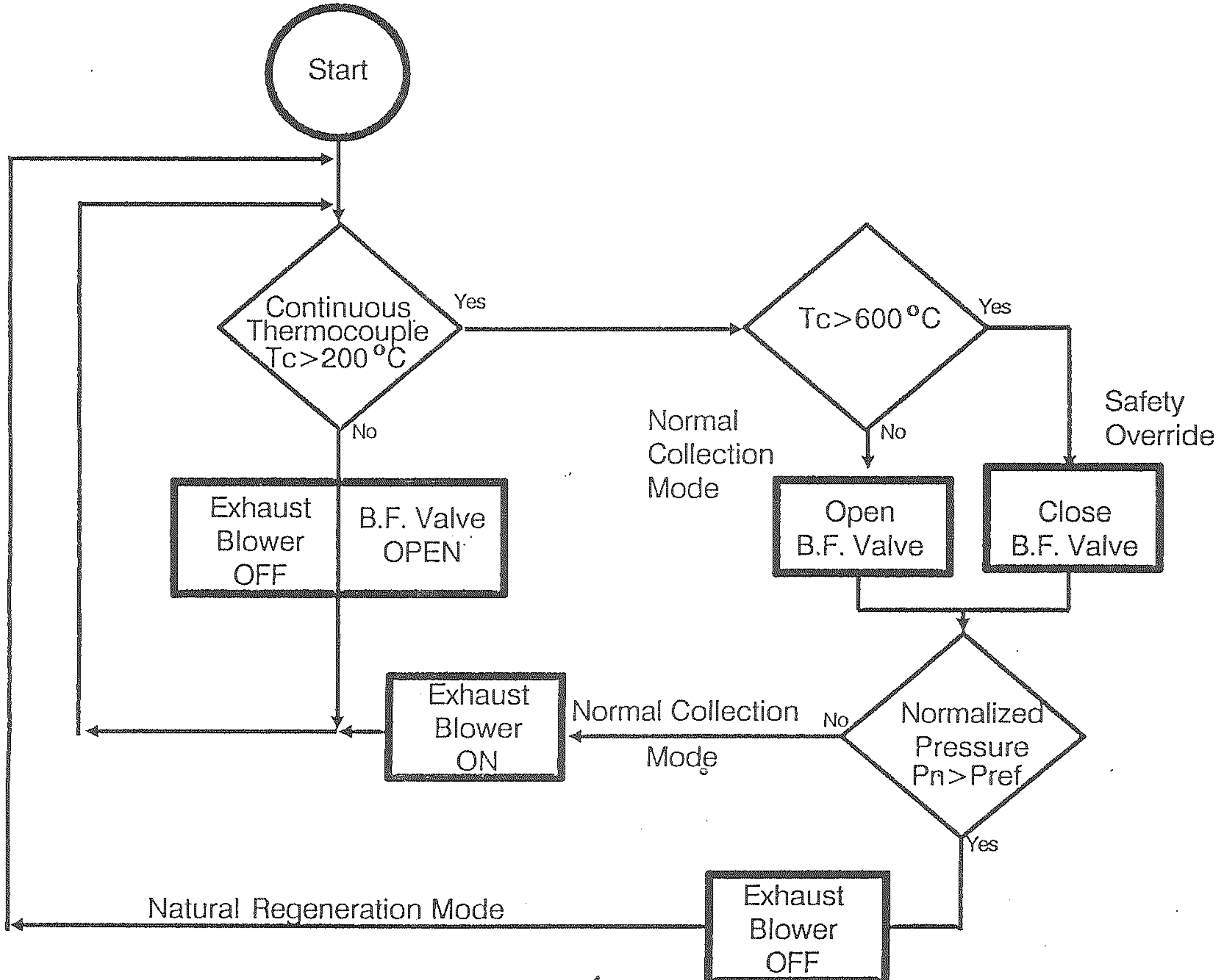
- EQUIPMENT
  - 1985 Carpenter Bus, GM 6.2 L Diesel Engine
  - C T I Diesel Particulate Trap
- SPONSORSHIP
  - Sponsored by Jackson Transportation Authority
  - Funding by Michigan Department of Transportation & C T I
  - Research funded through SBIR Phase I & II, U.S. EPA

HARDWARE LAYOUT

Mobile Data Acquisition and Trap on the Bus



NORMAL OPERATION & NATURAL REGENERATION CONTROL LOGIC DIAGRAM



DESIGN & CONSTRUCTION HIGHLIGHTS

- DESIGN FEATURES
  - -Compact Hardware
  - -Least complex and most reliable
  - -Very small net fuel penalty
  - -No interference with engine operation or performance
  - -Compliance with bus/truck emission standards

- SAFETY FEATURES are provided thru 4 levels of protection:
  - -Closed loop control system employing a continuous thermocouple
  - -Very high thermal inertia of the composite wire mesh
  - -Controlled trap loading
  - -Double wall construction

- SOUND ATTENUATION can be achieved through the unique design of the trap
  - -The trap replaces the muffler

COMPETITION ASSESSMENT

PARAMETERS	CERAMIC TRAPS	WIRE MESH	PRECIPITATOR	CTI'S CONVERTERS
Filtration Efficiency	Excellent	Good	Fair	Excellent
Durability	Very good	Very Poor	Excellent	Excellent
Vehicle Liability	Good	Very Poor	Excellent	Very Good
Reliability During Operation	Good	Very Poor	Fair	Very Good
Fuel Penalty	Good	Good	Good	Very Good
Maint. & Operating Costs	Poor	Very poor	Fair	Very Good
Muffling Effect	Fair	Very Poor	Very Poor	Excellent
Impact on Vehicle Design	Poor	Poor	Poor	Very Good
Use of Oxidizers, Etc.	Very Poor	Good	Excellent	Good
Fire Hazard	Poor	Poor	Good	Excellent
Frequency of Regeneration	Very Poor	Very Good	NA	Excellent
Initial Costs	Poor	Poor	Good	Good
Total hardware, Complexity	Poor	Poor	Fair	Very Good
Overall Rating 1 . . . low (on a scale of 1 - 10) 10 . . . high	6	3	4	9

INSTALLATION & MAINTENANCE

- Installation Hardware consists of:
  -Trap Unit
  -Microprocessor and wiring harness
  -Heat exchanger (optional)

- Installation Man-hours:
  -40 man-hours per bus for small volume
  -20 man-hours per bus for moderate volume

- Installation and operation of trap are completely independent of engine

- Maintenance
  -The microprocessor is equipped with diagnostic logic displaying warning signals
  -Maintenance is straightforward

SYSTEM OPERATION & NATURAL REGENERATION

- HEAT EXCHANGER is installed ahead of the trap to increase the collection of volatile organic fraction
- TRAP LOADING is detected via:
  - -Pressure drop across the trap
  - -Cumulative engine-out emission
- REGENERATION is achieved naturally by using Lubrizol fuel additives
- REGENERATION is initiated simply by turning blower off until temperature reaches 300 deg. C

The Economics of Pollution Cleanup

- TRANSIT BUS CASE
  - Sale price $5,000
  - Installation $1,000
  - Maintenance .... $800 / year

- ANNUALIZED COSTS = $715+ $142 + $800
  = $1,657 (based on 7 years)

- PARTICULATE REDUCTION is estimated at 278 lbs per bus per year

- CLEANUP COSTS
  Cost = 1,657/ 278 = $6.00 per pound of particulate
  = $12,000 per ton of particulate

ECONOMICS OF BUS RETROFITTING

COST CATEGORY	DIESEL BASE-LINE	METHANOL	CNG	LNG	CERAMIC TRAPS	CTI'S TRAPS
Capital Cost / Bus	$210,000	$240,000	$255,000	$250,000	$230,000	$216,000
Capital Cost Differential (including fuel facility)	-----	$30,335	$52,110	$41,970	$20,000	$6,000
Fuel Cost Differential (annual)		$4,792	$(258)	$(698)	$475	$95
Annualized Costs	$44,070	$53,891	$51,389	$49,273	$48,676	$45,822
Annualized Costs Differentials	0	$9,821	$7,319	$5,203	$4,609	$1,752
Total Cost / Mile (50,000 m/y)	$ .88	$1.07	$1.03	$ .99	$ .97	$ .91
Cost of Pollution Control dollars / lbs. of particulate	----	$31.78	$23.69	$16.84	$16.58	$6.00

*Cost data are based on a report by Booz, Allen, & Hamilton, April, 1991.

APPENDIX D

Muffling & Noise Data

Vibration Data & Related Information

CONVERTER TECHNOLOGY INC.

DEVELOPER & MANUFACTURER OF DIESEL EMISSION OXIDIZERS

414 N. Jackson Street
Jackson, Michigan 49201

(517) 784-3388

August 18, 1992

Mr. Garret W. Erb
Administrative Director, JTA
2350 E. High Street
Jackson, Michigan 49203-3490

Subject: Legal Noise Testing of CTI Trap at Walker Manufacturing

Dear Gary:

Legal noise tests were conducted at Walker Manufacturing's test track, Grass Lake, Michigan. The tests were performed per SAE J366 procedure. Simply stated, the bus was driven at a test track at about 30 mph in the second gear and when the bus passed the location where noise pickups are located on the road, the driver rapidly established wide open throttle (100% throttle). The bus accelerated and the maximum measured noise is recorded.

The test was conducted once with the trap installation, and another time with the original muffler. A new muffler was installed since the original muffler had leaks. The measurements were conducted at two stations on the test track, one was on the right side and the other on the left side of the bus. Note that the tail pipe is on the right side of the bus.

The test data are attached to this letter and will be incorporated in the final report. The trap displayed reduced noise in the low frequency region. However, the measured peak noise with the trap was 83 and 83 dB versus 79 and 78 dB with the muffler on at the two stations.

Assessing the noise data with 3 engineers from Walker Manufacturing, they think that for a retrofitting application the measured noise levels with the trap are acceptable. Reducing the noise level further would require additional testing and analysis. The outside shell of the trap appears to be radiating excessive noise. Two enhancements could be added to reduce the noise further and this will be incorporated on future traps.

The final report on the Jackson project will be issued once the EPA testing is performed. Due to unforeseen delays, our first meeting with the EPA in Ann Arbor is scheduled for Thursday, August 27, 1992 at 1:00 p.m.

Sincerely,

R.A. Kammel

R. A. Kammel, P.E.
President

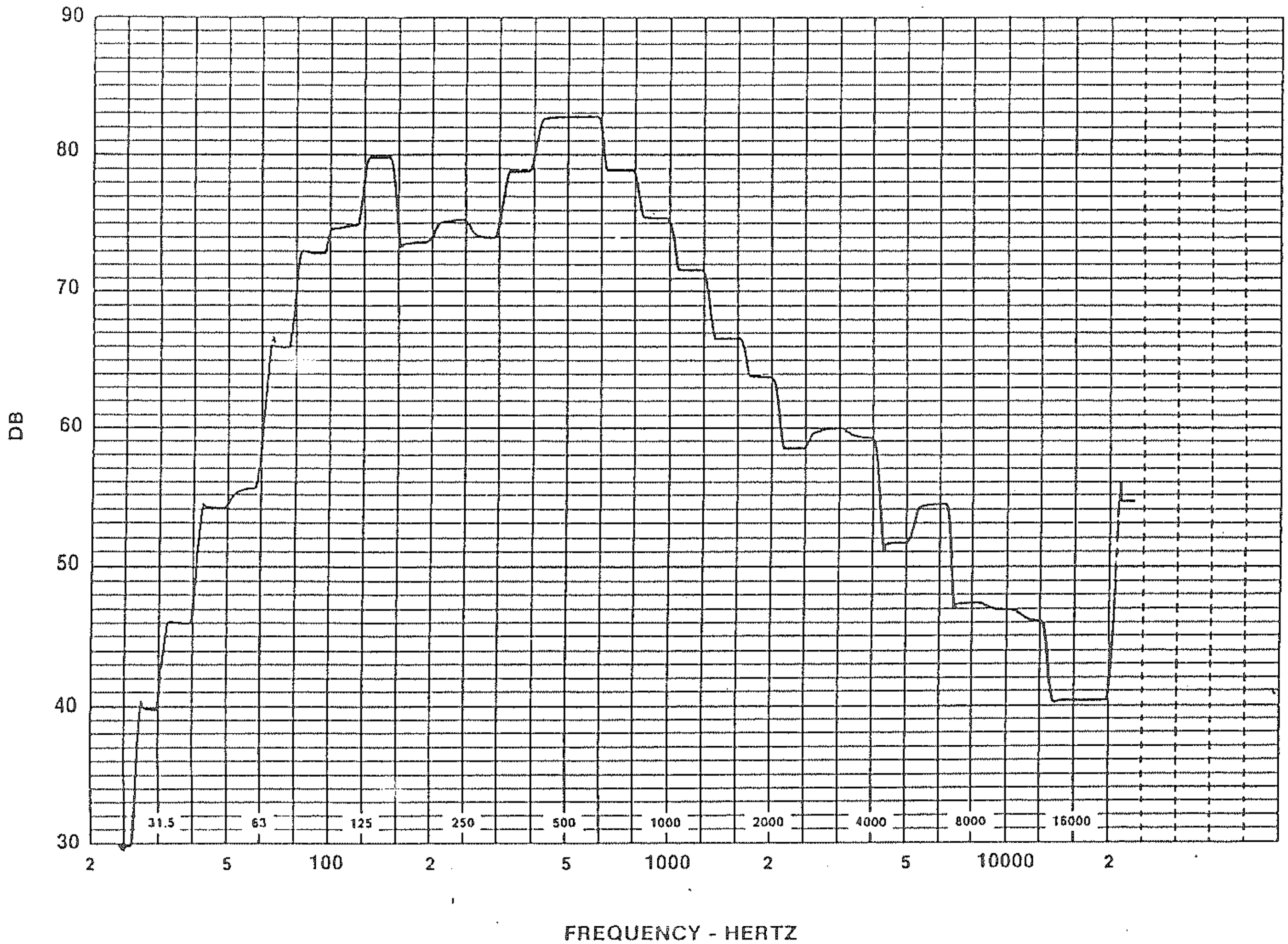
RAK/pjg

Attachments

Test Number Bus w/ Particulate Trap. Sys.

Trap Data

Pass-By DbA Frequency Analysis (1/3 Octave)



RUN:

RIGHT SIDE

1 2 (3) 4

LEFT SIDE

1 2 3 4

SPECTRUM:

(X) A Wtd.

( ) Flat

88.0 dbA

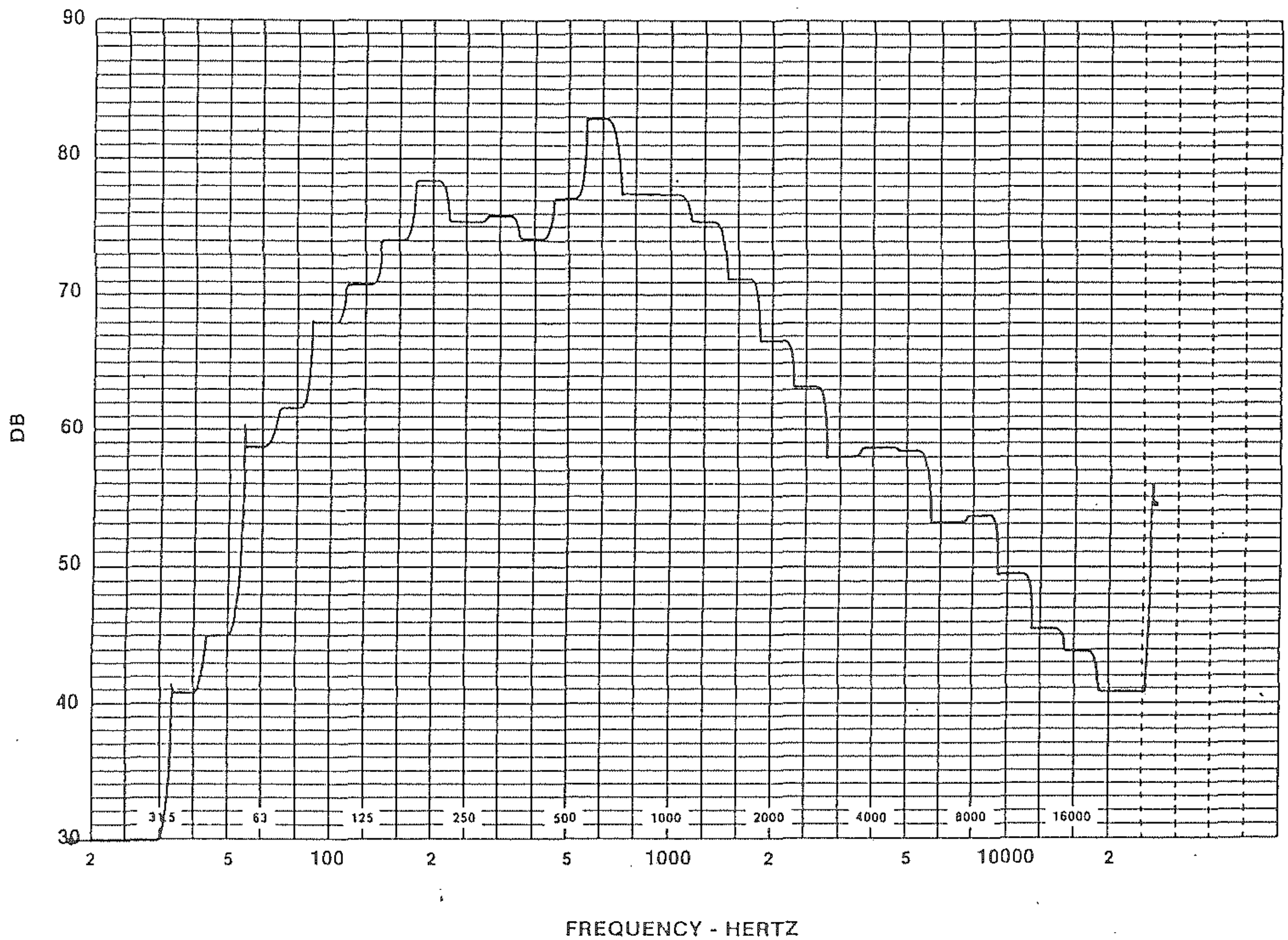
W Manufacturing Company

Form No. 22241 (1189)

Test Number Bus w/ Particulate Trap Sys.

Pass-By DbA Frequency Analysis (1/3 Octave)

Trap Data



RUN:

RIGHT SIDE

1 2 3 4

LEFT SIDE

1 2 3 (4)

SPECTRUM:

(X) A Wtd.

( ) Flat

86.8 dbA

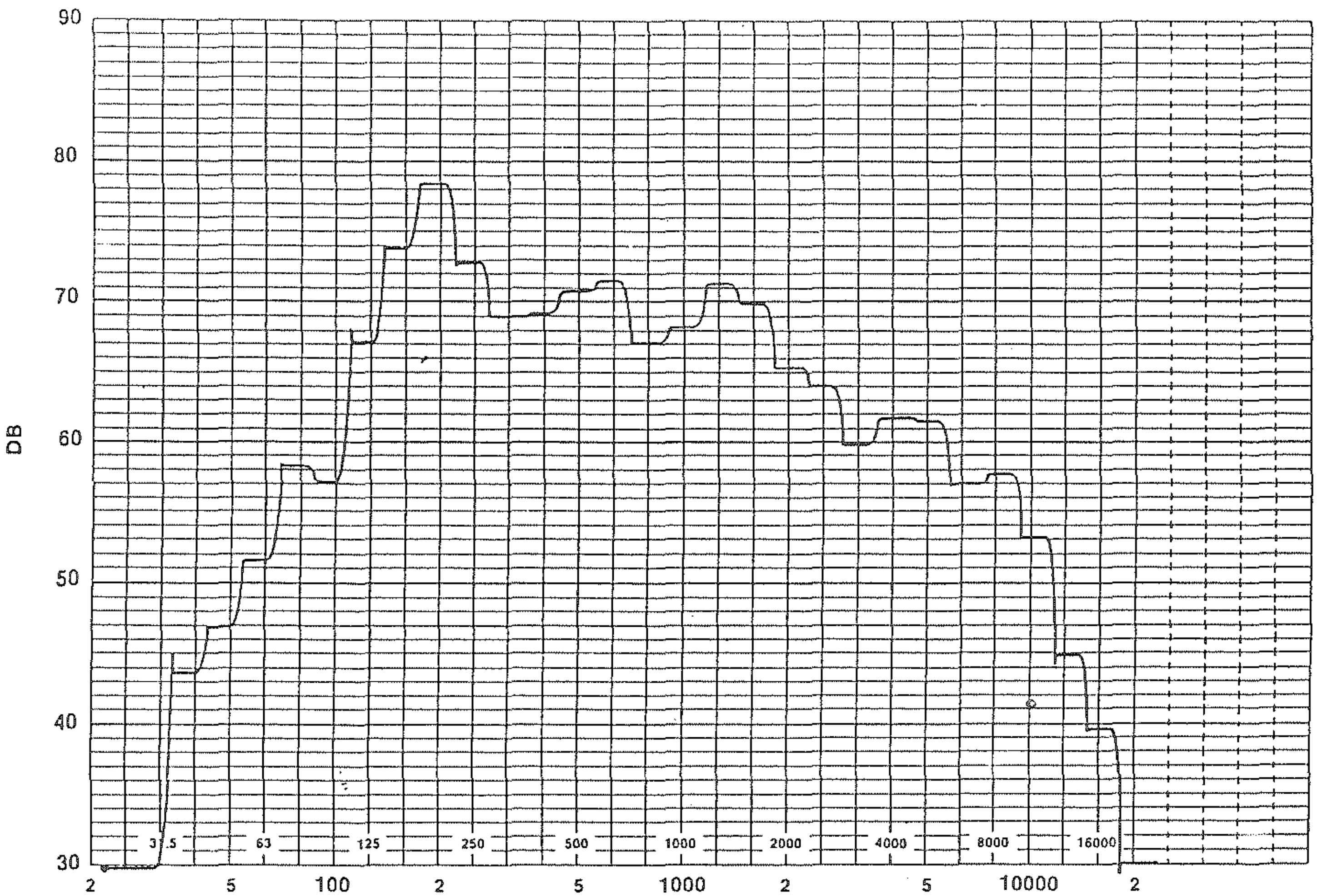
Walker Manufacturing Company

Form No. 22241 (1189)

Test Number Bus w/ Muff.

Muffler Data

Pass-By DbA Frequency Analysis (1/3 Octave)



RUN:

RIGHT SIDE

1 2 (3) 4

LEFT SIDE

1 2 3 4

SPECTRUM:

(X) A Wtd.

( ) Flat

81.5 dbA

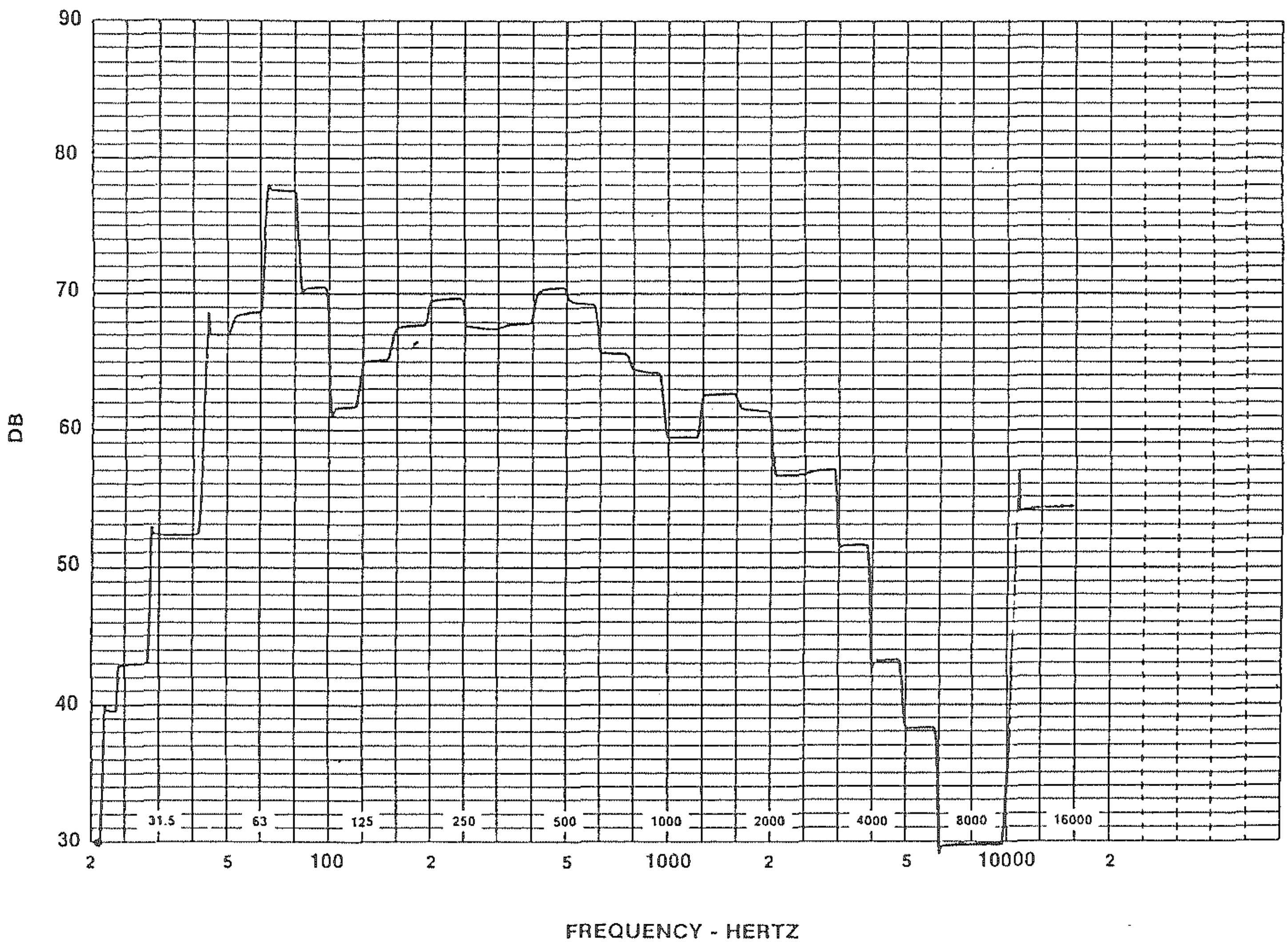
Walker Manufacturing Company

Form No. 22241 (1189)

Test Number *Bus w/ Muff.*

Pass-By DbA Frequency Analysis (1/3 Octave)

Muffler Data



RUN:

RIGHT SIDE

1 2 3 4

LEFT SIDE

1 2 3 (4)

SPECTRUM:

(X) A Wtd.

( ) Flat

80.6 dbA

Walker Manufacturing Company

Form No. 22241 (1189)

CONVERTER TECHNOLOGY INC.
DEVELOPER & MANUFACTURER OF DIESEL EMISSION OXIDIZERS

414 N. Jackson Street
Jackson, Michigan 49201

(517) 784-3388

September 9, 1991

Mr. Garret W. Erb
Administrative Director
City of Jackson Transit Authority
2350 E. High Street
Jackson, Michigan 49203-3490

Dear Gary:

Enclosed please find our assessment of the issues raised by Mr. Sam Castronova of MDOT regarding the durability and effect of vibration on the composite wire mesh. I am of the opinion that these issues should be addressed in the chronological order presented in the attached document. This document is being sent for your review and comments. A vibration program, as developed here, is the least expensive way to address this issue in a meaningful way and have concrete data on-hand. There are options as to how the program can be conducted that may trim some costs. However, trimming the scope as defined here may result in severe adverse effects as to the validity of the program.

I estimate it will take about three months to carry out this program. Let me know whether an action or no action will take place. In the meantime, if you have any questions please let me know.

Sincerely,

R. A. Kammel

R. A. Kammel, P.E.
President

RAK/pjg

Enclosures

Vibration Measurement, Analysis and Durability Assessment of Converter Technology's Particulate Trap

1. <u>Purpose:</u> The purpose of this supplementary program is to measure and analyze the dominant vibration and shock spectrum modes encountered during bus revenue services and establish design level of vibration the trap endures in its life cycle. In the second phase, the trap would be subjected to "design level vibrations" in a lab environment using a shaking table to determine durabilities. The lab test program may encompass a series of escalating vibration level tests until a failure mode is detected. Special emphasis would be placed on the durability of the composite wire mesh.

2. <u>Background:</u> Trap installation on the exhaust system of a bus during revenue services will produce a spectrum of random vibration. The majority of these vibrations results from exhaust gas pulsation, engine vibration and most importantly, road-induced shocks. The combination of all these vibrations is a complex form of vibration that is being defined as "input" or "exciting". The <u>response</u> of the trap system and its subcomponents, and <u>not</u> the level of input vibration, is the dominant vibration load factor crucial to the durability of the trap and the wire mesh. However, the response of the trap is a function of the input vibration and is largely dependent on the structural dynamic characteristics (eigen values) of the trap and its supports. To that effect, Converter Technology, strictly based on prudent judgement is taking measures such as: using rubber supports, using a cushion of dampening materials to support the wire mesh and the containment against the outershell of the trap. Using bellows on the exhaust pipe before and after the trap may be another option to improve the dynamic response so that most engine vibration and gas pulsations are muted through the bellows.

   The outcome of input shock and vibration along with the structural dynamic response of the trap system may or may not identify critical modes of vibration. The degree by which a vibration mode is classified as "critical" depends to a large extent on whether it creates a stress level in the trap components such as the wire mesh that can cause either loss of structural integrity or loss of function during the expected service life of the trap on the bus.

3. <u>Engineering Approach:</u> To our knowledge at Converter Technology, the subject vibration and durability of the composite wire mesh and the trap system and its supports are not covered by any national or automotive standards. The only reference to durability requirements is in the Code of Federal Regulations, CFR Title 40, Part 86. Durability requirements are expressed in mileage on the road, years in service, and maintenance intervals of critical parts of the emission control components, such as wire mesh. The task of how the durability can be achieved, for obvious reasons, depends on the product, its design, operation, components, etc. It is, therefore, Converter Technology's judgement, that the

task of achieving the required durability is a "design problem". This implies it is the responsibility of the manufacturer to account for this problem in the design process. To our knowledge, no guidance or standard exists addressing how to go about assessing the durability of the trap from a vibration point of view. Note that the same applies to regeneration. Regeneration temperatures, which are high, create "creep damage" on materials. There is no standard, to our knowledge, that addresses the problem of how to design traps for proper regeneration or what is the allowable regeneration cycles. In our judgement, again, this is a design problem.

The approach presented here is based on dealing with the complex problems of vibration response of critical trap components during revenue services and its impact on durability. The proposed approach is comprised of three steps:

a. Vibration measurements during revenue services.
b. Vibration analysis.
c. Vibration testing in a controlled lab environment.

3.1 <u>Vibration Measurements during Revenue Services:</u> This task is intended for the measurements of the "response" on the trap housing to all modes of vibration excitation encountered during revenue services. Vibration measurements will be performed by using an "acceleration pickup" suitable for the measurement of frequencies up to approximately 100 cps (Hz). Vibration measurements can take place in three directions, vertical, lateral to and longitudinal to the bus. Recorders and instrumentation required for the acquisition of data can be provided by MDOT instrumentation or by acquiring additional hardware and software for inclusion in the existing Mobile Data Acquisition System (MDAS) currently in operation on the bus. In case the MDAS is used, no other data could be collected from other channels during vibration measurements.

Should a dominant mode of vibration be determined during measurements, this mode will be verified through a shock test (using a hammer, for example) to determine the natural frequencies of the trap assembly. Modifications to trap supports, exhaust system or wire mesh supports may be deemed necessary. After such modifications are implemented, the shock test and vibration measurements on the road will be repeated to verify the adequacy of the new modification.

3.2 <u>Vibration Analysis:</u> The data collected in the foregoing task will be analyzed using specialty software to determine the maximum G forces and vibration frequencies. The engineering analysis of data will establish "spectrums" and "envelope" of operating vibration levels encountered during revenue services.

The outcome of the vibration analysis will determine whether a structural modification to the trap and supports is warranted to reduce the vibration response or not. Further, "envelopes" of vibration can be used as input for durability/accelerated durability/failure testing of the entire trap to take place in the following task.

3.3 Vibration Testing in a Controlled Environment: The purpose of this task is to determine the impact of vibration loads (determined in 3.1) on the durability of the trap and its components under controlled environs, perhaps in a laboratory environment. Since durability testing can evolve to a few hundred, if not a few thousand hours, accelerated durabilities may be the most practical to save on costs. Alternately, higher levels of vibration may be used to determine failure modes likely to be encountered in the trap operation. The assessment and development of the type of testing to be done is contingent on the outcome of task 3.2.

From a preliminary point of view, vibration testing could be accomplished by two alternatives:

a. Vibration testing on a one or three-dimensional shaking table capable of simulating "envelope" loads determined in task 3.2 in a laboratory environment under controlled conditions. This approach, although accurate, could be expensive.

b. "In-situ" vibration testing on the bus using the existing exhaust system and the trap as is. In this test, frequency generators and exciters could be mounted on the exhaust system/trap to create the "envelope" vibration level identified in task 3.2. This alternative yields still accurate data, but will be less expensive than the former alternative. The majority of savings are in assembly/disassembly and fixture designs and construction needed for testing on a shaking table.

4. Conduct of Vibration Program: Converter Technology has the experience and knowledge to conduct the entire vibration program described herein. The project manager, R.A. Kammel, has close to 20 years experience in the field of vibration measurements, testing, durabilities, analysis both in actual testing as well as the analytical side of vibration analysis on various products ranging from jet engines to mechanical and electrical components in nuclear power plants. Converter Technology will be in a position to conduct the entire program, if needed.

As an alternative, the vibration program may be segmented into tasks/subtasks. Each one will be conducted by a separate entity such as MDOT, MSU, Aeroquip, Consumers Power Company lab, or any other organization. Converter Technology would prefer to assume the role of coordinating such tasks to ensure proper and timely execution of such tasks and within budget allocations.

Budget Allocations

Vibration Measurement, Analysis and Durability Assessment

1. Task 1, Vibration Measurement during Revenue Services

Engineering, 30 x 72	$2,160	
Technicians, 40 x 27	$1,080	
Testing Equipment (pickup, software, hardware)	$3,000	
Subtotal Task 1		$ 6,240

2. Task 2, Vibration Analysis

Engineering, 50 x 72	$3,600	
Technician, 10 x 27	$ 270	
Subtotal Task 2		$ 2,870

3. Task 3, Vibration Testing (in-situ)

Engineering, 30 x 72	$2,160	
Technicians, 50 x 27	$1,350	
Equipment (lease/purchase)	$5,000	
Subtotal Task 3		$ 8,510