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# Low-Cost Small Gas Turbine

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This paper presents information on the NREC core engine development program. The subject engine is a 100-hp, two-shaft gas turbine that is the low-power end of a family of engines up to 500 hp, both nonregenerative and regenerative. The major goal of the program has been the development of a *low-cost* small gas turbine engine (less than $5/hp to produce in quantities of 15,000/yr). Other objectives include low emissions (meeting the anticipated EPA standards for the markets of interest), relatively high performance (design point SFC = 0.7 for the simple-cycle engine and 0.4 for the regenerative version), and relatively long life (10,000-hr life at design power and a minimum service period of 500 hr). Items specifically covered in this paper include the following: (*a*) A description of the core engine concept. Frame size, regenerative, recuperative, and air compressor versions are discussed. (*b*) A technical description of the core engine concept. The salient low-cost features are identified. (*c*) The development program results. Some of the engine performance and manufacturing cost analysis results are given.

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# Low-Cost Small Gas Turbine

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## INTRODUCTION

Northern Research and Engineering Corporation is currently developing a 100-hp small gas turbine engine. This engine is the basis for a range of engine sizes and cycles that are considered necessary to meet the needs of the industrial, small engine marketplace (specifically the marine and portable air compressor, generator, and pump markets).

The chief design goals of the engine have been:

1 Low manufacturing cost.
2 Adaptability to regenerative/recuperative cycles.
3 Low emissions.
4 Low simple-cycle fuel consumption.
5 10,000 hr design life.

High manufacturing cost is one of the chief obstacles to the development of the market for small gas turbine engines. Current industrial internal-combustion engines are being manufactured at shop costs ranging from $1 to $10/hp, depending on size and production numbers. Simple cycle gas turbine engines are reported to cost from $15 to $35/hp. Much of the above differential has been attributed to the high cost of temperature-tolerant materials, the more sophisticated accessories and controls used, and to small production quantities.

NREC has made an attempt to attenuate the cost problem while at the same time creating an engine that will be performance and life competitive in industrial applications. The general approach taken and some of the results to date are presented herein.

## CONCEPT REVIEW

The core engine reviewed herein is a simple Brayton cycle gas turbine engine with a free power turbine and an output speed reducer. The engine is arranged to facilitate adaptation without major changes into both recuperative and regenerative cycles.

The cycle pressure ratio of 5:1 was chosen both to obtain a reasonable simple cycle fuel consumption and to be near the optimum for the regenerative engine version. A turbine inlet temperature of 1700 F was selected to obtain the lowest specific power consistent with the low cost (uncooled turbine stator and rotor blades and state of the art materials) and long life (10,000 hr) features. Three core engine frame sizes were found necessary to cover the desired output power range of 100 to 500 hp. Each frame size is intended to produce several discrete design power ratings by adjustment of the gas-path flow area. This is provided for in the engine design by detail features that permit the gas-path radial height to be easily altered during manufacture. A schematic showing the frame sizes, output power bounds, outline dimensions, and weight is shown in Fig. 1; the data shown includes a 3600 rpm output speed reduction gearbox. The smallest frame size was selected for development because it presented the most difficult design and manufacturing cost obstacles. This engine has an air flow of 1.16 lb/sec. The estimated performance characteristics of both the core engine and the regenerated engine are shown in Fig. 2.

The core engine exterior and cross-section views are shown in Figs. 3 and 4. As can be seen, the engine has a single-stage centrifugal compressor, a slinger injected annular combustion chamber, a single-stage axial gasifier turbine, and a single-stage axial power turbine. The reduction gear is two-staged, with three parallel idler shafts. No accessory gearbox or engine mounted accessories are required, except for a starter and an alternator; the basic design philosophy has been to remove the requirements for as many external engine accessories as possible (for example, fuel pump, oil pump, and oil cooling systems).

The core engine is packaged to form a cylindrically shaped module. This module is arranged so it can be inserted into a larger structure that houses either regenerative or recuperative heat exchanger surfaces and the gas ducting. This is best understood by referring to Figs. 5 and 6. This packaging approach to a

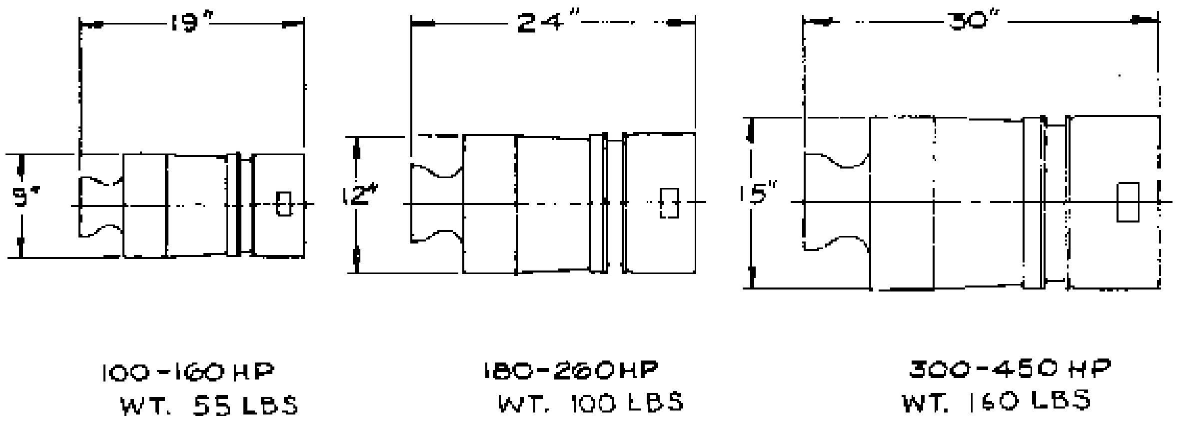

Fig. 1 Frame size specifications

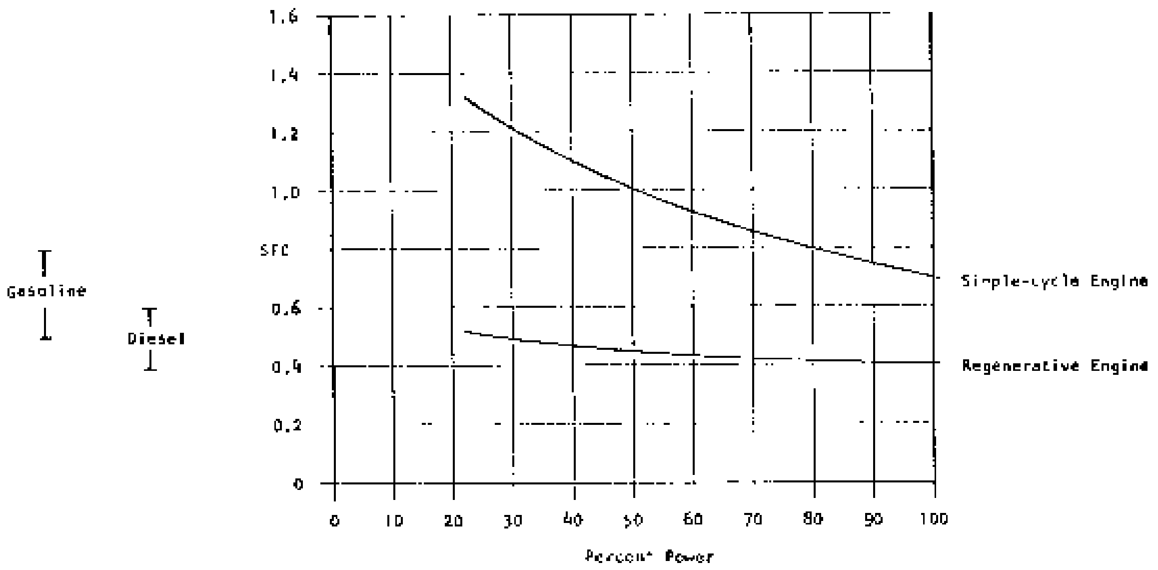

Fig. 2 Estimated performance characteristics

small gas turbine allows a great commonality of parts for a range of engine types, thus providing for cost reductions associated with quantity.

Another derivative version of the engine is a portable air compressor. This package is shown in Fig. 7. In this design the core engine is made into a single-shaft engine that can provide compressed air at pressure ratios of 9:1 and higher. The concept is mechanized by high flowing the core engine compressor, adding a second-stage compressor to the power turbine and locking the two rotors together. Intercooling between the compressors is required.

## CORE ENGINE DESCRIPTION

The design details of the core engine that are intended to reduce manufacturing cost are best understood by first giving a general description of the aerodynamic and mechanical systems.

The gas path through the engine is as follows. Air enters the compressor impeller axially past three radial struts. The impeller discharges into a single-stage radial, vaned diffuser. After leaving the diffuser, the air is turned axially and diffused further before entering the combustion chamber. A portion of this air passes down the

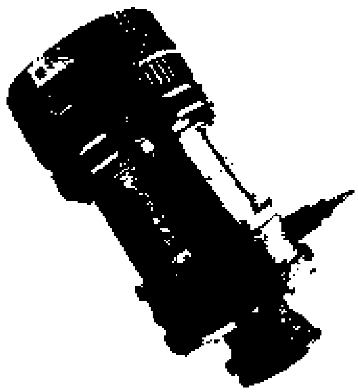

Fig. 3 Core engine assembly, exterior view

Fig. 5 Regenerative engine arrangement

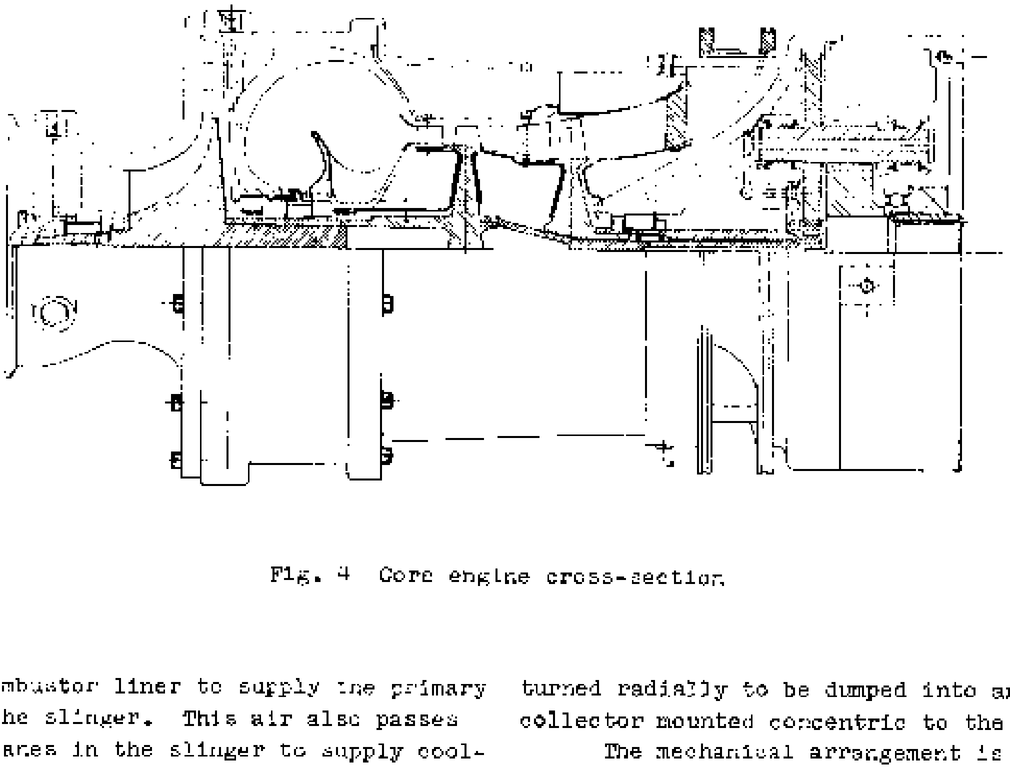

Fig. 4 Core engine cross-section

front of the combustor liner to supply the primary zone air near the slinger. This air also passes through axial vanes in the slinger to supply cooling air to the underside of the combustor liner and the rear portion of the primary zone. The remaining air passes through secondary and dilution zone holes in the top of the liner. Some muff-air is supplied past the underside of the liner to cool the hub surface of the gasifier stator. Additional cooling air is supplied to the front face of the gasifier turbine disk. The combustor discharges into the gasifier turbine stator. The gases then pass through the gasifier turbine, are slightly diffused, and then enter the power turbine stator and rotor. The exhaust from the power turbine is further diffused and turned radially to be dumped into an exhaust collector mounted concentric to the engine.

The mechanical arrangement is best understood by referring to Fig. 4. The rotor system is arranged to have cool bearing cavities or sumps remotely located from the hot section of the engine. The gasifier rotor assembly consists of an impeller, two front bearing thrust collars, two labyrinth air seals, the fuel slinger, the gasifier turbine, and its shaft. The front end of the assembly is supported by a combined radial and thrust sleeve bearing. The rear of the assembly is supported by a needle bearing located internal to the power turbine shaft. The gasifier rotor design speed is 76,600 rpm.

The power turbine rotor assembly consists

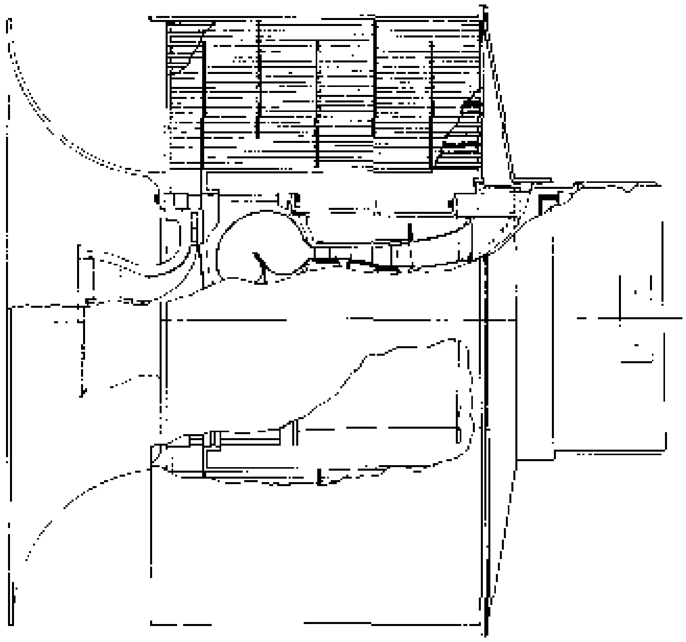

Fig. 6 Recuperative engine arrangement

of the power turbine, two thrust collars, and the output pinion. Its design speed is 69,000 rpm. This assembly is supported by one sleeve bearing and the three gears disposed around the output pinion. The power turbine is prevented from overrunning the gasifier rotor by a self-energizing clutch located in the annulus between the power turbine and gasifier shafts.

The output of the power turbine is reduced in speed to 3600 rpm by a two-stage gear train having three idler shafts. Roller bearings are used to support the idler shafts.

The engine static structure consists primarily of the compressor shroud, a main housing (surrounding the combustor), a turbine casing, and the gear case. This mechanical circuit is designed to operate cool and provide a stiff support for the rotor bearings located in the extremities of the structure. The pressurized hot gas from the combustor is contained by a ceramic turbine shroud, an exhaust duct, and an exhaust casing. The latter is a floating structure to permit thermal expansion; it is configured to permit five cool gear case supports to pass through and mate with the turbine casing.

The core engine has a total of 55 drawing number items and 97 items if standard is included. A photo of the major parts is shown in Fig. 8.

Cost Reduction Features

The salient design features of the core engine that are intended to reduce manufacturing cost are summarized as follows:

1 Fuel and Lubrication Systems. There are none of the conventional fuel and lubrication system accessories. The reduction gearing and the power and gasifier turbine bearings are splash lubricated by a novel oil circulating system assisted by a bleed air powered mixer. The heat load from this portion of the engine is rejected to ambient via a finned gear case exterior. The front or compressor bearing is lubricated by the engine fuel. This bearing system also acts as the fuel pump.

2 Accessory Gearbox. An accessory gearbox is not required for engine fuel and lubrication accessories. Therefore, it was decided to eliminate it and provide only wild frequency a/c power for customer use and battery charging. This will be generated by a small permanent magnet alternator operating at gasifier shaft speed and located inside the reduction gear case.

3 Combustor. The annular combustor with slinger fuel injector arrangement was chosen because it provided the best potential for cost

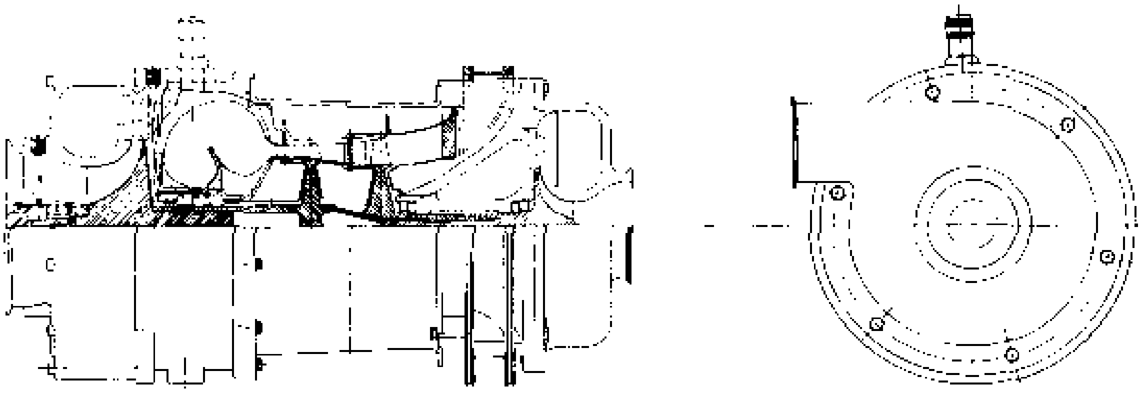

Fig. 7 Portable bleed air compressor arrangement

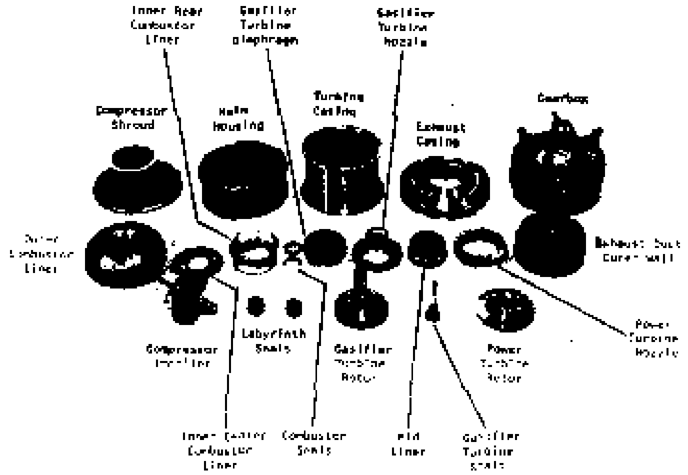

Fig. 8 Selected engine components

Fig. 9 Reduction gearbox and power turbine assembly

reduction, low emissions, and fuel system simplification. The fuel slinger system developed for the engine requires only minimal fuel pressure and has excellent fuel distribution and droplet size characteristics; in addition, it is tolerant of dimensional variations and dirt. These features are particularly important when the low fuel flows required by the engine are considered. The combustor liners are simple sheet metal spinnings that have no weldments, fussy cooling geometries, or critical dimensional tolerances. These features are gained because of the symmetry and cooling control that is possible with the annular configuration and specifically the unique primary zone design of the subject engine.

4 Gasifier Rotor Air Seal. A low-cost method of manufacturing an abradable labyrinth air seal was developed. The basic problem was that of attaching an abradable material to a backing ring in an economic fashion while permitting operation at high temperatures.

5 Turbine Stators. The gasifier and power turbine stators have similar design features. The stators are unshrouded, have constant section blades and are untwisted. This simplifies the tooling and permits a one-piece wax to be made for investment casting. The lack of a shroud also facilitates changing the blade height to increase or decrease the power rating of the engine and eliminates the thermal cracking problem of one-piece turbine stators. Both stators have been designed to minimize the amount of costly high temperature material required.

6 Turbine Shroud. A ceramic turbine shroud is used to reduce the strategic material content of the engines and provide a simple, heat-resistant and dimensionally stable structure. The control of turbine tip clearance in a small engine generally leads to costly designs involving cooled support structures and segmented hot parts. The use of a low expansion ceramic material such as CER-VIT solves the tip clearance problem while providing the noted advantages.

7 Gasifier Turbine. The gasifier turbine is designed to minimize the strategic material content and simultaneously facilitate the investment casting of a one-piece wheel. The turbine disk has been carefully shaped to optimize the stress distribution and stress levels to reduce the material content. The solid hub section of the disk permits a more efficient use of material. The turbine blades have a large cross-section taper ratio, a low aspect ratio, and straight-line element surfaces. These features facilitate the design of tooling that will allow one-piece waxes to be made.

8 Reduction Gear. The reduction gear train design was optimized for cost. The size of the gear casing and the total number of gear tooth-inches to be cut were found to be important factors. The resulting design is the more complex of the several considered because of the three idler shafts used. However, the manufacturing cost of the design chosen was found to be 28 percent of the design that by appearance was the simplest.

9 Rotor Shaft Attachments. Tapered, hydraulically floated shaft attachment techniques are used to join the gasifier turbine to the compressor and the power turbine to its output pinion. This design detail is less expensive than the spline, "curvic coupling," or bolted

arrangements generally used. Additional benefits are also obtained. Assembly balance repeatability is improved and assembly time reduced.

10 Shaft Oil Seals. The visco type oil seal is used to seal the compressor bearing cavity and the turbine shaft penetrations. This type seal was found to perform well, is easy to manufacture, and appears to have no assembly quality or wear problems.

11 Overrunning Clutch. The overrunning clutch between the gasifier and power turbine shafts eliminates the need for a power turbine overspeed control system.

## CURRENT PROGRAM STATUS

This engine development program was initiated some three years ago. Component tests have been conducted, and complete prototype engine assemblies have been manufactured and are now undergoing development tests. To date the engine has demonstrated good light-off characteristics (12 percent speed), a low idle speed (40 percent), and vibration-free performance over the operating speed range. The goals for output power and specific fuel consumption have not yet been fully realized but it is expected that they will be attained when a proper matching of the aerodynamic components is completed.

The core engine manufacturing cost has been computed by both NREC and several other qualified manufacturing concerns. The results to date indicate that this turbine engine can be manufactured at a shop cost that is competitive with those of conventional reciprocating engines. The results of the manufacturing cost studies are summarized in Table 1.

The initial emissions measurements indicate that the fully developed engine can be made to meet any EPA emissions requirements that are anticipated for the market applications being considered. Typical results are shown in Table 2.

All emissions are well below the 1975 and 1976 U. S. Federal automotive standards. The existing HC and CO emissions are also well below the 1977 automotive standards. Though the existing NOx results are three times the 1977 automotive standard, they are considered acceptable for industrial engines. In addition, further combustor development is expected to substantially reduce these values.

Table 1 Estimated Shop Cost (in Quantities of 15,000 Engines per Year) for the 100-160 hp Core Engine

| | |
|---|---|
| Compressor Components. . . . . . . . . . . | $ 20.4 |
| Combustor Components. . . . . . . . . . . . . | 36.3 |
| Gasifier Turbine Components. . . . . . . . | 159.5 |
| Power Turbine Components. . . . . . . . . . | 151.1 |
| Reduction Gear Components. . . . . . . . . . | 46.7 |
| Controls. . . . . . . . . . . . . . . . . . . | 72.5 |
| Miscellaneous and Hardware. . . . . . . . . | 4.7 |
| Assembly. . . . . . . . . . . . . . . . . . . | 48.5 |
| Total Shop Cost | $539.7 |

Table 2 Typical Test Results for Combustor Emissions and Performance as Measured on the High-Pressure Combustion Test Rig

| Test Number | 1 | 2 | 3 | United States Federal Exhaust Emissions Standards 1975 | 1976 | 1977 |
|---|---|---|---|---|---|---|
| Pressure, psia | 64.5 | 75.5 | 74.4 | | | |
| Air Flow Rate, lbm/sec | 0.90 | 1.02 | 1.06 | | | |
| Air/Fuel Ratio | 65.0 | 50.6 | 48.4 | | | |
| Combustion Efficiency, percent Emissions, milligrams per gram of fuel | 99.8 | 99.8 | 99.9 | | | |
| HC | 0.70 | 0.71 | 0.49 | 5.2 | 1.42 | 1.42 |
| CO | 4.62 | 3.49 | 3.54 | 52.0 | 11.8 | 11.8 |
| NOx | 5.21 | 5.55 | 4.34 | 10.7 | 6.90 | 1.72 |