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PROOF-OF-PRINCIPLE TEST FOR
THERMOELECTRIC GENERATOR FOR DIESEL ENGINES

Final Report

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PROOF-OF-PRINCIPLE TEST FOR THERMOELECTRIC GENERATOR FOR DIESEL ENGINES

1.0 Background

In September of 1987, the principals of what is now Hi-Z TECHNOLOGY, INC. applied to the National Bureau of Standards (now National Institute of Standards and Technology, NIST) under the Energy Related Inventions Program. The invention was entitled "Thermoelectric Generator for Diesel Engines."

The National Institute of Standards and Technology evaluated the invention and on January 12, 1989 forwarded Recommendation Number 455 to the Department of Energy (DOE). This recommendation informed the DOE that the invention had been selected for recommendation by the NIST for possible funding by the DOE.

Following the recommendation of the NIST, the DOE contacted Hi-Z to work out a development program for the generator. A contract for a grant to design, fabricate, and test a Proof-of-Principle exhaust powered thermoelectric generator for Diesel engines was signed October 19, 1989. Hi-Z provided the thermoelectric modules used in the generator as their contribution to the project. The purpose of this Grant Program was to design, build, and test a small-scale, Proof-of-Principle thermoelectric generator for a Diesel engine.

2.0 Generator Design and Manufacture

The design of the Proof-of-Principle generator developed under the Grant Program is shown in Figure 1. For the initial test, Hi-Z decided to design the components so that they could be easily machined from reasonably sized solids, and to use welding where necessary in order to minimize the initial generator fabrication cost. This design approach will have to be modified later to incorporate high production methods of manufacture.

In the design shown in Figure 1, the main module support structure was fabricated from six flat steel plates which were machined with fins on one side subsequently welded together to form a hexagonal cylinder. Heat transfer fins were machined on the inside surface of each plate prior to welding, as shown in Figure 2. The hexagonal cylinder was then welded to circular end fittings which were machined to make a low pressure loss transition from the circular inlet and outlet tubes to the hexagonal module support structure.

Figure 1. Design of Proof-of-Principle Generator

Figure 2. Module Support Structure Plate Being Machined

Figure 3. Complete Module Support Structure

Conical diffusers were fabricated and welded on each end of the main generator structure so that a transition could be made from the four-inch diameter turbosupercharger exhaust of a Cummins L-10 engine to the six-inch diameter engine exhaust system. The complete module support structure is shown in Figure 3.

Three thermoelectric modules, such as are shown in Figure 4, are pressed against the side of each of the hexagon flats of the module support structure. Each set of three modules is bonded to an aluminum heat sink using a high thermal conductivity silicone adhesive, as shown in Figure 5. The module/heat sink assembly is held in compression against the flat of the module support structure by four Belleville spring stacks located over each module position. The reaction of the forces generated by the spring stacks are balanced by three circular aluminum rings which encircle the generator at the level of each of the three modules. The forces applied to the heat sinks are controlled by adjusting the set screws which are threaded through clinch nuts pressed into the aluminum reaction rings at each spring stack location.

We now feel that the reaction ring design can be simplified in the next model by reducing the number of spring stacks from four to one per module. It may also be possible to totally eliminate the Belleville springs by the use of a flexible steel reaction ring instead of the rather stiff aluminum reaction ring. The flexible ring would also function as a spring so that only the force adjustment screws would be required.

All six of the anodized aluminum heat sinks are connected in series hydraulically. Identical coolant inlet and outlet fittings were provided near the gas outlet end of the generator.

The modules are wired, as shown in Figure 6, to provide two parallel electric circuits. These parallel circuits are cross-connected at two points. Electric connections to the external circuit are made through two threaded terminals located on the outside of the generator near the coolant connections.

A photograph of the generator with the outside dust cover removed is shown in Figure 7. It is easy to see the three aluminum reaction rings with their adjusting screws, as well as three of the six heat sinks and the two coolant lines. Figure 8 presents a view of the generator with the outside cover in place.

Figure 4. 13.4 Watt Thermoelectric Module

Figure 5. Three 13.5 Watt Modules Mounted On Heat Sink

Figure 6. Module Wiring Curcuit

Figure 7. Generator, Cover Removed

Figure 8. Generator, Cover In Place

3.0 Initial Checkout

It was necessary to check the generator out operationally prior to mounting and operating it on a Diesel engine. In order to do this, a heat source had to be designed and built that would deliver the gas flow and temperature required to operate the generator.

The heat source that was designed used a commercially available low cost burner normally used in home oil-fired furnaces, and came complete with all the control and safety systems required for operation. The unit was made by American Burner Corporation.

Some minor modifications were made to the fuel delivery system of the burner so that the fuel flow rate could be reduced below the original design value. This was required because the normal combustion temperature of the stock burner is much higher than that of the Diesel engine exhaust.

The burner system was mounted on the lid of a 30 gallon steel drum. The interior surfaces of both the lid and the drum body were covered fibrous thermal insulation. An outlet pipe was welded to the side of the drum. The end of the outlet pipe was configured like the outlet flange of the Cummins L-10 engine turbocharger exhaust flange so that the generator could be attached. The installation of the generator on the heat source is shown in Figure 9.

The generator was operated on the test heat source several times during the check phase. While the gas flow rate and temperature were not the same as that of the Diesel engine, we were able to operate the generator and successfully check it out. We were able to achieve a peak output of 200 Watts during these initial tests.

4.0 Test Setup

The Proof-of-Principle generator was mounted on a Cummins L-10 engine with the inlet end of the generator connected directly to the exhaust of the turbocharger. The coupling was made using the standard 4-inch V-band clamp normally used to connect the exhaust pipe to the turbocharger exhaust. The exhaust end of the generator was connected to the test cell exhaust system using a 6-inch V-band clamp.

The generator was supported on a bracket which was clamped to the engine block at the rear motor mount. Two band clamps were placed around the generator shell and support bracket and tightened to hold the

Figure 9. Generator Mounted on Checkout Heat Source

generator firmly in place. The initial installation, which provides a good view of the mounting, is shown in Figure 10, and the final installation is shown in Figure 11.

The generator inlet coolant line was connected to the engine coolant system at a point after the water pump. It was returned to the coolant heat exchanger inlet. A water-water heat exchanger was used in the test cell setup instead of a radiator. A 180°F thermostat was used to control the engine temperature during the test; however, some difficulty with temperature control was encountered during the course of the test.

Power from the engine shaft was dissipated through a hydraulic dynamometer in the test cell. The engine and dynamometer system were instrumented to obtain engine RPM and engine torque. Engine power was automatically calculated by the instrumentation controller and was presented on a power meter in real time along with the engine speed and torque. A view of the test cell control console is shown in Figure 12.

Figure 10. Generator, Initial Installation

Figure 11. Generator, Final Installation

Figure 12. Test Cell Control Console

The test generator was instrumented with thermocouples to read the exhaust gas stream temperature at both the inlet and outlet of the generator. The thermocouples were placed as close to the flow center line as possible.

Thermocouples were also spot welded to the outside of the generator central support structure. These thermocouples were placed as near as possible to the thermoelectric modules. One was placed near the module at the inlet end, near the middle, and at the outlet end. Three additional thermocouples were spot welded to the inside surface of the heat sink at points approximately adjacent to the thermocouples welded to the support structure.

Additional thermocouples were placed in the generator coolant lines. These thermocouples were positioned to sense the inlet and outlet water centerline temperature.

The power leads from the generator were connected to a load box which permitted the operator to vary the external circuit resistance from short circuit through open circuit, dissipating the power by means of a pair of water-cooled power transistors. The load box also

contained a calibrated 0.002 ohm shunt so that the current could be sensed by measuring the voltage drop across the shunt. Arrangements were also available to obtain instant open circuit voltage. All voltages were read on a Keithley digital multimeter.

A single line diagram of the test instrumentation in the test setup is presented in Figure 13. Two changes from Figure 13 were made. First, the relay, the power transistors for the load, and the shunt were actually located inside the control room instead of in the test cell as shown. Second, an ammeter was placed between the generator and the rest of the electric circuit. This ammeter was to create a problem later when the test data was reduced.

4.1 Test Procedure

The Cummins engine was started and allowed to warm up until the temperature was about 185°F and the operating conditions appeared to be stable. The engine was then brought to stable operation at 1300 RPM and a shaft output of 75 horsepower. The engine was then operated at that power and speed for a period of 5 minutes before the generator data was recorded.

After recording the generator and engine data at a given operating point, the shaft power and/or the RPM was increased to a new level and the engine conditions were again stabilized. After a waiting period of five minutes, data was recorded at the new operating conditions. This procedure was followed throughout the test.

4.2 Test Results

Table 1 presents the data obtained over the normal operating range from 1300 RPM and 75 horsepower to 1900 RPM and 200 horsepower. An additional set of data was obtained at idle conditions after the final power run was made.

The actual power obtained from the generator was higher than is indicated by multiplying the indicated matched load voltage, V_m , by the matched load current, I_m . The use of a low impedance ammeter in the circuit resulted in an unaccounted for voltage drop in the system. This voltage drop was corrected for by using the following equation for maximum power, P_m :

$$P_m = V_m^2 * I_m / (V_m - R_a * I_m)$$

where R_a is the resistance of the ammeter.

Figure 13. Instrumentation Single Line

The original plan was to take data up to 1900 RPM and 300 horsepower. However, difficulties were encountered with engine surge when we attempted to go above 200 horsepower at 1900 RPM so that stable data could not be obtained at powers above this point.

The engine surge problem which was encountered above 200 horsepower at 1900 RPM was believed to be due to a faulty control spring in the engine fuel control system. The parts required to fix the problem were not available during the test.

As previously mentioned, we also experienced difficulty with the engine cooling system. The problem was thought to be the result of a

Table 1
Test Data from HZ-180 Generator on Cummins L-10 Engine
Test Date 12/11/90

Engine Speed RPM	Engine Power HP	Exhaust Inlet Deg.F	Temperature Outlet Deg.F	Water Temperature Inlet Deg.F	Outlet Deg.F	Load Voltage Volts	Current Ampere	Peak Power Watts	Average Temperature Hot Side Deg.F	Cold Side Deg.F
1300	75	610	595	190	196	8.99 9.37 10.16 11.48	6.55 6.235 5.63 4.635	67	441.3	204.4
1300	150	780	760	195	210	9.44 10.11 10.98 12.25	9.335 8.85 8.245 7.39	102	560.7	221.8
1300	225	880	870	200	230	10.05 10.74 11.74 12.84	9.53 9.495 7.875 6.855	120.8	645.2	249.8
1500	75	570	570	195	200	7.71 8.57 9.68 10.61	6.96 6.28 5.43 4.725	61.5	437.0	201.8
1500	150	720	700	195	205	9.09 9.94 10.82 11.61 12.21	8.795 8.17 7.545 7.015 6.63	92.1	523.2	214.8
1500	225	785	770	205	225	10.77 10.92 11.86 12.87	8.44 8.32 7.665 6.975	126.6	580.2	233.7
1500	300	850	850	240	245	9.16 10.04 11.41 12.58	8.70 8.15 7.205 6.44	92.1	638.7	276.5
1700	75	555	550	194	200	1.64 8.37 9.30 10.08	6.78 6.185 5.45 4.855	59.2	431.7	201.0
1700	150	655	650	195	205	8.87 9.40 10.06 11.08	8.055 7.64 7.14 6.425	81.7	494.9	208.0
1700	225	720	705	200	220	9.41 10.22 11.05 11.81	8.415 7.835 7.24 6.7	90.4	542.7	229.1
1700	300	770	770	245	250	8.10 8.95 9.82 10.64 12.06	8.53 7.93 7.425 6.88 5.94	81.6	593.4	272.0
1900	75	550	545	195	200	6.75 7.59 8.28 8.98 10.41 12.04	7.165 6.485 5.94 5.39 4.315 3.09	56.3	427.1	201.4
1900	150	625	625	200	205	8.74 9.36 9.79 10.62 11.44 12.37	7.525 7.055 6.75 6.165 5.59 4.935	74.6	475.8	209.4
1900	200	670	650	205	215	8.45 9.38 10.26 11.12 12.07	8.155 7.455 6.835 6.235 5.575	79.3	509.9	225.0
700	0	345	345	185	195	2.10 3.04 4.10 5.01	3.725 2.78 1.75 0.885	10.1	285.9	187.7

Average hot side temperature is average of temperatures taken at three locations on the hot structure outer surface, i.e. the module side.
Average cold side temperature is average of temperatures taken at three locations on the inner surface of the heat sink, i.e. the module side.

faulty thermostat. Figure 14 is a graph of the coolant water temperature into the test generator as a function of engine power at various engine speeds. One can see how the engine coolant temperature increased at what appears to be the square of the engine power for most speeds reaching 245°F at one point, or 65°F above the nominal temperature of 180°F. This high coolant temperature resulted in a significant reduction in generator power output compared to the output which should be obtained at the same operating points at a normal coolant temperature.

The coolant problem may also have been partially a result of where the generator cooling system was connected to the engine coolant circuit. The Cummins L-10 used what is called an "optimized coolant system" which means that the intercooler was placed in the coolant stream between what would normally be the radiator and the engine coolant pump inlet. Using the coolant pump outlet as the source of coolant for the thermoelectric generator, as was done, subjected the generator to a higher temperature coolant than would have been available directly from the radiator outlet. Even so, this does not explain why the coolant temperature at the coolant pump outlet was excessively high.

Figure 15 presents a graph of the generator output as a function of engine power for various engine speeds. The data points at the higher engine power ratings which should be higher than shown in part because of the previously mentioned cooling problem.

From a preliminary review of the raw data, it appears that we were obtaining a gas side heat transfer about as expected. There could possibly be an additional contributing factor in heat exchange due to the pulsating nature of the gas flow. However, it is somewhat difficult to make a detailed evaluation because of the high coolant temperature problems and possible high thermal resistance on the cold side.

The liquid heat transfer appears to be good in the cold sinks. The temperature difference between the water and the metal of the heat sink could be decreased by the addition of water side heat transfer area.

As a first approximation, the output power of a thermoelectric generator is proportional to the square of the temperature difference across the device. This means that the difference between the 180 Watt design output and the 126.6 Watt output from the Proof-of-Principle generator is a temperature difference of 51°F.

The major result of the first test was that while the original maximum power goal of 180 Watts was not achieved, the generator functioned as designed throughout the test phase and produced significant amounts of power (126.6 Watts maximum). This proves the principle of operation. We believe that the power output can be improved significantly in the future as we continue to experiment with the generator and learn more about its operation and the interaction of the generator with the Diesel engine system.

One can see from inspecting Figures 14 and 15 that the decrease in generator power output which occurs above an engine output of 225 HP corresponds with a steep increase in coolant temperature. This is a good indication that the two are related in a cause-and-effect situation.

Figure 14. Coolant Temperature vs Engine Power

Figure 15. Generator Power vs Engine Power

5.0 Future Plans

Hi-Z plans to continue with a small Proof-of-Principle testing and development program as funds become available. There are no firm plans for the next round of engine testing currently scheduled. When the necessary arrangements can be made, we plan to make some minor modifications to the generator cold sink and instrument the hot and cold sides of the modules to determine where the high thermal resistance is occurring. We also plan to eliminate the ammeter from the circuit and have the engine high power surge and high coolant temperature problems corrected before these runs are made.

Hi-Z recently completed a study, HZ-021191-1, for DOE entitled "Evaluation of Novel Waste Heat Recovery Concepts for Heavy Duty Diesel Engines" under subcontract 86X-SF170C to Martin-Marietta Energy Systems, Inc., Oak Ridge. This study investigated the design of a generator for

a heavy duty Diesel Engine and used that design as the basis to study the economic aspects of such a system, including the estimated price of such a generator and an estimate of the cost break-even time with respect to a conventional shaft-driven alternator. We believe the results of the study were very favorable.

Based on the results of both the "Proof-of-Principle" program and the "Novel Waste Heat" program, Hi-Z applied to the California Energy Commission (CEC) for a matching fund grant under California's Energy Technology Advancement Program (ETAP) to continue the effort to develop a thermoelectric generator for Diesel Engines. The DOD has agreed in principle to join the CEC and provide the majority of the remaining matching funds for the program. Hi-Z and two other private companies will provide the remainder of the funds. The goal of this program is to design and build a 1 kW generator for a heavy duty Diesel truck and test it both on an engine in a test stand and in an over-the-road demonstration in a truck.

Hi-Z has been selected for funding by the ETAP program. The contract is due to be signed in August, 1991 and will run at least two years. We believe that completion of this program will lead to the introduction of the thermoelectric generator into Diesel trucks on a commercial basis in the 1994-95 time frame.