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PERFORMANCE OF THE ENGINE-GENERATOR USED IN THE JERSEY CITY TOTAL ENERGY PLANT

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ABSTRACT

Each of five 600-kilowatt (kw) diesel engine-generators which were to be installed in a total energy plant was performance tested under NBS direction at the engine-generator vendor's plant. These tests provided a basis for acceptance of the engine-generators and for comparison with installed performance.

This testing was performed as a part of a comprehensive study to assess engineering, economic, and environmental aspects of a total energy plant which supplies all electrical power, hot water, and chilled water to an apartment complex in Jersey City, New Jersey. Under sponsorship of the Department of Housing and Urban Development (HUD), the National Bureau of Standards (NBS) has instrumented the total energy site for engineering data and is collecting economic and environmental data.

The engines were tested at seven power levels ranging from 0 to 110% rated electrical load. In the tests, fuel consumption, electrical output, and jacket-water heat recovery were measured, as well as many other parameters. Results are reported for fuel consumption, electrical efficiency, and electrical-plus-thermal efficiency, and comparisons are made with measured data from the total energy plant.

Key words: Diesel engine performance; engine-generator performance; engine-generator efficiency; heat recovery; total energy systems.

TABLE OF CONTENTS

Abstract i

1. Introduction 1

2. Units Tested 5

3. Test Procedures and Test Conditions 5

4. Test Results 7

 4.1 Energy Input and Output 7

 4.2 Electrical Efficiency 7

 4.3 Electrical Plus Thermal Efficiency 14

5. Conclusions 16

Acknowledgments 17

Performance of the Engine-Generators Used in the Jersey City Total Energy Plant

by

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1. Introduction

An apartment complex in Jersey City, N.J. sponsored by the Department of Housing and Urban Development (HUD), is being evaluated as a total energy demonstration project by the National Bureau of Standards (NBS). The complex covers 2.4 hectares (6 acres) of land and consists of 485 dwelling units in four medium-and high-rise buildings, an elementary school, a 4600-square meter (50,000 square foot) office building, a community swimming pool, and a central equipment building. All of the electrical power, hot and chilled water for space heating, cooling and domestic hot water required by the site are provided by a central plant.

Electrical power is generated by five 600 kW diesel engine-generators. Thermal energy for space heating and domestic hot water production is recovered from the jackets of the engines and from heat exchangers on their exhausts. Supplementary thermal energy is supplied by two 4.0 MW ($13.6 \cdot 10^6$ Btu per hour) hot-water boilers. During the air-conditioning season, the recovered thermal energy is used in two 1.9 MW ($6.6 \cdot 10^6$ Btu per hour) absorption refrigeration machines to produce chilled water. The electrical power, hot water and chilled water are distributed from the central equipment building to the site buildings through underground conduits.

At the Jersey City Site, heat is recovered from the engine-generators and utilized by a primary hot water loop. As shown in Figure 1, the primary loop hot water which ranges in temperature from 82° to 99°C (180° to 210°F) passes through the engines, boilers, chillers, a site heat exchanger, dry cooler, and an emergency heat exchanger. The primary loop supplies 5000 kilograms (11000 pounds) of water per minute to the engine jackets and mufflers. From the engines, this water passes through two 25 HP circulation pumps and then through the boilers where additional heat can be added if necessary. In summer the primary water is routed through two 546 ton absorption chillers which provide chilled water at 7°C (45°F) for the site. The primary hot water also passes through heat exchangers transferring heat to the site secondary hot-water loop. A four-pipe network circulates the chilled water and the secondary hot-water to the site buildings. In the rare event that both heating and cooling demands are extremely low, dry coolers release excess primary heat to the atmosphere to prevent the engines from overheating. An emergency heat exchanger using raw city water backs up the dry coolers.

The five 600 kW diesel engine-generators used in the total energy plant were selected to match the combined plant and site electrical demand and provide the necessary standby capacity. At the lowest demand (∿600 kW), two engine-generators can meet the demand without operating below a 50% load factor. At the highest demands (∿1400 kW), three units can meet the demand without operating above 80% of their rated full load. This design promotes engine longevity, maintains high average efficiency, and allows the maximum electrical load to be met while one spare engine is being maintained and the other spare engine is on standby. Figure 2 shows one of the five engines as it has been installed.

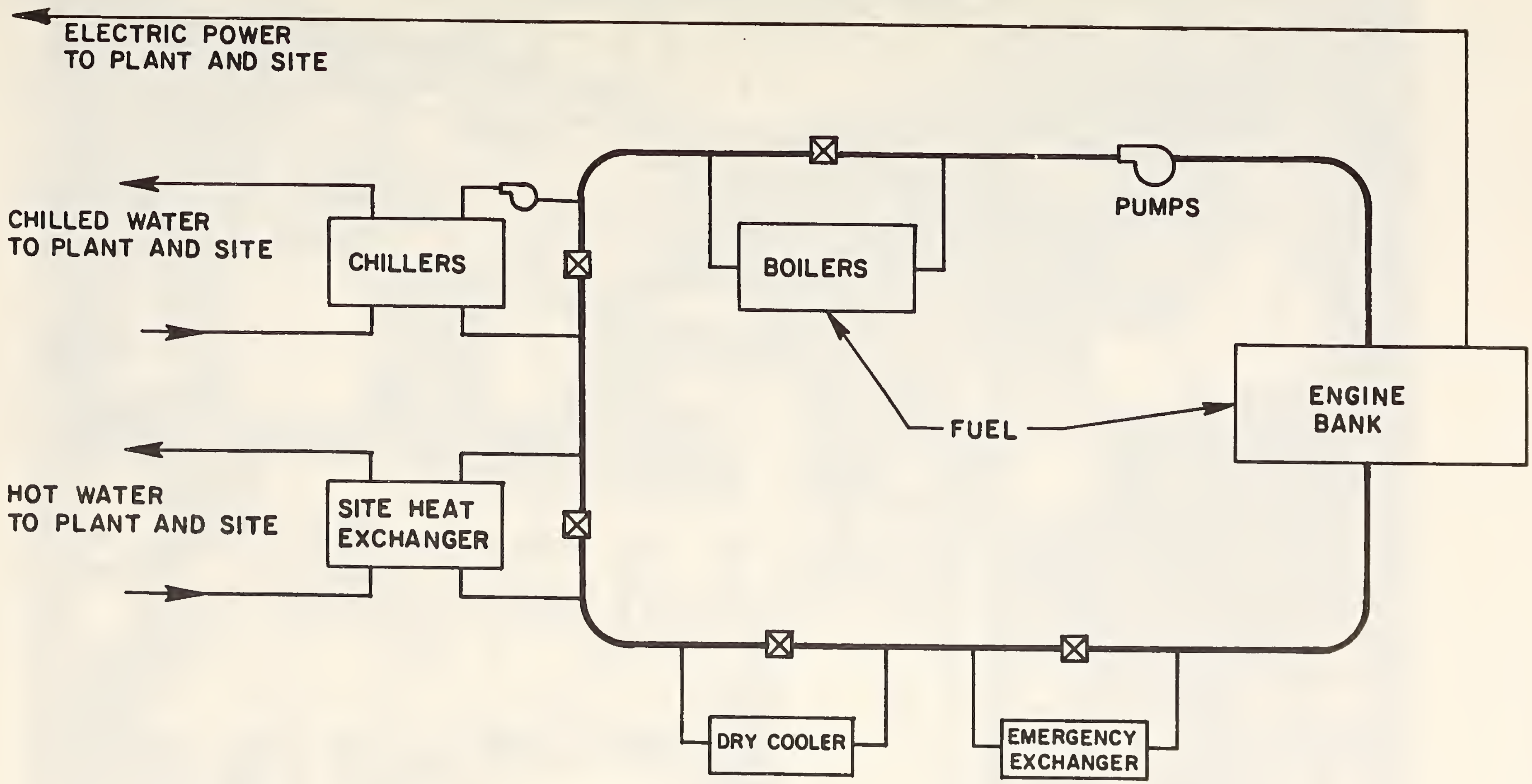

Figure 1. Schematic of Primary Hot-Water Loop Which Recovers Heat From Engines and Boilers for Site Hot Water and Chilled Water Production

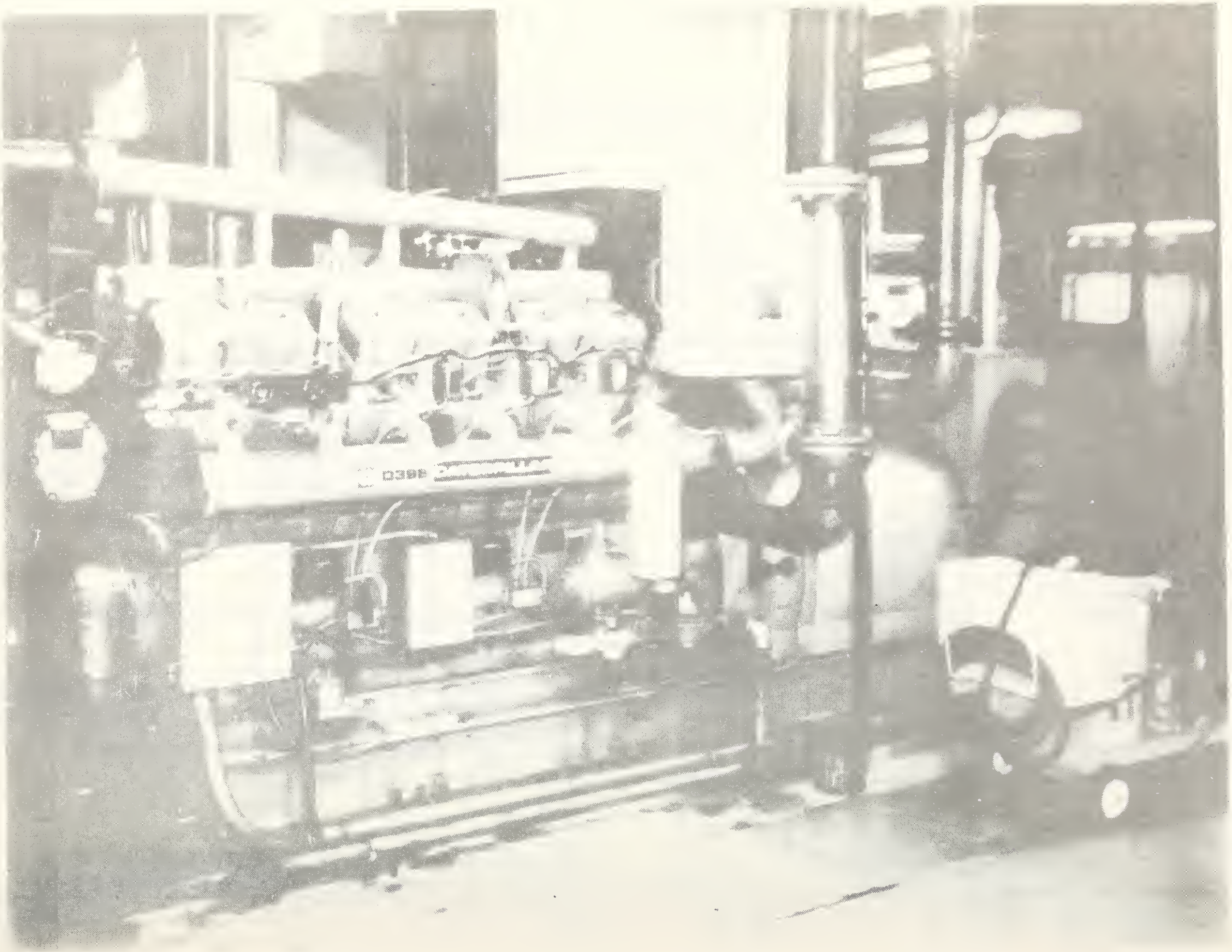

Figure 2. Photograph of One Engine-Generator as Installed at the Jersey City Total Energy Site

The tests of the engine-generators were conducted at the vendor's facilities according to the purchase specification under the direction of the National Bureau of Standards (NBS). The purchase specification was based upon a performance specification for the Jersey City total energy plant.* These acceptance tests covered electrical and thermal efficiency, speed control, operating temperatures, and several other factors.

2. Units Tested

The V-12 diesel engines were of the 4-cycle type designed to operate at 1200 RPM, and were equipped with turbochargers and after-coolers. The electrical generators were designed to deliver 600 kW at 480 volts, three-phase, and 60 hertz. The units were tested simulating anticipated plant conditions. Fuel temperature, intake air temperature, cooling water temperatures and flow rates, and load power factor values were adjusted in accordance with site design. One exception was that cooling water was circulated by unit-driven mechanical pumps for the tests; at the site, cooling water is pumped by external electrical pumps. Also, heat was not recovered from the engines' exhaust gases during the factory tests.

3. Test Procedures and Test Conditions

Fuel consumption and jacket water heat recovery were measured for all five units at constant electrical loads of 0, 20, 40, 60, 80, 100 and 110% full load. During each load test, the pertinent electrical, mechanical and thermal variables were recorded.

Tests were conducted and data were recorded by vendor personnel and contractors under NBS supervision. Test results were analyzed by NBS staff.

*National Bureau of Standards Interagency Report NBSIR 10313-A Performance Specification for a Total Energy Plant at the Jersey City Breakthrough I Site - (Dec. 1970).

Each unit was set up in an individual test cell. Electrical loads were applied from a load bank having a constant power factor of 0.8. The frequency of the delivered power was maintained at 60 hertz and the voltage was maintained between 472 and 480 volts.

The water flow rate through the engine jacket was maintained constant for all tests at 1136 liters (300 gallons) per minute. The water flow rate through the oil cooler and aftercooler was maintained constant at 379 liters (100 gallons) per minute. The water passed through the oil cooler first and then through the aftercooler. Below 100% full load, jacket water inlet temperatures were kept below 109°C (228°F). At 100 and 110% load, jacket inlet temperatures were kept below 93°C (200°F).

Number 2 fuel oil was burned in each engine throughout the tests. The higher heating value for this fuel averages 45.36 MJ per kg (19500 BTU per pound).

Units were tested under steady-state conditions and data were recorded only after all parameters stabilized. Each unit was operated initially at 110% full load for two hours followed in order by one-hour tests at 100%, 80%, 60%, 40% and 20% load conditions and finally at no load conditions for one-half hour. During the tests, data were recorded every 15 minutes so that four sets of data points were taken for each unit at each test load (except at 110% and 0% loads).

4. Test Results

The average values and the range of values for each of the load-independent variables observed on the five units during the tests are summarized in Table 1. The corresponding average values of load-dependent variables are shown separately in English and SI units in the two parts of Table 2. From this data, energy input-output rates, engine-generator electrical efficiency, and electrical-plus-thermal efficiency have been computed.

4.1 Energy Input and Output

The energy-equivalent of the engine fuel consumption, the electrical output, and the jacket heat recovery at the 6 power levels are expressed as kilowatts in Figure 3. These results are summarized in Table 3.

4.2 Electrical Efficiency

Electrical efficiency is equal to the total electrical load divided by the rate of fuel consumption times the fuel's higher heating value.

Because engine-driven mechanical pumps were used to circulate the water through the jackets, oil coolers, and aftercoolers during these acceptance tests, a correction must be made for the shaft power required for these pumps in order to allow a comparison of engine-generator efficiencies during the acceptance tests with operation at the Jersey City site. The engines' manufacturer determined that these pumps required approximately 17 horsepower during the tests. To correct for the pump power during the tests, the 17 additional horsepower required by the pumps is assumed to be available for electric conversion. A 92% efficient generator would convert 17 horsepower to 11.7 kW. Thus, in computing the engine-generator efficiency for these tests 11.7 kW was added to the generator electrical power output.

The corrected electrical efficiency results are graphed in Figure 4 and summarized in Table 3. Electrical efficiency ranged from 31.6%

Table 1

Performance of Five Diesel Engine-Generator Units

Average Values of Load-Independent Variables Measured During Tests

	Mean	Range*
Fuel Pressure	$1.65 \cdot 10^5$ Pa (24 psi)	± 8%
Lubrication Oil Pressure	$3.72 \cdot 10^5$ Pa (54 psi)	± 15%
Oil Cooler Inlet Pressure (water side)	$4.69 \cdot 10^5$ Pa (68 psi)	± 7%
Oil Cooler Outlet Pressure (water side)	$4.65 \cdot 10^5$ Pa (67.5 psi)	± 7%
Aftercooler Inlet Pressure (water side)	$4.55 \cdot 10^5$ Pa (66 psi)	± 7%
Aftercooler Outlet Pressure (water side)	$4.41 \cdot 10^5$ Pa (64 psi)	± 7%
Generator Output Voltage	479 volts	472 - 480
Generator Output Frequency	60 Hz.	negligible
Load Power Factor	0.8	negligible
Engine Speed	1200 rpm	1200 - 1201
Fuel Temperature	31°C (88°F)	26°C - 35°C
Inlet Air Temperature	31°C (88°F)	23°C - 38°C
Jacket Water Flow	$1.89 \cdot 10^{-2}$ m^2/s (300 gpm)	negligible
Jacket Water Pressure Drop	$3.45 \cdot 10^4$ Pa (5 psi)	± 6%
Oil Cooler/Aftercooler Water Flow	$6.31 \cdot 10^{-3}$ $m3/S$ (100 gpm)	negligible
Oil Cooler/Aftercooler Water Pressure Drop	$2.07 \cdot 10^4$ Pa (3 psi)	± 18%

*Range includes variations among engines, variation from load changes, and apparatus drift. Variables which were strongly load dependent are not listed on this table but are listed in Table 2.

Table 2
(English Units)
Performance of Five Diesel Engine-Generator Units

Average Values of Load-Dependent Variables Measured During Tests

% Load	110%	100%	80%	60%	40%	20%	0%
Generator Load (KW)	660	600	475	356	237	118	0
Jacket Inlet Temp. (°F)	197.0	196.6	227.0	220.4	213.04	207.8	215.1
Jacket Outlet Temp. (F°)	210.6	208.4	235.3	226.8	218.1	211.2	216.1
Oil Cooler Water Inlet Temp.(°F)	130.1	128.9	128.5	127.5	127.0	126.6	126.1
Oil Cooler Water Outlet Temp.*(°F)	136.0	134.4	134.5	133.2	132.0	130.5	129.3
Aftercooler Water Outlet Temp. (°F)	143.5	140.5	138.4	135.5	132.8	131.0	129.3
Inlet Manifold Temp. (°F)	157	151	144	137	132	129	127
Exhaust Manifold Temp. (°F)	1036	987	888	787	655	506	333
Exhaust Back Pressure (psi)	.60	.50	.33	.21	.13	.08	.05
Fuel Consumption Rate (lb/hr)	377.2	340.2	269.6	206.6	145.5	91.5	12.0
Generator Temp. (°F)	171	151	137	124	113	106	104
Exciter Current (amperes)	3.5	3.1	2.7	2.4	2.0	1.7	1.5

*Value is also aftercooler water inlet temperature

Table 2

(SI Units)

Performance of Five Diesel Engine-Generator Units

Average Values of Load-Dependent Variables Measured During Tests

% Load	110%	100%	80%	60%	40%	20%	0%
Generator Load (KW)	660	600	475	356	237	118	0
Jacket Inlet Temp. (°C)	91.7	91.4	108.3	104.7	100.8	97.7	101.7
Jacket Outlet Temp. (°C)	99.2	98.0	112.9	108.2	103.4	99.6	102.3
Oil Cooler Water Inlet Temp. (°C)	54.5	53.8	53.1	52.8	52.6	52.6	52.3
Oil Cooler Water Outlet Temp.*(°C)	57.8	56.9	56.9	56.2	55.6	54.7	54.1
Aftercooler Water Outlet Temp. (°C)	61.9	60.3	59.1	57.5	56.0	55.0	54.1
Inlet Manifold Temp. (°C)	69	66	62	58	56	54	53
Exhaust Manifold Temp. (°C)	558	531	476	419	346	263	167
Exhaust Back Pressure (Pa)	$4.1 \cdot 10^3$	$3.4 \cdot 10^3$	$2.3 \cdot 10^3$	$1.4 \cdot 10^3$	$8.9 \cdot 10^2$	$5.5 \cdot 10^2$	$3.4 \cdot 10^2$
Fuel Consumption Rate (kg/hr)	171.1	154.3	122.3	93.7	66.0	41.5	5.4
Generator Temp. (°C)	77	66	58	51	45	41	40
Exciter Current (amperes)	3.5	3.1	2.7	2.4	2.0	1.7	1.5

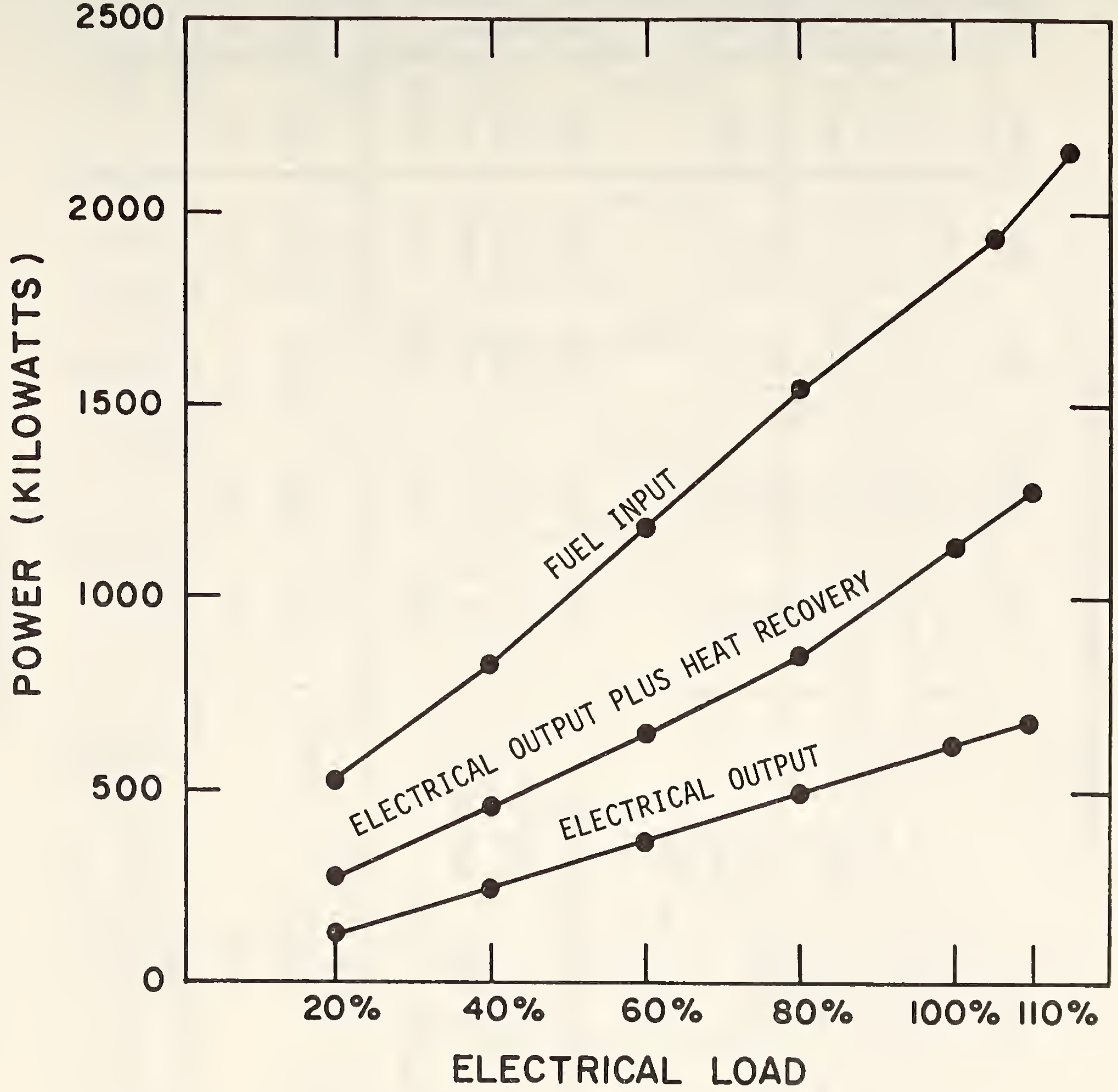

Figure 3. Energy Equivalents of Fuel Input, Electrical Output, and Electrical Output Plus Jacket Heat Recovery

Table 3

Performance of Five Diesel Engine-Generator Units

Efficiency Computations and Results

% Load	110%	100%	80%	60%	40%	20%
Electrical Output (KW)	660	600	475	356	237	118
Electrical Equivalent of Pump (KW)	11.7	11.7	11.7	11.7	11.7	11.7
Total Electrical Output (KW)	671.7	611.7	486.7	367.7	248.7	129.7
Jacket Water Flow Rate (L/S)	1136	1136	1136	1136	1136	1136
(gpm)	300	300	300	300	300	300
Jacket Water Temp. Rise (°C)	7.56	6.50	4.61	3.56	2.61	1.89
(°F)	13.6	11.7	8.3	6.4	4.7	3.4
Heat Recovered from Jacket (KW)	598	515	365	282	207	150
(KBtu/hr)	2042	1757	1246	961	706	511
Electrical Plus Thermal Output (KW)	1269.7	1126.7	851.7	649.7	455.7	279.7
Fuel Consumption (kg/h)	171.1	154.3	122.3	93.7	66.0	41.5
Heat Content of Fuel (MJ/Kg)	45.35	45.35	45.35	45.35	45.35	45.35
Power Input (MJ/h)	7759	6998	5546	4249	2993	1882
(KW)	2155	1944	1541	1180	831	523
Electrical Efficiency	31.2%	31.5%	31.6%	31.2%	29.9%	24.8%
Electrical Plus Thermal Efficiency	58.9%	58.0%	55.3%	55.1%	54.8%	53.5%

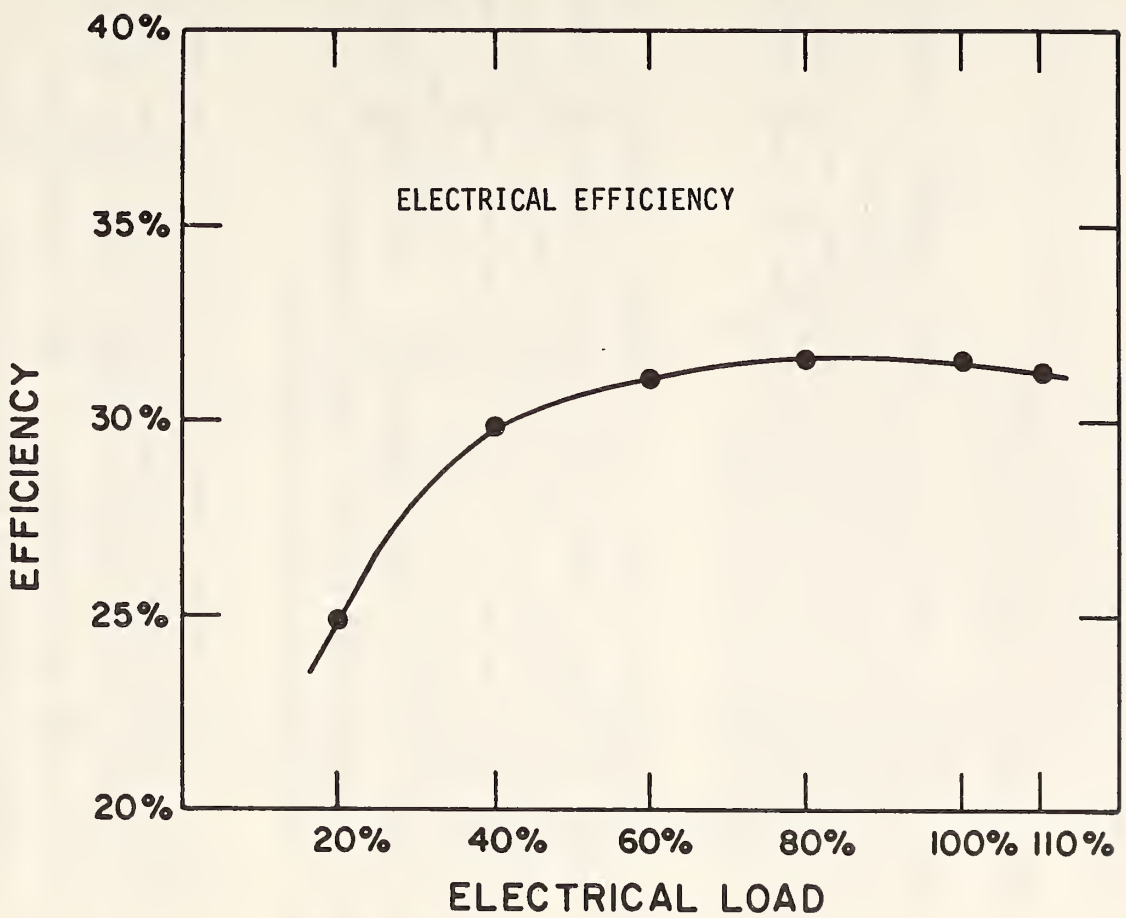

Figure 4. Gross Electrical Efficiency of Engine-Generators versus Generator Load

at 80% load to 29.9% at 40% load. Individual unit results had a standard deviation of 0.9%. Individual results are not reported because their standard deviation was in the range of the probable fuel-consumption measurement accuracy.

4.3 Electrical Plus Thermal Efficiency

Electrical-plus-thermal efficiency was computed by summing the total electrical load (including the circulating-pumps electrical-load equivalent) with the rate of jacket heat recovery and dividing that quantity by the rate of fuel consumption times the fuel's higher heating value using consistent units.

Results are graphed in Figure 5 and summarized in Table 3. Electrical-plus-thermal efficiency ranged from 55.3% at 80% load to 54.8% at 40% load. Figure 5 shows a 3 to 5 percent increase in the electrical-plus-thermal efficiencies at 100% and 110% percent loads in comparison with the efficiencies at 40% to 80% loads. This increase in efficiency corresponds to the lower inlet temperature of the jacket water used during the tests at 100% and 110% loads and appears to be a direct result of this change in operating conditions.

The jacket inlet and outlet temperature differential was determined by two separate temperature measurements each having minimum uncertainty of ±.3°C (±.5°F). Errors in the calculated jacket heat recovery from 5% to 23% may have resulted because of the relatively small (1.9°C to 7.5°C) temperature difference between the jacket's inlet and outlet water. It should be noted that heat recovered from the units' oil coolers and aftercoolers is not included in the thermal efficiency computation, because its temperature is too low for use in the primary loop at the site.

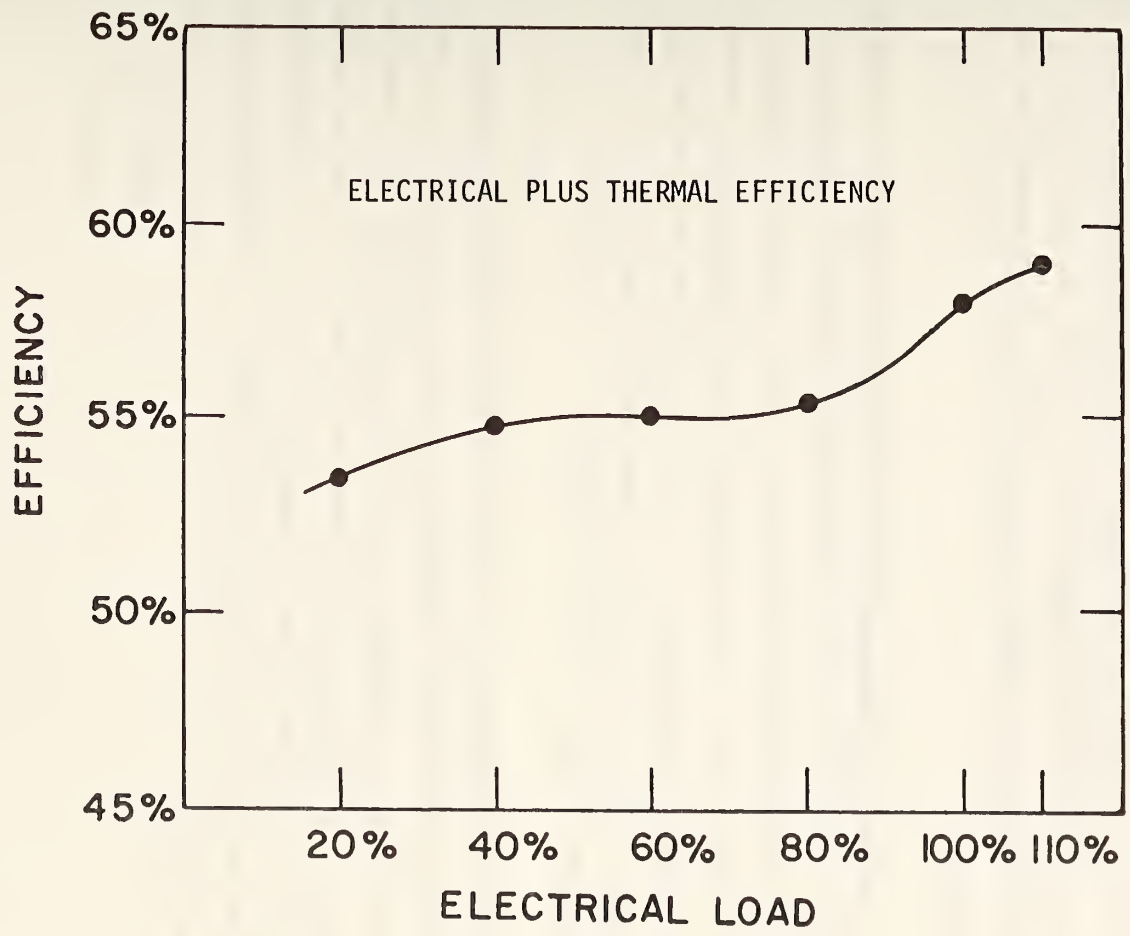

Figure 5. Gross Electrical Plus Jacket-Heat Recovery Efficiency versus Generator Load

5. Conclusions

The test results indicated that the five units have very similar efficiencies, since the standard deviation among the values for the five engines was only 0.9%. Over the 40% to 80% load range, which comprises the major part of the operating duty, average electrical efficiency of the five units ranged from 29.9% to 31.6%, electrical-plus-thermal efficiency ranged from 54.8% to 55.3% (exhaust heat was not recovered).

Performance of the engine-generators at the Jersey City total energy plant has been monitored by an on-site data acquisition system. It should be noted that several differences exist between the factory test set-up and the plant installation of the engines. For instance, at the site, heat is recovered from both the engine jackets and the exhaust gases. Also, at the site, jacket water heat is lost because it is circulated through the idle engines.

After 10,000 to 15,000 hours of engine running time, preliminary results from measured data indicated that the engine-generator gross electrical efficiency averaged 32.4% during a period of 60% load on three engines. Electrical-plus-thermal efficiency, including exhaust recovery and idle engine losses, averaged 61.4% during the same period. A summary of the plant operating performance will be available in a future publication.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Each of five 600-kilowatt (kW), diesel engine-generators which were to be installed in a total energy plant was performance tested under NBS direction at the engine-generator vendor's plant. These tests provided a basis for acceptance of the engine-generators and for comparison with installed performance.

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17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

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