

A REAL TIME STUDY OF  
POLLUTANT GASEOUS EXHAUST STACK  
EMISSIONS FROM A STATIONARY  
GAS TURBINE

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A Thesis  
Presented To  
the Faculty of the Department of Civil Engineering  
The University of Houston

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In Partial Fulfillment  
of the Requirements for the Degree  
Master of Science  
in Civil Engineering

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by  
Howard S. Wright  
May, 1970

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## ABSTRACT

This thesis presents the results of a study of pollutant stack emissions from a gas turbine performed on a real time basis.

Field studies were made at the site of a stationary industrial gas turbine utilizing natural gas fuel. Equipment for measuring stack pollutant emissions was obtained and located on the gas turbine site. Nitrogen oxides, carbon monoxide, hydrocarbons, aldehydes and sulfur dioxide were measured. An evaluation of the emissions related to gas turbine exhaust stack mass flow was made.

A literature review of stack emissions from combustion sources was made. Results of the study are presented and discussed. Conclusions are made relating to the emissions measured and the equipment used. The results are related to the Houston area environment.

Recommendations are made for further study and developmental activity.

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CHAPTER I  
INTRODUCTION

The combustion of hydrocarbon and fossil fuels is now the principal contributor to air pollution in urban areas located in the United States. The total of fossil fuels being consumed approximately doubles every 20 years. Obviously, until the total quantity of these fuels diminishes, the demand for energy and the present economics for their use will make them the primary energy source. All combustion including internal combustion for transportation and stationary power sources and external combustion involving power plants, house heating and incineration tend to contribute to the general quality of the air environment. The automobile, for example, contributes approximately 40% of the estimated 200 million annual total tons of pollutant emissions attributable to combustible sources. Power plants contribute 13% of the total pollutant emissions. The by-products of combustion make up approximately 85% of the total air pollutants in the United States.

The primary noxious pollutants from combustion are particulates; sulphur dioxide ( $\text{SO}_2$ ), the product of the combustion of sulfurous fuels, carbon monoxide ( $\text{CO}$ ), result of incomplete combustion; oxides of nitrogen ( $\text{NO}_x$ ), the result of high combustion temperatures, excess air, compression ratios, and other factors and a great many complex hydrocarbons, also a result of incomplete combustion.

The Clean Air Act of 1967 due to public and governmental pressures is currently under study for major revision. The President of the United States has proposed that the federal government's authority over interstate air pollution be extended to intrastate situations. At the present time, the enforcement of the Clean Air Act is through the Department of Health, Education and Welfare (HEW) and other federal agencies acting in conjunction with the states. The primary authority in control of air pollution rests with the state. All emission standards, unless the pollution problem is classified as interstate, are set by state law. However, each state must satisfy federal officials that its pollution program is effective. As long as the pressures to improve the air environment exist, the possibility of federal intervention with emission standards becomes a greater possibility.

In connection with the air pollution problem the federal government and various other groups are attempting to develop combustion sources which will result in a drastically reduced level of pollutant emissions. One of the low contaminant combustion sources discussed prominently is the gas turbine, both for mobile and stationary use. Gas turbines, since they operate under stable conditions, emit less carbon monoxide than piston engines per pound of hydrocarbon fuel, however, because of their low efficiency and high cost they are not yet suitable for transport except in the case of marine, aircraft, trucking and railway applications. It is the purpose of this thesis to examine the stationary gas turbine as a potential pollutant emission source, the characteristics of its emissions and some aspects of its relation to the air pollution situation

in the Houston area. At the present time there are 40 stationary gas turbines in the Houston area with horsepower totaling 630,000. In the United States there are approximately 3,500 gas turbines located primarily in or near urban areas. Since gas turbines have been presented as an alternative combustion source which would reduce pollutant emissions there is need for study of the emissions which, in the case of the Houston area, are the result of combustion of natural gas with high excess air. Although it would appear that with complete combustion that air pollution emissions would be very low, operation at high excess air and high temperatures can contribute high quantities of nitrogen oxides which are a primary pollutant and contribute to photochemical smog in urban areas. Although there have been studies made and underway relative to emissions from aircraft jet engines and stationary turbines and studies made concerning the use of liquid fuels there have been no studies which relate to the Houston area and relate to the use of natural gas as a turbine fuel. It is proposed in this thesis that several aspects relating to gas turbine emissions be studied:

1. Measure and determine emission velocities and volumes
2. Measure the emission organic and inorganic gases with particular emphasis on nitrogen oxides.
3. Relate the amount of pollutant gases with effluent velocities and quantities. Compare this data with criteria and standards relating to other similar combustion sources.
4. Determine the correlation between various techniques for measuring nitrogen oxides.
5. Based on the results of the test, and a review of available literature, discuss the factors contributing to nitrogen oxide production.

CHAPTER II  
LITERATURE REVIEW

GENERAL

The effect of stationary combustion power sources on the air environment is becoming of more importance as public and governmental interest focuses on air pollution. Legislative emission standards are now being developed which may limit the use and/or location of stationary power sources. For example, although electrical power generally now produces only 13% of the pollution tonnage it now accounts for the 50% of the production of sulfur dioxide and 27% of the oxides of nitrogen (26). The implication in this case is that elimination of transportation produced pollution, primarily by the automobile piston engine may be feasible but the resultant air pollution could be worse than at the present. There is, however, an advantage in stationary power sources in that to some extent emissions can be controlled.

Based on the literature, natural gas, a predominate energy source in the Houston area, emits lower quantities of nitrogen oxides, sulfur oxides and hydrocarbons than coal, the main power plant fuel source. Natural gas, however, is the least plentiful of the fossil fuels - a fact or a problem which will eventually effect the Houston and other urban areas as the supply of fossil fuels dwindles. Installation of nuclear power plants, while ahead of schedule, are resisted by local

communities because of the fear of radioactive material and/or thermal pollution produced by the installation.

Summing up, it would appear that the rapid expansion of electrical power, the primary energy source of the future, is not without its own particular air pollution problems.

The contribution of stationary gas turbines to air pollution has not been studied to any extent. Hurn (22) in relation to mobile combustion sources states that, while it is widely assumed that gas turbines have favorable pollutant emission characteristics, it remains to be demonstrated that use of gas turbines would produce these low emission levels. Tests of automotive gas turbines have revealed no significant pollution problems, however, literature sources (22) would indicate some weaknesses in the test techniques (measurements made on highly diluted exhausts). Jet aircraft pollution in the vicinity of airports has been a principle area of interest because of noxious odors and particulates (along with noise). Starting in about 1960, various investigators have studied the problem of emissions from aircraft jet engines. The primary areas of study have been as follows:

1. Hydrocarbons and other organic gases
2. Carbon Monoxide
3. Nitrogen oxides
4. Sulphur oxides
5. Particulate matter
6. Aldehydes

These studies have centered around the use of JP-4 or related liquid turbine fuels which are roughly equivalent to kerosene. Certain additives to these fuels have been made in order to eliminate fuel line clogging. Vanadium, chromium, and ash content of these fuels have been

reduced to a minimum in order to avoid turbine blade deposition and/or erosion (sulfur has caused no significant problems in this area) (28).

Data and results covering recent gas turbine emission test work have been published by George, Verssen, and Chass (aircraft jet engines) (7); Lozano, Melvin and Hochheiser (aircraft jet engines) (9) and Smith, Sawyer and Starkman (aircraft jet engines) (26). Smith, Sawyer and Starkman (26) studied the relation of fuel-air ratios, combustion pressures and temperatures using liquid fuels on the production of nitrogen oxides and CO. These studies showed that theoretical NO and CO production increased as power increased. Theoretical NO and CO production were also expected to increase with firing temperature. Axial or centrifugal flow air compression ratios theoretically have no effect on NO and CO emissions. Up to combustion temperatures of approximately 3100 °F, NO production is low. Actual NO measurements showed extreme variations from theoretical depending on combustor design, power and compression ratio. NO production increased with each of these factors and was slightly higher than predicted. CO production was also higher than predicted. CO production dropped as power increased contrary to theoretical predictions. Studies by Lozano, Melvin and Hochheiser (9) produced results similar to the investigations by Smith et al (26).

George, Verssen and Chass (7) showed the following concerning Los Angeles County.

1. Jet Aircraft emit about 30% of the pollution in the winter and 80% in the summer as Los Angeles County Power Plants.
2. Motor vehicles produced about 100 times as much pollution as jet aircraft.

3. Jet aircraft emit about twice the particulates of Los Angeles County power plants.
4. Jet aircraft emit about 1/4 the particulates as are emitted daily from 4 million motor vehicles.
5. Jet aircraft hydrocarbon emissions are 10 times that emitted by power plants and 1/30 the amount by motor vehicles.

The main reason for the George, Verssen and Chass tests (7) was to evaluate the "near airport" pollution problem caused by jet aircraft, the effect of fuel additives and re-designed combustion systems on particulate emission. All fuel emissions and total emission relationships were on a flight basis. Finally the literature would indicate that in general, nitrogen oxides are found mainly in the NO form. CO and hydrocarbon concentrations increase with decreasing power. NO production is directly proportional to power generated. Basically the above authors were interested in three aircraft jet engine power settings; idle, takeoff (maximum power) and cruise.

Based on the above investigations, it would be expected that primary air pollutants for a stationary gas turbine might range as follows:

	ppm	LBS./HR.
1. Sulfur Oxides as SO <sub>2</sub>		20
2. CO	10-550	3 - 30
3. Nitrogen Oxides	5-100	3 - 100
4. Hydrocarbons	2-700	1 - 50
5. Particulates		116
6. Aldehydes	0.5-10	0.1-0.5

It is evident that there is a wide range in the available emission data. No information exists for the primary turbine fuel used in the Houston

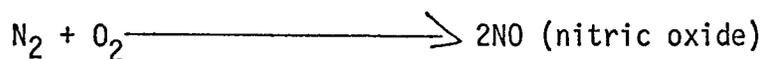
area, specifically natural gas. It is also evident that with the larger quantities of excess air used in stationary gas turbines, usually about 200%, high heat producing compression ratios and high combustion temperatures it is possible that high nitrogen oxide levels could be emitted by natural gas fired turbines. Most stationary gas turbines operate on natural gas (28). Overall, jet aircraft pollution in the case of Los Angeles or other major cities presents a significant pollution in the airport area, but is not a general area problem.

#### GAS TURBINE AS A POLLUTION SOURCE

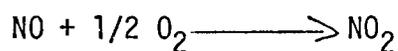
Gas turbines date back as far as the discovery of fire. The date of the first gas turbine is unknown, however, in 130 B.C. a small gas turbine was constructed in Alexandria, Egypt that moved symbolic figures on an altar. The rapid advance of the gas turbine has been due to the metallurgical technological advances that were started during the later stages of World War II as a result of the requirement for engine development. The stationary gas turbine consists basically of an axial or centrifugal compressor section used to compress air, a combustion section and a reaction or impulse turbine section to extract usable power. Normal turbine inlet temperatures range from about 1200°F to 2200°F and are a function of the blade metallurgy and/or cooling. The higher combustion or firing temperatures produce higher thermal efficiencies. Low thermal efficiencies have thus far made the gas turbine relatively unattractive, particularly in automotive systems. Gas turbine thermal efficiencies range from 15-35% depending on machinery efficiency and the use of waste heat.

In general, gas turbines operate at high speeds ranging from 5,000 - 20,000 RPM for the typical stationary models. The forty gas turbines located in the Houston area are the industrial type, simple cycle and operate using natural gas as the primary fuel. Basically, in order to obtain high thermal efficiencies, two routes can be taken. Low compression ratios at approximately 6:1 with use of waste heat extraction or high compression ratios at approximately 10:1 with no use of waste heat (28). In any successful stationary gas turbine design, the use of exhaust restrictions is minimized in order to eliminate back pressure on the turbine which can reduce usable power. The basic difference between the aircraft or jet powered turbine and a standard industrial turbine is in the technique for achieving the proper combustion inlet temperatures. In the aircraft turbine this is achieved by utilizing high compression ratios. In industrial turbines the same effect is achieved with low compression ratios and use of exhaust waste heat.

Since natural gas is the primary fuel used for turbine combustion in the Houston area, the only probable pollutant based on the literature, would be oxides of nitrogen ( $\text{NO}_x$ ). Weisburd (25) discusses some of the factors involved in the generation of  $\text{NO}_x$ . Emission of  $\text{NO}_x$  from combustion equipment results from fixation of atmospheric nitrogen in the fire box or combustion chamber. The reaction is as follows:



$\text{NO}$  is further oxidized to  $\text{NO}_2$  as follows:



The oxidation of NO is very slow at normal ambient temperatures and reaches a maximum at approximately 600°F. NO<sub>2</sub> is considerably more reactive than NO and is a primary air pollutant. In the combustion process other oxides of nitrogen are formed in small quantities - N<sub>2</sub>O, N<sub>2</sub>O<sub>4</sub>, N<sub>2</sub>O<sub>5</sub> and NO<sub>3</sub>. Oxides of nitrogen produced by combustion are generally collected as NO<sub>x</sub> and results reported as NO<sub>2</sub>. The formation of NO in the combustion process has been calculated (25) at low excess air or oxygen levels. Below 1800°F (25) combustion temperatures relatively small amounts of NO are produced by the fixation process. Table 1 (25) indicates the relation between combustion temperature, time of formation and equilibrium concentrations of NO produced. Summarizing, Weisburd (25) details the following variables that figure in the formation of nitrogen oxides:

1. Combustion Temperature - As combustion temperatures increase NO<sub>x</sub> formation increases.
2. Excess Air - Formation of NO<sub>x</sub> tends to increase as the concentrations of nitrogen and oxygen increase.
3. Fuel - In general, fuels with higher carbon/hydrogen ratios produce higher flame temperatures and greater NO<sub>x</sub> concentrations.
4. Residence Time - As residence times in the combustion zone increase, NO<sub>x</sub> formation increases (Table 1)
5. Combustion System Configuration - Fuel nozzle or burner design tends to effect, in some cases greatly, the formation of NO<sub>x</sub>.
6. Flame Cooling - Flame cooling tends to retard NO<sub>x</sub> formation.
7. Preheat of Combustion Air - If combustion air is preheated to 600°F or above NO<sub>x</sub> formation is greatly enhanced.
8. Nitrogen Content of Fuel - Nitrogen content of the fuel is generally considered to have little effect on NO<sub>x</sub> formation.

EQUILIBRIUM CONCENTRATIONS  
AND TIMES OF FORMATION OF NITRIC  
OXIDE AT ELEVATED TEMPERATURES AT  
75 PERCENT NITROGEN AND  
3 PERCENT OXYGEN

Temperature, ° F	Equilibrium concentration of nitric oxide,  ppm	Time of formation of 500 ppm NO,  seconds
2,000	180	
2,400	550	1,370
2,800	1,380	16.200
3,200	2,600	1.100
3,600	4,150	0.117

TABLE 1

Weisburd (25) concludes that the number of variables involved in  $\text{NO}_x$  formation make exact estimates of quantities produced in a specific combustion process difficult.

#### CLASSIFICATION AND EFFECTS OF GAS TURBINES GASEOUS EMISSION

This thesis will not cover particulate emissions, although of great importance in gas turbine operation, since they have no real current significance in the Houston area.

Chambers (20) discusses the history of air pollution. Air pollution problems have existed since the middle ages. Records of severe air pollution as early as 1272 exist. In London the gradual development of smoke problems, culminated in the related deaths in a few days of 4,000 persons in December of 1952. Killing and/or irritating effects of air pollution also occurred in Los Angeles in 1945. The term smog appears to have originated in England and is a combination of the word smoke and fog.

As discussed above, the primary significance of air pollution production by gas turbines as related to the Houston area are:

1. Sulphur compounds
2. Organic compounds
3. Nitrogen compounds (most important pollutant)
4. Carbon compounds

Possible secondary pollutants that could be produced as a result of turbine combustion include; ozone, formaldehydes, organic hydroperoxides, PAN, and other very reactive compounds. In the case of stationary gas turbines the reaction of interest is the photochemical reaction involving nitrogen dioxide resulting in the production of smog and the production

of nitrogen oxide.

Discussion of primary and secondary gas turbine emissions and their significance are as follows: Global and Houston background levels of these gases are as listed in Table 2 (20) (3).

A. Carbon Monoxide - Carbon monoxide is of interest, although in the case of the gas turbine assumed to be minor significance, because of the large quantity of excess air used in combustion. Complete combustion would indicate low carbon monoxide levels. Carbon Dioxide also emitted in the combustion process is a stable carbon oxygen compound which may have significant future potential. Robinson (20) states that the steady increase in  $\text{CO}_2$  could result in a general rise in the ambient temperature of the earth. This air temperature change has been postulated because of the infrared absorption characteristics of  $\text{CO}_2$ . The hundreds of millions of tons of  $\text{CO}_2$  vented to the atmosphere every year have increased approximately 25% in the last 100 years and are anticipated to increase another 25% by the year 2000 (26). The greenhouse effect produced by  $\text{CO}_2$  as discussed by Robinson (20) may be offset by the production of particulates, smog, and other visibility deterrents which would tend to have the effect of lowering ambient temperatures. Robinson (20) concludes that the probable long term environmental effects of  $\text{CO}_2$  production in the atmosphere are difficult to evaluate. Immediate climate changes linked to  $\text{CO}_2$  are probably doubtful.  $\text{CO}_2$  concentrations are, at the present time, about 340 ppm in the atmosphere.  $\text{CO}_2$  in low concentrations have no known biological effects.

GLOBAL BACKGROUND  
OF POLLUTANT GASES

<u>Pollutant</u>	<u>Global Background</u>	* <u>Urban Background</u>
SO <sub>2</sub>	0.001 - 0.002 ppm	0.20 ppm
NO <sub>2</sub>	0.001 - 0.002 ppm	0.15 ppm
Ozone	0.015 - 0.03 ppm	
Methane	1.2 ± 0.2 ppm	6 ppm
Olefins	0.01 ppm	
CO	.03 ppm	15 ppm

HOUSTON BACKGROUND

<u>Pollutant</u>	<u>Average</u>	<u>Maximum</u>
SO <sub>2</sub>	0.015 ppm	0.275 ppm
H <sub>2</sub> S	0.013 ppm	
NO <sub>2</sub>	0.006 ppm	0.018 ppm
Ozone	0.014 ppm	0.080 ppm
Hydrocarbon Vapor	0.27 ppm	0.94 ppm

\* Mean concentrations - Annual Basis (20)

Table 2

In the United States CO is present in trace quantities in the atmosphere ranging from about 5-60 ppm in urban areas with a mean of approximately 15 ppm.

The effect of CO exposure varies, however, the literature would indicate that levels over 100 ppm for an 8 hour exposure period would result in harmful side effects. Stokinger and Coffin (20) have related CO concentration levels to blood vessel diseases in addition to the common effects of exposure ranging from headaches, dizziness and nausea to fatalities.

#### B. HYDROCARBONS

Hydrocarbon levels in urban areas, vary in concentration from 3-20 ppm with a mean concentration of approximately 6 ppm. The hydrocarbons of interest are those that react photochemically with nitrogen oxides. Tebbens (20) points out that incomplete combustion can be a source of organic compounds which due to atmospheric photochemistry produce free radicals, organic peroxides, peracids, hydroxyperacids and the compound of specific interest in the stationary gas turbine case, peroxyacyl nitrate (PAN). The practice of measuring oxidant precursors or formers of ozone in the presence of sunlight and nitrogen oxides has been, in Los Angeles, replaced by measuring hydrocarbons. While of interest, high hydrocarbon levels do not necessarily relate to potential or existing air pollution problems. Recent information (20) indicates that 50-55% of the atmospheric hydrocarbons measured are methane which for all practical purposes is a non-reactive gaseous

compound.

For the above reasons, natural gas, the primary turbine fuel in the Houston area, should result in little air contamination since  $\text{CH}_4$  usually constitutes approximately 95-98% of the total fuel volume. Small quantities of more complex hydrocarbons and distillates also exist which could be potentially reactive. Based on the literature, it is unlikely that combustion of natural gas produces the complex hydrocarbons such as the unsaturated olefinic hydrocarbons (oxygenated hydrocarbons) which under photochemical oxidation produce formaldehyde or PAN.

### C. Sulfur Oxides

Sulfur dioxide levels mentioned earlier contributed to the 1952 London smog disaster.  $\text{SO}_2$  levels measured during this period were about 1.34 ppm (20).  $\text{SO}_2$  atmospheric concentrations normally vary from .02 - 1.62 ppm in urban areas. Mean urban  $\text{SO}_2$  levels are approximately 0.20 ppm. Tebbens (20) states that the conversion rate of  $\text{SO}_2$  to  $\text{SO}_3$  is slow and varies with environmental conditions.

$\text{SO}_2$  enters vegetation as a gas and acts directly on the functional cells near the stomata, Brandt and Heck (20). The cells apparently convert the sulfite (solution product of the gas) to sulfate. If sulfites build up in excess of a certain rate, cell collapse occurs. The effect is a pattern of light colored splotches, mainly intraveinal.

Biologically,  $\text{SO}_2$  acts as an irritant to the upper respiratory tract and, under massive exposures, to the lower digestive tract. Exposures to very high concentrations of  $\text{SO}_2$  (100-500 ppm have caused

susceptability to infection in animals. Man, Stokinger and Coffin (20), is more sensitive to  $\text{SO}_2$  than animals. Exposures at above 10 ppm (22) will produce eye, nose, and throat irritation in those unconditioned to the gas. At 100 ppm strong irritation occurs. Greatly enhanced effects occur when  $\text{SO}_2$  is inhaled with an aerosol.

As far as the natural gas fired turbine is concerned,  $\text{SO}_2$  production is low because natural gas usually contains only trace quantities of sulfur components or  $\text{H}_2\text{S}$ .

#### D. Nitrogen Oxides

The most significant primary gaseous pollutant of the group, because of the fuel characteristics of the gas turbine, are nitrogen oxides. Urban atmospheric concentrations of nitric oxide varies from .03 - 1.35 ppm with a mean concentration of approximately 0.30 ppm (20).  $\text{NO}_2$  urban concentrations vary from .03 to .80 ppm with a mean concentration of approximately .15 ppm. High ambient  $\text{NO}_x$  concentrations generally occur during periods when combustion processes are at a maximum. Lower atmospheric  $\text{NO}_x$  concentrations, in Los Angeles County, accompany the most intense photochemical smog. On a daily basis high  $\text{NO}_x$  concentrations occur in the morning and evening before photochemical reactions occur. Certain of the photochemical reactions with nitrogen oxides will be discussed below.  $\text{NO}_2$  causes light brown atmospheric discoloration because the gas is strongly absorbant over the blue-green area of the visible spectrum.

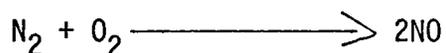
Known ambient levels of  $\text{NO}$  or  $\text{NO}_2$  are not considered of major concern

to plant species, however, vegetation can be damaged at exposures of 2-10 ppm for several hours. Damage is similar to that produced by  $\text{SO}_2$ . Recent studies (20) indicate that  $\text{NO}_2$  may inhibit plant growth rate. Little is known of this phenomena.

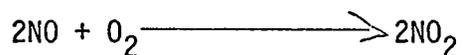
Stokinger and Coffin (20) report biological effects associated with  $\text{NO}_2$  ranging from nose and eye irritation, pulmonary congestion and edema, bronchiolitis and pneumonia. At present ambient levels,  $\text{NO}_2$  presents no threat to health. Chronic long term exposure to  $\text{NO}_2$  in the order of 10-80 ppm can produce the more severe effects mentioned above.  $\text{NO}$  in combination with  $\text{NO}_2$  and exposure to  $\text{NO}_2$  with nitric acid vapors is more toxic than  $\text{NO}_2$  alone. Summing up,  $\text{NO}_2$  is primarily a pulmonary irritant. The response threshold in man is approximately 0.1 ppm. 1-2 ppm can cause minor irritation. 10-20 ppm exposure can result in methemoglobin formation.

#### E. Photochemically Produced Pollutants

The production of nitrogen oxides specifically  $\text{NO}$ , as a result of gas turbine or any standard combustion process plays a role in the production of photochemically produced pollutants. In the combustion process:



Nitric Oxide,  $\text{NO}$ , reacts with Oxygen as follows:

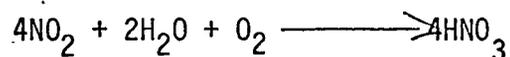


At equilibrium conditions the formation of  $\text{NO}_2$  is almost total. For example Haagen - Smit and Wayne (20) report that at 1000 ppm,  $\text{NO}$  is

oxidized to  $\text{NO}_2$  in a matter of seconds. At 0.1 ppm the NO oxidation process takes approximately 1000 hours. Photochemically,  $\text{NO}_2$  absorbs light and is strongly active over the entire visible and ultraviolet light range available in the lower atmosphere. From about 6000 to 3800 Å the spectrum indicates the formation of excited molecules. Below 3800 Å  $\text{NO}_2$  disassociates to produce NO and oxygen atoms, a starting point in the production of photochemical pollutants. In areas where ozone concentration is high the following occurs:



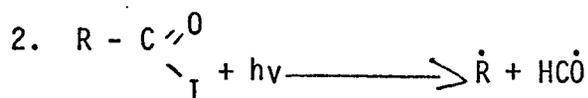
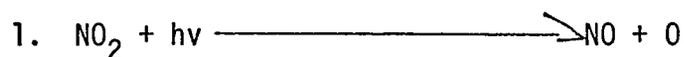
$\text{N}_2\text{O}_5$  is subsequently hydrated to nitric acid. If water is present, the same end result can occur:



Both nitric and nitrous acid may be photochemically decomposed, however, in general the natural process of NO removal is by the production of nitrates which are removed from the nitrogen oxide atmospheric pool by rain.

Haagen - Smit and Wayne (20) report that areas where atmospheric retention times are sufficient the two primary photochemical processes are as follows:

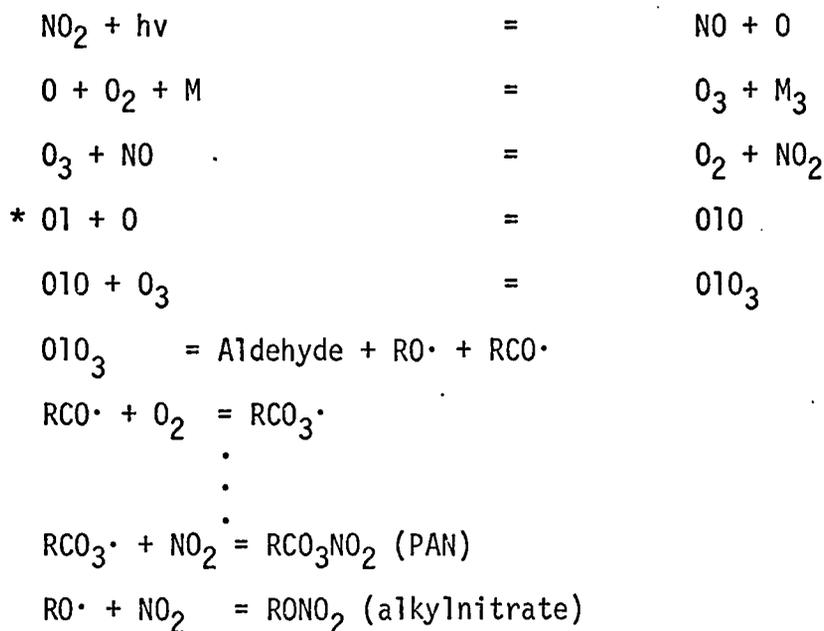
(3000 - 4000 Å)



The second reaction is the photodisassociation of aldehydes into free radicals. The important mechanism in the first case is the production of oxygen atoms by the photodisassociation of  $\text{NO}_2$  with the subsequent

production of ozone, a powerful oxidizing agent. The problem in modeling photochemical smog reactions is that the materials feeding the process do not disappear - but accumulate. Haagen - Smit and Wayne (20) suggest that reaction chains involving molecular oxygen start with hydrocarbons reacting with oxygen atoms yielding free radicals which consume nitric oxide without disassociating  $\text{NO}_2$  at an equally rapid rate. Stephens (19) reaches a similar conclusion, finding that, although  $\text{NO}_2$  is the primary light absorber, the concentration of the compound increases when a mixture of  $\text{NO}$  and olefinic hydrocarbons are irradiated. The double bonded olefinic hydrocarbons seem to be especially reactive.

The production of PAN, peroxyacyl nitrate may be as follows:



Even though the behavior of the photochemical reactions is complex the behavior of such systems is relevant to legislative considerations,

\* O1 = Olefin

pollutant criteria and pollutant control.

Robinson (20) discusses the effect on visibility by the photochemical production of aerosols. Light scattering characteristics of smog are produced by the ultraviolet irradiation of hydrocarbon vapors combined with nitrogen dioxide. The effects on visibility are a function of the "hold time", meteorological factors and relative humidity.

Ozone and PAN, both components of the photochemical smog complex have been identified as injurious to vegetation. Plant injury by ozone in severe cases, is similar to that produced by  $\text{SO}_2$  i.e., a pattern of light colored splotches, mainly intraveinal, and a change in leaf thickness. PAN produces a characteristic undersurface silvering, glazing or bronzing resulting in leaf collapse. The general PAN damage pattern is a cross-leaf banding. Smog damage has been severe enough in Southern California to cause spinach and lettuce crop failures (20).

Ozone can be detected by its characteristic odor at .02 to .05 ppm. At levels approaching 0.1 ppm Stokinger and Coffin (20) report that exposure for 30 minutes will produce headache in most individuals. At levels in the range of 1-2 ppm accompanied by substantial exposure, ozone causes dryness in the mouth, nose and throat; changes in visual acuity, headache, and, in some cases, functional problems in the lungs, pulmonary congestion and edema. It might be stated that response to gaseous air pollutants discussed herein varies among individuals studied. In addition, studies relating to biological effects of ozone and other recently defined gaseous pollutants have not been extensive.

PAN toxicity values are, in general, lower than those for ozone. Stokinger and Coffin (20) report the toxic effects are similar to those produced by  $\text{NO}_2$  i.e., eye irritation and pulmonary effects. Exposure for long periods at levels in the order of 100 ppm have proved lethal in animal experiments.

#### CURRENT AIR POLLUTION SITUATION IN HOUSTON AND LEGISLATIVE REVIEW

A review of the literature relative to source emissions in the Houston area resulted in review of a four year old study made by the Southwest Research Institute for the Houston Chamber of Commerce (3). This report indicated that air pollution problems in the Houston area were, at that time, relatively localized. At any given time, the areas effected were immediately downwind from different individual sources. The situation which allowed mixing of pollutants from several sources occurs with the wind in the east - northeast or east. With the wind in this area moving parallel to the Houston ship channel, mixing can occur with resultant air pollution in the ship channel area and central business area. Pollutant levels measured along freeways compared with those measured in Los Angeles, however, due to prevailing south-east ventilation or to different weather conditions, photochemical contributors to smog and accompanying irritants were low. Automobile registrations at that time were about 600,000. Photochemical smog had started to become a problem with an increase in combustion activities.

It is obvious the situation has changed even more. Automobile registrations have increased. Industrial activity has increased. Sources

at the Houston Public Health Department indicate however, that for its size, Houston and the surrounding area does not have a severe air pollution problem, but the situation could change. The situation, as stated in the introduction, regarding legislation and emission standards is in a process of change. The 1967 Federal Clean Air Act has proposed revisions which would define and limit nitrogen oxide emissions from automobiles. The Clean Air Act of Texas, 1967, contains emission criteria for SO<sub>2</sub> but not oxides of nitrogen - a potential problem in this area. Under the Federal Clean Air Act, States have 90 days in which to inform the Secretary of HEW of their intention to establish air pollution control standards and another 180 days to submit the actual standards. The primary responsibility rests with the States.

Emission standards vary from area to area and depend on the severity of local problems, the expertise of the air pollution control staff and staff size. For example, emission standards for gases in the Houston area requiring stack sampling cannot be well defined because no stack sampling is performed at present.

As far as could be determined only California, mainly because of its current problems has developed extensive stationary power source emission criteria. These are as detailed below. In Chapter V, Conclusions, the significance of these standards as related to gas turbines in the Houston area is discussed.

LOS ANGELES COUNTY, CALIFORNIA

<u>Pollutant</u>	<u>Emission</u>	
NO <sub>x</sub> as NO <sub>2</sub>	140 lb/Hr.	maximum
Sulfur as SO <sub>2</sub>	200 lb/Hr.	maximum
Particulates	10 lb/Hr.	maximum

VENTURA COUNTY, CALIFORNIA

<u>Pollutant</u>		<u>Emission</u>
NO <sub>x</sub> as NO <sub>2</sub>	250 ppm	20 Tons/24 Hrs.
Particulates		0.3 grains/SCF (14.7 psia, 60°F)
SO <sub>2</sub> (At "fenceline")		0.2% by volume or 2000 ppm
		0.5 ppm average/1 Hr.
		0.1 ppm average/24 Hrs.

HOUSTON, TEXASPollutant

SO <sub>2</sub> (At property line)	0.2 - 0.3 ppm average/24 Hrs.
	0.4 - 0.5 ppm average/30 Min. with no more than 1 incident in a 12 hour period
H <sub>2</sub> S (At property line)	0.8 ppm average/30 minutes

SO<sub>2</sub> emission rates are calculated using Sutton's diffusion equation at ground level which has the form:

$$X = \frac{20_m}{C_y C_z u x^{2-n}} \exp \left( -\frac{1}{x^{2-n}} \left( \frac{y^2}{C_y^2} + \frac{h_e}{C_z^2} \right) \right) \quad (20)$$

Whereas:

X = Gas concentration at given point in mass per unit volume

Q<sub>m</sub> = Mass emission rate of stack gas

$C_y$  = Lateral diffusion co-efficient

$C_z$  = Vertical diffusion co-efficient

$u$  = Wind speed at given location

$n$  = Turbulence index

$x$  = Distance downwind of stack

$y$  = Lateral distance from vertical plane through stack and parallel to mean wind direction

$h_e$  = Stack height and height of plume above stack

### TESTING TECHNIQUES

Testing techniques discussed in the literature for aircraft (particulates not included) jet engines are as follows:

#### I LOZANO, MELVIN AND HOCHHEISER (9)

<u>Pollutant</u>	<u>Collection System</u>	<u>Technique</u>
$NO_x$	50 cc syringe	Griess - Ilosvay and Saltzman
NO	50 cc syringe	Saltzman
Aldehydes	Bubbler	Sawicki, MBTH Reagent
CO	Stainless Steel Collection Cylinder	Mass Spectrometry
Total Hydrocarbons	Continuous System	Flame ionization detector

#### II GEORGE, VERSSEN AND CHASS (7)

<u>Pollutant</u>	<u>Collection System</u>	<u>Technique</u>
------------------	--------------------------	------------------

Not discussed, however, would appear to be wet chemistry techniques (16).

#### III SMITH, SAWYER AND STARKMAN (27)

<u>Pollutant</u>	<u>Collection System</u>	<u>Technique</u>
$NO_x$	Sample bottle diluted with $O_2$ to convert NO to $NO_2$ . Sample taken with a syringe	Ultraviolet Spectrophotometer
CO	Continuous	Beckman IR 315 infrared Spectrophotometer
Hydrocarbons (as Hexane)	Continuous	Beckman 106E Flame Ionization Detector

## CHAPTER III

### EXPERIMENTAL INVESTIGATION

#### GENERAL

In the objectives of this thesis it was proposed that several aspects relating to natural gas fueled stationary gas turbine exhaust stack emissions be studied on a real-time basis. Selected organic and inorganic emissions measured would be those generally considered air pollutants.

These were as follows:

<u>Pollutant</u>	<u>Sampling Basis</u>
1. Hydrocarbons	Continuous
2. Nitrogen Oxides	Continuous
3. Sulfur Dioxide	Composite Sample (16)
4. Aldehydes	Composite Sample (16)
5. Carbon Monoxide	Continuous
6. All Above	Composite Sample - Stainless Steel or Glass Sample Bottle

SO<sub>2</sub> and aldehydes were not measured on a real time basis because a test gas analysis indicated no appreciable quantities could be measured on test, Table 3. As an additional objective of this project, two test instruments were used to measure nitrogen oxides in order to allow a correlation between the various types of equipment used to monitor a single pollutant. In addition, all onsite data was checked by obtaining samples and measuring pollutants of interest on a mass spectrometer.

In order to study gas turbine emissions a turbine unit located on the authors company's natural gas pipeline was chosen. Although,



FRACTIONAL ANALYSIS - TEST FUEL GAS

<u>COMPOSITION</u>	<u>CONCENTRATION GRAINS/100 FT.</u>
S	0.038
H <sub>2</sub> S	0.027
CH <sub>3</sub> SH	0.035
C <sub>2</sub> H <sub>5</sub> SH	0.036
C <sub>4</sub> H <sub>5</sub> SH	0.007
C <sub>6</sub> H <sub>5</sub> SH	Trace
COS	Nil
SO <sub>2</sub>	Nil
C <sub>6</sub> H <sub>4</sub> S (thiophene)	0.009
2.3,CH <sub>3</sub> -C <sub>6</sub> H <sub>4</sub> S (methyl thiophene)	0.007
<hr/>	
TOTAL	0.159

Table 3

as mentioned earlier, there are 40 units of various sizes located in the Houston area, the operators would not allow someone outside of their companies to measure potential pollutant emissions which might draw unfavorable attention to their operation.

The gas turbine selected for the tests consisted of a Cooper-Bessemer RT-105 turbine driving RF2B-24 centrifugal pipeline compressor. The RT-105 gas turbine is shown in outline Figures 1 and 2. The Cooper-Bessemer RT-105 turbine consists of Pratt and Whitney Aircraft GG3C-1 gas generator driving a RT-48 free turbine coupled to the pipeline compressor. A schematic of the PWA GG3C-1 gas generator is shown Figure 3. NEMA (80°F and 1000 ft. altitude) data for this unit is as follows:

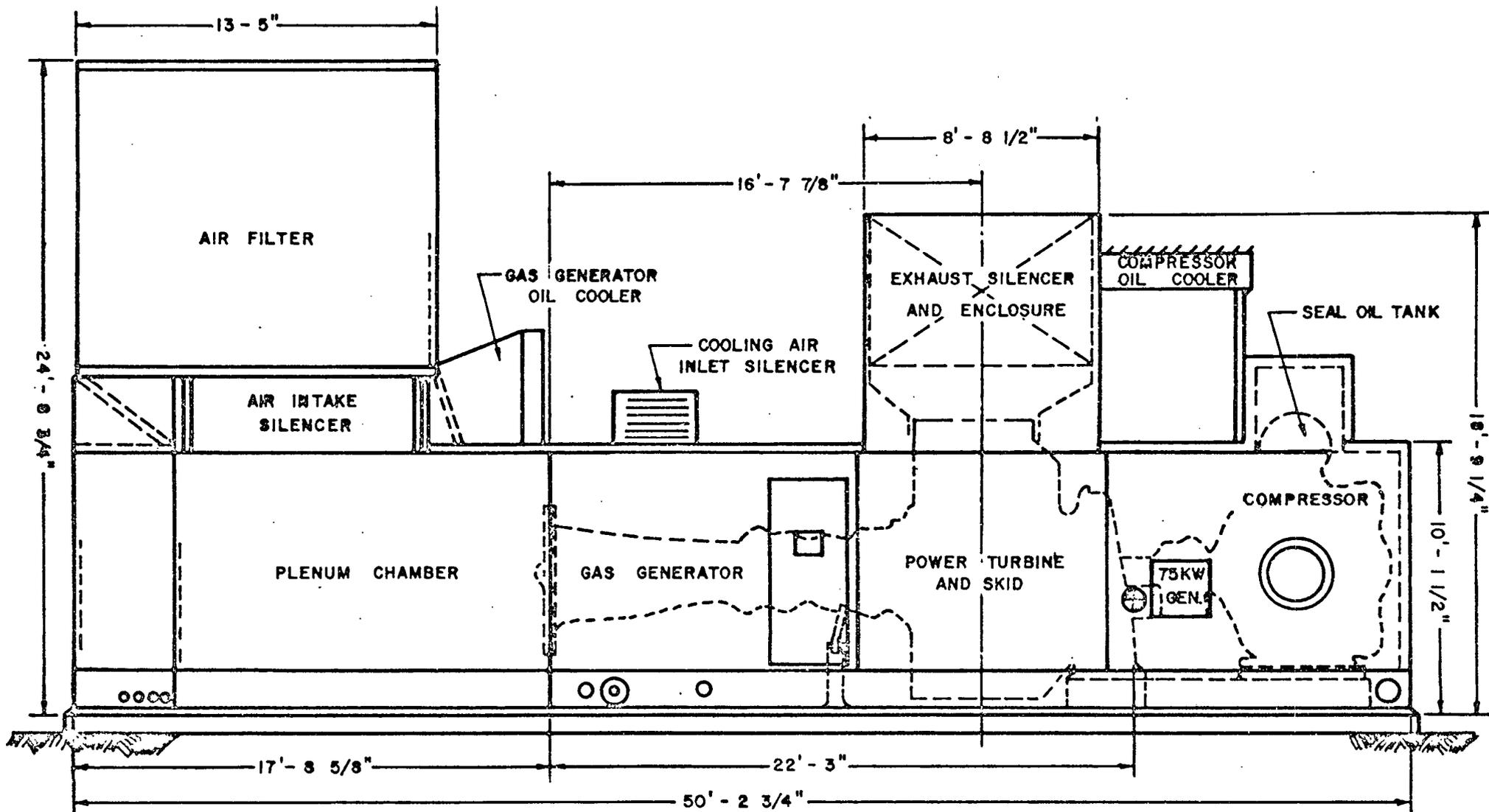
10,500 BHP  
 Thermal Efficiency - 25%  
 Fuel Consumption - 10,200 BTU/BHP - Hr (LHV)  
 GG3C-1 Low Stage AFC Speed (N1) - 6,000 RPM  
 Combustion Air Flow - 147.5 lbs/sec.  
 Free Turbine Inlet Temperature - 865°F, 29 psia  
 Turbine Inlet Temperature (GG3C-1) 1380°F, 148 psia  
 Compression Ratio AFC - 2.10

#### EXHAUST STACK TRAVERSE

It should be noted here that each stack sampling test arrangement has its own peculiar problems which must be solved if meaningful results and data are to be obtained. In this case, velocities approaching 200 ft./sec. and high vibration levels resulted in the selection of equipment types and equipment location which will be discussed in more detail below.

The exhaust stack for the gas turbine is configured as shown Figure 4. The stack has seven flow splitters or exhaust silencers. The velocity traverse was run at rated power at the top of the stack. It can be seen

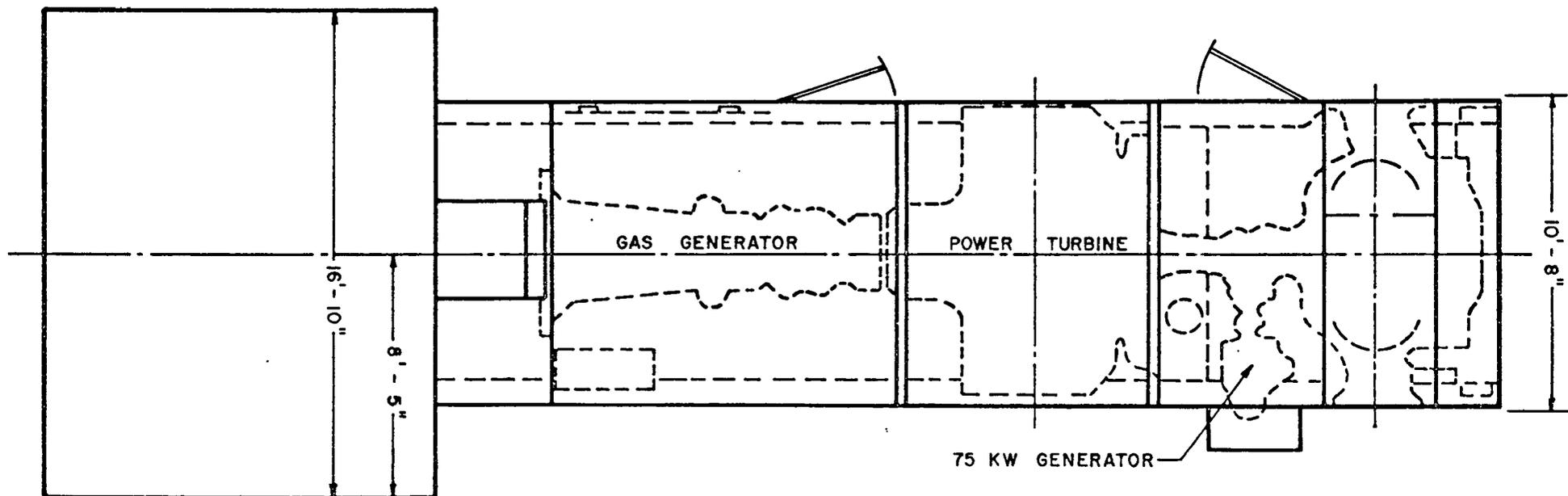
COOPER - BESSEMER RT-105 GAS TURBINE



ELEVATION

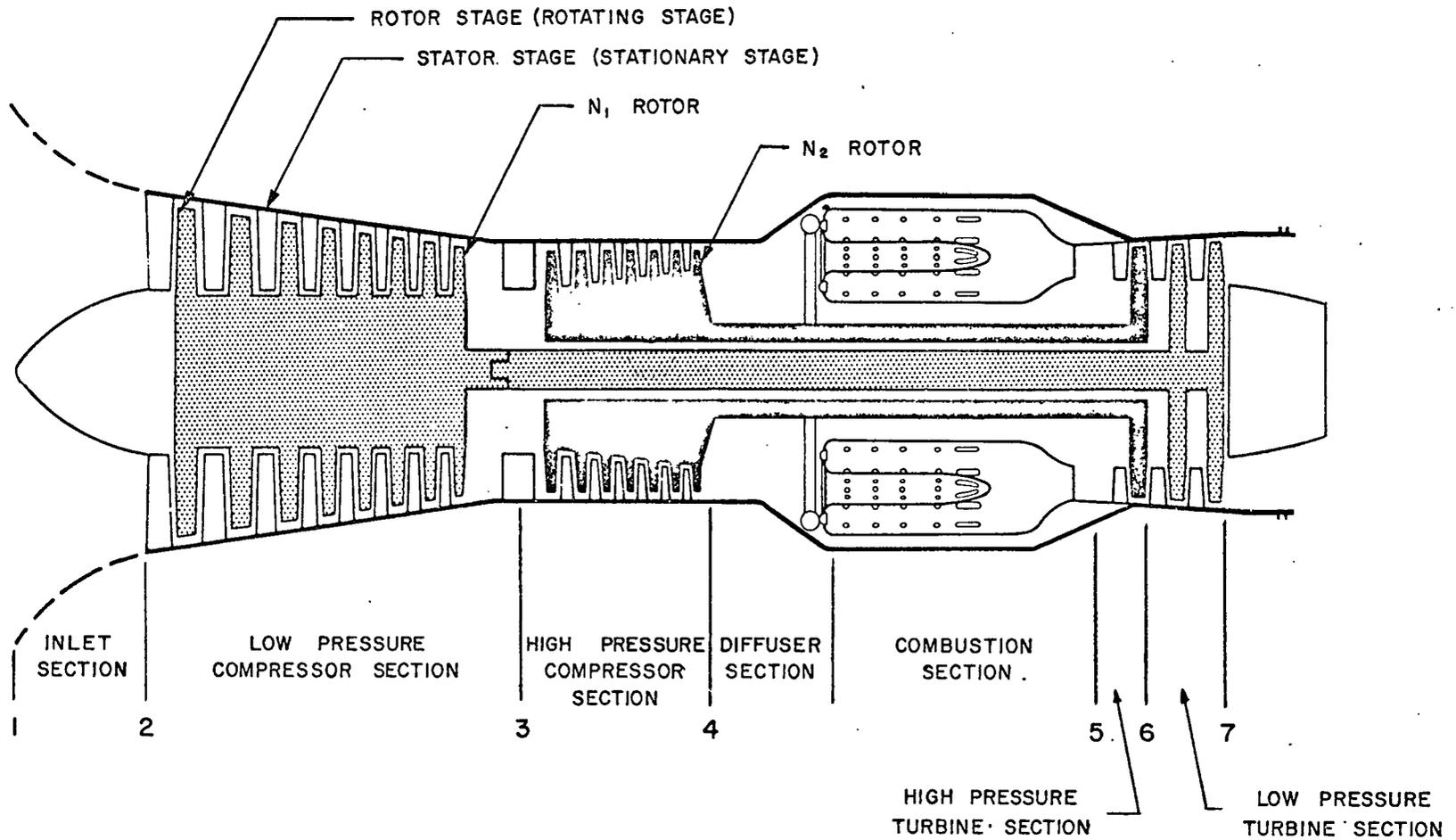
FIGURE 1

COOPER - BESSEMER RT-105 GAS TURBINE



PLAN

FIGURE 2



GG3C - 1  
SCHEMATIC

FIGURE 3

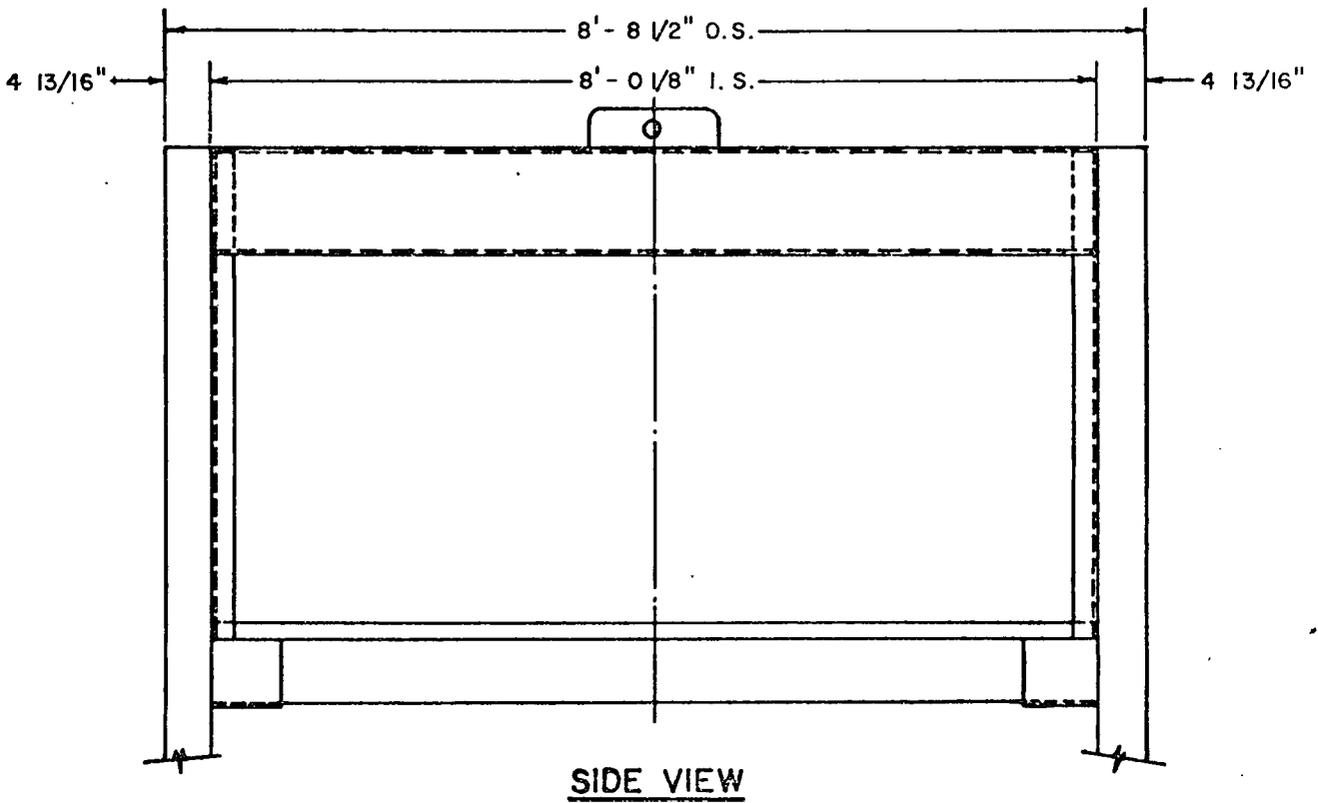
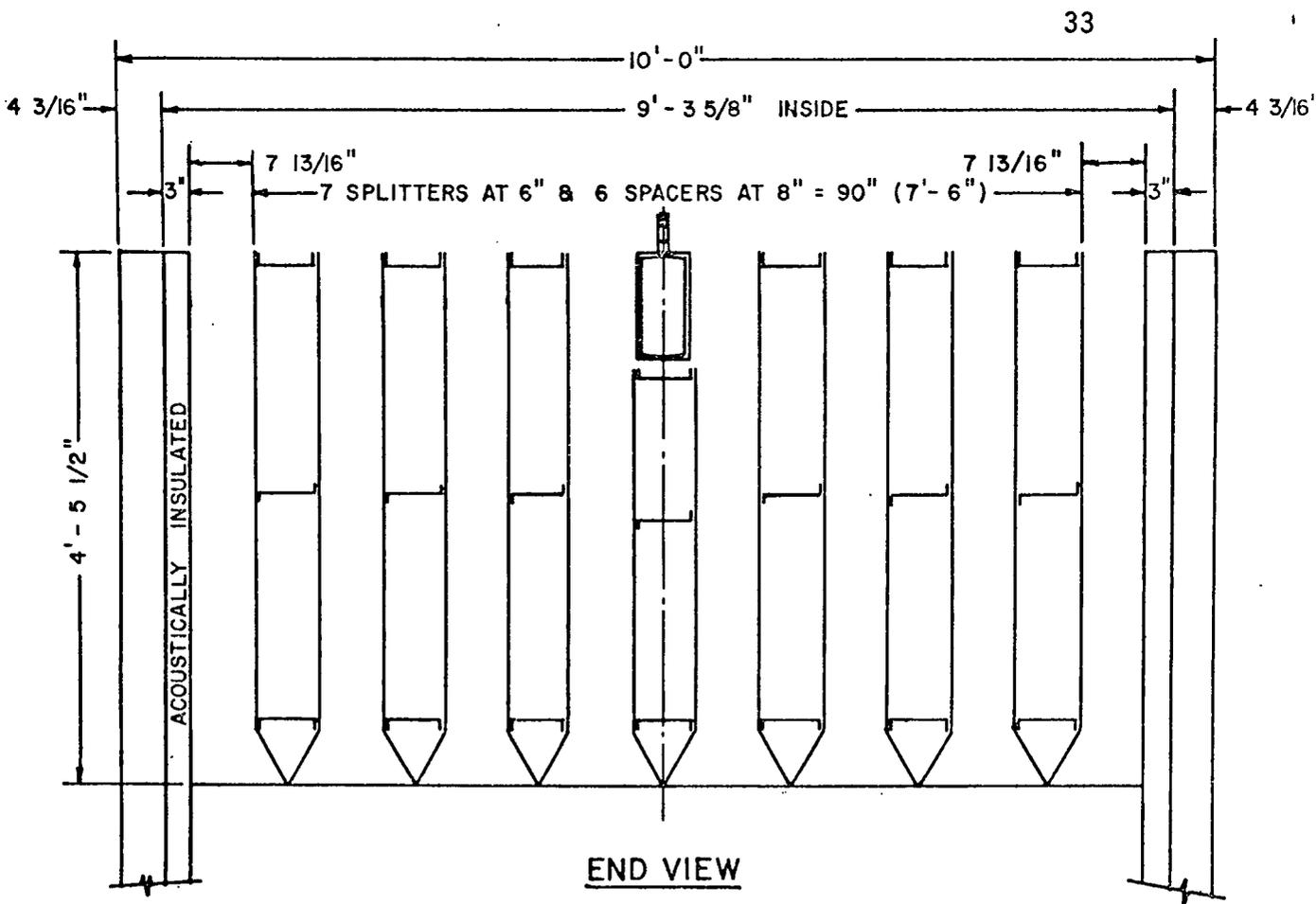


FIGURE 4

that the highest velocities were at edges of the stack with lower velocities in the center. The results of the velocity traverse at full power and the point selected for sampling are shown Figure 5.

The gas sampling procedure for the turbine emission analysis was not isokinetic, but the point selected was in an area at approximately the average velocity for the top of the stack. It was not possible to sample through the side of the stack because of structural limitations (holes in the stack tend to enlarge with associated cracks due to vibration). The determination of velocities was made using a pitot tube with the velocity determined as follows:

$$\begin{aligned} \text{In general } V_s &= C_p (2gh)^{1/2} \\ \text{Specifically } V_s &= 5130 C_p \left( \frac{T_s \Delta h_p}{P_s M_s} \right)^{1/2} \quad (21) \end{aligned}$$

Where:

$V_s$  = Stack Velocity - ft/min.

$T_s$  = Stack Temperature - °R

$\Delta h_p$  = Velocity Head - inches H<sub>2</sub>O

$P_s$  = Stack Pressure - inches H<sub>g</sub> absolute

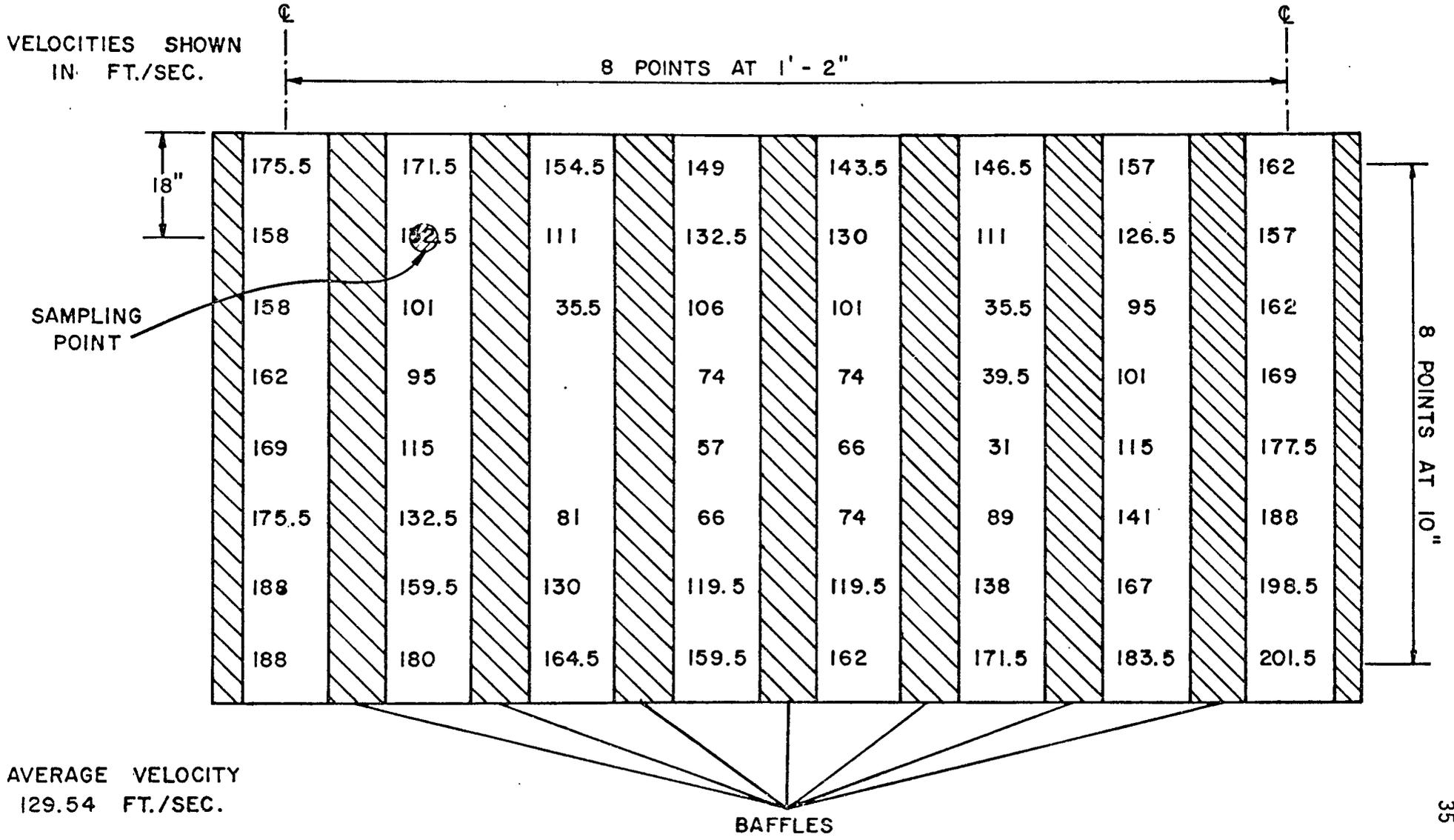
$M_s$  = Molecular Weight of Stack Gas

5,130 = Velocity factor in SCFM @ 14.7 psia, 60° F

$C_p$  = Pitot Coefficient

A point 18 inches from the edge of the stack and 12 inches vertically down on the GG3C-1 side was selected as the sampling location. (See Figure 5).

GAS GENERATOR SIDE



COMPRESSION SIDE

FIGURE 5

## SAMPLING TRAIN

The sampling train was installed as shown Figure 6, "Schematic of Turbine Stack Emission Test". The sampling probe and other tubing was constructed of 316 1/2 inch stainless steel tubing. The water "knock out" or condensation portion of the system was constructed of four 316 stainless steel .020 inch X 2.50 inch X 6.00 inch tubes with bottom drains. All of the metal in contact with stack gas was 316 stainless steel in order to minimize reactions with the trace gases being measured. An insulated box was fitted around the condensation or impinger tubes and kept filled with ice in order to insure complete condensation of water vapor. The sampling and water separation system was made of stainless steel because standard glass impingers or liquid separators could not withstand stack vibration levels.

After the exhaust stack gases were cooled to ambient temperatures they flowed through tygon tubing to the flow meters, pumps and test instrumentation. The sample line flow rate to the instrumentation location was maintained approximately 3.5 lpm (70°F, 29.92" H<sub>g</sub>). After balancing all the test instrumentation flow rates the main flow rate was 0.95 lpm. The flow rate to the hydrocarbon flame ionization unit and the stainless steel sample bottle was 2.50 lpm (70°F, 29.92" H<sub>g</sub>). Each test device in the sample train had its own specific flow rate as noted Figure 6. Test equipment was located as close as feasible to the water condensation locations in order to reduce undesirable reactions in the tygon tubing ( $\text{NO} \longrightarrow \text{NO}_2$ ). The distance between the test equipment and the condensation system was approximately 25 feet.

# SCHEMATIC OF TURBINE STACK EMISSION TEST

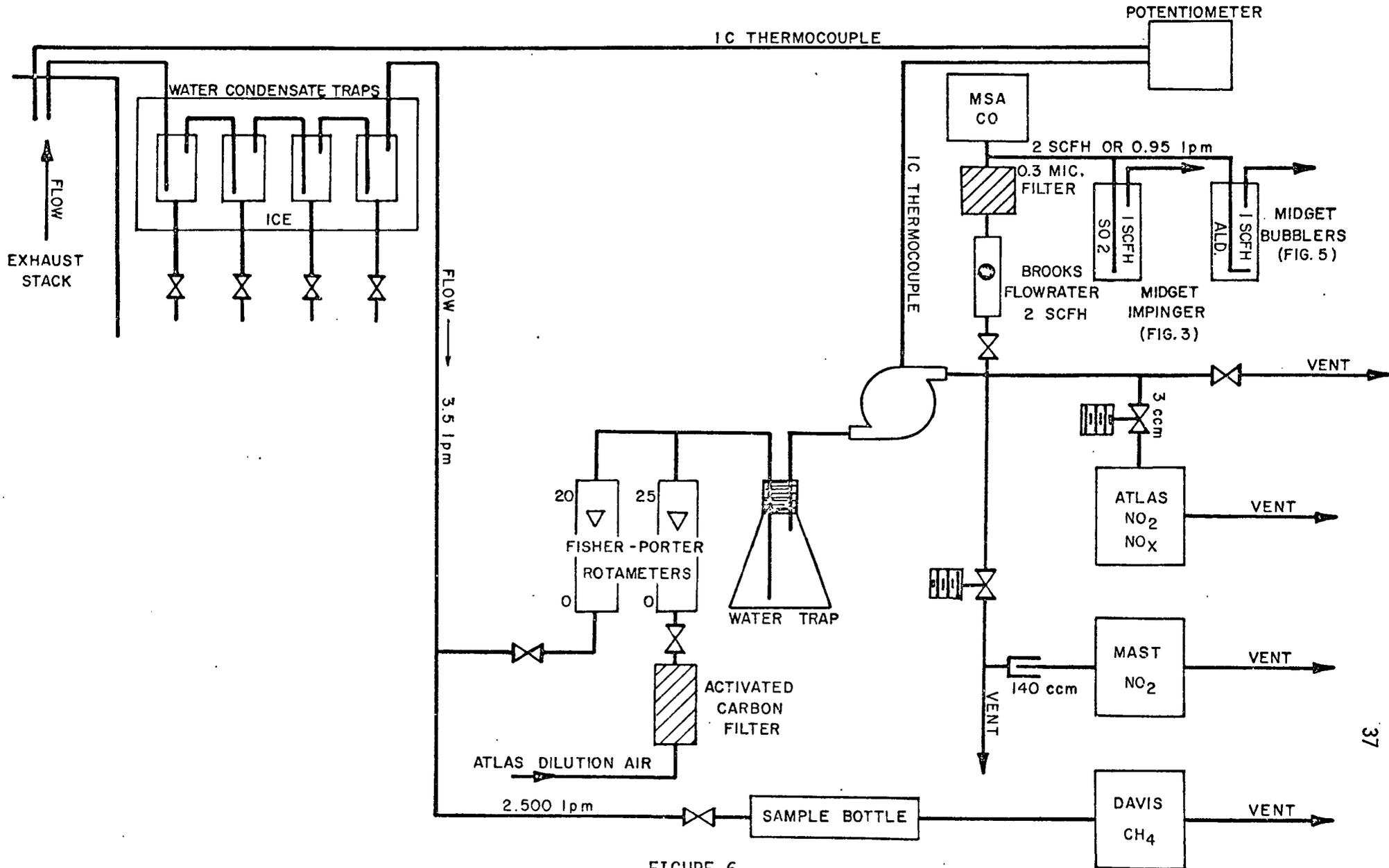


FIGURE 6

The nitrogen oxide analyzers were connected in parallel. Because the Atlas device was calibrated at 0-8 ppm for both  $\text{NO}_2$  and  $\text{NO}_x$ , it was necessary to dilute the flow at an 8:1 ratio for the Atlas Analyzer and operate it separately. The dilution air was filtered through an activated carbon column to remove potential interfering gases.

#### EXPERIMENTAL TEST PROCEDURE

As noted above, the primary pollutant measured was oxides of nitrogen. The gas turbine reaction turbine has a speed range of 3800 RPM (Idle) to 4700 RPM (Rated or full power). After several trial instrumentation and stack gas cooling and condensation arrangements had been made, the scheme shown as Figure 6 was adopted. With the limitation of no allowable stack holes, severe vibration, high stack temperatures (600°F to 700°F) and high stack gas exhaust velocities available test equipment arrangements were somewhat limited.

The test procedure consisted of "leveling" the turbine at a point in the speed range for a period of 15-30 minutes until the load stabilized. The load stabilization point was determined by observing the variation in the pipeline compressor suction and discharge pressures and the turbine exhaust temperature. A complete set of data at a minimum of 200 RPM increments including the following, was obtained for the full speed range of the turbine. It was anticipated that pipeline load conditions and/or ambient temperatures might make it impossible to obtain a complete range of data.

## DATA

1. GG3C-1 Low Compressor Speed (N1) - RPM
2. GG3C-1 High Compressor Speed (N2) - RPM
3. Free Turbine Speed (N3) - RPM
4. Ambient Pressure (Pamb) - Inches H<sub>g</sub> absolute
5. Ambient Temperature (Tamb) - °F
6. GG3C-1 Inlet Temperature (T<sub>t2</sub>) - °F
7. GG3C-1 Low Compressor Station Discharge Pressure (P<sub>s3</sub>) - Inch H<sub>g</sub> Gauge
8. GG3C-1 High Compressor Station Discharge Pressure (P<sub>s4</sub>) - Inch H<sub>g</sub> Gauge
9. GG3C-1 Total Discharge Pressure (P<sub>t7</sub>) - Inch H<sub>g</sub> Gauge
10. GG3C-1 Exhaust Temperature (T<sub>t7</sub>) - °F
11. RT-105 Exhaust Sample Point Temperature (T<sub>exh.</sub>) - °F
12. Davis Flame Ionization Unit Hydrocarbons as CH<sub>4</sub> - ppm
13. Mast Coulometric NO<sub>2</sub> Meter - ppm
14. Atlas Colorimetric NO<sub>2</sub> and NO<sub>x</sub> Analyzer - ppm
15. Fuel Flow - Differential, Pressure, Temperature (SCFM)
16. Pipeline Compressor Flow - Differential, Pressure, Temperature (SCFD)
17. Test Time - Minutes
18. MSA Infrared CO Analyzer - ppm
19. Water Collected - ml
20. Bubbler - Aldehydes - ppm
21. Impinger - SO<sub>2</sub> - ppm

As mentioned earlier, because of trace quantities of sulfur and absence of complex hydrocarbons in the fuel gas (Table 4) aldehydes and SO<sub>2</sub> were measured at a single load point. All other data was recorded every 10 minutes utilizing continuous monitoring equipment.

A stainless steel or glass cylinder was placed in series with the flame ionization unit for the duration of each test. These bottles had been cleaned, heated and evacuated prior to use.

Flow rates to each instrument were adjusted per operating manual instructions. Instrument calibrations, reagents, dye and other preparations were made prior to the onsite tests.

## INSTRUMENTATION AND TEST EQUIPMENT

Unfortunately, only a limited number of methods available for trace gas analysis of stack gases may be designated as specific. Most methods are essentially non-specific and depend on oxidation-reduction,

acid-base reactions, measurements of electrical conductivity, colorimetric procedures or general techniques that yield a measure of the algebraic sum of absorbed pollutants having similar chemical properties.

At full power the oxidizing column used in the Atlas NO<sub>x</sub> and NO<sub>2</sub> instrument was removed and used with the Mast NO<sub>2</sub> Meter. This allowed an opportunity to compare total NO<sub>x</sub> emissions for both instruments and to determine if the oxidizing column (CrO<sub>3</sub> + H<sub>3</sub>PO<sub>4</sub>) might be a useful adjunct to a coulometric device designed to measure NO<sub>2</sub>.

Summarizing the test procedure as follows:

1. Determine the location of the gas turbine exhaust emission sampling point.
2. Run the 10,500 BHP RT-105 gas turbine through the full available speed and power range.
3. Monitor gas turbine data at selected power settings.
4. At the selected power settings using test arrangement and equipment, measure emission pollutants.

Discussion covering the major test equipment components as follows:

#### A. GAS TURBINE

Gas turbine instrumentation consisted of bellows type (Heise) gauges for pressures. Turbine speeds and temperatures were measured using existing instrumentation installed in connection with the turbine control system. Fuel flow was measured using a 2.125 inch X 3.068 inch standard orifice meter (AGA Report 3). Compressor gas flow was measured using an orifice 18.750 inch by 22.750 inch meter (AGA Report 3).

#### B. NITROGEN OXIDES

- (1) Atlas Electric Devices Company  
Chicago, Illinois  
Instrument Serial Number GA-150  
Model 2340 NO<sub>2</sub> and NO<sub>x</sub>

The Atlas  $\text{NO}_2$  and  $\text{NO}_x$  unit is basically an automated Griess - Saltzman (16) colorimetric device modified so that real time or continuous values of  $\text{NO}_2$  and  $\text{NO}_x$  as  $\text{NO}_2$  can be determined. The basis for the analyzer is a modified Griess reaction which involves the reaction of sulfanilic acid with  $\text{HNO}_2$  (nitrite solution) to form a diazotized sulfanilic acid. This is then further reacted with a naphthylamine derivative to produce a pink dye. The transmittance of the dye is measured colorimetrically.

To make this system suitable for use as a continuous analyzer, the reagents have been modified by the use of 2-amino-benzene disulfonic acid as the diazotizable component and N- (1 Naphthyl) ethylene dihydrochloride as the coupling dye compound so that color development is obtained in 60-90 seconds instead of 6-15 minutes required by the conventional Griess - Saltzman Reaction.

The analysis method is specific for  $\text{NO}_2$  and the sample is taken directly into the Atlas Analyzer without the use of a scrubber column. The reagent is prepared by the manufacturer and the exact formulation is proprietary. Katz (21), however, discusses a similar absorbing reagent which has absorption efficiencies in excess of 90%. Before activation the reagent has a long storage life but after activation can develop a dark color which may be removed by the filter column of the analyzer.

The Atlas Analyzer was calibrated on the 0-800 pphm scale. Calibration is accomplished by varying the liquid to sample ratios and then standardizing the recorder against a calibrated glass filter. The liquid flow rate is held constant and the air flow rate is varied to

achieve the pre-selected range. In order to achieve optimum absorption (99 +%) the highest liquid flow rate possible is selected based on the pre-selected operating range. The response rate is based on the liquid flow rate.

The Atlas Analyzer includes a filter column (A) which is packed with a special treated nylon and decolorizing carbon which, as the reagent is pumped through, removes all developed and undeveloped dye. The analyzer also includes a separator column (B) where the reagent is separated from the air stream and collected and stored for reuse. The air and reagent from the helical absorber enters the top of the column where the liquid drops down and is stored. The air then passes out through another tubing connection located on the top of the column then through a filter column and out through a vacuum pump. The dye is maintained in a separate column (C). The Atlas Analyzer includes built-in rotameter flow meters.

The Atlas Analyzer can measure total  $\text{NO}_x$  by oxidizing  $\text{NO}$  to  $\text{NO}_2$  and measuring the total as  $\text{NO}_2$ . The exact makeup of the oxidizing material is proprietary. The efficiency is 99+% (manufacturer).

In order to operate the Atlas Analyzer at  $\text{NO}_2$  concentrations greater than 0-8 ppm it is necessary to dilute the sample stream using air pulled through an activated carbon filter. The dilution rate depends on the total amounts of  $\text{NO}_x$  being sensed in the sample gas stream.

The efficiency of collection for the Atlas Analyzer is unknown, however, it is assumed to be high (99+%).

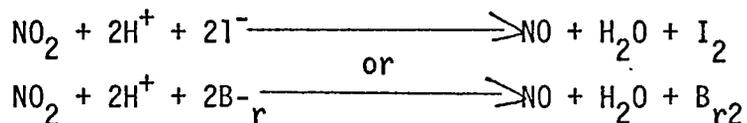
The collection efficiency is accounted for in the calibration procedure.

(2) Mast Development Company  
 Davenport, Iowa  
 Mast Nitrogen Dioxide Meter  
 Model 724-11

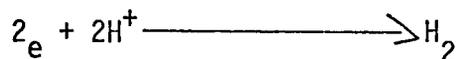
The Mast Nitrogen Dioxide Meter, Figure 7, is a coulometric device. A chemical solution containing the proper amounts of sensing reagents, is metered into the sensor by way of the sensing supply tube. The solution flows in a thin film down the electrode support upon which are wound many turns of a fine wire cathode and a single turn of a wire anode and is deposited into a waste reservoir. The air sample enters adjacent to the top of the electrode support and is pumped through the sensor by way of a narrow annulus where it comes into contact with the solution contained on the support and exits at the base.

A small potential is supplied across the cathode and anode and the current is measured by a microammeter.

The sensing of  $\text{NO}_2$  in the gas sample is accomplished by the oxidizing reduction of potassium bromide (or iodide) contained in the sensing solution. This reaction takes place on the cathode portion of the electrode support. In this region a definite portion of the  $\text{NO}_2$  reacts with the sensing solution as follows:



At the cathode, a thin layer of hydrogen gas is produced by a polarization current:



When the voltage is applied to the electrodes (about 0.56 volts), the hydrogen layer builds to its maximum and the polarization current

# SCHEMATIC MAST NO<sub>2</sub> METER

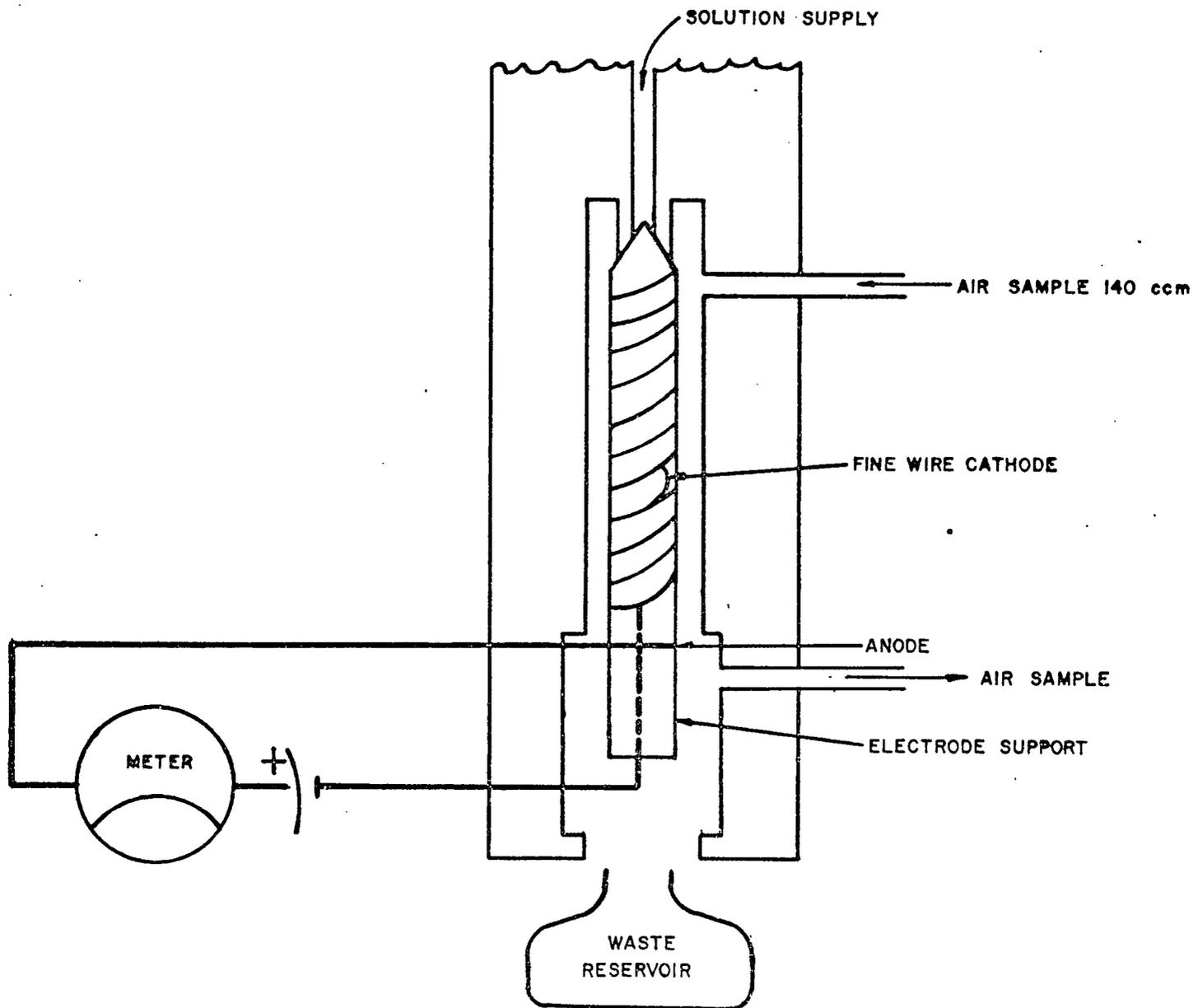
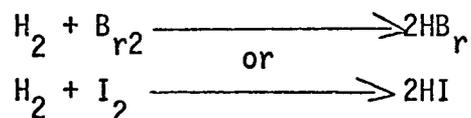


FIGURE 7

ceases to flow.

When free bromine is produced by the reaction of  $\text{NO}_2$ , it immediately reacts with  $\text{H}_2$  as follows:



The removal of the hydrogen from the cathode causes a re-polarization current of two electrons to flow in the external circuit, re-establishing equilibrium, thus, for each  $\text{NO}_2$  molecule reacting in the sensor, two electrons flow through the external circuit. Therefore, the rate of electron flow or current is directly proportional to measurement of  $\text{NO}_2$  entering the sensor.

In the test procedure, in order to convert the Mast  $\text{NO}_2$  Meter to an  $\text{NO}_x$  analyzer, the oxidizing column used for the Atlas Analyzer was removed and utilized with the Mast device.

The Mast device used in the test was calibrated by the manufacturer by injecting a known quantity of  $\text{NO}_2$  into the meter. The instrument was operated on the 0-140 ppm full scale range. Sensitivity as reported by the manufacturer is 0.1 ppm on the low range.

It should be noted that both the Atlas Analyzer and the Mast  $\text{NO}_2$  Meter are essentially ambient air devices. Use of these devices to sample stack gases can result in errors because of improper installation. Consultation with the manufacturers hopefully resolved these problems.

If ozone exists in large quantities (five times  $\text{NO}_2$  concentration) or  $\text{SO}_2$  exists in large quantities (thirty times  $\text{NO}_2$  concentration) the Atlas colorimetric device can give readings in error.

### C. HYDROCARBONS

- (1) Davis Instrument Company  
Newark, New Jersey  
Davis Flame Ionization Meter  
Bottle #11-654

The Davis Flame Ionization Meter was operated on a continuous basis. The sample being analyzed is continuously drawn into the detection cells where it contacts a hydrogen flame. A portion of the carbon compound present in the sample burns in the hydrogen flame. This produces carbon ions in the flame. An electrical potential across the flame jet and an electrode located above the flame results in a ion current which is measured by a electrometer circuit. The sensitivity of the flame ionization analyzer is less than 2 ppm (benzene) and the reproducibility of the instrument is 2% of full scale. The instrument was operated on the "5" scale with a response to methane at full scale of 80 ppm.

#### D. CARBON MONOXIDE

- (1) MSA (Mine Safety Appliance)  
Pittsburgh, Pennsylvania  
Lira Model 300  
Infrared CO Analyzer

Carbon Monoxide absorbs radiation in the infrared region of the spectrum. The Lira Analyzer consists of a pressurized, non-dispersive infrared spectrometer with a 40" cell path and the following components: a source of infrared radiation, beam chopper, sample and comparison cells, a beam combiner, a detector, signal amplification system and control circuit. The range is determined by injecting a known concentration of CO in nitrogen. The zero setting of the instrument is accomplished with pure nitrogen. The instrument was operated 0-1000 ppm full scale. According to the

manufacturer accuracies of  $\pm 2\%$  are attainable. Water vapor in the air sample constitutes an interference which as indicated by Figure 6 is eliminated by water condensation and a 0.3 micron filter.

#### E. SULFUR DIOXIDE AND ALDEHYDES

Sulfur Dioxide was measured using the West-Gaeke colorimetric method (16). Sulfur Dioxide in the sample is absorbed in 0.1 M sodium tetrachloromercurate. Nonvolatile dichlorosulfitomercurate ion is formed in this process. Addition of acid-bleached paraosaline and formaldehyde to the complex ion produces red-purple pararosaniline methylsulfonic acid, which is measured colorimetrically. The West-Gaeke method is subject to interferences from ozone and  $\text{NO}_2$ . The concentration of which should be less than that of the  $\text{SO}_2$  being measured.  $\text{NO}_2$  interference can be eliminated by addition of sulfamic acid in the absorbing reagent.

Determination was made of aliphatic aldehydes using the MBTH method (16). The MBTH method measures the total water-soluble aliphatic aldehydes (measured as formaldehydes) in a test sample. Aliphatic aldehydes react with MBTH in the presence of ferric chloride to form a blue cationic dye in acidic media. The aldehydes in an air sample are collected in a 0.05% aqueous MBTH solution. The resulting azine is then oxidized by ferric chloride-sulfamic acid solution to form the blue dye which can be measured colorimetrically. Aldehydes were sampled for 24 hours (16). The West-Gaeke sulfur dioxide determination was also operated for a period of 24 hours.

The error for the combined sampling and analysis of the test gas is approximately  $\pm 10\%$  for the  $\text{SO}_2$  West-Gaeke analysis. Several

compounds react with MBTH (16), however, most of these compounds are not water or gaseous soluble and should not interfere with the analysis of water-soluble aliphatic aldehydes in the test sample. Since formaldehyde generally makes up about 50% of the total aldehydes in the atmosphere, the test is considered valid (21).

In the MBTH test, Beer's law study is linear for formaldehyde concentrations up to 1.72 micrograms per ml of test solutions (16). For the  $\text{SO}_2$  test, the system follows Beer's law up to about 10 microliters of  $\text{SO}_2$  per 10 ml of absorbing solution (16).

#### F. GAS ANALYSIS

As indicated by Figure 6 and in the previous discussion, stainless steel and/or glass bottles were filled with composite samples during the tests and analyzed using a CEC mass spectrometer (Number 21-614-1, Cycloidal Residual Gas Analyzer).

Concluding, test readings were taken at 10 minute intervals at each power setting of the turbine for a period of from one to three hours. The Atlas Analyzer and the Mast  $\text{NO}_2$  Meter included chart recorders. The Atlas Analyzer utilized for the test is based on the Griess - Saltzman technique and is the preferred or standard determination method of  $\text{NO}_2$ .

CHAPTER IV  
RESULTS AND DISCUSSIONS

GENERAL

The purpose of this thesis and the associated tests was to measure exhaust stack emissions from natural gas fired stationary gas turbine on a real time basis. A secondary objective was to make a comparison of the performance and results of the instruments used, particularly the results from the instruments measuring nitrogen oxides. The tests and the test results in this case indicated that all instruments used to measure trace gas stack emissions have calibration and operating problems (in some cases repeatability) and the processed data below reflects some of these problems. In most cases, the variation between instruments are of magnitudes which, in dealing with trace gas emissions, are acceptable and tend to confirm emission levels rather than absolute emission values.

In terms of emissions, both on a concentration and/or mass basis, the gas turbine tested had lower values than expected. Measured levels fell well below the standards discussed in Chapter II. It is difficult to compare the data obtained on test with previous results found in the literature search, Chapter II, except that processed data for the tests was within published ranges. Exact correlations are not possible because fuel-air ratios, BHP, exhaust mass flow and/or other parameters are generally not noted in sufficient detail although most of the published data is correlated with at least one of the above parameters with the exception

mass flow. In general, however, exhaust stack emission trends and levels in the tests associated with this thesis and published data are comparable.

As mentioned previously, there were several difficulties involved in obtaining the field data. Utilization of instrumentation primarily designed for laboratory use for short intervals and associated voltage requirements resulted in delays and operational problems. Finally, use of this equipment in a field environment involved long periods of operation, wide ambient temperature and humidity variations and problems with voltage and/or power frequency sensitivity devices. The difficulty of sampling high temperature gas turbine exhaust stack gases has been discussed previously. Reviewing, in order to adequately sample, a stainless steel water vapor condensation system was installed as close as possible to the stack sampling point. Standard condensation equipment utilizing ground glass connections and glass impingers could not be used. After the gas was collected, it was routed to the instrumentation as shown Figure 6, through tygon tubing. There is no indication in the literature that tygon tubing will react with any of the pollutant gases measured, particularly the nitrogen oxides.

#### CALCULATIONS

Emissions (real time) were measured on ppm basis and converted to a mass-time basis, pounds/hour (lbs/hr.). The conversion to lbs/hour related emission quantities to the mass flow of the turbine exhaust stack gases. 29.92 inches mercury and 70 degrees Fahrenheit were selected as the standard pressure and temperature base. All pertinent data and associated calculations were corrected to this base. A listing of nomenclature used in this section is as follows:

N1 - Low compressor speed - GG3C-1 (axial flow compressor)

N3 - Reaction turbine drive speed, RT-48

$P_{s4}/P_{t2}$  - Compression ratio GG3C-1

EPR - Pressure ratio across GG3C-1

$w_a$  - Weight of combustion and cooling air

$w_{fg}$  - Weight fuel gas

F/A - Fuel-air ratio

BHP or SHP - Brake or shaft horsepower, gas turbine

$T_{t7}$  - Exhaust temperature GG3C-1

$T_{test}$  - Gas test sample temperature

$T_{exhaust}$  - Turbine exhaust stack or sampling point temperature

All test readings were made using onsite instrumentation as discussed in Chapter III including the initial velocity traverse discussed in Chapter II. All combustion or cooling air velocities or mass flows were calculated using the manufacturer's calibration curve which was developed using a pitot tube traverse located in the inlet of the engine. This data is more accurate than a single pitot tube (accuracy  $\pm 3\%$ ) located in the exhaust stack. Fuel gas flow was calculated from orifice meter data using AGA REPORT 3, "Orifice Metering of Natural Gas", 1969 (accuracy  $\pm 1\%$ ) as follows:

$$Q_s = KA (2gh)^{1/2}$$

Where:

$Q_s$  = Cubic feet per second flow

K = Co-efficient of discharge

A = Area of the orifice in square feet

g = 32.2 feet/second/second

$h$  = differential head in feet of the flowing gas and at the average specific weight at the orifice

Theoretical output of the gas turbine, brake or shaft horsepower can be calculated using the relationship as follows:

$$\text{Output} = (\text{Turbine work}) - (\text{AFC Work}) - (\text{Losses})$$

Losses refer to pressure losses in the separators and steam extraction system.

$$\text{Output} = C_p T_3 \left( 1 - \frac{1}{\frac{P_3}{P_4} \left( \frac{P_2}{P_1} \right)^{\frac{n-1}{n}}} \right) - C_p T_1 \left( \frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1$$

Where:

$$n = \frac{C_p}{C_v}$$

$T_1$  = AFC inlet temperature

$P_2$  = Combustion Section inlet pressure

$P_3$  = Expander Turbine inlet pressure

$P_4$  = Expander Turbine discharge pressure

$T_3$  = Expander Turbine inlet temperature

First, it can be seen from the above that the pressure drop across the entire turbine must be equal to one for maximum efficiency. If this drop is greater than one then available HP is reduced. Losses in the order of 50 - 75 HP for each one-half inch of water pressure drop are typical.

Shaft horsepower (SHP) was actually calculated using the manufacturer's test calibration data. Since SHP is a function of the engine pressure ratio (EPR) and EPR can be calculated with greater

precision than SHP, EPR is used instead of SHP in the graphical representations which follow.

Emission volumes as measured at flow meters or test equipment were adjusted for water condensed from the test sample flow. The fraction of dry gas was calculated as follows:

$$F_d = \frac{V_t}{w (g) \times 1 (lb) \times 1 (lb-Mole) \times 359 (CF) \times T_m \times 29.92'' H_g + 453 (g) \times 18 (lb H_2O) + 1 (lb-Mole) \times 530'' R \times P_m (''H_g ab)}$$

$F_d$  = Dry gas fraction

$V_s$  = Sampled volume total

$w$  = Weight of water

$T_m$  = Temperature at meter °F

$P_m$  = Pressure at meter inches of mercury absolute

#### INSTRUMENTATION

All of the instruments used in the field were operable during duration of the tests. The Atlas Analyzer and the Mast NO<sub>2</sub> Meter appeared, based on the data correlation, to have operated satisfactorily during the test.

The MSA Lira Infrared Carbon Monoxide Analyzer performed satisfactorily. This device could be calibrated in a relatively "clean" atmosphere each day before tests were started so that the instrument performed as specified. However, because of the extremely low CO levels and the range of the meter, 0-1000 ppm full scale, the accuracy of the device in the area being utilized is probably questionable. The order of magnitude, however, is probably

correct.

The Davis Flame Ionization Hydrocarbon Meter used to monitor hydrocarbons ( $\text{CH}_4$ ) was of limited use during the tests as a continuous monitoring device. Because of high background hydrocarbon levels at the test site due to the proximity of gas facilities, it was difficult to accurately calibrate the instrument for measuring trace gases since stack emission concentrations were apparently lower than background concentrations. It was possible, however, to determine  $\text{C}_1$  and  $\text{C}_2$  concentrations from the CEC Mass Spectrometer data. This data confirmed that stack hydrocarbon concentrations were, in fact, very low. Both of the nitrogen oxide analyzers were pre-calibrated and the associated recorders "zeroed". Data and calculations are summarized in Tables 4-8.

TURBINE STACK EMISSION TESTS

TURBINE DATA SHEET SUMMARY

Test No.	N1	N3	$P_{s4}/P_{t2}$	EPR	$w_a$	$w_{fg}$	$w_a$	$w_{fg}$	F/A	SHP	$T_{t7}$
	RPM	RPM			#/Hr	#/Hr	SCFM (LHV)	SCFM (LHV)			°F
1.	5953	4697	9.49	2.08	576,000	5904	128,606	2288	.0119	11,975	904
2.	5801	4492	9.015	1.97	550,800	5616	123,753	2120	.0117	10,530	866
3.	5439	3994	7.88	1.77	489,660	4788	110,000	1852	.0113	8,180	814
4.	5708	4317	8.66	1.91	532,800	5508	119,709	2133	.0119	9,436	860
5.	5978	4684	9.60	2.07	583,200	5940	131,033	2306	.0194	11,884	915
6.	6007	4795	9.82	2.12	568,800	6048	131,841	2350	.0119	12,295	918
7.	5866	4592	9.32	2.03	565,200	5688	126,988	2210	.0115	13,730	880
8.	5724	4413	8.89	1.95	540,000	5436	121,327	2100	.0115	9,967	860
9.	5450	4017	7.98	1.80	493,200	4968	110,812	1900	.0114	9,235	795

Table 4

(70°F, 29.92 "Hg)

TURBINE STACK EMISSION TESTS

EMISSION DATA SHEET SUMMARY

Test No.	T test OF	Texhaust OF	MASS SPEC. - CH <sub>4</sub>		MAST - NO <sub>2</sub>		ATLAS - NO <sub>x</sub>		ATLAS - NO <sub>2</sub>	
			Conc. ppm	Lbs/Hr.	Conc. ppm	Lbs/Hr.	Conc. ppm	Lbs/Hr	Conc. ppm	Lbs/Hr
1.	77.3	705	2.7	0.98	25.0	26.4	38.0	40.2	7.5	7.9
2.	75.0	686	2.6	.87	22.0	22.4	32.4	31.0	7.7	7.8
3.	73.5	642	2.2	.72	24.0	20.7	38.2	24.4	11.9	10.3
4.	68.0	620	2.5	.82	22.5	22.3	30.0	29.7	12.2	11.5
5.	68.0	640	2.8	.90	*46.0	*50.5				
6.	70.0	680	0.9	.32						
7.	70.0	656	5.1	1.77						
8.	70.0	636	4.2	1.40						
9.	70.0	622	3.6	1.09						

Note: \*NO and NO<sub>2</sub> oxidized to NO<sub>x</sub>

Table 5

(70°F, 29.92 "Hg)

TURBINE STACK EMISSION TESTS

EMISSION DATA SHEET SUMMARY

Test No.	MSA - CO		DAVIS - CH <sub>4</sub>	
	Conc. ppm	Lbs/Hr.	Conc. ppm	Lbs/Hr.
1.	28	42	<1	0
2.	28	35	<1	0
3.	28	35	<1	0
4.	28	24	<1	0
5.			<1	0
6.			<1	0
7.			<1	0
8.			<1	0
9.			<1	0

Table 6

(70°F, 29.92 "Hg)

TURBINE STACK EMISSION TESTS

EMISSION DATA SHEET SUMMARY

Test No.	MAST - NO <sub>2</sub>		ATLAS - NO <sub>2</sub>		ATLAS - NO <sub>x</sub>		MASS SPEC. - CH <sub>4</sub>		MSA - CO	
	$\frac{E}{T}$	$\frac{E}{F}$	$\frac{E}{T}$	$\frac{E}{F}$	$\frac{E}{T}$	$\frac{E}{F}$	$\frac{E}{T}$	$\frac{E}{T}$	$\frac{E}{T}$	$\frac{E}{F}$
1.	4.6	4.5	1.4	1.3	7.0	6.8	.17	.16	7	7
2.	4.1	4.0	1.4	1.4	5.6	5.5	.16	.15	6	6
3.	4.2	4.3	2.1	2.1	5.0	5.0	.15	.15	4	4
4.	4.2	4.1	2.2	2.1	5.6	5.4	.15	.15	4	4
5.	*8.7	*8.5					.17	.17		
6.							.05	.05		
7.							.31	.31		
8.							.25	.25		
9.							.22	.22		

Note: \*NO and NO<sub>2</sub> oxidized to NO<sub>x</sub>

E = Emissions (NO<sub>2</sub>, NO<sub>x</sub>, etc.) lbs/hr

T = Total Stack Emissions lbs/hr

F = Total Fuel lbs/hr

$$\frac{E}{T} \times 10^{-5}$$

$$\frac{E}{F} \times 10^{-3}$$

Table 7

(70°F, 29.92 "Hg)

MASS AND INFRARED SPECTROMETER DATA - TURBINE STACK EMISSION TESTS

<u>COMPOSITION</u>	<u>Concentration, ppm</u>								
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>
Methane	2.7	2.6	2.2	2.2	2.8	0.9	5.1	4.2	3.6
Ethane	1.0	.8	.9	1.1	0.5	0.7	1.1	1.2	0.6
Propane	<0.1	0.2	0.1	0.1	<0.1	0.2	<0.1	<0.1	<0.1
Butane	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Acetylene	0.2	0.2	0.2	0.2	0.2	0.3	0.1	0.1	0.1
Ethylene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Hydrogen Sulfide	<0.1	<0.1	<0.1	<0.1	<0.1	T	<0.1	<0.1	<0.1
Methyl Mercaptan	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Ethyl Mercaptan	<0.1	<0.1	T	T	<0.1	<0.1	<0.1	<0.1	T
Carbonyl Sulfide	<0.1	<0.1	T	T	<0.1	<0.1	<0.1	<0.1	<0.1
Sulfur Dioxide	0.2	0.2	0.4	0.4	0.1	0.4	0.3	0.1	0.1
Thiophene	<0.1	<0.1	T	<0.1	<0.1	<0.1	0.1	<0.1	<0.1
Methyl Alcohol	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	0.2	0.1	<0.1
Ethyl Alcohol	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	0.2	0.2	<0.1
Nitrous Oxide	<0.1	<0.1	0.1	0.1	<0.1	0.1	0.2	0.1	0.2
Nitric Oxide	0.3	0.3	0.4	0.2	<0.1	0.5	0.3	0.5	<0.1
Nitrogen Pentoxide	<0.1	<0.1	T	T	<0.1	T	<0.1	<0.1	<0.1
Nitrogen Dioxide	0.3	0.5	0.7	0.7	0.3	0.7	0.4	0.4	0.4
=====									
	Mole %								
Carbon Dioxide	.09	.08	0.07	0.34	.08	.08	0.07	0.10	.05
Carbon Monoxide			3.36				4.95		2.15
Oxygen	22.94	22.24	22.90	21.30	21.98	22.93	22.01	22.95	22.54
Argon	.95	.93	.87	.92	0.61	.91	.84	.94	0.75
Water	.79	.84	.74	.75	.13	.86	.64	1.22	.08
Nitrogen	75.23	75.91	72.56	76.69	77.20	75.22	71.49	75.71	74.43

Table 8

CHAPTER V  
CONCLUSIONS

As stated previously the gas turbine stack pollutant emission concentrations and/or levels were lower than expected, especially for nitrogen oxides. It was anticipated that certain of the factors present for nitrogen fixation, as detailed in Chapter II, were present, i.e.,

1. High Combustion Temperatures
2. High Excess Air (low fuel-air ratios)
3. Combustion air preheat

which could result in high nitrogen oxide emissions. The highest measured NO<sub>x</sub> emission was 50.5 lb/hr or 8.7 lb NO<sub>x</sub> per lb of combustion and cooling air. The corresponding NO<sub>x</sub> concentration was 46 ppm. The maximum NO<sub>x</sub> emissions occurred at maximum gas turbine power. As seen, Figure 8, which was developed from data by Weisburd (25), actual NO<sub>x</sub> concentrations are higher than theoretical values.

Theoretically, combustion of natural gas in a gas turbine with high excess air should result in complete combustion. Combustion of hydrocarbon fuels is in accordance with the following relationship:



In terms of gas used, Table 3, the fuel-air ratio on a stoichiometric basis would be 0.058. During the tests actual fuel-air ratios varied from 0.0113 to 0.0119 indicating a large percentage of excess air.

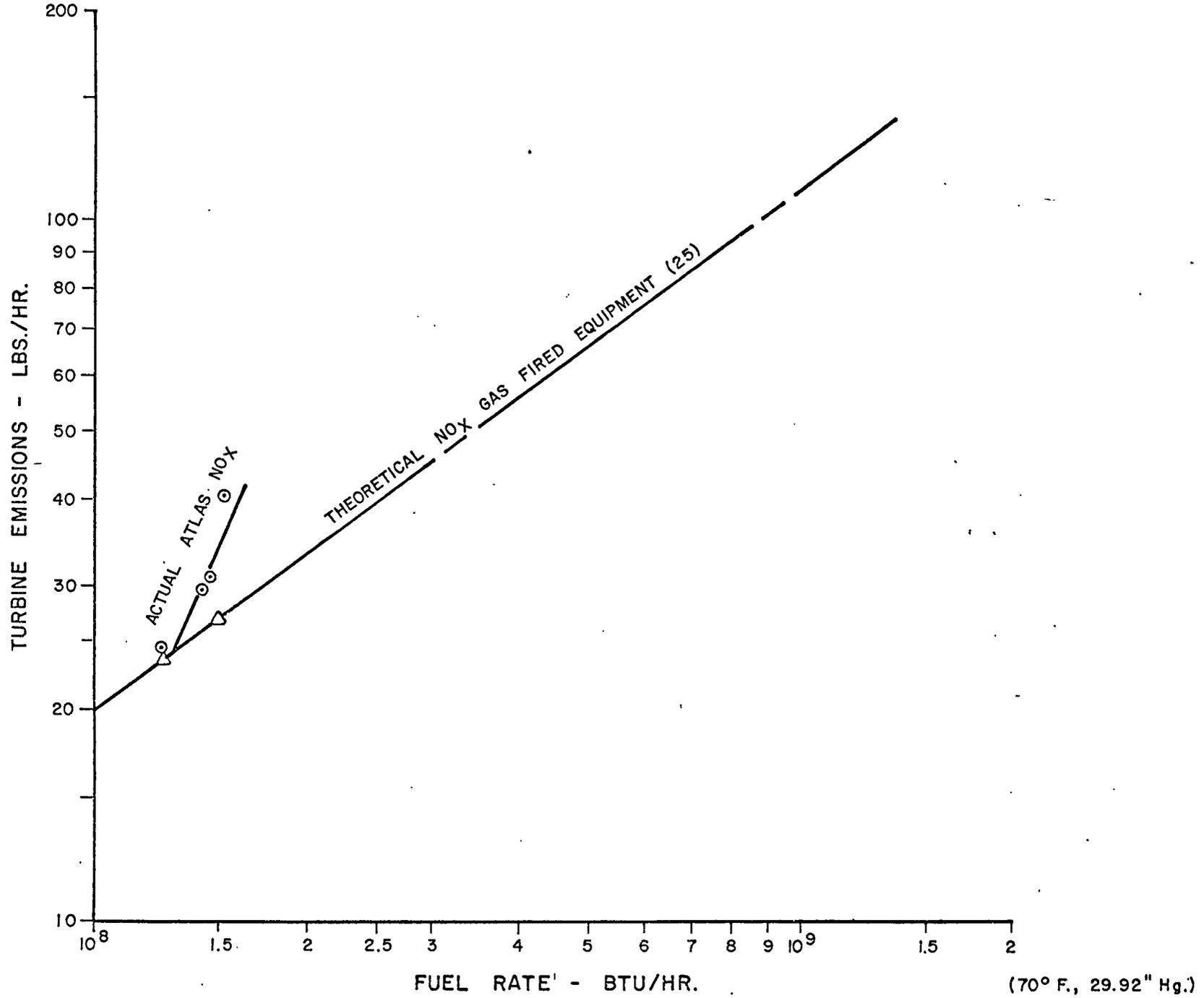


Figure 8

## NITROGEN OXIDES

Nitrogen oxides, except for the Atlas Analyzer  $\text{NO}_2$  concentrations and mass emissions, generally increased with increased power, fuel rate, speed or any of the variables measured or calculated. This was probably due to the narrow allowable operating range of the gas turbine tested.

Atlas  $\text{NO}_2$  emission levels decreased as power and speed increased indicating that NO was being oxidized to  $\text{NO}_2$  at a rate which increased as power and stack temperatures increased. This result was not confirmed by the Mast  $\text{NO}_2$  Meter emission values. Figures 9 - 14 show the effect of various operating parameters on nitrogen oxide stack emissions and concentrations.

It should be noted that the water collected in the condensation traps during each of the test runs appeared to be relatively high in nitrous acid ( $\text{HNO}_2$ ). This was determined by adding a certain amount of Atlas (Greiss - Saltzman) reagent and dye to the water collected and noting a deep red color.

The Mast  $\text{NO}_2$  Meter values were generally higher than those measured by the Atlas Analyzer by a magnitude of approximately 2 - 3. There is some question concerning the calibration of the Atlas Analyzer. Battelle Memorial Institute, Columbus, Ohio, is now undertaking studies which could shed additional light on nitrogen oxide values as determined by the Atlas Analyzer. The Mast  $\text{NO}_2$  Meter used with the oxidizing column would seem to be useful for measuring  $\text{NO} + \text{NO}_2$  emissions as  $\text{NO}_x$ . The Mast  $\text{NO}_2$  Meter is smaller and easier to operate than the large "wet chemical" Atlas Analyzer, however, based on the literature the

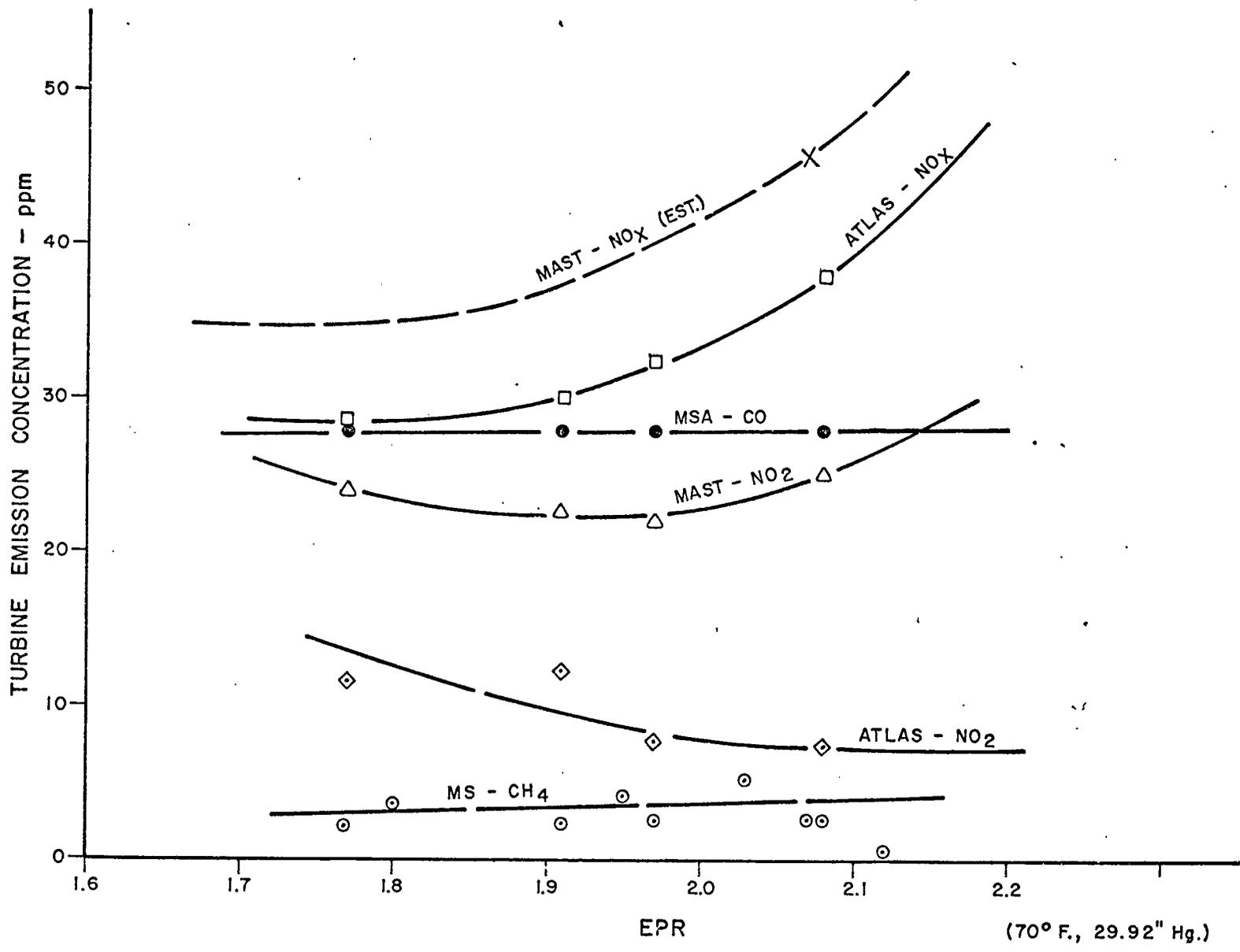


Figure 9

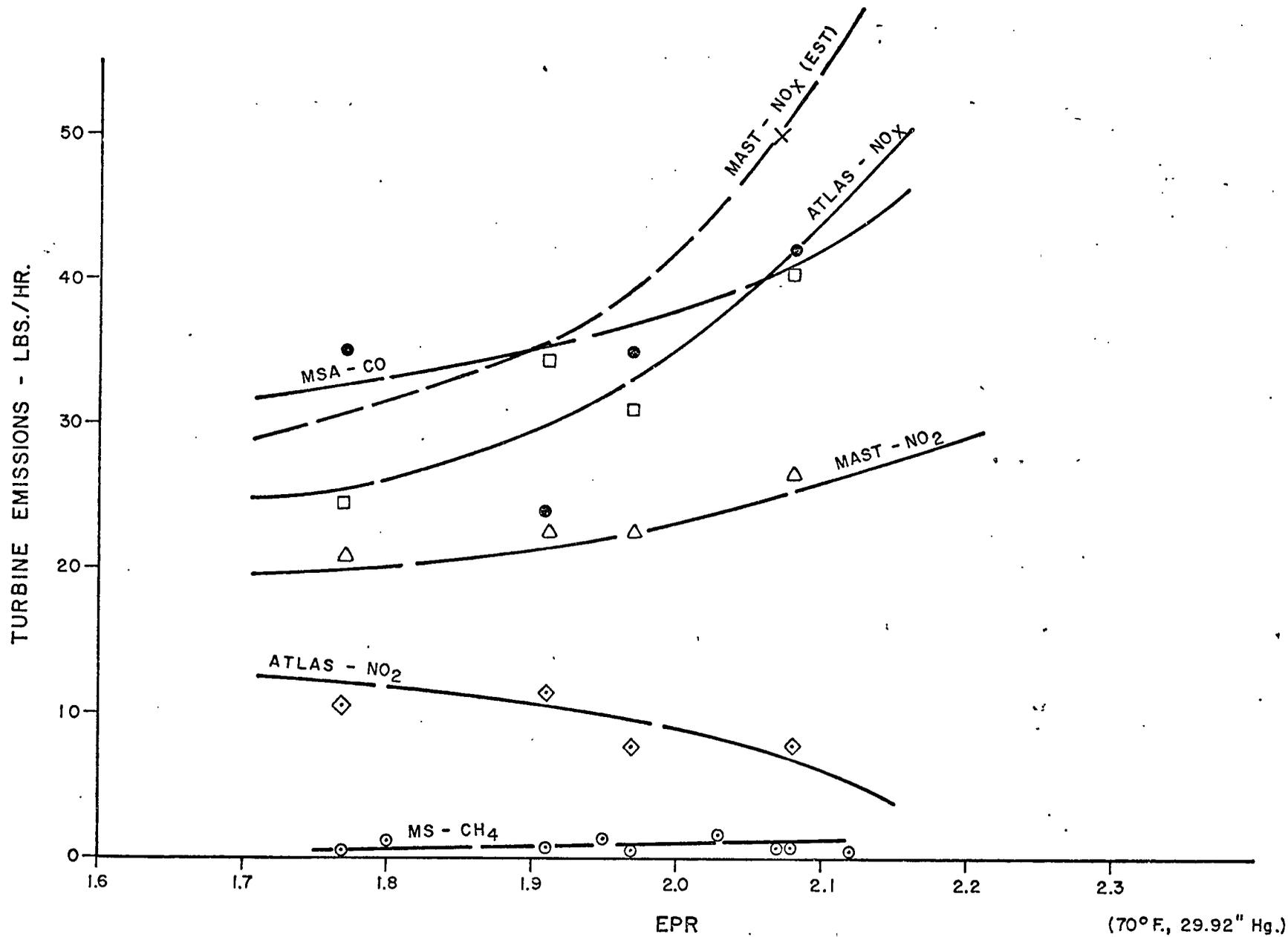


Figure 10

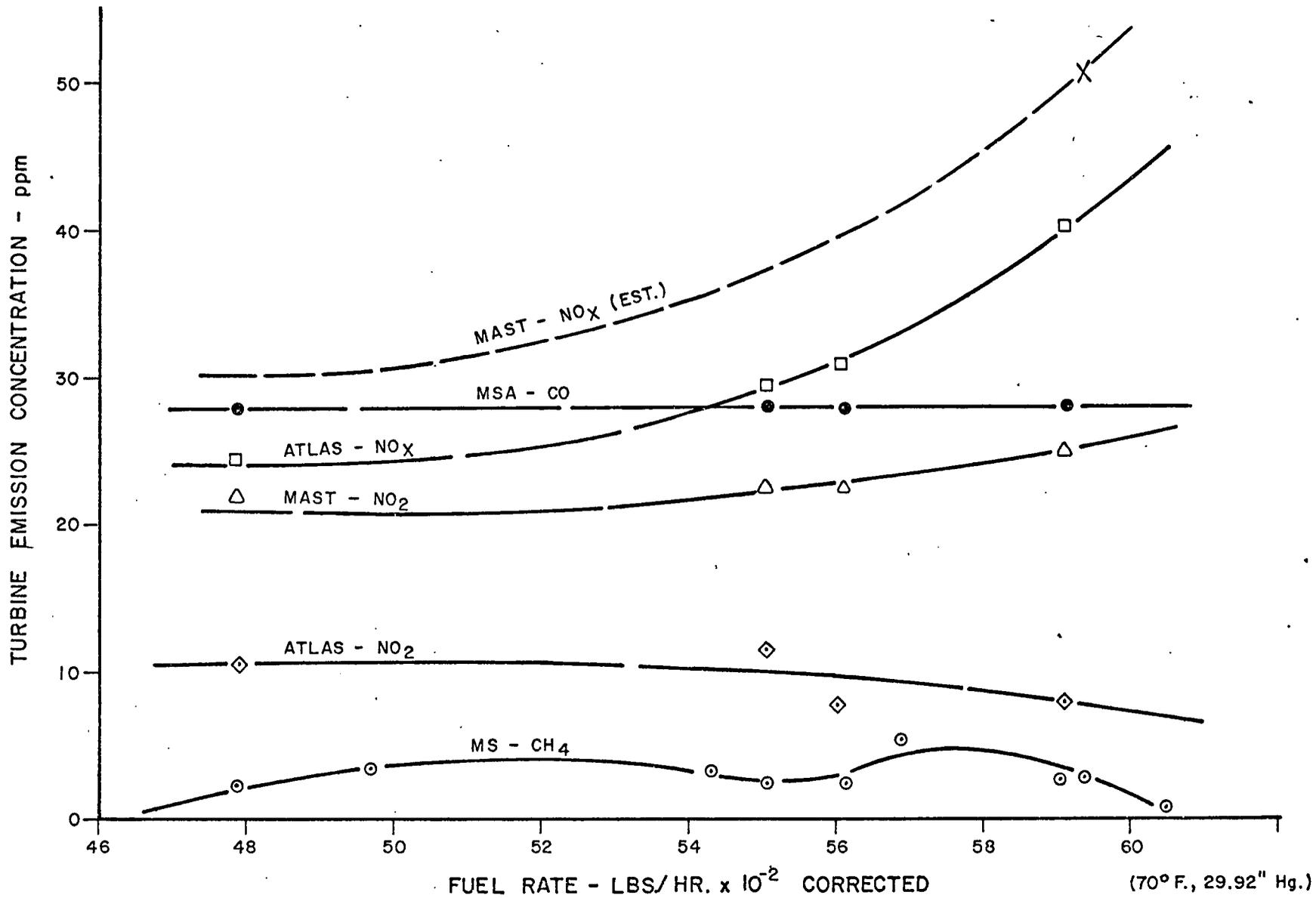


Figure 11

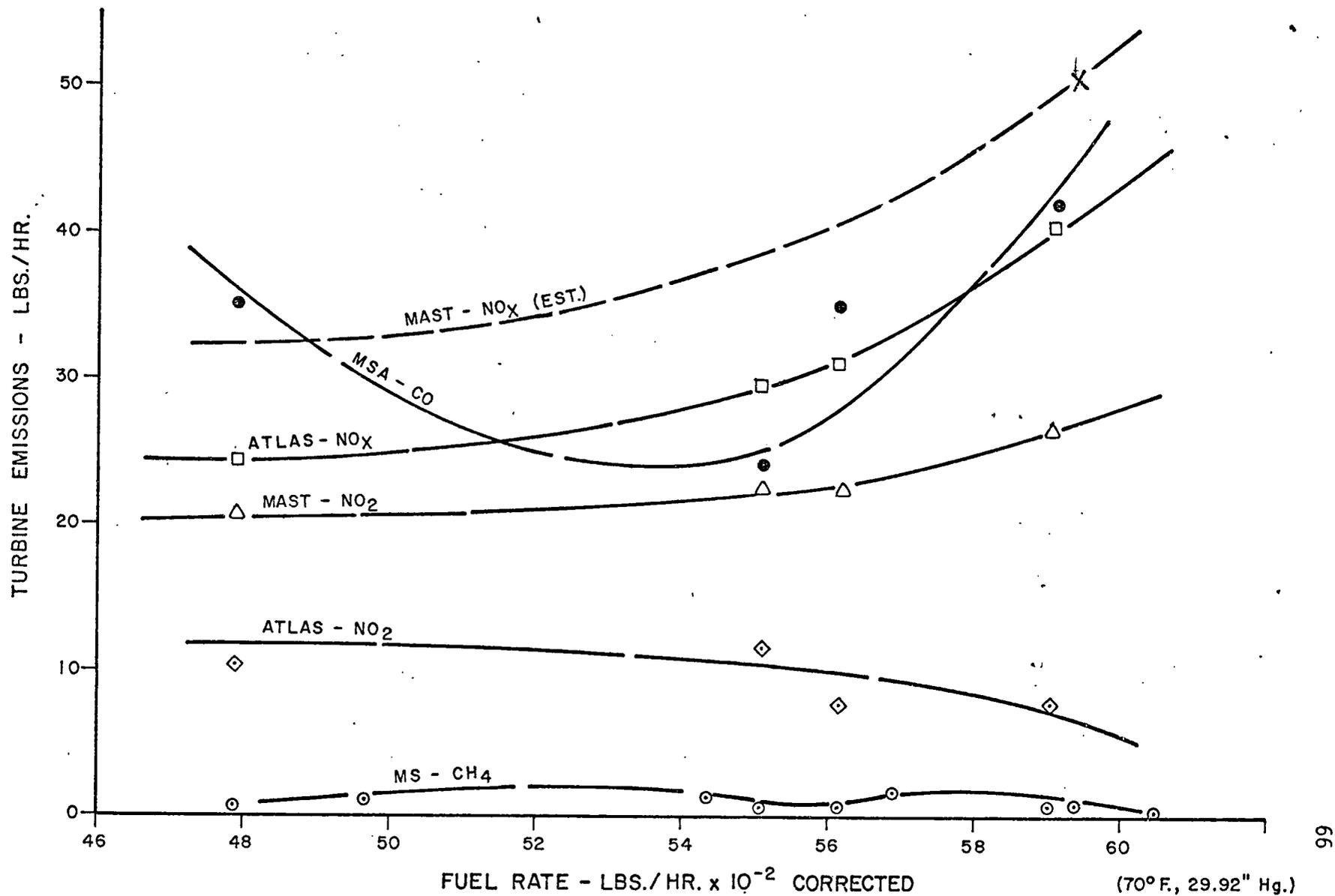


Figure 12

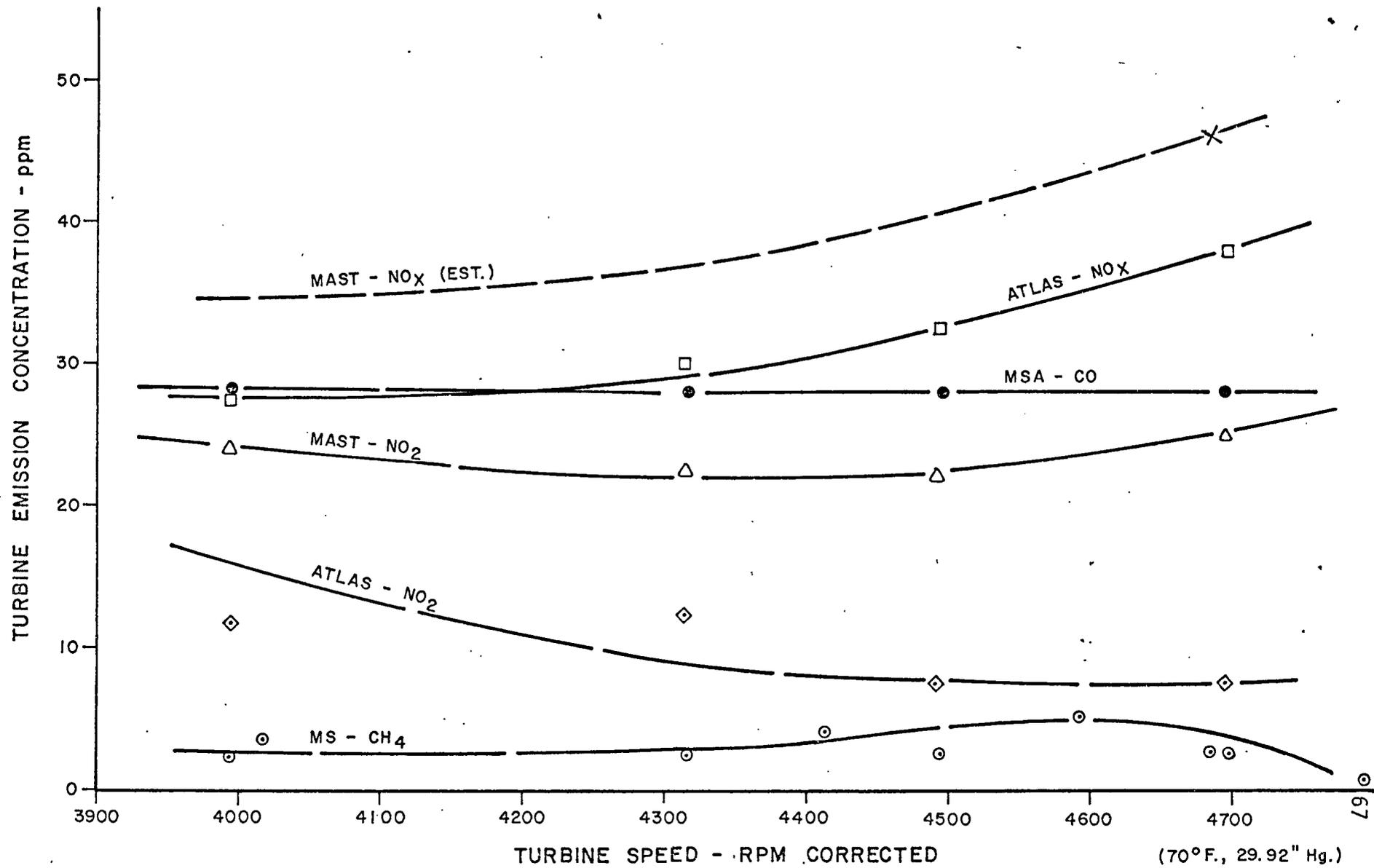


Figure 13

67

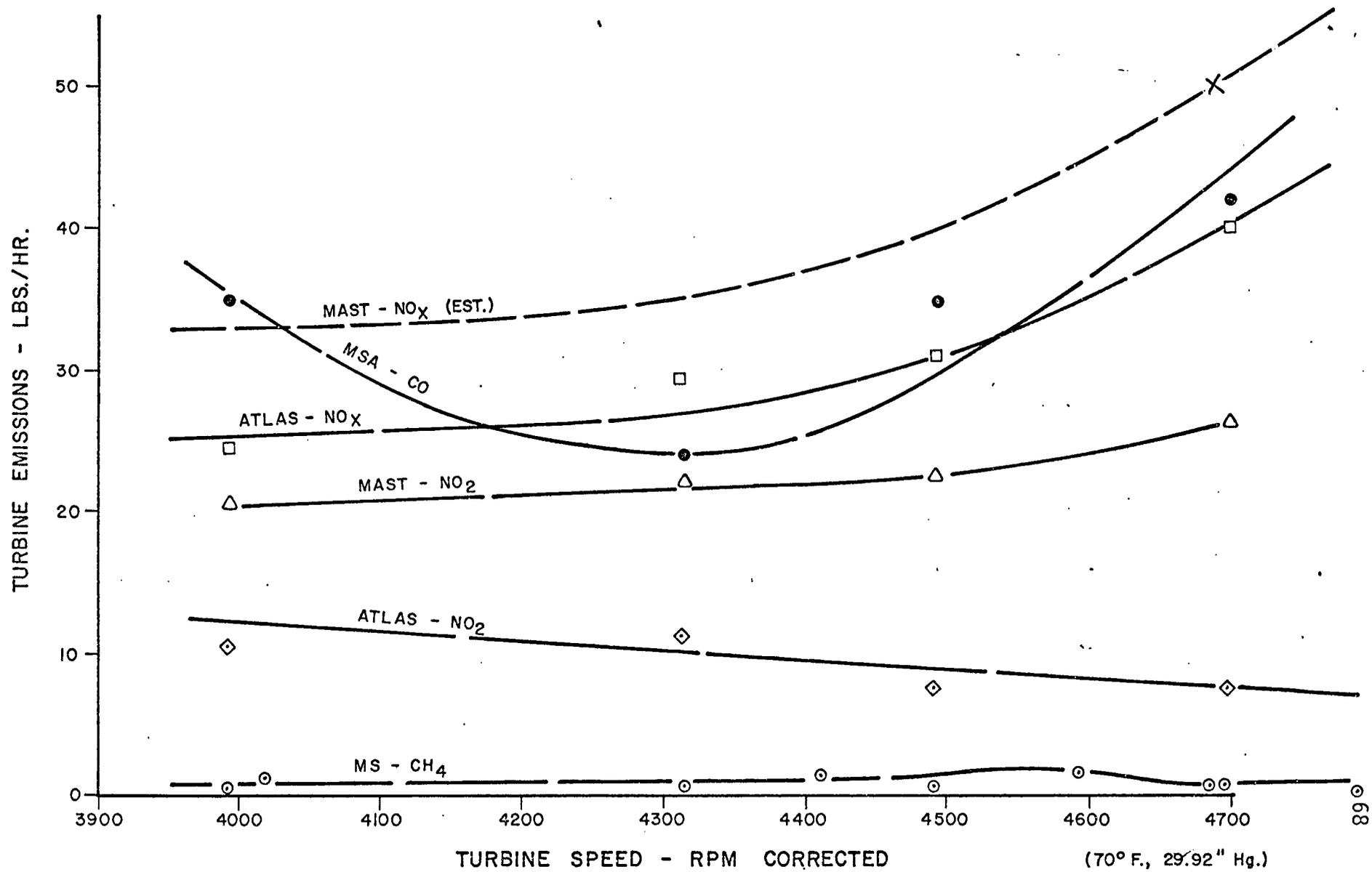


Figure 14

Atlas Analyzer is probably more accurate.

Concluding, low residence time coupled with cooling flame and/or lower combustion temperatures may explain the low nitrogen oxide values measured on test. Flame cooling in the gas turbine would also partially explain the lower than anticipated  $\text{NO}_x$  emissions and concentrations. Flame cooling tends to retard  $\text{NO}_x$  formation. In addition, significant amounts of nitrogen oxides may have been lost in the stack gas water condensation system. As an additional correlation, a 2000 HP conventional engine-compressor was checked with the Mast  $\text{NO}_2$  Meter.  $\text{NO}_2$  concentrations averaged approximately 70 ppm for the period tested which is approximately 2 - 1/2 times the concentration level measured at the gas turbine unit. Since stack flow rates were not determined total mass emission data for the engine could not be determined.

#### SAMPLE BOTTLES

The data accumulated in stainless steel and glass sample bottles was evaluated with the Infrared and CEC Mass Spectrometer indicated reasonable values for hydrocarbons present in the stack emissions. The only components present which could assist in the formation of photochemical smog were ethylene and thiophene and were at very low levels. Nitrogen oxides were measured at very low levels indicating the probable formation of nitrous acid in the sample cylinders as a result of the reaction of nitrogen oxides and water.

#### CARBON MONOXIDE

Carbon Monoxide emissions varied from 24 to 42 lbs/hr or 4 - 7 lbs per lb of combustion and cooling air. Carbon monoxide appeared, generally, to increase with power, speed and other variables measured.

Exact correlations and calculations due to the inaccuracy of the instrument, as mentioned above, are difficult and are probably in error.

#### SULFUR DIOXIDE AND ALDEHYDES

Aldehydes and  $\text{SO}_2$  were present in very small concentrations. The colorimetric tests (16) indicated less than .1 ppm for these components. The CEC Mass Spectrometer indicated  $\text{SO}_2$  levels at 0.1 - 0.4 ppm.

The 40 gas turbines currently operating in the Houston area total 629,700 BHP. The listing of gas turbines, fuel, location type, BHP and utilization is shown in the Appendix. Data for gas turbines shown Table 9 is compared with information obtained from an unpublished study made by the Houston Public Health Department. The study concerned the total daily estimated pollutant emissions for gas and diesel powered vehicles in the Houston area. The data shown Table 9 would indicate the significance of the gas turbine contribution to air pollution in the Houston area.

Concluding, the gas turbine while, apparently, a "clean" combustion source should be controlled, as all combustion sources, on an area basis. Pollutant emissions from a number of units on a mass basis could contribute to the pollution control problem in urban areas. Further research is needed in the study of gas turbine stack emissions. In addition, reliable relatively simple techniques are needed to measure pollutant stack emissions.

COMPARISON OF POLLUTANT EMISSIONS  
FROM HOUSTON AREA  
GAS TURBINES AND  
VEHICLES

Pollutant	Gas Turbines ** Tons/Day	Vehicles * Tons/Day
NO <sub>x</sub>	32.1	32.4
CO	26.8	10,915.0
Hydrocarbons	1.3	21,424.0
SO <sub>2</sub>	Negligible	6,237.3
Aldehydes	Negligible	2.6

\* Includes gasoline and diesel vehicles

\*\* Continuous operation assumed

Table 9

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APPENDIX

HOUSTON AREA GAS TURBINE  
INSTALLATION AND INFORMATION LISTING

UTILIZATION	MANUFACTURER	DESIGNATION	FUEL	LOCATION	BHP
Power Generation (B)	General Electric	5000 Simple Cycle	Gas	Union Carbide Corp. Houston	18,400
Power Generation (B)	General Electric	5000 Simple Cycle	Gas	Southland Paper Mills, Inc. Houston	18,400
Power Generation (B)	General Electric	5000 Simple Cycle	Gas	Southland Paper Mills, Inc. Houston	18,400
Power Generation (B)	General Electric	5000 Simple Cycle	Gas	American Oil Company Texas City	16,800
Power Generation (B)	General Electric	5000 Simple Cycle	Gas	Humble Oil Baytown	19,500
Power Generation (B)	General Electric	5000 Simple Cycle	Gas	Humble Oil Baytown	20,500
Process Drive (B)	General Electric	3000 Simple Cycle	Gas/ Diesel	Hydrocarbon Research, Inc. Pasadena	7,500
Process Drive (B)	General Electric	3000 Simple Cycle	Gas/ Diesel	Hydrocarbon Research, Inc. Pasadena	7,500

UTILIZATION	MANUFACTURER	DESIGNATION	FUEL	LOCATION	BHP
Process Drive (B)	General Electric	3000 Simple Cycle	Process Gas	Tenneco Pasadena	7,500
Process Drive (B)	General Electric	3000 Simple Cycle	Process Gas	Tenneco Pasadena	7,500
Process Drive (B)	General Electric	3000 Simple Cycle	Gas	Humble Oil Baytown	6,000
Process Drive (B)	General Electric	3000 Simple Cycle	Gas	Humble Oil Baytown	6,000
Process Drive (B)	General Electric	5000 Simple Cycle	Gas	Humble Oil Baytown	12,150
Process Drive (B)	General Electric	5000 Simple Cycle	Gas	American Oil Texas City	12,550
Process Drive (B)	General Electric	5000 Simple Cycle	Gas	Union Carbide Corp. Texas City	12,000
Process Drive (B)	General Electric	5000 Simple Cycle	Gas	Rohm & Haas Deer Park	17,000
Process Drive (B)	General Electric	5000 Simple Cycle	Gas	Petro-Tex Chemical Corp. Deer Park	16,200
Process Drive (B)	General Electric	3000 Simple Cycle	Gas	Union Carbide Corp. Texas City	7,000

UTILIZATION	MANUFACTURER	DESIGNATION	FUEL	LOCATION	BHP
Electric Utility (P)	General Electric	5000 Simple Cycle	Gas	Houston Light & Power Houston	22,000
Electric Utility (P)	General Electric	5000 Simple Cycle	Gas	Houston Light & Power Houston	22,000
Electric Utility (P)	General Electric	5000 Simple Cycle	Gas	Houston Light & Power Houston	22,000
Electric Utility (P)	General Electric	5000 Simple Cycle	Gas	Houston Light & Power Houston	22,000
Electric Utility (P)	General Electric	5000 Simple Cycle	Gas	Houston Light & Power Houston	22,000
Electric Utility (P)	General Electric	5000 Simple Cycle	Gas	Houston Light & Power Houston	22,000
Power Generation (B)	General Electric	5000 Simple Cycle	Gas	Shell Oil Company Deer Park	16,800
Power Generation (B)	General Electric	5000 Simple Cycle	Gas	Shell Oil Company Deer Park	16,800
Process Drive (B)	General Electric	5000 Simple Cycle	Gas	American Oil Company Texas City	18,500
Process Drive (B)	General Electric	5000 Simple Cycle	Gas	Humble Oil Company Katy	19,800

UTILIZATION	MANUFACTURER	DESIGNATION	FUEL	LOCATION	BHP
Process Drive (B)	General Electric	5000 Simple Cycle	Gas	Humble Oil Company Katy	19,800
Power Generation (B)	Westinghouse	W-101 G Simple Cycle	Gas	Texas City Refining Company Texas City	9,500
Power Generation (B)	Westinghouse	W-171 G Simple Cycle	Gas	Diamond Shamrock Corp. Deer Park	16,800
Electric Utility (P)	Westinghouse.	W-191 G Simple Cycle	Gas	Houston Light & Power Houston	21,000
Electric Utility (P)	Westinghouse	W-191 G Simple Cycle	Gas	Houston Light & Power Houston	21,000
Electric Utility (P)	Westinghouse	W-191 G Simple Cycle	Gas	Houston Light & Power Houston	21,000
Electric Utility (P)	Westinghouse	W-191 G Simple Cycle	Gas	Houston Light & Power Houston	21,000
Electric Utility (P)	Westinghouse	W-191 G Simple Cycle	Gas	Houston Light & Power Houston	21,000
Power Generation (B)	Westinghouse	W-191 G Simple Cycle	Gas	Union Carbide Corp. Texas City	20,800
Electric Utility (P)	Westinghouse	W-301 G Simple Cycle	Gas	Houston Light & Power Houston	39,000

UTILIZATION	MANUFACTURER	DESIGNATION	FUEL	LOCATION	BHP
Process Drive (B)	Solar (Division International Harvester)	Saturn	Gas	Humble Oil Company Tomball	1,000
Power Generation (B)	Solar (Division International Harvester)	Saturn	Gas	Houston Natural Gas Company Houston	4,000

<u>SUMMARY</u>	<u>NO. OF UNITS</u>	<u>BHP</u>
Total Process Drive	16	178,000
Total Power Generation	12	196,700
Total Electric Utility	<u>12</u>	<u>255,000</u>
Grand Total	<u>40</u>	<u>629,700</u>

(1) B - Base Load; P - Peak Load

(2) BHP - NEMA 80°F, 1000' Altitude