COSTS OF SELECTED HEAVY-DUTY DIESEL ENGINE EMISSION CONTROL COMPONENTS

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FINAL REPORT

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I. INTRODUCTION

Background

The Environmental Protection Agency (EPA) is currently developing rules applicable to the control of NO_x and particulate emissions from heavy-duty engines (HDE). The cost of emission control components and/or systems is one of the factors which is considered during the development of these rules. This report presents some estimated costs of selected heavy-duty diesel engine emission control components. The effort was conducted for Jack Faucett Associates under their prime contract with the U.S. Environmental Protection Agency (EPA Contract No. 68-03-3244).

The remainder of this section provides some considerations surrounding the approach to estimating costs, while the remaining sections of the report describe the systems or system configurations considered and the components that were costed. The systems/components addressed include: turbocharging a naturally aspirated engine, engine coolant air-to-liquid intercooling (also referred to as aftercooling), separate air-to-liquid intercooling, air-to-air intercooling, high pressure unit injectors, high pressure injection pump, electronic controls, ceramic monolith particulate trap with electrical heat regeneration, catalytic material for ceramic fiber trap, and burner housing and ignition system for a diesel fuel burner regeneration system.

Cost Estimation Methodology

The method used to generate cost estimates draws heavily on previous experience in estimating new component costs. Developing engineering estimates of finished product costs is a predictive exercise similar to other types of forecasting commonly performed. Engineering cost analysis has an advantage over most other types of forecasting in that more "hard" information is usually at hand and very analogous manufacturing activities have been performed in the past for which information is available. The best approach would have been to perform a rigorous "bottom-up" engineering and cost analysis which addressed each part of every component. However, the time and effort committed to this task precluded such a rigorous approach. Experience has shown that the most straightforward approach is to utilize analogous hardware for cost estimating and contacting several industrial and/or commercial sources for cost quotations. Two types of prices are considered here. One is a retail price which is essentially an aftermarket selling price and the other is a manufacturer's price equivalent (MPE). The MPE is a cost that is representative of that incurred by a manufacturer or charged by a vendor for a specific component or part of a vehicle. (Lindgren has estimated this cost to be about one-fourth to one-fifth of the retail price.(1)* For estimating purposes within this report, a markdown factor of 0.225 is used in going from retail to MPE cost.) The MPE is not the retail price equivalent (RPE) of the component or part in an assembled vehicle. However, the MPE can be used to derive an RPE by using an appropriate markup factor, that is: MPE x Markup Factor = RPE, where the markup factor accounts for the asembler's corporate overhead and profit. A discussion of this markup factor and its components can be found in (2).

II. TURBOCHARGING

Most heavy-duty diesel engines are now turbocharged primarily because of the increased power output turbocharging provides. A turbocharger is a device which increases the density of the charge air by compressing it before it enters the combustion chamber. By forcing a greater mass of air into the cylinder, the output of the engine can be increased since it is proportional to the energy released by burning that particular mass of fuel and air.

Turbocharger designs vary from one manufacturer to another, but basically all have a compressor on one end and a turbine on the other, supported by bearings in between. The turbine is the device which converts the energy of the engine exhaust gases to shaft power. Figure 1 schematically illustrates a generic turbocharger installation.

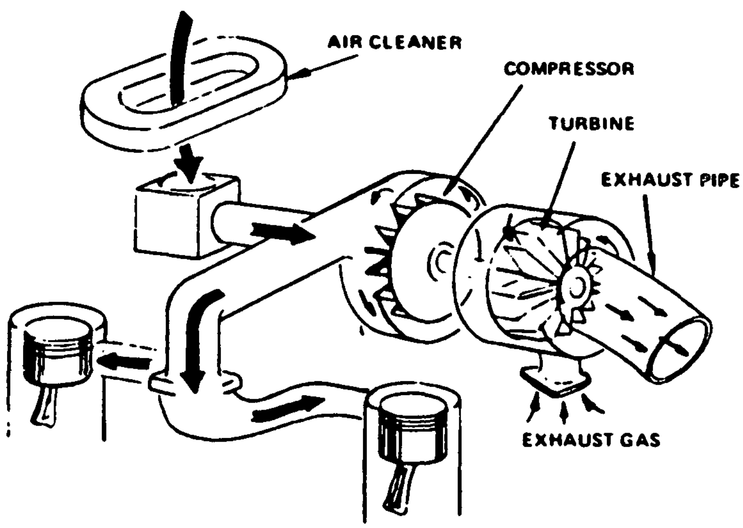


Figure 1. Turbocharger Installation

Source: MacInnes, H., Turbochargers, H. P. Books, Tucson, Arizona (Ref. 3)

Virtually all current new model heavy-heavy duty (HHD) trucks have turbocharged diesel engines. Therefore, the addition of turbocharging is not an option for emission control for virtually all HHD trucks. Turbocharging is not being applied as universally to light and medium heavy duty (LHD and MHD) trucks and may be added to these trucks as part of an overall strategy for particulate control without sacrificing significant power output.

Turbocharging an engine involves far more than the incorporation of the turbocharger and its related hardware. Many internal engine modifications are usually required as well. These modifications include piston redesign, increased oil system capacity (to spray cool the undersides of the pistons), increased cooling system capacity, strengthened connecting rods and/or crankshaft, redesigned exhaust valves, larger injectors, and revised injection pump calibration. The extent of the modifications depends on the particular engine design. Some engine lines were designed from inception to incorporate naturally aspirated and turbocharged versions. The cost differential between naturally aspirated and turbocharged versions of these engines will understate the true cost of adding turbocharging because design and R&D expenditures will likely be written-off over all the engines produced. Those engines not designed from inception to incorporate turbocharged versions will cost more to develop turbocharged versions.

Because of the difficulty in itemizing the cost of internal engine component design changes, and the fact that most current engines are designed from inception to incorporate turbocharging, the only accurate method of estimating the cost of turbocharging is to compare complete engines. This is the approach used to develop the rough estimate noted in Table 1.

Table 1. Estimated Turbocharger Cost

System/ Component	Description	Estimated Retail Price	Reference(s)
Turbocharging a Naturally Aspirated Engine	Includes turbocharger, modified manifolds, oil lines, piping, hoses, clamps, gaskets, modified pistons, high capacity oil system, and revised injection pump and injectors.	$1000-$3000	4,5,6

III. ENGINE COOLANT AIR-TO-LIQUID INTERCOOLING

An intercooler, sometimes referred to as an aftercooler, is a heat exchanger which is installed somewhere between the compressor discharge of a turbocharger and the engine to cool the inlet air (see Figure 2). By reducing the temperature of the air, the density of the charge to the engine is increased, thus allowing more fuel to be burned with a resultant increase in power output. Intercooling is also a means of allowing leaner operation which reduces peak flame temperatures and lowers NO_x emissions. This may also have a beneficial effect on particulate emissions. It also has the generally beneficial effect of reducing the overall engine operating temperature (relative to non-intercooled engines).

Current production air-to-liquid intercoolers use engine coolant as the cooling medium. This limits the temperature drop of the inlet air to some value slightly above that of the temperature of the engine coolant (how much depends on the efficiency of the intercooler). Estimated retail prices for an intercooler which uses the engine coolant as a heat sink are provided in Table 2.

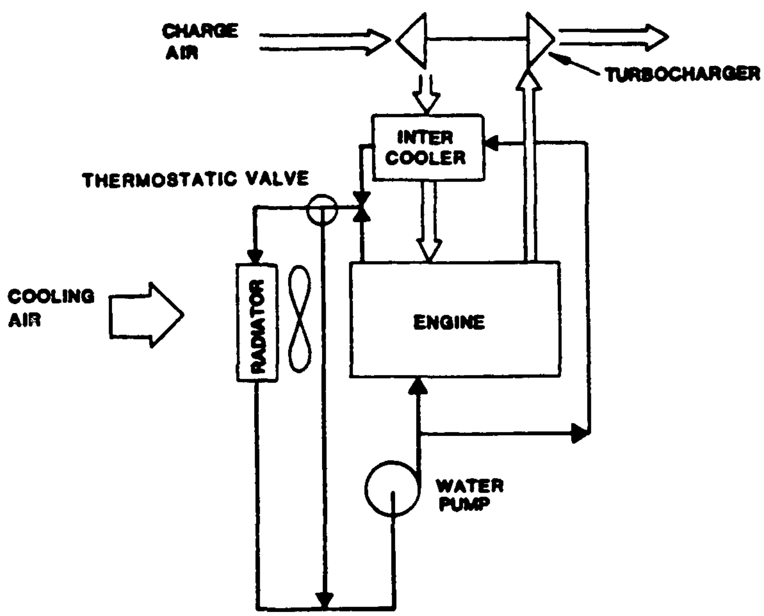


Figure 2. Turbocharged Engine with Intercooler

Source: Alpha United, Inc., El Segundo, California (Ref. 7)

Table 2. Estimated Costs of Engine Coolant Air-to-Liquid Intercooling[a]

System/ Component	Description	Manufacturer's Price Equivalent	Reference(s)
Intercooler	Furnace-brazed core with headers and fittings (assuming $30,000 of tooling and 2500 units/year volume)	$325-$475	8,9
Silicone Hose	Six (6) inch hose (2 three inch couplings) between turbocharger and intake manifold	$1.20	10,11
Clamps (2)	Stainless steel for silicone hose	$0.23	10
Coolant Supply Tubing	Six (6) foot, 5/8 inch I.D. rubber reinforced hose	$0.68	12
Intake Manifold	Assumes revised casting with no increase in material requirements.	$16[b]	1,13

[a]Assumes intercooler is mounted in the intake manifold.

[b]Incremental Cost.

IV. SEPARATE SYSTEM AIR-TO-LIQUID INTERCOOLING

As noted in the previous section, an intercooler using the engine coolant as the heat sink is limited in its ability to reduce the charge temperature. A separate cooling circuit using 2 air-to-liquid heat exchangers could attain lower temperatures. This system is the same as the system in Section III except that the coolant flowing through the intercooler is cooled by a second air-to-liquid heat exchanger mounted in front of the engine radiator (see Figure 3). An external pump is required to circulate the coolant. The performance of this system is limited by the temperature of the ambient air and the efficiency of the two heat exchangers. Although such systems are not currently commercially available, Table 3 provides estimated costs for components required for such a system.

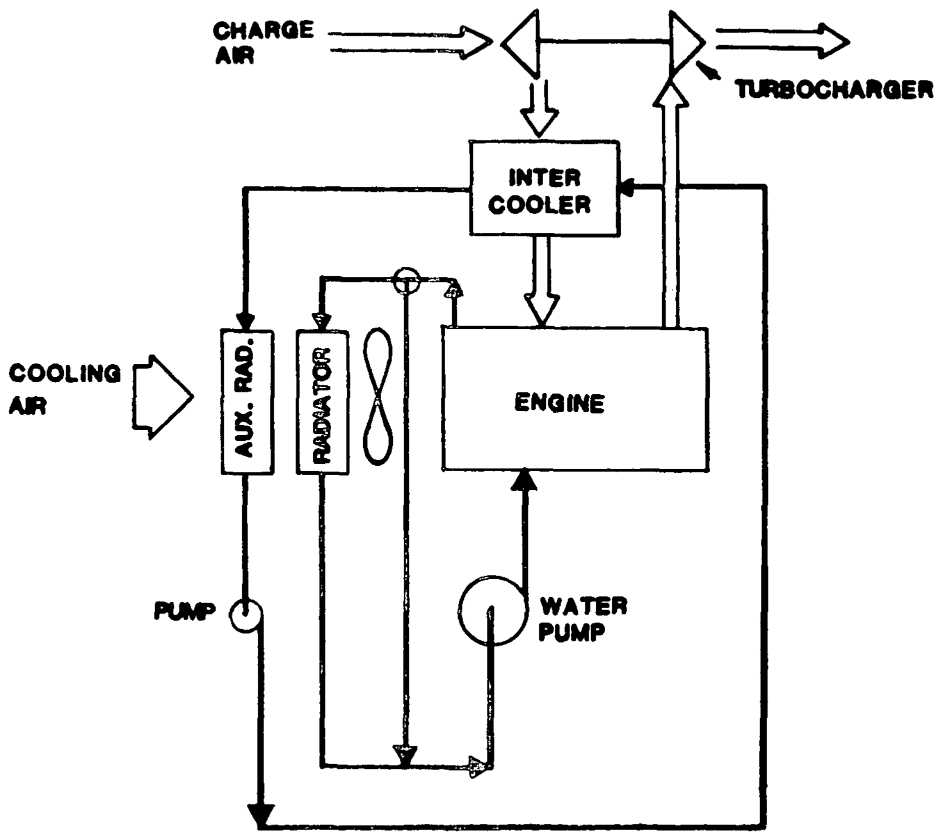


Figure 3. Separate Liquid Loop Intercooler System

Source: Alpha United, Inc., El Segundo, California (Ref. 7)

Table 3. Estimated Costs of Separate System Air-to-Liquid Intercooler[a]

System/ Component	Description	Manufacturer's Price Equivalent	Reference(s)
Intercooler	Furnace-brazed core with headers and fittings (assuming $30,000 of tooling and 2500 units/year volume)	$325-$475	8,9
Silicone Hose	Six (6) inch hose (2 three inch couplings) between turbocharger and intake manifold	$1.20	10,11
Coolant Supply Tubing	Twelve (12) foot, 5/8 inch I.D. rubber reinforced hose	$1.40	12
Water Pump	Belt-driven from the engine	$11-$17	14,15
Belt	To drive water pump	$1.40	16
Radiator	Automotive-grade cross flow	$14-$16	12
Mounting Brackets	For intercooler water pump	$3.60-$6.80	17
Misc. Fasteners	Clamps, gaskets, screws, bolts	$2.30	18
Modified Intake Manifold	Assumes a revised casting with no increase in material requirements	$16[b]	1,13

[a]Assumes intercooler is mounted in the intake manifold.

[b]Incremental Cost.

V. AIR-TO-AIR INTERCOOLING

Air-to-air intercoolers can also be used on turbocharged engines. Air-to-air intercooling uses a single heat exchanger to cool the inlet air. As depicted in Figure 4, ambient air is the cooling medium. The intercooler is mounted in front of the truck radiator, and the inlet air is ducted to it from the turbocharger compressor on one side, and from it to the intake manifold on the other side. Because only one heat exchanger is involved (the intercooler) and the cooling medium is ambient air, this system offers the best performance in terms of heat rejection and decrease in inlet air temperature. Air-to-air intercooling is fast becoming standard on all HHD highway trucks.

The estimated costs for components required for such a system are noted in Table 4.

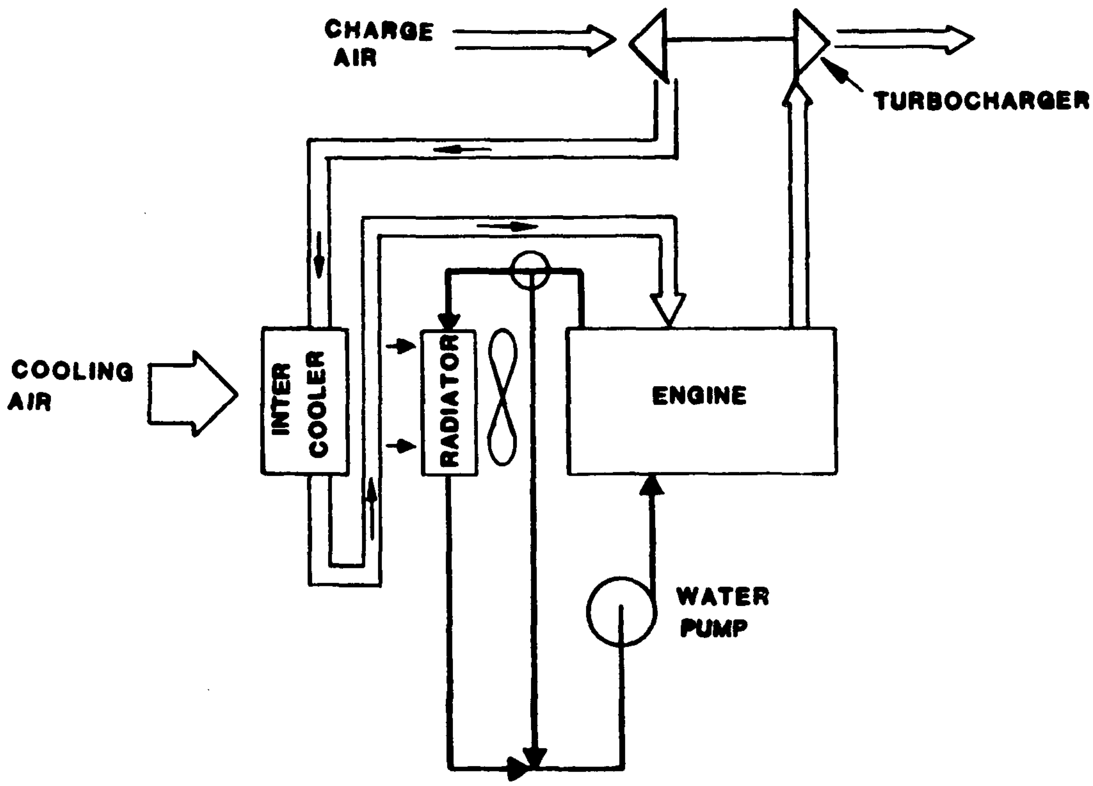


Figure 4. Air-to-Air Intercooler System

Source: Alpha United, Inc., El Segundo, California (Ref. 7)

Table 4. Estimated Costs of Air-to-Air Intercooler

System/ Component	Description	Manufacturer's Price Equivalent	Reference(s)
Intercooler	Air-to-air furnace brazed with headers (assumed $25,000 for tooling and 2500 units/year volume)	$315-$465	8,9,19
Steel Tubing	2-1/2" to 3" tubing to go to and from intercooler; some 45° bends	$4.50-$6.80	20
Silicone Hose	To connect steel tubing and allow movement between engine and intercooler; 2-1/2' to 3'	$3.20-$3.80	10,11
Clamps	Stainless steel clamps for silicon hose (6-8)	$0.68-$0.90	10
Intake Manifold	Assumes a revised casting with no increase in material requirements	$16[a]	1,13

[a] Incremental Cost

VI. UNIT INJECTOR FUEL INJECTION SYSTEM

All diesel engines use injection systems to meter and inject the fuel at the appropriate time during the compression stroke. The diesel engine requires that the fuel be injected directly into each cylinder just before maximum cylinder compression pressure. Because of this requirement, diesel injection systems must be capable of generating extremely high injection pressures relative to gasoline fuel injection systems. The following tasks must be accomplished by all diesel injection systems:

- Meter the amount of fuel demanded by the speed of (and load on) the engine,
- Distribute the metered fuel equally among all cylinders,
- Inject the fuel at the correct time during the cycle,
- Inject the fuel at the correct rate,
- Inject the fuel with the correct spray pattern and atomization demanded by the design of the combustion chamber, and
- Begin and end the injection sharply without dribbling or after-injections.

The following components are necessary for diesel fuel injection systems to perform the activities listed above:

- Pumping elements to move the fuel from the fuel tank to the cylinder (plus associated piping, etc.),
- Metering elements to measure and supply the fuel at the rate demanded by the speed and load,
- Metering controls to adjust the rate of the metering elements for changes in load and speed of the engine,
- Distributing elements to divide the metered fuel equally among the cylinders,
- Timing controls to adjust the start and stop of injection.

There are many types of fuel injection systems, and they vary from one manufacturer to another, but they all have the basic elements listed above (in one form or another). Two such fuel injection systems which are common for trucks and buses are the jerk-pump system (see Section VII) and the unit injector system.

The unit injector system is used almost exclusively by General Motors (Detroit Diesel Allison), and specifically consists of the following items:

- A low pressure gear pump which is used to move the fuel from the tank, through the fuel filter, and to the camshaft operated unit injectors.
- The injectors which are used to meter, time, and pressurize the fuel. The injector is operated by the camshaft through a push rod and rocker arm assembly. One injector is used for each cylinder.
- The fuel filters which are used throughout the system to protect the highly machined parts from water and dirt.
- The governor (hydraulic or mechanical) which is connected to the fuel control rack that controls the position of the injection plunger.

The unit injector system is also known as the individual pump system since this system does not have one central fuel injection pump, and the individual injectors act as injection pumps. While actual pressures vary with each specific design, some systems are capable of injection pressure up to 40,000 psi.

Cost estimates for the unit injectors (only) are provided in Table 5.

Table 5. Estimated Costs of Unit Injectors

System/ Component	Description	Manufacturer's Price Equivalent	Reference(s)
Unit Injector	Detroit Diesel Allison (6 cyl.)	$6.50 ea.	21
	Detroit Diesel Allison (8 cyl.)	$7.20 ea.	21

VII. HIGH PRESSURE FUEL INJECTION (JERK-PUMP) SYSTEM

As discussed in Section VI, all diesel engines use some type of fuel injection system. One common type of fuel injection system is the high pressure jerk-pump system. This system, as shown schematically in Figure 5, consists of the following elements:

- The engine-driven injection pump which is used to meter, time, pressurize, and control the fuel being delivered to each injection nozzle,
- The governor which controls fuel delivery to regulate the fuel delivery at each engine speed (variable speed governor) or controls high idle and low idle only (limiting speed type),
- High pressure steel lines which deliver the fuel from the injection pump to the injection nozzles,
- Injection nozzles (injectors) which are used to atomize the injected fuel, and are spring-loaded, hydraulically operated valves inserted into the combustion chamber (see Figure 6), and
- Fuel filters (including water traps) which are used throughout the system to prevent damage to the system by dirt and water.

Until recently, most jerk-pump fuel injection systems operated at a maximum injection pressure of 10,000 psi. In the last few years, however, injection pumps with pressures up to 15,000 psi have become the norm. While for some systems, this has not required significant changes in the injectors or lines (which must also withstand the high pressure) due to their initial safety factors, some injectors and lines have had to be redesigned.

Estimated costs of both high and low pressure fuel injection pumps and injectors appear in Table 6.

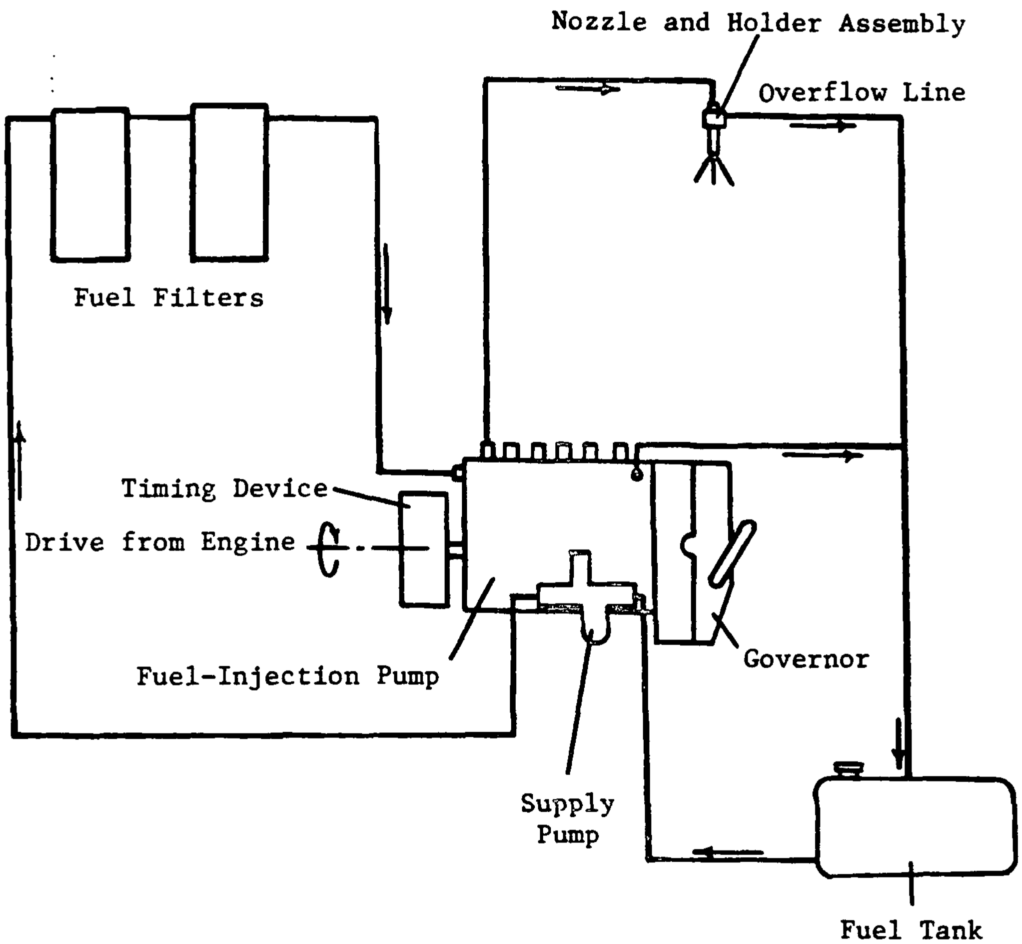
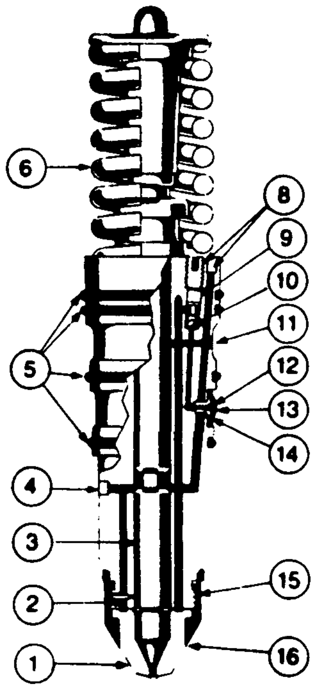


Figure 5. Diesel Fuel Injection System



1. Cup
2. Metering orifice
3. Plunger
4. Plug
5. O-ring seals
6. Injector spring
7. Injector link
8. Plugs
9. Stop
10. Check ball
11. Fuel out
12. Fuel in
13. Fuel screen
14. Orifice plug
15. O-ring seal
16. Cup retainer

Figure 6. Cummins Diesel Fuel Injector

Source: Goetz, W. A., et al., Methanol Substitution and Control Technology for a Cummins NTC Engine, presented at the VI International Symposium on Alcohol Fuels Technology, Ottawa, Canada, May 21-25, 1984 (Ref. 22)

Table 6. Estimated Costs of Fuel Injection Pumps and Injectors

System/ Component	Description	Manufacturer's Price Equivalent	Reference(s)
Fuel Pump	High-Pressure Jerk-type (13,000-15,000 psi)	\$250 (6 cyl.) \$320 (8 cyl.)	23
	Lower-Pressure Jerk-type (10,000-11,000 psi)	\$200 (6 cyl.) \$270 (8 cyl.)	23
Injection Nozzles (Fuel Injectors)	High-Pressure (13,000-15,000 psi)	\$5.60 ea.	23
	Lower-Pressure (10,000-11,000 psi)	\$5.60 ea.	23

VIII. ELECTRONIC CONTROLS

This section addresses some general components which are likely to be used as parts of various particulate trap oxidizer systems. In an earlier report, cost estimates were developed for an exhaust back pressure sensor, exhaust temperature sensor, engine speed sensor, rack position sensor, throttle angle sensor, and electronic control unit (24). Components for which cost estimates were developed in this current study include:

- Engine Temperature Sensor
- Sensor/Control Wiring Harness
- Fuel Injector (including Solenoid)
- Exhaust Bypass Damper Actuator
- Air Injection Control Valve and Solenoid

Engine Temperature Sensor

The function of the engine temperature sensor is to prevent operation of the trap regenerator until the engine is at normal operating temperature. For example, if the engine were just started and the back pressure sensor were to signal the need for a regeneration cycle, the electronic control unit (ECU) would permit the trap bypass to open but would not permit the regeneration cycle to proceed until a signal is received from the engine temperature sensor indicating that the engine temperature was near normal.

The engine temperature sensor is usually mounted on an accessory mounting bolt on the engine cylinder head. It is usually a bimetallic, factory-calibrated, snap-action electrical switch. When the set temperature is reached, the switch would snap closed, grounding a digital circuit from the ECU.

Sensor/Control Wiring Harness

A durable wiring harness is necessary to interconnect the various components of the trap/regenerator system. It appears that a harness with 5-10 wires with standard automotive connectors would suffice. Existing wiring harnesses for trucks cost from $75 to $150 and involve from 15 to 40 wires. This was used as the surrogate to estimate the wiring harness.

Fuel Injector

The fuel injector is used to spray diesel fuel into the burner assembly which is used to heat the trap to a sufficient temperature to combust the accumulated particulate matter. This is a light-duty, low-pressure application which can be adequately handled by injectors typically used in automotive applications with port-injected gasoline engines.

Exhaust Bypass Damper Actuator

When the trap is being regenerated, the exhaust flow must be diverted around it until regeneration is completed. This system receives an electrical signal from the ECU which actuates a solenoid valve which in turn admits pressurized air to move a piston or bellows which moves the bypass damper. The bypass damper itself it not part of this subsystem but is described later in Section IX.

Air Injection Control Valve and Solenoid

After the regeneration process is started by actuating the exhaust bypass damper actuator, the air injection control valve is actuated to admit air into the trap. The fuel injector also is actuated, and the ignition system then ignites the air/fuel mixture to begin the regeneration process. This subsystem is composed of an electrical solenoid which is actuated by the ECU. This bleeds pressurized air into a bellows that admits combustion air into the burner.

Cost Estimates

The cost estimates for the components discussed above are presented in Table 7. These estimates were developed through direct contact with manufacturers of analogous subassemblies and comparisons to prices of similar automotive parts in high volume production.

Table 7. Estimated Costs of Electronic Control Components

System/Component	Description	Manufacturer's Price Equivalent	Reference(s)
Electronic Controls			
Engine Temperature Sensor	Bimetal electric switch that grounds and opens a logic line for the ECU to monitor engine operating temperature to allow regenerator operation only after engine warmup. Mounted to engine block.	$1.60-$2.30	25
Sensor/Control Wiring Harness	5-10 wires with end fittings designed to be integrated with the existing 12 volt vehicle harness. Provides a wiring assembly for electrically interconnecting all of the regenerator components. Located in engine compartment, exhaust system, and particulate trap. External components should be armored.	$11-14[a]	12,26
Fuel Injector (Including Solenoid)	A low pressure fuel injector similar to the type used in gasoline fuel injection systems. Sprays fuel into particulate trap. Approximately 1 minute on per 20-30 minutes of operation. Flow rate is modulated by variation of square wave pulses from the ECU, if necessary. Located in upstream area of the particulate trap.	$9	12

Table 7. Estimated Costs of Electronic Control Components (Cont.)

System/Component	Description	Manufacturer's Price Equivalent	Reference(s)
Exhaust Bypass Damper Actuator	12-volt solenoid and three-way air valve located at junction between regenerator bypass pipe. Controls the flow of pressurized air to the bypass actuator.	$15	27
Air Injection Control Valve and Solenoid	12-volt solenoid and two-way air valve that controls the flow of air to the trap during regeneration.	$11	27

[a]This is the unit cost of a separate 5-10 wire harness connecting the data acquisition system and the various sensors and controls. The low end of the range reflects the Light Heavy-Duty class, while the upper end of the range is representative of the Medium to Heavy Heavy-Duty classes.

IX. ELECTRIC REGENERATION WITH CERAMIC MONOLITH TRAP

In this section, cost and other information is provided on a ceramic monolith particulate trap with an electrical heat regeneration system. As depicted in the block diagram in Figure 7, this system captures particulates on a ceramic monolith which is regenerated using electric resistance heaters to increase the exhaust gas temperature high enough to combust the accumulated particulates. Components discussed include:

- Ceramic Monolith
- Ceramic Mat
- Trap Housing
- Baffles, Flanges, and Piping
- Exhaust Bypass Valve and Piping
- Regenerator Power Supply System (Alternator, Mounting Hardware, Batteries, Wiring Harness, Battery Box, Relays, Cable, Circuit Breakers, and Electric Heaters)

Cost estimates are also provided for three general classes of vehicles, namely, light-heavy duty, medium-heavy duty, and heavy-heavy duty.

Ceramic Monolith

The particulate trap uses an extruded ceramic monolith to filter the exhaust gases as they leave the engine. The monolith is a matrix of alternatively open and closed cells as illustrated in Figure 8. The cell walls are porous to allow the exhaust gases to pass through them. Presently, the extrusion of the monoliths is limited to sizes of about six (6) inches in diameter; however, equipment to produce sizes up to 12 inches in diameter is under development. Costs shown are based upon 12 inch diameter components.

Ceramic Mat

The monolith is securely attached to the trap body by a surrounding ceramic mat that also cushions and insulates the monolith. These mats are similar to those used in automotive catalytic converters.

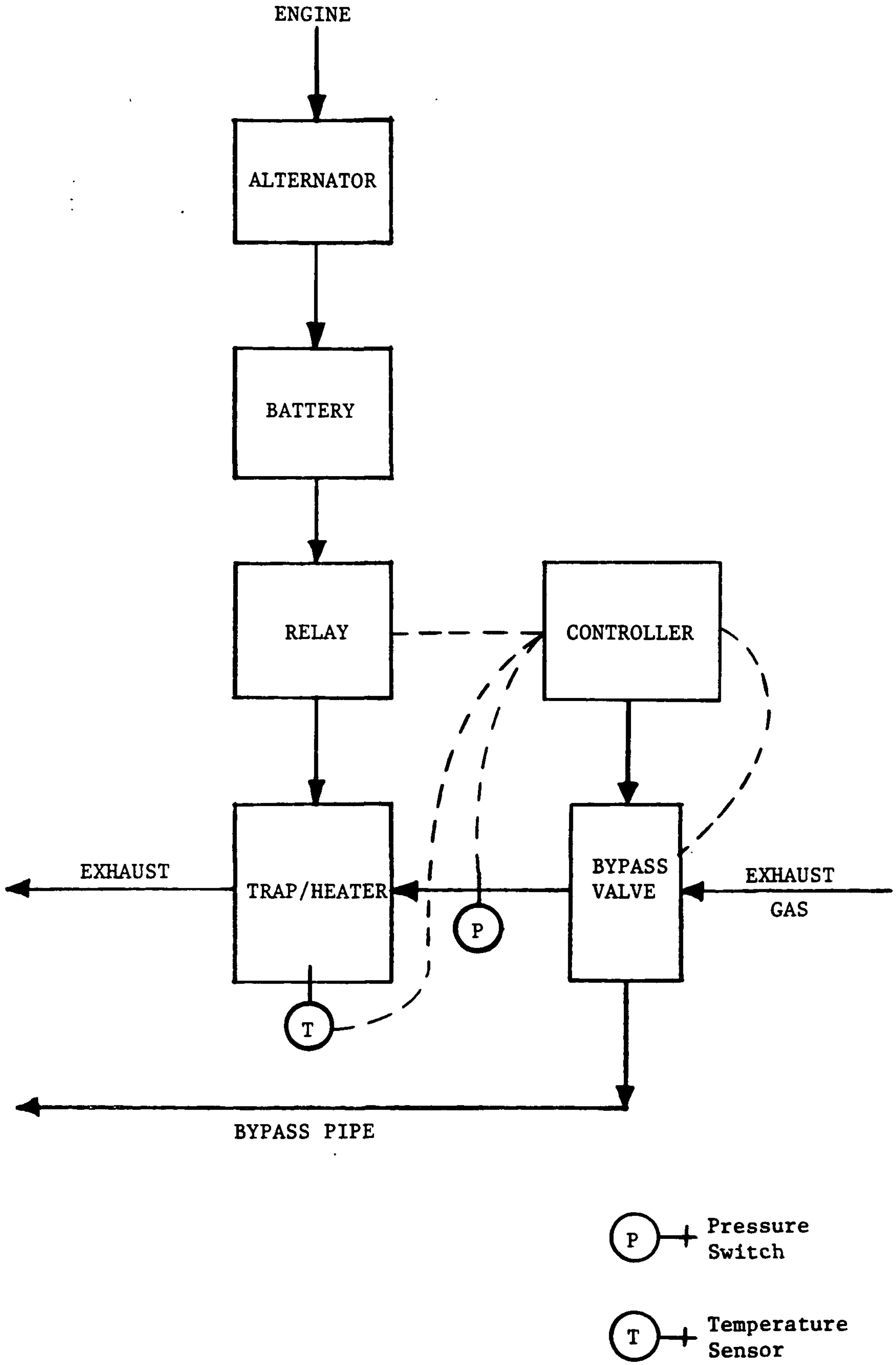


Figure 7. Electric Regeneration System Block Diagram

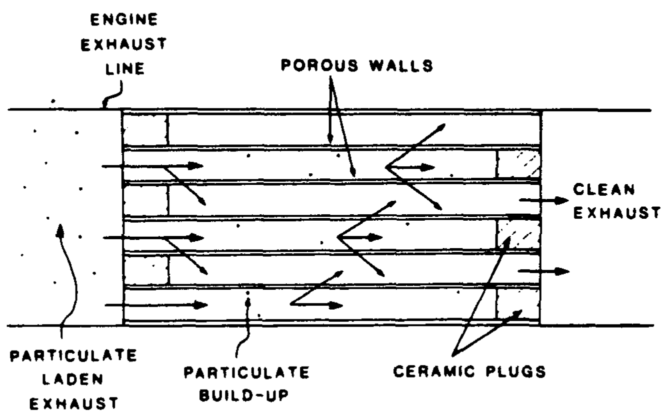


Figure 8. Ceramic Monolith Trap

Source: Weaver, C.S., Particulate Control Technology and Particulate Standards for Heavy Duty Diesel Engines, SAE Paper 840174 (also in Diesel Particulate Traps, SAE P-140, February 1984) (Ref. 27)

Trap Housing

In general, the trap housing consists of stainless steel tubing, flanges and entrance/exit cones, and locations for mounting sensors and other hardware. The actual size of the housing will depend on the particular vehicle application (i.e., trap volume and monolith number and size). The trap housing would be designed so that the monolith can be easily replaced if it should fail structurally. This is accomplished by making one end of the trap housing removable through the use of a bolted or clamped flanged joint arrangement.

Baffles, Flanges, and Piping

These stainless steel components are used to connect the trap housing to the truck exhaust system and the bypass valve assembly. An interior flange is used to support the regenerator heater. The piping size selected was 4 inches.

Bypass Valve and Piping

The bypass valve and piping is used to control exhaust flow through and around the particulate trap. The bypass valve can be a butterfly type valve and is controlled by a bypass actuator (see Section VIII).

Regenerator Power Supply System

The regeneration of the monolith is accomplished with controlled energy input provided by electric heating elements. The power supply for the trap regeneration requires an on board source of electrical power. It should be noted that heavy duty truck electrical systems are more complex than those of light duty vehicles. The heavy duty truck category includes vehicles that use 12, 24 or 36 volt charging systems. The 24 and 36 volt charging systems allow the use of additional batteries which are used only during engine starting. These batteries are combined in series with a simple 12 volt battery (or two - 6 volt batteries) to provide the 24 volts or 36 volts to the engine starter motor. The higher voltage allows the use of a smaller, lighter-weight starter motor. It also allows greater battery capacity to be utilized. For example, a heavy-heavy duty truck might use a 24 volt charging system and two sets of 6 volt batteries. This additional capacity guarantees the necessary starting power is available during low temperature conditions. The required 12 volts for vehicle light and accessories is available through tapping one half of the vehicle's battery system. Special 24/12 volt alternators are also used on medium-heavy and heavy-heavy duty trucks. This system uses a 12 volt alternator with an "add on" or built-in transformer-rectifier unit. This additional unit steps up the 12 volt AC to 24 volt AC, then converts it to 24 volts DC. The 12 volt output is delivered to the vehicle system 12 volt battery. The transformer-rectifier charges another 12 volt battery which is connected in series with the system battery to provide 24 volts to the starter motor. When the engine is running, the additional battery system "floats on the line" and receives a low charge rate to maintain its full state of charge.

With the various charging system hardware available and the different systems configured by the many manufacturers, it is difficult to select a system which represents a true baseline upon which to develop a cost estimate for the regenerater power supply system. The approach taken in this costing effort was to assure that the required power for electrical regeneration would be provided by an "add-on" system. This baseline approach does not require a detailed knowledge of the specifics of each of the existing electrical systems of the heavy duty diesel truck classes. The "add-on" approach also results in the greatest cost situation, since an additional alternator and a separate battery system is required. It is very difficult to anticipate the approach the different manufacturers will take, but it can be safely assumed that they will attempt to integrate the regenerator power requirements into their standard "on-board" power systems. If this approach is properly handled for a portion of the heavy truck classes, an on-board power system with an upgraded alternator, an increased battery capacity (through the use of two 6 volt batteries to replace 12 volt batteries), and a fusible link to replace circuit breakers could substantially reduce the overall system cost. The costs for this integrated approach were also estimated to provide the lower bound for the system cost of the electrical regeneration approach. Descriptions of the individual components are provided below.

Regenerator Power Supply Components - Baseline

Alternator - A standard truck alternator is driven by existing truck engine drive pulleys. The alternator contains an internal regulator and rectifier to supply 24 V dc to charge the batteries.

Mounting Hardware - The alternator is mounted to the engine using hardware specific to each engine. This will include mounting brackets, flanges, pulleys and/or idlers, and belts.

Batteries - Two 12-volt batteries in series will provide storage of energy for the resistance heating elements. A typical size for the 3 to 7 kW power requirement is a 908-D battery (1000 cold cranking amps and 42 minute reserve capacity).

Wiring Harness - The wiring will connect the alternator windings to the control unit and ignition switch in the truck. This wiring will be similar to conventional truck charging system wiring.

Battery Box - This component also will be similar to conventional truck hardware. However, ample space will need to be allocated to mount the batteries on the chassis.

Relays, Cable, and Circuit Breakers - The power supply to the electric heater is controlled by an electromechanical relay energized by the control system. Conventional truck type cables connect the battery, relay, and circuit breakers to the heaters. The circuit breakers protect the batteries and charging system in the event of a short circuit.

Electric Heaters - The energy addition to the exhaust gas stream is provided by resistance heating elements. These will be either wound wire or ribbon elements attached to a support structure. The heating assembly could be placed in the front of the trap housing and secured in place by the flange. Each element will be about 1000 watts and the number used will depend on the capacity required.

Regenerator Power Supply Components - Integrated System

Alternator - A modified alternator with an increased amperage rating would be used in an integrated system. This 24 volt alternator would replace the existing 12 or 24 volt alternator. The increase in the power rating of the alternator would have to be sufficient to handle the additional regeneration power requirements based on the required regeneration duty cycle. The modified alternator system can be treated as an incremental cost above the standard alternator.

Mounting Hardware - Since a larger alternator will be utilized, the standard mounting hardware may require modification. The modification should be relatively minor and can be treated as an incremental cost.

Batteries - No change from the baseline battery system should be necessary, except in the light-heavy duty situation where one additional 12 volt battery could be combined with the standard 12 volt battery to supply required power to the electrical resistance heaters. Additional battery cables (for connecting together the batteries) will be required in cases where additional batteries are used.

Wiring Harness - No change.

Battery Box - One battery box and mount will be required for the light-heavy duty class; see batteries.

Relays, Cable, and Circuit Breakers - Instead of using resettable circuit breakers to protect the batteries and the alternator, a fusible link may be used in the connecting cable from the batteries to the electrical resistance heaters.

Electric Heaters - No change.

Cost Estimates

The cost estimates for the components discussed above are presented in Table 8. These estimates were developed through direct contact with manufacturers of analogous subassemblies and comparisons to prices of similar automotive parts in high volume production.

Table 8. Estimated Costs of Selected Components for an Electrically Regenerated Ceramic Monolith Trap - Baseline and Integrated Systems

System/Component	Description	Retail Price	Estimated MPE			Ref(s)
			LHD[a]	MHD[a]	HHD[a]	
Ceramic Monolith	Caldorite mullite material	$4.65/liter[b] (based on MPE cost of $140/30 liter unit)	$51[c]	$98[c]	$183[c]	29
Ceramic Mat	Insulating mat attaching monolith to trap housing	$.22/liter[b] (based on $7/30 liter unit)	$2	$5	$9	30,31
Trap Housing	Stainless steel cylindrical housing		$19	$24	$27	11,32
Housing Baffles, Flanges, and Piping Connectors			$6	$7	$8	11
Exhaust Bypass Valve and Piping	Stainless steel piping and flow diverter valve		$38	$41	$45	32,33
Power Supply System						
• Alternator	New accessory alternator, 60-105 amp, 24 V dc		$150[d] [$56][e]	$150[d] [$56][e]	$160[d] [$60][e]	17,34
• Alternator Mounting Hardware	Mounting brackets, flanges, pulleys, idlers, belts		$7[d] [$1][e]	$8[d] [$1][e]	$9[d] [$1.50][e]	17

Table 8. Estimated Costs of Selected Components for an Electrically Regenerated Ceramic Monolith Trap - Baseline and Integrated Systems (Cont.)

System/Component	Description	Retail Price	Estimated MPE LHD[a]	Estimated MPE MHD[a]	Estimated MPE HHD[a]	Ref(s)
Power Supply System (cont.)						
⊛ Batteries	12 volt, heavy duty; one for LHD and two for MHD and HHD	$170/unit	$38[d,e]	$77[d,e]	$77[d,e]	17,33
• Wiring Harness	Alternator wiring to battery and cab	$25	$5.60[d,e]	$5.60[d,e]	$5.60[d,e]	34
• Battery Box	Container and mounting hardware		$9[d,e]	$10[d,e]	$11[d,e]	34
• Relay - low amp	Heavy duty, 24 V dc, 600 amp rating	$15/unit	$10[d,e,f]	$17[d,e,g]	$24[d,e,h]	34
• Cable	#2 gage, from battery to relays		$2.30[d]	$2.50[d]	$2.70[d]	34
• Cable	#2 gage, from relays to heaters	$3/unit	$2.00[d]	$3.40[d]	$4.70[d]	34
• Circuit Breaker	Heater protection; fused disconnect, circuit breaker, or timer; 50 amp	$6.50/unit	$4.50[d,f]	$7.40[d,g]	$10[d,h]	35
⊛ Fusible Link	Circuit protection, replaces circuit breaker	$0.75/unit	$0.60[e,f]	$1.00[e,g]	$1.40[e,h]	
• Electric Heater (with mounting hdw.)	Wound wire or ribbon type; 3-7 kW	$4/unit	$2.70[d,e,f]	$4.50[d,e,g]	$6.30[d,e,h]	36

Table 8. Estimated Costs of Selected Components for an Electrically Regenerated Ceramic Monolith Trap - Baseline and Integrated Systems (Cont.)

System/Component	Description	Retail Price	Estimated MPE LHD[a]	Estimated MPE MHD[a]	Estimated MPE HHD[a]	Ref(s)
Exhaust Back Pressure Sensor	Low voltage, pressure activated switch	$60/unit	$13	$13	$13	1,37,38
Exhaust Temperature Sensor	Heavy-duty thermocouple	$20/unit	$4.00	$4.00	$4.00	39
Controller	High temperature or temperature rise, high pressure activated controller for heater relay and bypass valve actuator	$120/unit	$27	$27	$27	40
Control Wiring	Sensors, actuator, relay, and controller wiring	$25	$5.60	$5.60	$5.60	11,32

[a] LHD - light heavy duty; MHD - medium heavy duty; HHD - heavy heavy duty.
[b] MPE Price
[c] Cost dependent on size. Assumed 11 liters for LHD, 21 liters for MHD, and 39 liters for HHD.
[d] Baseline System
[e] Integrated System
[f] 3-1000 kW units
[g] 5-1000 kW units
[h] 7-1000 kW units

X. CATALYTIC MATERIAL

In an earlier report (24), cost estimates were provided for a number of components associated with a ceramic fiber trap metal catalyst which is illustrated in Figure 9. In this current study, the cost of the catalytic material, copper chloride, was estimated. In bulk quantities (>24,000 lb in 300 lb. fiber drums), copper chloride can be obtained for approximately \$1.16/lb (41). Repackaging costs (e.g., 50 lb fiber drums) can add another \$0.10/lb to the bulk cost. For small orders (<4,000 lb), the cost increases to approximately \$1.46/lb in 300 lb drums.

For the system considered here, it was assumed that the units produced would consist of a throw-away container approximately six tenths of a gallon in size. Such a container would contain approximately 12 lb. of copper chloride. Assuming a cost of approximately \$5 for a structural plastic throwaway container, the estimated cost can be calculated as:

12 lb. x \$1.46/lb. + \$5.00 = \$22.52

Table 9. Estimated Cost of Catalytic Material

System/ Component	Description	Manufacturer's Price Equivalent	Reference(s)
Catalytic Material			
Solid Catalyst Plus Container	Solid catalyst (copper chloride) is produced in a sealed 1-gallon throwaway plastic container. Solid catalyst is sprayed into the trap during regeneration to reduce the particulate combustion temperature. Located at rear of tractor, near the trap.	\$5.00	41

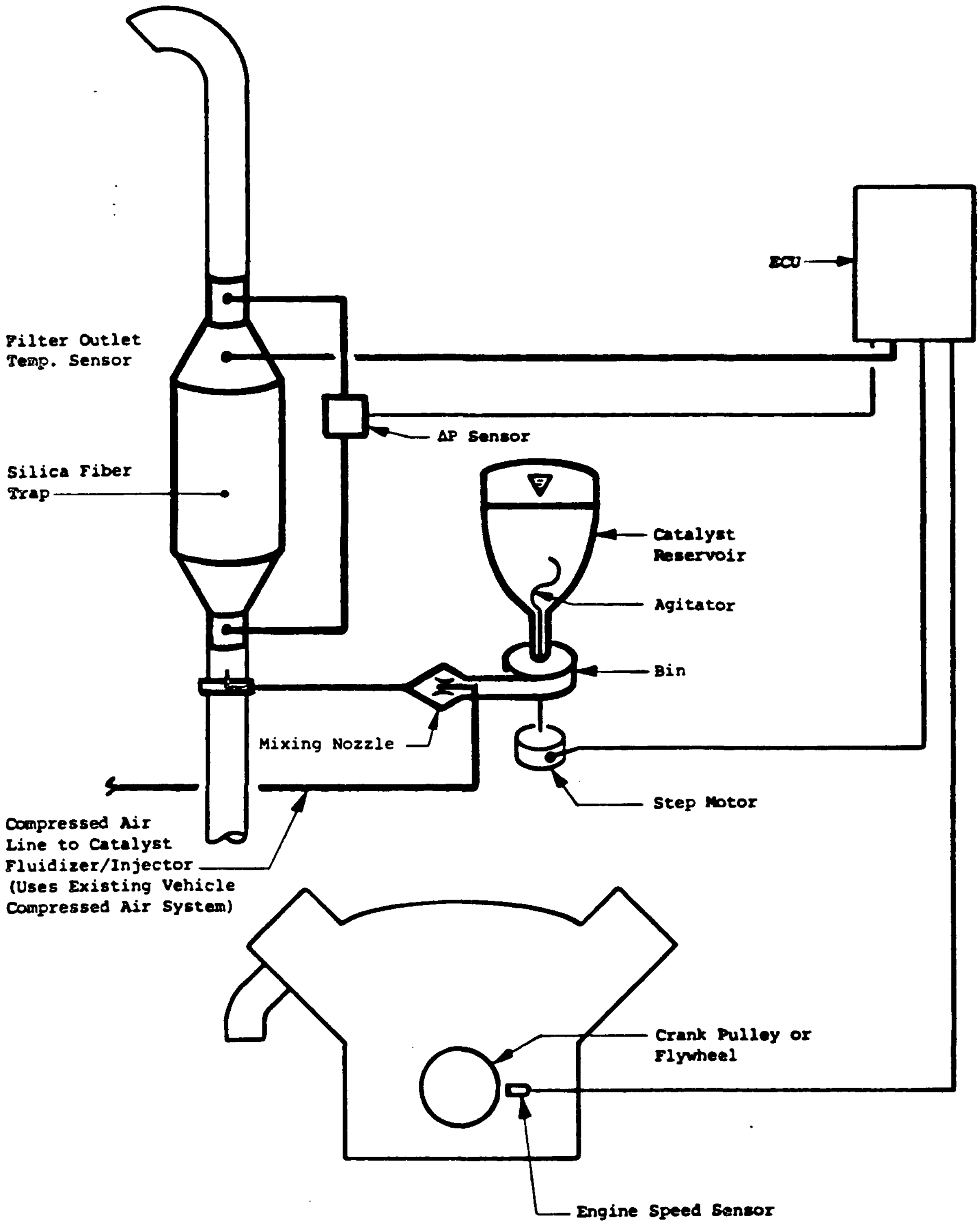


Figure 9. Ceramic Fiber Trap Metal Catalyst

Source: Ref. 24

XI. BURNER HOUSING AND IGNITION SYSTEM

In an earlier report (24), cost estimates were provided for several components (fuel injector, fuel pump and combustion air blower) associated with a diesel fuel burner regeneration system. This system is illustrated schematically in Figure 10. Two additional components for which cost estimates were developed in this current study are a burner can and ignition system.

Burner Can

The burner can is designed to hold the flame of the fuel burner and to direct the flames and heated air into the trap. Since it is subject to relatively high temperatures (>1200°F), materials used largely are made of a high-grade stainless steel for strength, corrosion resistance, and long life. Heat output necessary for reliable ignition of the trap is approximately 100,000 Btu/hr.

Ignition System

A continuous spark is necessary to initiate and maintain combustion in the regenerator burner can during the regeneration cycle. A high-voltage (12 kV+) AC power is needed. Also, a flame sensor and sensor relay are necessary to assure that ignition has occurred. Otherwise, the ECU must cut off the fuel flow to the burner.

Cost Estimates

The cost estimates for the two components noted above are presented in Table 10.

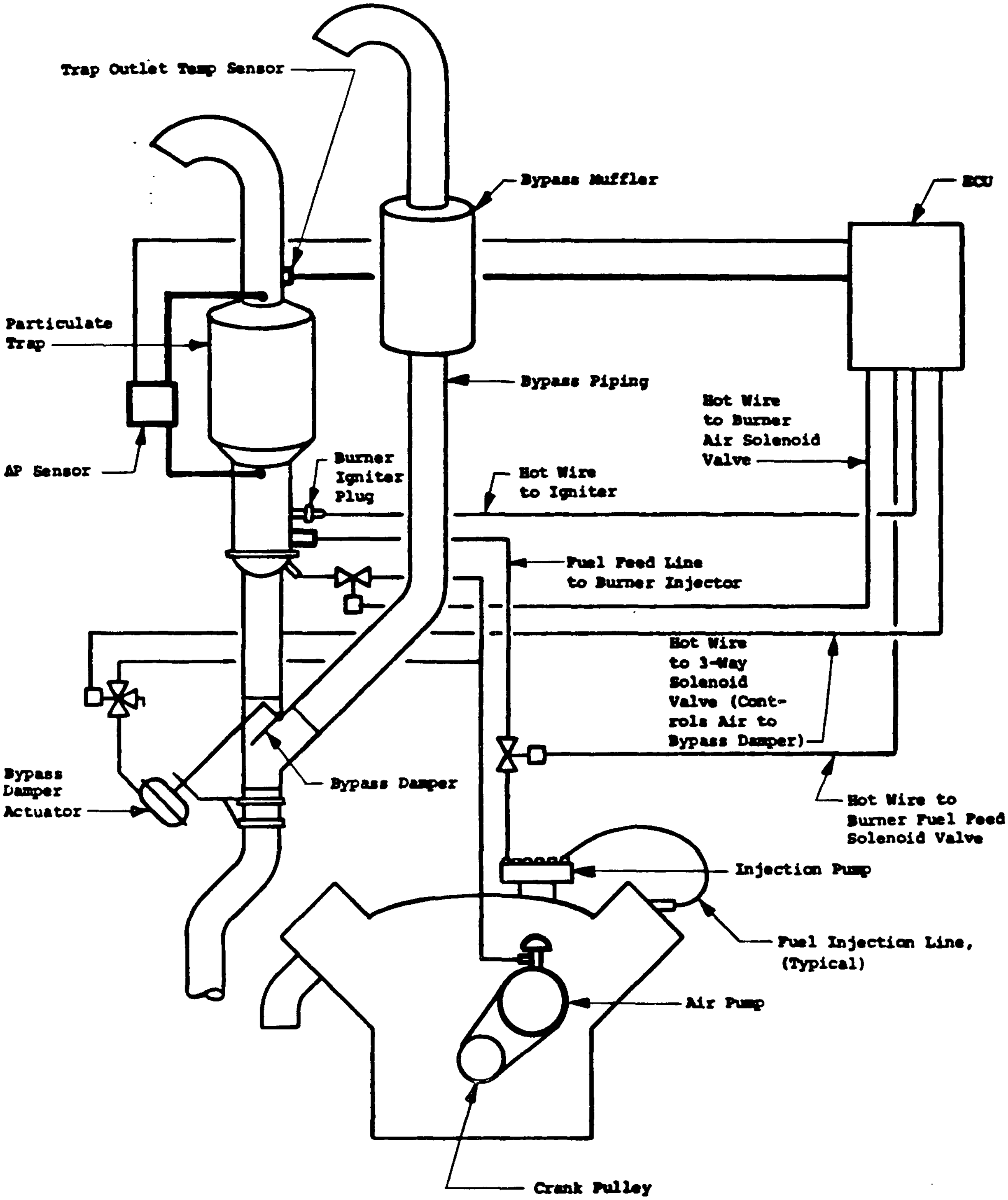


Figure 10. Diesel Fuel Burner Regeneration System Schematic Diagram

Source: Ref. 24

Table 10. Estimated Costs of Burner Can and Ignition System for Diesel Fuel Burner Regeneration System

System/ Component	Description	Manufacturer's Price Equivalent	Reference(s)
Burner Housing and Ignition System			
Burner Can	Outer steel tube--4-6 inches in diameter, 24 inches long. Inner stainless steel flame holder, various heat shields. Provides an enclosed space for the mixing of air and fuel and subsequent ignition and combustion. Located upstream of trap.	$16	37
Ignition System	Inverter, transformer, electrode, flame sensor, and sensor relay. Provides spark ignition and flame control for the burner. Located at rear of tractor.	$34	37

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