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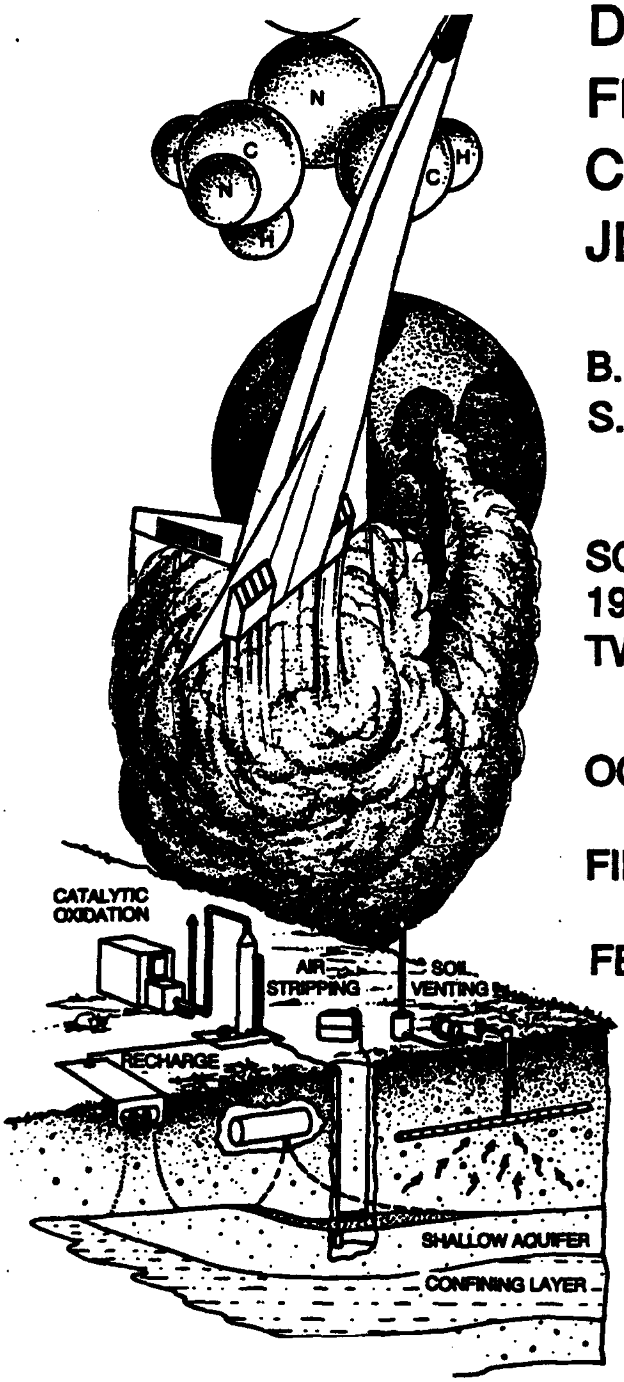
DEVELOPMENT AND DEMONSTRATION OF A NEW FILTER SYSTEM TO CONTROL EMISSIONS DURING JET ENGINE TESTING



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Measurable quantities of NOx, CO and small particulates are produced and are emitted into the atmosphere during the testing of aircraft engines in jet engine test cells (JETCs). These emissions have been and are a concern to the Air Force and to others who test aircraft engines. The large quantities of exhaust gases that are generated, the wide range of testing conditions that are normally employed, and the sensitivity of engines to back pressures make control difficult and the use of conventional control technologies impractical. A need exists for a simple, low-cost method to control the emissions.

In a Phase I SBIR project, Sorbent Technologies Corporation (Sorbtech) explored the ability of vermiculite to reduce or capture contaminants in exhaust gas streams. During the Phase II SBIR project described in this report, Sorbtech investigated how vermiculite might be employed in a commercial system to control emissions from JETCs and how chemical additions to vermiculite might enhance its NOx-removal abilities. The objectives of the Phase II project were to develop and to demonstrate a suitable filter design involving vermiculite that will control NOx, CO, and small-particulate emissions during jet-engine testing.

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19. Abstract (cont'd)

This report traces the development of a new control technology through the laboratory, bench-scale, slipstream, and prototype stages of testing and demonstration. The result of this work is a simple filter design that was recently evaluated at Tyndall AFB. The new filter design consists of two thin panel beds that capture contaminants as gas passes through them at the end of the exhaust-gas chimney. The filters consist of a primary bed of vermiculite/MgO and a secondary bed of virgin vermiculite or activated carbon. The secondary bed is placed in front of the primary bed. The filters were found to remove 40 to 83 percent of the NOx, more than 50 percent of the particulates by mass, and significant amounts of CO. An activated carbon secondary bed also removed substantial amounts of toxic gaseous organic compounds from exhaust gases. The filter design was effective during all testing conditions and was particularly effective in reducing smoke opacity.

A second filter system for NOx and particulates was also developed in the project. This system consists of a conventional zeolite SCR catalyst, ammonia additions to the gas, and a vermiculite bed in front of the zeolite bed. Unfortunately, during slipstream testing this system was found to be impractical for test-cell use because of the temperature requirements of the zeolite catalyst, the high probability of ammonia slip, and anticipated high pressure-drop problems and high costs.

EXECUTIVE SUMMARY

A. OBJECTIVE:

The objectives of this effort were stated in two stages. The first stage was to evaluate, at bench scale, all reported amendments to vermiculite as candidate materials to remove NOx and particulates from simulated gas-turbine combustion exhaust streams. The second stage, after selection of the most promising material(s) for use in controlling NOx and particulate emissions during jet-engine testing, was to develop and test one or more test-cell emission-control technologies, initially on a split of the exhaust from an operating hush house and finally as a prototype system treating the complete exhaust stream from subscale drone jet engines.

B. BACKGROUND:

Jet engine test cells (JETCs) are a relatively minor, nominally stationary, source of visible soot (which has been regulated for decades) and oxides of nitrogen (NOx, not yet regulated). Control of visible soot emissions has been accomplished by injection of water into the exhaust plume (which creates a dirty, acidic fallout near the JETC) or by addition of fuel-soluble metal complexes to fuels consumed during test-stand firing (which decreases the mean particle size, amplifying the respiratory liability). Regulation of NOx emissions from JETCs may be implemented as part of the Clean Air Act Amendments of 1990.

Several principles have been proposed to support development of NOx-control devices. Selective catalytic reduction (SCR) affords marginal control, creates large back pressures, and is exorbitantly expensive. Thermal DeNOx technology was rejected by the study that proposed SCR, and its extreme sensitivity to conditions is incompatible with the drastic swings of temperature and gas flow rate encountered during a typical test-firing sequence. Analogous processes using alternative reducing agents also proved unsuitable for NOx control from non-steady-state processes. Injection of fuel and reburning the exhaust stream might be engineered to lower NOx emissions, but the cost would be impractical, and emissions of carbon dioxide and consumption of fuel during a test would be increased by an order of magnitude. Thermal, photo-, and electrocatalytic methods showed promise in treating oxygen-free surrogates, but were ineffective in the presence of significant quantities of oxygen. Of seven technologies evaluated as candidate NOx control methods for JETCs, only coated vermiculite adsorption appeared to offer promise of practicability. This report details bench, slipstream, and subscale full-stream implementation and testing of two NOx control methods for JETCs.

C. SCOPE:

During this study, approximately 20 amendments to vermiculite were prepared and evaluated as NOx-emission control possibilities at bench scale. The best candidates for low-temperature use (magnesium oxide on vermiculite) and high-temperature use (zeolite SCR catalyst behind uncoated vermiculite) were then tested on a small slipstream from the exhaust of 906 TFG's hush house. Because exit temperatures were incompatible with SCR, only the vermiculite system was carried forward and implemented as a large unit on a full-size JETC, testing subscale engines. Collected data included air flow rates, NOx concentrations before and after treatment, particulate distributions before and after treatment, temperatures, and pressure drops. This document is the final report of the R&D effort conducted under Phase II Small Business Innovation Research Contract F08635-90-C-0053, and it summarizes significant observations and data generated between the start of this project (February 1990) and October 1992.

D. METHODOLOGY:

Bench tests were conducted in an apparatus constructed from manufactured components and custom-built pipe sections. The zeolite SCR catalysts were used as they were received from commercial suppliers. Amended vermiculite materials were generally prepared using procedures recommended in the patent literature. In some cases, expanded vermiculite was mixed with a slurry of the respective coating materials in water; after the coating had been thoroughly distributed, the entire batch was allowed to air dry and was then heated. In other cases, vermiculite was mixed initially with water and then with the coating material; drying and heating followed. In many cases, additional steps were involved. NOx was measured with commercial instruments, as were CO, O_2, NH_3, and CO_2. Flowmeters and thermocouples were used to measure flow rates and temperatures. The bench apparatus, after a 6-month laboratory test program, was transported to Wright-Patterson AFB OH and connected by ducting to a gas-collection pipe secured at the lower seam along the deflector. The collection pipe was later relocated to the middle of the augmenter tube, and finally directly behind the jet-engine exhaust. Measurements were made with the same devices that were used in the laboratory. Particulate density was measured by weight gains of filters through which the gas was drawn at a rate equal to the nominal flow rate entering the sorbent bed. (Values so determined should differ only slightly from isokinetic measurements.) A prototype treatment system was then designed and installed on Building 239 (475 WEG/XRM) Tyndall AFB FL. A stainless steel gas-sampling system consisting of multiple collection points was installed on both faces of the sorbent bed. Samples were drawn directly into a commercial gas analyzer, into length-of-stain detector tubes, and into the filter assembly for analysis. Resident thermocouples measured temperature, and air velocity was calculated as the average of pitot tube measurements across the inner or outer face.

E. TEST DESCRIPTION:

For bench tests, a simulated jet-engine exhaust gas was produced by employing a system consisting of a compressor, burner, and fan and burning natural gas and/or jet fuel. Exhaust gas was passed through special pipe and filter sections before exiting to the atmosphere. One or more beds of sorbent or catalyst were placed into the filter sections, with vermiculite and amended vermiculite materials being held in place by stainless steel screens. Fittings along the way allowed introduction of extra NOx and of reagents, when required, and measurement of gas compositions and properties. Most of the same apparatus was later moved and employed to treat a portion of the exhaust gases produced in an operating hush house. The apparatus was connected to insulated conduit drawing gas from the hush house stack or augmenter tube. For prototype tests, a separate filter structure was designed, built, and attached to the top of the exhaust stack of a full-size test cell. This structure was fitted with stainless steel collection ports and conduits, from which gas samples were drawn for chemical and particle analyses. Temperatures were also measured with resident thermocouples, flow rates with an anemometer and a pitot tube, and pressures on both sides of the bed with manometers. The series of measurements in the JETC were repeated after about 120 days in service.

F. RESULTS:

Bench data showed good-to-poor removal of NOx, the best performers being MgO on vermiculite, activated carbon, and (at temperatures above 500°F) a zeolite. In the slipstream tests, the zeolite was not effective in removing NOx at the base of the deflector nor near the middle of the augmenter tube. Marginal activity was observed near the engine, but the amount of motion and force experienced at all locations within the augmenter tube at fairly low engine-power settings was enough to ensure very short lifetimes for any devices so placed. In addition, the temperature profile in the augmenter tube was observed to change drastically with changes of power setting. Such changes make zeolite use at fixed augmenter-tube locations impractical. MgO on vermiculite operated with about the same good efficiency (45 to 70 percent NOx removal) at the base of the deflector and within the augmenter tube, as it had in earlier laboratory tests. The temperature environment at the base of the deflector varied from 100° to 180°F over the full range of power settings.

In prototype tests, an 8-inch-thick panel of MgO coated on vermiculite behind a 4-inch-thick panel of untreated vermiculite also removed 40 to 75 percent of NOx, and a comparable fraction of the particulates, from the JETC stack gases. A slight improvement in NOx removal was observed upon replacement of the vermiculite in the 4-inch bed with granular activated carbon. Also, the carbon appeared to be more effective in removing organic gases present in the exhaust streams. Under conditions of partial bypass of the beds, the pressure drop across the filter beds remained about 1.0 inch W.G., and smoke and heat accumulated in the JETC. Analysis of samples of the sorbent after exposure to exhaust gases indicated no measurable accumulation of metals through the duration of the tests, and partial conversion of the magnesium oxide coatings into a nitrate, which could be regenerated back to the oxide by heating above 850°F. Alternatively, the spent bed material could serve as a beneficial soil modifier in horticultural applications.

G. CONCLUSIONS:

Results in hand suggest that these sorbents could be designed into a technically workable NOx control method that is compatible with the nonsteady-state conditions in operating JETCs. Replacement and maintenance costs should be significantly lower than for catalytic technologies. No hazardous reactants are introduced, and, if the spent beds are replaced soon enough, no hazardous residues will result. The problems of back pressure and heat accumulation should respond to straightforward engineering changes (e.g., an exhaust blower or increasing the surface area of the beds).

H. RECOMMENDATIONS:

Implement a reasonably flexible design on a JETC testing full-sized engines and evaluate the effect of engineering refinements. Quantitatively characterize the emissions from the JETC before and after treatment, to determine the net benefit from treatment and the unit cost to remove combustion-derived pollutants by this technology.

PREFACE

This report was prepared by Sorbent Technologies Corporation (Sorbtech, formerly Sanitech Inc.), 1935 East Aurora Road, Twinsburg, OH 44087, under DoD Small Business Innovation Research Contract No. F08635-90-C-0053, for the Air Force Civil Engineering Support Agency (HQ AFCESA/RAVS, formerly the Air Force Engineering and Services Center [HQ AFESC/RDVS]) 139 Barnes Drive, Tyndall AFB FL 32403-5319.

This Phase II final report describes the development and demonstration of a new emission control technology for jet engine test cells (JETCs). The work was performed between February 1990 and September 1992. The Air Force project officer was Dr. Joseph D. Wander.

The authors were members of the research staff at Sorbtech. Other Sorbtech personnel who participated in the project included Mr. N. E. Thomas, Mr. K. A. Peterson, Ms. C. A. Turek, Mr. M. O. Higgins, and Mr. L. E. Mahoney. Slipstream testing at Wright-Patterson AFB was conducted with the cooperation and assistance of 906 TFG, and we are especially grateful for the assistance provided by Capt. Robert Eardley. Prototype testing at Tyndall AFB was performed with the cooperation and assistance of 475 WEG/XRM personnel, and we are especially grateful for the help provided by Capt. William Hodges and TSgt. Cecil Smith, and for the participation of Dr. Wander and Capt. Larry Kimm during the installation and testing of the prototype unit.

This report has been reviewed by the Public Affairs Officer (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for public release.

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SECTION I

INTRODUCTION

A. PROJECT OBJECTIVES

Detectable quantities of NOx, CO and small particulates are generated during testing of aircraft engines in test cells. Because these pollutants are a health hazard and are subject to emissions regulations, a need exists to develop and determine the cost to apply a practical control method. In a Phase I SBIR project, Sorbent Technologies Corporation (Sorbtech) engineers demonstrated that expanded vermiculite can effectively remove NOx, CO and particulates from simulated exhaust gases. The objective of this Phase II project was to carry the research forward: (1) to determine the effects of additives to vermiculite on NOx-capture performance, to examine vermiculite's performance after multiple exposure–regeneration cycles, and to examine the disposability of vermiculite residues; (2) to design and construct a laboratory facility to scale up the system(s) to simulate actual engine-test conditions, to design one or more control systems incorporating vermiculite, and to evaluate these systems by performing parametric studies; (3) to select at least one system and to demonstrate the system on a slipstream of actual engine waste gases; and (4) to scale up the system one step further, to the prototype stage, capable of treating full small-engine exhaust-gas streams, and to demonstrate this system at an Air Force site.

B. BACKGROUND

The Air Force has long been aware of possible environmental costs of emissions produced during testing of aircraft engines in test cells(1). Emissions receiving particular attention in recent years include carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), sulfur oxides (SOx), and particulates(2).

Of the constituents present in test-cell exhaust gases, NOx, CO and fine particulates (smoke or soot) are of special concern. NOx is considered a precursor to smog and to acid rain(3). CO is a highly toxic gas, and fine particulates can darken a normally clear sky. NOx, CO and fine particulates are all believed to be detrimental to the general health of individuals. As a result of these concerns, the U.S. Environmental Protection Agency (EPA) has established limits for the amounts of these constituents that can be emitted. Some states, such as California, have set even more restrictive standards. Because aircraft engines in the future most likely will produce higher-temperature exhaust gases than are seen today, it is likely that NOx levels will increase. A need therefore exists today and in the future for an efficient, low-cost method to control these emissions from aircraft-engine test cells.

1. Aircraft Engine Test Cell Design

Test cells are structures that are employed to hold jet engines and suppress noise during static operational tests after maintenance and/or overhaul. They can be found at Air Force, Navy and Army sites, at civilian airline facilities, and at gas-turbine manufacturers' plants(4). Test cells located in the U.S. and operated by the Air Force, Navy and Army number well over 490(5). They exist in a large variety of sizes and shapes. Generally speaking, no two test cells are exactly alike, although recently there has been a move toward some degree of standardization.

Test cells occur as two general types: (1) facilities designed for engines alone, that require that the engines be removed from the aircraft for testing and (2) larger facilities that are able to test both engines alone and engines attached to aircraft.

All test cells normally contain three principal components: (1) a building, room, or enclosure inside which the engine (or aircraft containing the engine) is secured in place, (2) an augmentor tube, and (3) a blast room and/or exhaust chimney. Figure 1 shows the longitudinal cross-section of a typical test cell. During the testing of aircraft engines, the gaseous emissions that are produced, along with ambient air drawn along by the flow of the engine exhaust gases, are directed into and through the augmentor tube. In this long tube, which usually takes the form of a circular or oval-shaped tunnel, the exhaust gases mix with ambient air and are cooled. The gases exiting the augmentor tube then enter and pass through the blast room and/or exhaust chimney before they are expelled to the atmosphere.

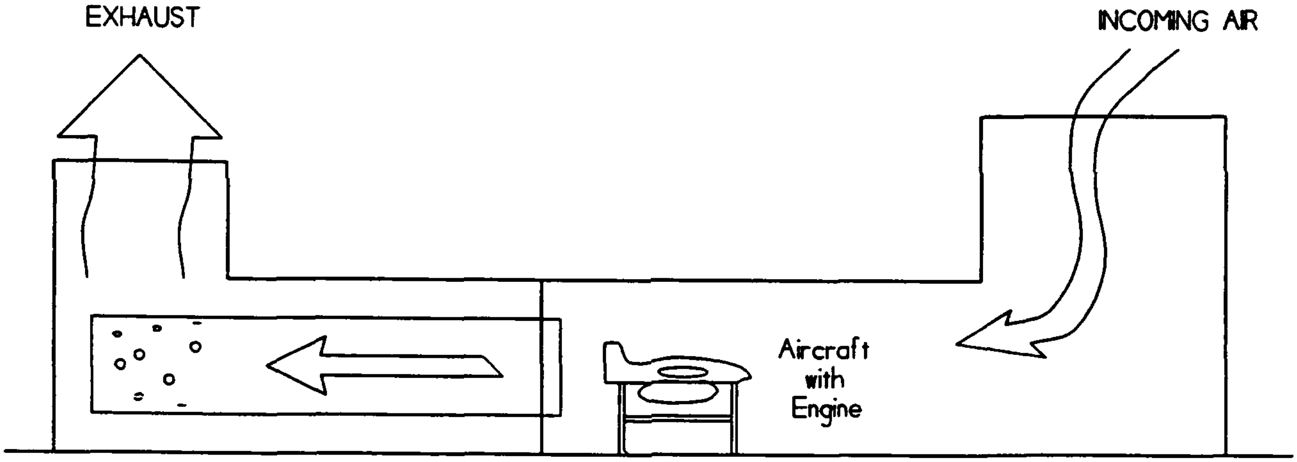


Figure 1. Cross-Section of a Test Cell

2. Typical Engine Test Cycles

Static firing tests are performed to simulate conditions observed in the air. Although testing procedures and power settings vary with the type and size of engine being tested, four power settings are usually employed to cover the range of tests. These are typically idle; 30 percent; 75 percent; and 100 percent. Also, measurements are usually made in the afterburner mode for afterburning engines.

The concentrations of NOx, CO, particulates and other components in the exhaust gases vary widely with the testing conditions. Typically, NOx concentrations are the highest at 100 percent power (80 to 200 ppm) and decrease with thrust level. At idle, NOx concentrations are usually about 10 ppm or lower. At high power settings the principal NOx species is nitric oxide (NO); at idle, it is nitrogen dioxide (NO_2).

The level of particulates in the exhaust gas, as indicated by Smoke Number, varies in the same manner as NOx. That is, particulate loadings are highest at 100 percent power and decrease with power setting. The size distribution of particles also varies with power setting. At idle, finer sizes (less than 0.05 μm) are most common; at 100 percent power, coarser sizes are favored. The particle size distribution seen in afterburner exhaust gases is similar to that which occurs with 30 percent power.

The CO level in aircraft engine exhaust gases normally varies in a manner opposite to that of NOx and particulates. Highest levels occur at idle and in the afterburner mode, and lowest levels occur during 100 percent power. Typical data collected and reported by Battelle(6) for a TF 30-P103 engine are given in Table 1.

TABLE 1. EMISSIONS DATA FOR A TF 30-P103 ENGINE (FROM REF. 6)

Power Mode	NOx (ppm)	NO (ppm)	CO (ppm)	CO_2 (%)	HC (ppm C)	Smoke No.
Idle	6.5	2.4	276	0.51	413	0.0
30%	19.3	6.2	168	0.93	99	18.8
75%	51.4	42.0	32	1.18	4	23.4
100%	84.2	75.0	15	1.45	1	40.9
Afterburning	15.0	8.0	170	0.44	125	Not Taken

3. NOx Control Using Conventional Technologies

In an EPA program performed for the U.S. Navy, Radian Corporation considered selective catalytic reduction (SCR) and thermal de-NOx control systems for aircraft-engine test-cell applications. Of these two technologies, Radian concluded that SCR was the preferred technology. Subsequently, it performed a detailed evaluation of SCR, which included the design and costing of two alternative full-scale systems(7).

The two SCR designs investigated by Radian were (1) a system that treated the entire flow of exhaust gas and (2) a system that extracted and treated only a NOx-rich portion of the flow. After detailed study, the system to treat the entire flow was dropped because of the expected high back pressures of the SCR system. Radian assumed a maximum pressure drop allowed for a test-cell NOx control system of 5 to 6 in W.G. With this assumption, it designed an extractive system that would remove 80 percent of the total NOx mass flow, and would give an overall system NOx removal of 50 percent. The estimated capital cost of the system for application with an F404 engine in a T-10 test cell was $1,105,600 (1985 dollars). The catalyst replacement cost was estimated at $714,600. The system was designed to reduce NOx levels at intermediate and high power settings; however, it would not remove NOx in the afterburner mode, owing to the high gas velocities expected. Radian did not consider the idle condition, where gas temperatures are too low for satisfactory SCR NOx removal. Radian's system did not remove particulates, CO or other contaminants.

4. Summary of Results of Phase I and Other Related Projects

In the Phase I SBIR project, Sorbtech engineers conducted small laboratory experiments to examine the use of static beds of vermiculite and of vermiculite modified with additions of MgO and $MgSO_4$ for the removal of NOx from combustion waste gases. Also examined was the use of such additives as ammonia and urea to the waste gas, in combination with vermiculite beds. The results of these studies showed that appreciable NOx, sometimes as much as 50 percent, can be removed from waste gases by passage through a bed of expanded vermiculite, particularly if CO levels in the waste gases are high and the gas face velocities are low. Even higher NOx removals were observed when MgO and $MgSO_4$ were coated onto the vermiculite particles and when reactive additives were delivered into the waste gas stream. In addition, the vermiculite beds efficiently scavenged hydrocarbon droplets and soot particles and lowered CO levels. In a one-cycle test, a sample of vermiculite that had been coated and deactivated by soot deposits was restored to 95 percent of its original activity by heating to 500°C (930°F) in flowing air for 15 minutes(8).

The mechanism by which expanded vermiculite alone reduces NOx in exhaust gases is not completely understood. However, the concurrent removal of CO from the waste gases that commonly occur in direct proportion to NOx reductions suggests that vermiculite may act as a catalyst for the reduction of NOx by CO, resulting in N_2 and CO_2.

Behrens investigated the use of perlite (a mineral similar to vermiculite) as a catalyst for NOx control in a test cell. By passing simulated combustion exhaust gases through a bed of expanded perlite, Behrens achieved NOx removals of up to 64 percent(9).

Ruch, et al.(10), studied the NOx-removal mechanisms that occur when MgO-coated vermiculite is exposed to NOx-containing gases. The study disclosed that the principal NOx-removal mechanism is reaction of NOx with MgO to form $Mg(NO_3)_2$ (magnesium nitrate). A secondary mechanism, called capillary micropore condensation, was also proposed. In this latter mechanism, acid–H_2O complexes are formed and physically trapped in the micropores of the sorbent.

C. SCOPE

This program included (1) bench-scale tests to select sorbents or catalysts for development testing at a larger scale; (2) testing of two concepts–a reactive sorbent that performs well at temperatures below 200°F, and a zeolite that catalyzes reduction in the presence of ammonia or carbon monoxide at moderately high temperatures–on slipstreams of actual JETC exhaust gases; and (3) a full-exhaust test of a prototype NOx control system on subscale drone engines in an air-augmented JETC. This is the final technical report for this phase of the program.

SECTION II

ADDITIONAL STUDIES TO IMPROVE NOx REMOVAL PERFORMANCE

A. SCREENING TEST WORK

1. Approach

During Phase I we determined that vermiculite alone can remove significant quantities of NOx from exhaust gases and that coating magnesium oxide (MgO) onto the vermiculite improves NOx removal efficiency. The objective of the initial research in Phase II was to examine the addition of other chemical species to vermiculite and to vermiculite–MgO combinations to determine if NOx removal performance can be improved even further.

The approach followed in this work included the following activities:

a) Identifying chemicals that researchers have reported effective in removing NOx from waste gases.

b) Obtaining these chemicals and combining them with vermiculite or vermiculite–MgO using procedures described by the researchers.

c) Exposing the new combinations to simulated exhaust gases at room and elevated temperatures while monitoring NOx removal efficiency.

2. Patent Literature Survey

Technical publications and patent literature were reviewed to identify potential chemical additions. The patent literature proved to be a particularly rich source of reports of compounds claimed to promote or to result in the removal of NOx from waste gases. Included were many chemicals reported to be effective in removing NOx from a waste gas in the absence of any reducing gas, such as ammonia or methane. Some examples of chemicals reported in the literature are given in Table 2.

Bent (U.S. Patent 1,888,547) states that chromous salts are effective catalysts or reactants in reducing the NOx levels in furnace exhaust gases. He cites in particular four salts: chromous acetate, chromous chloride, chromous sulfate, and chromous hydroxide. The chromium (III) ion is said to react with NOx forming a stable compound.

Activated coke will remove NOx from industrial flue gases according to Feustel, et al., (U.S. Patent 2,992,895), if the activated carbon is used at temperatures below 200°C in the presence of water vapor. Karwat (U.S. Patent No. 3,149,907) claims that sodium chlorite ($NaClO_2$) is effective in reducing NOx levels in furnace gases.

Kitagawa (U.S. Patent 3,382,033) provided a long list of compounds that he claims will reduce NOx levels in waste gases containing very low (less than 3 ppm) NOx concentrations. His list included $FeSO_4$, $PdSO_4$, $KMnO_4$, $KClO_3$, $NaClO$, $NaClO_2$, Na_2O_2, $CuCl_2$, ICl_3, Na_2HPO_4, As_2O_3 and $Na_2S_2O_3$.

TABLE 2. CHEMICALS REPORTED TO BE EFFECTIVE IN REMOVING NOx FROM WASTE GASES

CuO
MgO
$NaClO_2$
Na_2O_2
$KMnO_4$
$CuCl_2$
Urea
Melamine
$NaHCO_3$
Na_2CO_3
$FeSO_4$
$PdSO_4$
Thiourea
Sodium Acetate
Activated Carbon
ZnO
Al_2O_3–Ni–K
TiO_2
Co_2O_3
V_2O_5
NiO
K_2CO_3
Sodium Formate
$Na_2S_2O_3$
Calcium Formate
Cu–Ag
Polyvinylpyrrolidone
I_2O_5
$NaOH$
KOH
Ni-Co-MnO_2
Cu $(NO_3)_2$
Mn Chromite
Ni Chromite
Monel, Inconel
As_2O_3

Copper compounds and alloys are claimed to be effective catalysts by several researchers for automobile exhausts. Cooper (U.S. Patent 3,374,183) cites $CuO–Al_2O_3$; Hansford, Baker and others (U.S. Patents 3,842,158 and 3,398,101) recommend $CuO–Co_2O_3$; Gehri (U.S. Patent 3,718,733) cites copper or copper–nickel wire mesh; Kearby, et al., (U.S. Patent 3,565,574) suggest copper alloys, such as monel and inconel; Frevel (U.S. Patent 3,682,585) cites copper–silver on alumina; Stephens, et al., (U.S. Patent 3,271,324) state that $CuO–Fe_2O_3$ is effective; and Kranc (U.S. Patent 3,576,596) reports the commercial use of copper–chromium compounds.

A number of organic compounds have been suggested for removing NOx. The salts of carboxylic acids, such as sodium and calcium formate or acetate, will remove NOx according to a patent by Dwyer (U.S. Patent 3,162,516). Cyanuric acid is recommended by Perry (U.S. Patent 4,731,231). Polyvinylpyrrolidone with vermiculite is claimed to be effective by Evanshen (U.S. Patent 3,757,489). Lawson (U.S. Patent 3,826,810) states that solid urea on charcoal or alumina will remove NOx from exhaust gases at temperatures below 150°C. Young (U.S. Patent 4,626,417) states that a combination of urea and H_2SO_4 performs well.

Some sodium compounds have been reported to be effective in reducing NOx. Kyllonen (U.S. Patent 3,498,743) states that Na_2CO_3 is effective at temperatures below 120°C if significant moisture is present in the gas. McCrea, et al., (U.S. Patent 3,880,618) reports that alumina alkalized with Na_2CO_3, K_2CO_3, trona, Na_2O and K_2O will remove NOx from flue gases. Takeyama, et al., (U.S. Patent 3,864,450) claim that NaOH (or KOH) on coke particles effectively removes NOx. In this case, the NOx reacts with the coke and the NaOH serves as a catalyst.

Klimisch (U.S. Patent 3,674,423) states that zinc oxide (ZnO) is better than copper oxide (CuO) in removing NOx from automobile exhausts. Howk (U.S. Patents 3,216,954 and 3,228,746) claims that complex manganese–chromium compounds are also particularly effective. Negra and Warshaw (U.S. Patent 3,701,822) recommend the use of nickel–cobalt–MnO_2 combinations on alumina for treating automobile exhaust gases.

In recent years there has been significant research on catalysts for the selective catalytic reduction (SCR) of NOx in exhaust gases. In SCR processes, ammonia is generally recommended as a necessary addition to the exhaust gas stream. V_2O_5 on a TiO_2 support structure is suggested as a catalyst by Baiker, et al., (U.S. Patent 4,889,533). The use of zeolite by itself is recommended by Krishnamurthy (U.S. Patent 4,778,665). Zeolite with ZrO_2 is proposed by Gerdes, et al., (U.S. Patent 4,735,930) and zeolite with TiO_2 and copper is proposed by Kato, et al., (U.S. Patent 4,798,813). Schneider, et al., (U.S. Patent 4,792,439) state that TiO_2, V_2O_5, CeO_2 or WO_3 with a silicate is a good SCR catalyst. Flockenhaus, et al., (U.S. Patent 4,742,036) claim that iron oxide (Fe_2O_3), molded into a plate shape with an H_2SO_4 binder, is also a satisfactory catalyst.

Of the many compounds claimed to remove NOx from exhausts, only a handful were worth considering for test cell applications. Many compounds were claimed to be effective only at temperatures above 600°F, and many required high CO levels and/or low O_2 levels to be present in the exhaust gas. Because these conditions were not likely to occur at a filter placed downstream and away from the jet engine, some compounds were excluded from consideration as an additive to vermiculite for improved performance. The excluded compounds and the reasons for their exclusions are listed as follows:

CuO, NiO	-	(Effective only above 600°F; requires high CO levels; are heavy metal salts)
$PdSO_4$	-	(Compound is very expensive)
ZnO	-	(Effective only over narrow temperature range, 700°-900°F; requires high CO levels; is a heavy metal salt)
Al_2O_3-Ni-K	-	(Difficult to prepare; low O_2 requirement)
TiO_2, V_2O_5	-	(Require NH_3 additions; effective only at high temperatures)
Cu-Ag	-	(Expensive; toxic heavy metals)
I_2O_5	-	(Uncommon oxide; must be employed between 32° and 86°F)
Ni and Mn Chromites	-	(Low O_2 required)
Ni-Co-MnO_2	-	(Low O_2 and high temperatures required; difficult to prepare)
Monel, Inconel	-	(Metal alloys only somewhat effective at high temperatures)
$Na_2S_2O_3$, As_2O_3	-	(Difficult to prepare as specified in patents; As is a heavy metal)

The remaining chemicals listed in Table 2 were prepared using procedures described by their proponents. The chemicals in all cases were coated onto expanded vermiculite particles.

3. Room-Temperature Screening Tests

A simple test was then developed to screen individual samples of the different coated materials to determine their potential in removing NOx from exhaust gases. The test consisted of exposing separate 1-inch diameter, 3- to 4-inch long beds of material to a simulated flue gas produced by mixing NO, O_2, and N_2 from commercial cylinders. The tests were performed at room temperature using a constant gas flow rate of 4 liters per minute for 60 minutes. The results of these tests are listed in Table 3.

TABLE 3. ROOM-TEMPERATURE SCREENING TEST RESULTS

Addition to Vermiculite	Incoming Gas		Average NOx Removal During 1-Hr Exposure Period (%)
	O_2 (%)	NOx (ppm)	
None	21	145	20.7
$FeSO_4$	21	640	16.1
Na_2O_2	21	770	10.9
Melamine	21	830	11.6
Na_2CO_3	21	495	12.8
K_2CO_3	21	555	16.6
Na Acetate	21	500	6.8
Polyvinylpyrrolidone and $Ca(NO_3)_2$	21	500	8.6
Urea	21	328	10.8
Thiourea	21	328	12.1
KOH and C, Activated	21	305	22.4
C, Activated (F816)	21	305	100.0
MgO	21	500	97.4
MgO and Melamine	21	300	10.7
MgO and Urea	21	330	10.8
MgO and Thiourea	21	300	1.0
Na_2O_2 and NaOH	0	445	29.0
MgO, Na_2O_2 and NaOH	0	470	81.7
Na_2O_2	0	470	27.1
$KMnO_4$	0	770	11.6
$NaClO_2$ and NaOH	0	770	13.7
Ca Formate	0	460	5.5
$CuCl_2$	0	500	4.1
C, Activated (F816)	0	500	12.5
MgO	0	315	61.1

The initial set of runs was performed on a simulated flue gas containing about 21 percent O_2, a level perhaps slightly higher than one might expect in a heavily augmented exhaust gas. A second set of runs was performed on a gas containing essentially no O_2. Many of the compounds evaluated in this series were recommended for low-oxygen gas streams by their promoters. The results of the high-O_2 runs showed that only two additions, Grade F816 activated carbon and MgO, increased NOx removal significantly. The results of the low-O_2 runs showed only MgO and MgO with additions of Na_2O_2 and NaOH gave average NOx removals above 60 percent for a 1-hour exposure period.

Selection of the F816 grade activated carbon for the screening tests was based on the results of earlier tests, in which different grades were examined. The results of the earlier tests, in which 3-inch-long beds of pure activated carbon were exposed to 4 liters per minute of gas, are summarized in Table 4.

TABLE 4. NOx REMOVALS BY DIFFERENT GRADES OF ACTIVATED CARBON

Activated Carbon Grade	Incoming Gas O_2 (%)	Incoming Gas NOx (ppm)	NOx Removal After 1/4-Hr Exposure Period (%)
BPL 4 x 10	21	385	67.0
CPG 12 x 40	21	385	89.5
SGL 8 x 30	21	420	88.9
PCB 4 x 10	21	420	85.9
F816	21	420	97.2

In addition to the vermiculite combinations listed in Table 3, a number of other materials were also examined in screening tests. The results of these screening tests are given in Table 5. Here it can be seen that only coated activated carbon exposed to high-oxygen streams gave good results. The results for coated activated carbon, however, were not as good as those seen for uncoated activated carbon or for a carbon–vermiculite mixture.

TABLE 5. ADDITIONAL SCREENING TEST RESULTS

Material Combination	Incoming Gas O_2 (%)	Incoming Gas NOx (ppm)	Average NOx Removal During 1-Hr Exposure Period (%)
$CuCl_2$ on Alumina	21	315	8.2
Urea on Alumina	21	770	12.2
Urea on Carbon	21	830	76.0
Melamine on Carbon	21	640	95.8
$NaHCO_3$ on Perlite	21	495	7.9
Urea on Carbon	0	500	12.5
Melamine on Carbon	0	440	3.6

4. Elevated-Temperature Laboratory Tests

Performing laboratory screening tests at elevated temperatures proved to be a more difficult task than expected. A relatively simple apparatus was constructed and employed in this work (See Figure 2). The apparatus consisted of a natural gas burner, a series of short sections of 2-inch diameter iron pipe connected by flanges to form a straight tube, and an in-line pump. The entire unit was about 10 feet long. One 10-inch flanged section held the catalyst/sorbent bed that was being tested. The beds were 2 to 6 inches in thickness and were supported by stainless steel screens that were pressed into the pipes. The beds were generally located about 3 to 4 feet from the burner. Between the burner and the beds were ports for taking gas samples for analyses, for thermocouples, for pressure measurements, and for separate introductions of ammonia, additional air, and NOx. Other ports for temperature and pressure measurements and for gas analysis samples were located in the bed areas themselves and in pipe sections between the beds and the pump.

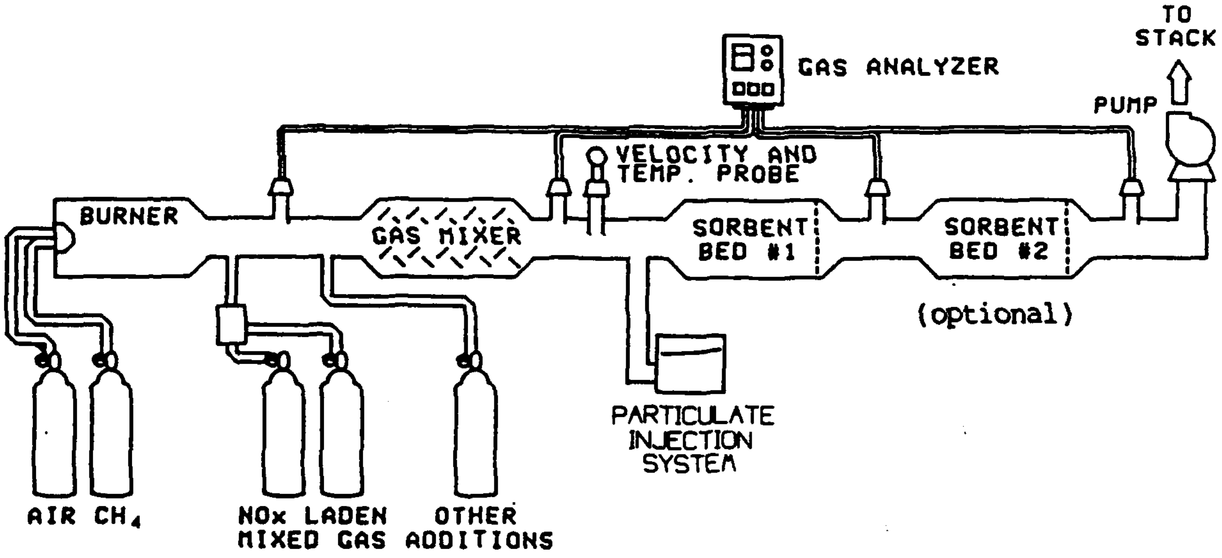


Figure 2. Elevated-Temperature Test Apparatus

One problem in employing a relatively small bed of vermiculite material in a horizontal design was that, when packed loosely, the bed tended to settle, leaving a void space at the top of the bed. Exhaust gases passing through the pipe then preferentially passed through this void space, and the result was poor overall NOx removal. This problem was solved by squeezing the screens inward to pack or compress the beds. The void spaces were eliminated in this manner, but the compression resulted in a significant reduction in bed interstitial void spaces, which, in turn, resulted in a large pressure drop across the beds.

Another problem, not immediately recognized, was that both of the continuous chemical analyzers employed (an Energy Efficiency System Model 2000 for NOx, O_2 and CO analyses and a Land Combustion Model 2000 for NOx analysis) give false readings at negative pressures greater than 0.5-inch W.G. and positive pressures above 1.0-inch W.G. Both systems employ chemical cells for analysis. The pump downstream drawing against well-compacted beds created large negative pressures behind the beds and often in front of the beds, as well. This problem was solved by pumping gas samples into separate collection vessels at near atmospheric pressure and then removing gas from the collection vessels for analyses.

Control of temperatures and of the amount of oxygen in the incoming exhaust gases was also a problem initially. The temperature of the gas was observed to be a function of the burner and burning characteristics (the amount of fuel and air employed, etc.) and of the rate of cooling that occurred in the apparatus and in the bed. Because the amount of air (oxygen) employed in burning generally affects the temperature of the gas, adjustments can be tricky to achieve preselected exhaust-gas temperatures and oxygen levels. Heat losses were limited by insulating the apparatus, but were not eliminated. The temperatures of the exhaust gases were invariably reduced as the gases passed through the sorbent beds. Owing to heat losses and to the slow heating of the vermiculite materials, steady-state conditions were rarely attained in runs lasting two hours or less.

Thirty high-temperature runs were performed. Of these runs, approximately half were discarded because of equipment malfunctions or because the results were questionable owing to the problems discussed above.

The large majority of the runs were performed on very hot gases, above 700°F in temperature, because it was assumed that the catalyst/sorbent would require exposures to gases at high temperatures in a test-cell application. The conditions and results of the 15 satisfactory runs are provided in Table 6. These results show the following:

1. Vermiculite alone and vermiculite with MgO removed appreciable NOx from the exhaust gases, but NOx removal performances generally fell off with time during long exposures.

2. At temperatures of about 800°F, an SCR catalyst with ammonia additions gave higher NOx removals than did vermiculite or vermiculite with MgO.

3. Perlite, vermiculite coated with $FeSO_4$, and vermiculite coated with NaOH/activated carbon demonstrated poor NOx-removal performance.

TABLE 6. ELEVATED-TEMPERATURE TEST RESULTS

	TEST				
	1	2	3	4	5
Length of Test	1 hr, 18 min.	1 hr, 22 min.	1 hr, 20 min.	1 hr.	3 hr.
Bed Material	Vermiculite	Vermiculite	Vermiculite	Vermiculite	Vermiculite
Flue Gas Temperature					
Ranges (°F)	620-861	571-686	494-921	560-822	671-750
Average (°F)	836	614	769	704	742
Flue Gas					
NOx (ppm)	120	101	870	1441	414
O_2 (%)	9.9	9.0	1.3	10.5	13.4
Velocity (fps)	ND	ND	2.0	2.0	2.0
Bed Size (in)	2 x 2D	2 x 2D	4 x 2D	4 x 2D	4 x 2D
ΔP Across Bed (in W.G.)	1.4	2.6	22.0	19.6	>25.0
Avg. NOx Removal	31	42	24	26	34
Max. NOx Removal	62	74	54	30	56
Comments	+1.5 in. Draft; Kitagawa Analysis for NOx	-0.7 in. Draft; Three methods of NOx analysis employed; all in general agreement.	0.0 in. Draft;	-0.2 in. Draft	Long-term run at fairly constant temperatures, NOx removal fell off to 4% at the end.

TABLE 6. ELEVATED-TEMPERATURE TEST RESULTS (CONTINUED)

	TEST				
	6	7	8	9	10
Length of Test	1 hr.	2 hr, 10 min.	2 hr, 5 min.	1 hr, 10 min.	25 min.
Bed Material	Vermiculite (Test 5 Matl re-tested)	Vermiculite & MgO	Vermiculite	Perlite	Vermiculite
Flue Gas Temperature					
Ranges (°F)	667-764	425-823	660-778	678-783	85-134
Average (°F)	728	800	765	745	116
Flue Gas					
NOx (ppm)	221	524	352	24	44
O_2 (%)	13.4	10.8	10.7	8.3	2.3
Velocity (fps)	2.0	1.3	1.5	2.0	0.5
Bed Size (in)	4 x 2D	4 x 2D	4 x 2D	4 x 2D	3 x 2D
ΔP Across Bed (in W.G.)	>25.0	22.5	>25.0	5.4	0.3
Avg. NOx Removal	6	26	37	0	3
Max. NOx Removal	8	43	51	0	8
Comments	An attempt to regenerate this material in place by heating it to 900°F in air was not successful; NOx removals did not increase.	0.0 in. Draft;	0.0 in. Draft;	0.0 in. Draft	NH_3 added to gas during last half of run. Low ΔP indicates hole in bed.

TABLE 6. ELEVATED-TEMPERATURE TEST RESULTS (CONCLUDED)

	TEST				
	11	12	13	14	15
Length of Test	45 min.	2 hr, 30 min.	55 min.	1 hr, 5 min.	55 min.
Bed Material	Vermiculite	Vermiculite (Test 11 Matl re-tested)	SCR Catalyst	Vermiculite + NaOH + Activated Carbon	Vermiculite + $FeSO_4$
Flue Gas Temperature					
Ranges (°F)	542-724	658-745	617-921	800-926	135-146
Average (°F)	676	719	801	872	142
Flue Gas					
NOx (ppm)	85	291	487	250	319
O_2 (%)	8.0	15.0	8.9	0.4	1.1*, 11.0**
Velocity (fps)	0.8	1.2	2.5	32.0	1.6
Bed Size (in)	3 x 2D	3 x 2D	4 x 1D	2 x 2D	2 x 2D
ΔP Across Bed (in W.G.)	2.6	12.0	1.6	1.0	0.7
Avg. NOx Removal	1	7	0*, 70**	14*, 0**	5*, 1**
Max. NOx Removal	1	11	82	18	7*, 1**
Comments	0.0 in. Draft; Hole in bed suspected.	Continuation of Run 11	*Before NH_3 additions **After NH_3 additions	*Before NH_3 additions **After NH_3 additions; ΔP across the bed dropped to 0.8 in, indicating a hole developed.	*Reducing conditions **Oxidizing conditions

SECTION III

BENCH-SCALE TESTING

A. BENCH-SCALE TEST PROGRAM

1. Approach

The bench-scale phase of the program involved two steps:

a. designing and installing in the laboratory a relatively large burner and exhaust system to simulate the operation of a turbine engine; and

b. employing this system to investigate important aspects of the performance of catalyst/sorbents in treating exhaust gases.

The principal purpose of bench-scale work was to determine how selected bed materials perform when exposed to conditions that one might see in jet-engine testing. The goal was to define one or more systems for evaluation in slipstream trials at an Air Force test-cell site. The emphasis in bench-scale work was on NOx control, although capture of fine particulates and CO was also addressed.

The bench-scale test program consisted of a series of baseline tests, parametric tests, long-term cycling tests, and tests addressing special areas of interest, such as the regenerability of the catalyst/sorbents and the leachability of used and discarded materials.

Of the many catalyst/sorbents examined in the laboratory, three materials stood out as most promising--virgin vermiculite, vermiculite with MgO, and activated carbon. Emphasis in early bench-scale work was on these materials. For comparison purposes, a selective catalytic reduction (SCR) system employing a commercial zeolite catalyst with ammonia additions was installed. After much experimental work, it became clear that, for very high temperature use, an SCR system with a zeolite honeycomb catalyst, particularly when it was prefaced with a virgin vermiculite bed, demonstrated significant promise for NOx control. Because high temperatures were anticipated in the test-cell exhaust gases at the time, emphasis in bench-scale work shifted to modified SCR systems.

As in earlier laboratory tests, the vermiculite and activated carbon materials were placed as fixed beds between parallel, stainless steel screens, and the exhaust gases were passed through the beds. The screens were approximately 7-inch by 7-inch in size. Whenever two beds in series were employed, three parallel screens were used. Sampling ports placed before and after the beds permitted continuous measurements of gas composition, flow rate, and temperature and of the pressure drops across the beds.

Whenever SCR catalysts were employed, special ports were used to inject controlled additions of ammonia, supplemental additions of NOx and air, and measured quantities of particulates into the exhaust gas streams. The SCR catalysts were employed as approximately 4-inch by 4-inch honeycomb blocks, each 3 or 6 inches long.

2. Apparatus

A layout drawing of the apparatus designed and installed for bench-scale testing is shown in Figure 3. A photograph of the apparatus is given in Figure 4. Principal components of the apparatus

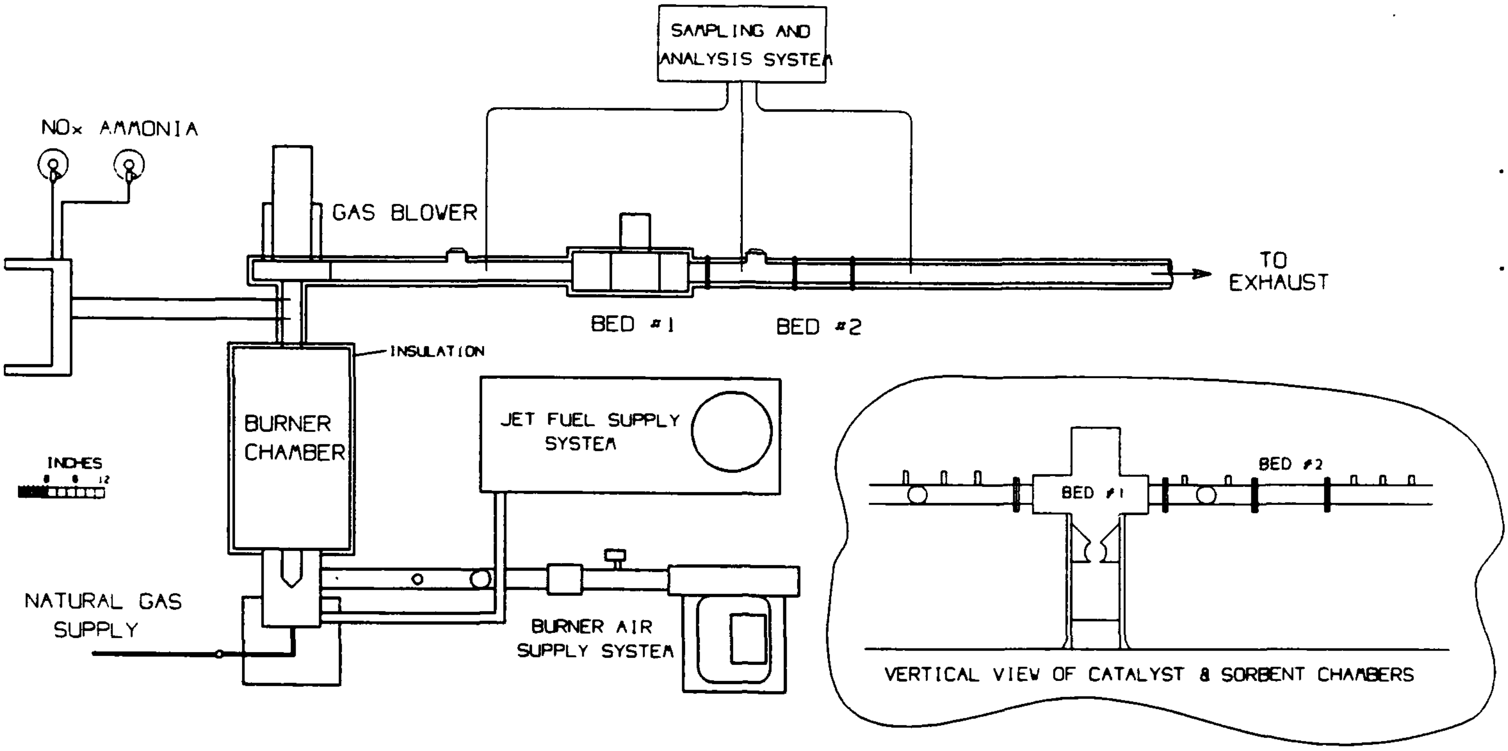


Figure 3. Bench-Scale Test Apparatus Floor Plan

Figure 4. Photograph of the Bench-Scale Test Apparatus

include the fuel supply system, the air compressor, the burner and burning chamber, the fan, the NOx removal system, and a sampling and analysis system. The computerized data acquisition and storage system is shown schematically in Figure 5. Temperature and pressure data were collected and recorded every 20 seconds during each run. Other data were collected and recorded every 3 to 6 minutes.

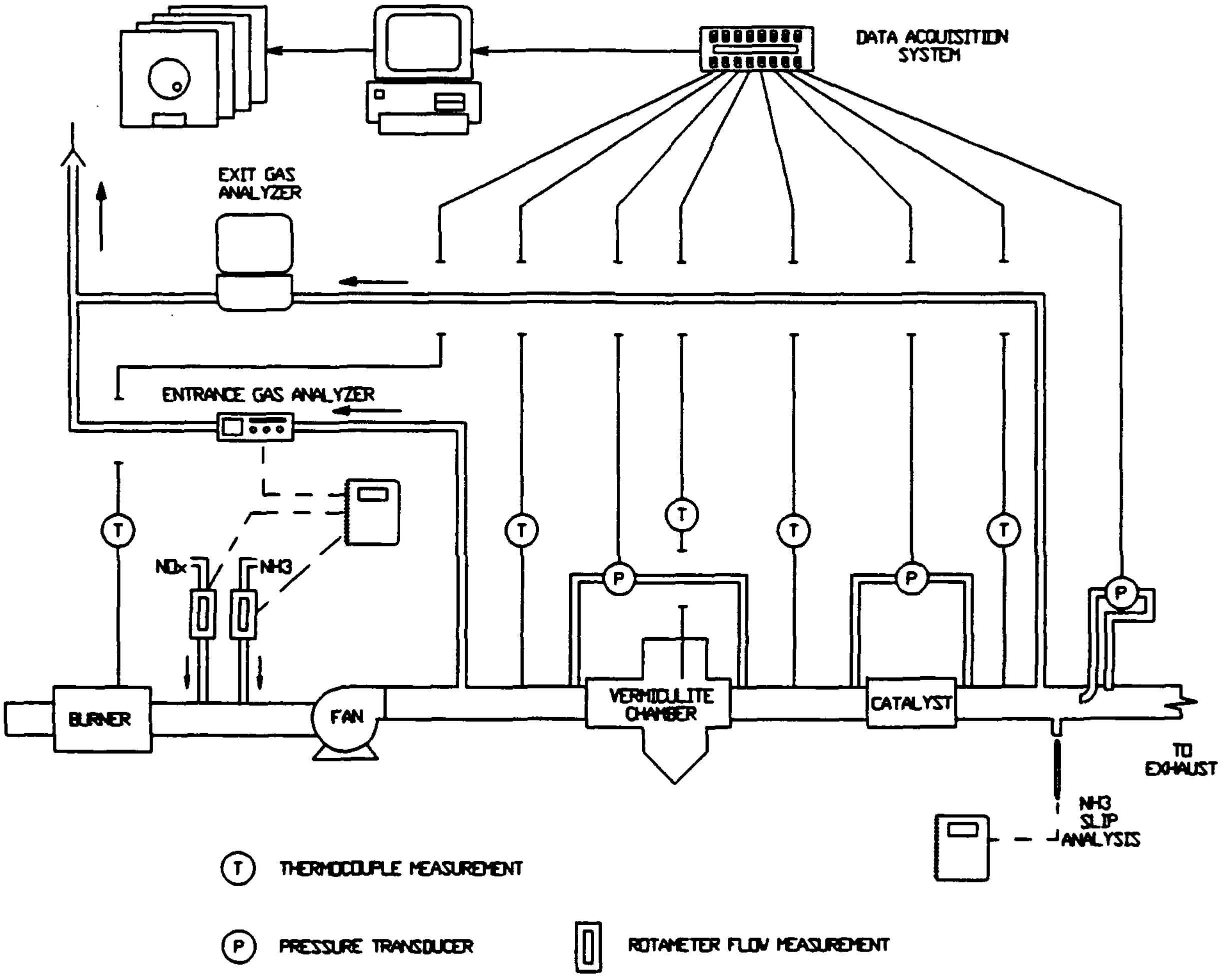


Figure 5. Data Acquisition and Storage System Employed in Bench Testing

The burner system was designed and supplied by Pyronics, Inc., of Cleveland, Ohio. The system had the capability of burning natural gas, liquid jet fuel, or a combination of the two. The maximum burning capability of the system was 2 cubic feet per minute for natural gas or 1.2 gallons per hour for jet fuel. Natural gas was supplied to the apparatus through a specially installed high-pressure line. Jet fuel (Grade JP-2) in barrels was acquired from Lakefront Airport in Cleveland. The air compressor, a 36-inch diameter fan driven by a 20-horsepower motor, was supplied by Robinson Industries of Zelienople, Pennsylvania.

The carbon steel burner chamber was 24 inches in diameter and 42 inches long. The outside of the burner chamber was insulated with 1-inch refractory wool. A Dayton 10-9/16-inch diameter fan was employed to propel the exhaust gas from the burner chamber and to mix the gas with additions of NOx and/or ammonia. This fan was modified by (1) replacing the 1-horsepower ac motor with a 1-1/2-horsepower dc motor and adding a variable speed controller; (2) replacing the internal aluminum blades with steel blades; and (3) replacing the conventional steel bearings with high-temperature graphite bearings. The latter two changes were required to handle the very hot exhaust gases. A special air valve was installed in front of the fan to allow dilution air to enter the system, when desired.

The waste-gas-treatment system consisted of two bed units in series. The initial bed unit held the vermiculite materials. The second unit held the SCR catalysts and was removed from the system when SCR catalysts were not employed. Well-insulated 4-inch-diameter steel piping carried the exhaust gases from the fan to the gas-treatment system and away from the system to exhaust.

B. EXPERIMENTAL WORK

In practice, aircraft engines are tested under a series of conditions in test cells. These conditions vary from site to site. Power levels are commonly idle, 30 percent, 75 percent, 100 percent, and afterburner. The temperature, composition, and velocity of the exhaust gas will differ for each condition. They will also vary with the dimensions and configuration of the augmentor and chimney, with the amount of augmentation air that is introduced, and with the type and size of the engine being tested.

1. Baseline and Parametric Runs

Approximately 75 bench-scale runs were performed. These runs varied in duration from 40 minutes to 26 hours. The majority of the runs were conducted at elevated temperatures because high temperatures were expected to be seen in typical test-cell applications.

The results of initial baseline tests (Table 7) indicated that, for high-temperature NOx control, a system consisting of a honeycomb zeolite catalyst bed and ammonia additions showed most promise, and that the efficiency of NOx removal by the zeolite is enhanced by the passage of the gas stream through a vermiculite bed in front of it. Vermiculite beds alone showed the ability to reduce the NOx levels of exhaust gases, but removal levels appeared to be limited to about 33 percent. For low-temperature NOx control, a bed of vermiculite modified with MgO showed most promise, particularly at low gas velocities.

In earlier laboratory tests, activated carbon demonstrated the ability to remove NOx from exhaust gases. A series of bench-scale runs were performed with Grade F816 activated carbon. The results of these runs are provided in Table 8.

From an exhaust gas at a relatively constant temperature, NOx removal by activated carbon decreased slowly with increases in gas velocity. The NOx removal performance of the activated carbon also fell off sharply with increased temperature. Above 325°F, it removed essentially no NOx. At 357°F, it ignited. Introducing ammonia into the gas stream did not improve NOx removal performance.

TABLE 7. BASELINE RUNS ON VERMICULITE AND OTHER MATERIALS

	Conditions			
Material	Avg. Gas Temp (°F)	Gas Velocity (fps)	ΔP, Bed (in. W.G.)	Avg. NOx Removal (%)
10" MgO–Vermiculite	100	0.8	0.41	91
"	151	0.8	0.59	61
"	179	0.8	0.59	30
"	386	0.7	0.59	15
10" Vermiculite	122	0.8	0.65	26
"	201	0.7	0.80	26
"	403	0.7	0.80	25
"	530	0.6	1.00	24
"	622	3.2	2.60	31
"	648	4.0	2.80	33
"	684	4.0	2.80	32
10" Vermiculite	103	4.4	5.80	26
"	175	3.8	4.80	30
"	567	3.9	3.80	29
"	718	3.7	3.80	28
10" MgO–Vermiculite	99	4.3	3.40	21
"	465	2.3	3.00	5
"	601	4.4	3.00	2
"	719	4.9	3.00	3
10" Vermiculite + Zeolite A				
+ NH_3	96*/96**	2.9	2.20	18
"	112/99	2.9	2.00	23
"	621/354	2.0	1.80	48
"	498/382	2.1	1.80	73
10" Vermiculite + Zeolite A				
No NH_3	104/104	3.8	3.20	16
"	262/193	2.5	1.80	23
"	413/215	2.5	1.80	18
"	551/269	2.2	1.80	39
No Bed (punched metal plate inserted to provide pressure drop)	91	2.9	3.00	0
"	376	2.2	3.40	0
"	527	3.4	2.00	0
Zeolite A + NH_3	190	2.9	4.40	21
"	225	3.4	4.40	18
"	585	2.8	3.60	86

*Temperature entering the vermiculite bed.
**Temperature entering the zeolite catalyst.

TABLE 8. EXAMINATION OF AN ACTIVATED CARBON BED

Material	Conditions: Avg. Gas Temp (°F)	Conditions: Gas Velocity (fps)	Conditions: ΔP, Bed (in. W.G.)	Avg. NOx Removal (%)
10" Activated Carbon (PCB 4 x 10)	91	0.5	0.6	86
	91	0.5	0.6	83
	95	1.7	1.4	75
	93	1.7	1.4	73
	98	2.7	2.6	65
	145	0.8	0.6	63
	151	1.6	1.2	54
	155	2.5	2.4	47
	163	2.9	4.0	39
	325	2.9	4.0	0
	473	2.9	3.4	0
	200	3.2	4.0	16
	224	2.4	2.6	22
	237	1.7	1.6	23
	243	0.8	0.8	20
	95	2.9	3.2	66
	99	2.9	3.2	63
	103	2.9	3.2	61
	106	2.9	3.4	57
	115	2.9	3.4	55
	125	2.9	3.4	55
	143	2.9	3.6	45
	159	2.9	3.8	41
With NH_3 Additions	124	2.9	3.4	48
	120	2.9	3.4	43

A series of runs was performed with vermiculite coated with sodium formate, with a mixture of copper and cobalt oxide, and with magnesium oxide. The bed materials were prepared following the procedures outlined by Dwyer(11), Hansford(12), and Nelson(13), respectively. The results of bench-scale runs with these materials, shown in Table 9, indicated that sodium formate and copper oxide–cobalt oxide provided no significant improvement in NOx removals over virgin vermiculite, and that magnesium oxide offered only a small improvement. The addition of ammonia to the exhaust gas did not improve NOx removals by any of these beds.

Three different zeolite catalysts, all in honeycomb form, were examined in bench-scale tests. Two materials (Zeolites A and B) were supplied by Engelhard Industries, Zeolite B being Engelhard's latest development. The third material (Zeolite C) was supplied by Norton Industries.

Appreciable NOx reductions were seen when a vermiculite bed and Zeolite A were used in series without ammonia additions (See Table 10). With ammonia additions, NOx removals in the 90-plus percent range were observed. Zeolite catalysts appear to be able to capture ammonia during periods of exposure, and to retain it in some manner. Release of ammonia resulting in ammonia slip was observed in a number of cases at times well after ammonia additions to the gas stream had ceased. This ammonia retention is also believed responsible for the excellent NOx removals with no ammonia additions that are commonly seen when zeolite beds are employed after long periods out of use.

The initial results for vermiculite–zeolite bed combinations suggested an approach that might be utilized with these materials to control NOx in hot exhaust gases that are at relatively constant temperature and flow rate. The approach involves making ammonia additions as small, regularly-spaced injections. Because the vermiculite bed, like the zeolite, appears to capture and hold ammonia and because the vermiculite bed appears to release it at a relatively constant rate, the capability to reduce NOx persists. The results in Tables 11 and 12 are consistent with this interpretation.

A series of parametric runs were then performed involving Vermiculite–Zeolite B beds. Both at low and high temperatures, Zeolite B did not perform as well as Zeolite A. (See Table 13).

The ability of sorbent/catalyst beds to remove CO was examined during most runs. At low temperatures, vermiculite materials routinely removed about one-third of the CO present. However, as the temperature of the waste gases increased above 200°F, CO removals decreased. An exception was vermiculite coated with a combination of CuO and Co_2O_3. This material removed more than 50 percent of the CO at temperatures of about 400°F and became more effective at higher temperatures. Hansford(12) stated that CuO/Co_2O_3 can remove CO and NOx from waste gases, CO being converted into CO_2. The bench-scale test results show that CuO/Co_2O_3 will reduce CO levels appreciably, but not NOx. The zeolites and activated carbon were not effective in reducing CO. Test results are summarized in Table 14.

Exhaust gases in the bench-scale test program were produced by burning one of two fuels, natural gas and jet fuel. Approximately 90 percent of the runs were performed with natural gas, because combustion was more easily controlled and the exhaust gas was cleaner. Both fuels, however, produced a significant amount of fine particulates, mostly carbon, and the jet fuel produced far more. Vermiculite exposed during the burning of jet fuel (right) and natural gas (left) and vermiculite before exposure (center) are shown in the photograph in Figure 6.

TABLE 9. EXAMINATION OF BEDS OF VERMICULITE WITH ADDITIVES

	Conditions			
Material	Avg. Gas Temp (°F)	Gas Velocity (fps)	ΔP, Bed (in. W.G.)	Avg. NOx Removal (%)
10" Vermiculite				
+ Sodium Formate	121	2.6	3.7	25
	180	2.3	3.6	23
	211	2.4	3.6	25
	822	2.0	3.2	19
	940	2.2	3.0	14
With NH_3 Additions	365	3.5	3.8	15
(Avg. NOx–330 ppm	518	3.4	3.8	25
Avg. NH_3–400 ppm,	530	2.4	3.6	28
constant additions)	668	2.1	3.0	20
10" Vermiculite				
+ CuO/Co_2O_3	190	3.4	3.0	23
	201	3.4	3.0	21
	229	3.3	3.0	21
	249	3.3	3.0	23
	495	5.4	3.0	31
	629	3.2	2.6	28
	679	3.4	2.6	34
10" Vermiculite				
+ MgO	95	2.9	2.0	44
	103	2.9	2.0	44
	458	2.4	2.6	15
	477	2.7	2.8	14
	495	2.4	2.8	13
With NH_3 Additions	97	2.9	2.0	22
(Avg. NOx–240 ppm	106	2.9	2.0	24
Avg. NH_3–230 ppm				
increasing additions)				
With NH_3 Additions				
(Avg. NOx–260 ppm	444	2.9	3.8	30
Avg. NH_3–300 ppm	524	2.9	2.8	41
increasing additions)	637	2.9	2.8	18
	663	2.9	2.8	17
10" Vermiculite	435	2.9	3.8	40
	686	2.9	3.8	26

TABLE 10. SEQUENCE OF PARAMETRIC RUNS WITH A VERMICULITE–ZEOLITE A BED

10" Vermiculite with 6" Zeolite A

	Conditions			
Time After Start (Min)	Gas Temp (°F)	Gas Velocity (fps)	ΔP, Bed (in. W.G.)	Avg. NOx Removal (%)
16	339	2.8	2.6	25
30	448	2.8	2.8	27
35	566	2.8	2.8	46
40	636	2.8	2.8	64

Added NH_3 for 22 minutes (Avg. NOx–238 ppm; Avg. NH_3–285 ppm)

Time After Start (Min)	Gas Temp (°F)	Gas Velocity (fps)	ΔP, Bed (in. W.G.)	Avg. NOx Removal (%)
46	688	2.9	3.0	64
51	725	2.9	3.0	73
56	755	3.0	3.2	78
62	778	3.0	3.2	92

Heavy ammonia slip

Next day, same bed with no further ammonia additions; increased, decreased and increased temperature.

Time After Start (Min)	Gas Temp (°F)	Gas Velocity (fps)	ΔP, Bed (in. W.G.)	Avg. NOx Removal (%)
73	466	2.7	2.8	31
78	576	2.8	2.8	44
85	643	2.8	3.0	64
92	700	2.8	3.0	66
98	538	2.9	3.4	62
103	460	2.8	3.4	41
111	359	2.9	3.2	38
116	324	3.2	3.2	35
135	553	3.0	3.0	33
145	680	3.4	3.0	40

The above bed was then exposed to a constant-velocity gas with no ammonia additions.

Time After Start (Min)	Avg. Gas Temp. (°F)	Gas Velocity (fps)	NOx in Exhaust Gas (ppm)	Avg. NOx Removal (%)
9	607	3.4	40	43
16	624	3.4	39	54
22	633	3.4	39	46
29	613	3.4	100	45
37	548	3.4	104	35
53	535	3.4	147	26
64	535	3.4	204	26
72	535	3.4	250	27
78	535	3.4	247	27
104	535	3.4	38	21

TABLE 11. RUNS WITH INTERMITTENT AMMONIA ADDITIONS TO ZEOLITE A AND VERMICULITE–ZEOLITE A BEDS

10" Vermiculite with 6" Zeolite A

	Conditions			
Time After Start (Min)	Gas Temp (°F)	Gas Velocity (fps)	ΔP, Bed (in. W.G.)	Avg. NOx Removal (%)
15	818	1.0	1.0	13
Added 100 ppm NH_3 for 15 minutes; observed 50 ppm slip concurrently.				
21	833	1.2	0.8	67
30	825	0.9	0.8	100
37	826	0.9	1.0	92
54	826	1.3	0.9	91
66	829	1.7	0.8	84
77	829	1.5	1.0	70
87	831	1.5	0.9	49
96	830	1.5	0.9	26
106	830	1.2	0.9	17
120	832	1.2	0.9	12
Added 100 ppm NH_3 for 5 minutes; no slip.				
130	830	0.9	1.0	89
Burner turned off and bed cooled to room temperature.				
Replaced the vermiculite bed and the test was restarted the next day.				
18	836	0.6	1.0	69
29	836	1.0	0.9	43
42	842	1.0	0.9	26
56	849	1.3	0.8	19
69	855	0.9	1.0	8
84	882	0.6	0.9	6
97	858	0.4	0.7	1
Added 100 ppm NH_3 for 10 minutes; observed 20 ppm slip.				
110	843	0.4	0.5	93
120	833	0.4	0.6	93
Burner turned off and cooled to room temperature.				
Test restarted the next day.				
9	806	0.4	1.2	86
17	814	0.4	1.2	80
25	829	0.5	1.1	58
37	845	0.4	1.2	37
49	835	0.7	1.1	28
58	794	0.6	1.2	22

TABLE 11. RUNS WITH INTERMITTENT AMMONIA ADDITIONS TO ZEOLITE A AND VERMICULITE–ZEOLITE A BEDS (CONCLUDED)

	Conditions			
Time After Start (Min)	Avg. Gas Temp (°F)	Gas Velocity (fps)	ΔP, Bed (in. W.G.)	Avg. NOx Removal (%)
Replaced the zeolite bed with a bed that was used before, and the test was continued.				
11	655	0.9	0.8	82
19	722	0.4	1.0	82
26	743	1.2	0.9	81
34	708	0.6	0.9	75
45	767	0.7	0.7	57
53	771	0.6	0.9	33
75	720	0.7	0.7	6
6" Zeolite A Catalyst Alone				
16	662	1.0	>0.1	4
28	724	1.1	>0.1	0
33	705	1.0	>0.1	0
44	706	1.2	>0.1	0
Added 100 ppm NH_3 for 15 minutes; 30 ppm NH_3 slip.				
52	708	0.5	>0.1	90
65	716	0.8	>0.1	100
75	721	0.8	>0.1	100
95	731	0.7	>0.1	91
109	729	1.0	>0.1	0

TABLE 12. EXAMINATION OF AMMONIA DISTRIBUTION IN A VERMICULITE–ZEOLITE A SYSTEM

Sorbent/Catalyst Bed: 10" Vermiculite + 6" Zeolite A (Fresh)
Average NOx Level in Gas: 90 ppm; Average Velocity: 0.7 fps

Time After Start (Min)	Ammonia Added to Gas (ppm)	Ammonia Leaving Vermiculite Bed (ppm)	Ammonia Leaving Zeolite Bed or Slip (ppm)	% NOx Removal
17	0	0	0	12
24	0	0	0	0
38	0	0	0	0
50	650	150	100	93
61	400	100	0	92
75	150	20	0	92
90	100	30	0	91
99	50	30	0	90
109	30	15	0	88
132	40	40	0	86
147	16	2	0	80

TABLE 13. PARAMETRIC RUNS WITH VERMICULITE–ZEOLITE B BEDS

Conditions			
Avg. Gas Temp (°F)	Gas Velocity (fps)	ΔP, Bed (in. W.G.)	Avg. NOx Removal (%)
10" Vermiculite with 6" Zeolite B			
277	1.0	1.3	1
303	0.9	1.2	1
320	1.0	1.2	6
332	0.9	1.2	4
10" Vermiculite with 9" Zeolite B			
178	0.9	1.2	13
203	0.9	1.1	12
219	0.7	1.1	13
233	0.9	1.1	4
458	1.0	0.9	6
519	0.5	0.9	0
553	0.7	0.9	0
Excess Ammonia Additions Made			
585	0.5	0.8	36
627	0.7	0.7	44
			Heavy ammonia slip
Increasing Temperature Same bed as above (no further ammonia additions)			
424	1.3	0.9	19
448	1.0	0.9	25
474	0.7	0.9	35
478	0.9	0.9	39
483	1.1	0.9	39
488	0.8	0.9	36
495	1.3	0.9	19
10" Vermiculite with 6" Zeolite B			
Excess Ammonia Added For 1-Hr.–Ammonia Slip Observed			
496	1.3	0.8	30
585	1.2	0.9	30
634	1.5	0.8	41
Additional Ammonia Added for 2-Hrs.–Ammonia Slip Observed			
661	1.4	0.8	60
693	1.5	0.8	65
703	1.6	0.8	80

TABLE 14. CARBON MONOXIDE (CO) REMOVALS WITH SELECTED BED MATERIALS

Bed Material	Gas Temp (°F)	Bed Temp (°F)	CO Level		% CO Removed
			Entering	Exiting	
10" Vermiculite	170	128	334	218	35
	201	146	218	141	35
	232	161	216	140	35
	173	167	269	280	24
	178	173	491	286	26
	567	335	974	960	1
10" Vermiculite–MgO	82	82	6	0	100
	151	115	147	103	30
	180	128	413	310	25
	214	131	855	570	33
	243	158	881	421	52
	261	190	314	267	15
	458	338	1067	924	13
10" Vermiculite–CuO/Co_2O_3	229	184	363	314	13
	249	203	366	311	15
	495	433	38	25	34
	629	402	655	321	51
	679	448	604	274	55
10" Activated Carbon	98	91	3	3	0
	224	164	513	514	0
	325	287	450	450	0

Figure 6. Photograph of Virgin Vermiculite Bed Material (Center) and Materials After Exposure to Exhaust Gases

Generally speaking, NOx removals were better when jet fuel was burned than when natural gas was burned. Table 15 gives typical data that were collected. Perhaps the presence of unburned carbon and other hydrocarbons play a part in the higher NOx removals seen.

Two runs were performed in which Zeolite C was compared with Zeolite A. On the basis of the results given in Table 16, it was concluded that both gave about the same performance, although not under equivalent conditions.

2. Long-Term Cycling and Regeneration Studies

A series of long-term runs was performed to determine if the performances that were observed in 2- to 4-hour runs would continue for long periods, and to determine if the bed material could be regenerated and used again. Example data collected during one long-term run carried out on an exhaust gas having temperatures in the range of about 450° to 550°F are provided in Table 17. The results of this run showed that no loss in performance occurred even after 26 hours of operation. Brief additions of ammonia were made to the exhaust gas at seven times during the run.

After the 26-hour run, the vermiculite bed in front of the zeolite bed was grey in color (indicating carbon pick-up). The zeolite bed, however, remained clean.

In an early run (See Table 11), a Zeolite A bed was employed without a vermiculite bed. At the end of this run, the zeolite was heavily covered with carbon. When this catalyst was used again in a new run, with or without a vermiculite bed, NOx-removal performance was not good. The carbon depositions on the zeolite honeycomb structure were then successfully burned off by heating the zeolite to 1000°F in air. The performance of the zeolite after this treatment, however, was very poor.

A series of experiments was performed in which virgin vermiculite samples well-coated with carbon during exposure to exhaust gases were heated in air for 30 minutes at different temperatures. The results of these experiments are summarized in Table 18. Heating the vermiculite at 932°F (500°C) eliminated all traces of carbon.

Heating the vermiculite materials exposed in the 26-hour run at 1000°F in air for 1 hour eliminated the carbon deposits as well. The resulting vermiculite had the appearance of virgin vermiculite. This material was then used in a second long-term test, was regenerated again, and was employed in a third long-term test, all tests being successful. The results of the first, second, and third long-term tests are summarized in Table 19. Note that none of these runs were terminated because of reduced performance; they were stopped for convenience only.

Plots of NOx removal as a function of gas temperature for fresh and regenerated vermiculite–zeolite A beds are shown in Figure 7. These plots show that vermiculite regenerated at 300°F results in better subsequent performance than vermiculite regenerated at 550°F.

TABLE 15. NOx REMOVALS DURING THE BURNING OF JET FUEL VERSUS NATURAL GAS

10" Vermiculite with 12" Zeolite A with No Ammonia Additions

Conditions Avg. Gas Temp (°F)	Gas Velocity (fps)	ΔP, Bed (in. W.G.)	Avg. NOx Removal (%)
Jet Fuel			
660	2.0	2.2	46
675	1.7	1.9	65
Natural Gas			
669	2.0	2.2	15
675	1.7	2.0	10

TABLE 16. COMPARATIVE RUNS WITH TWO DIFFERENT ZEOLITE CATALYSTS

Conditions Avg. Bed Temp (°F)	Gas Velocity (fps)	NH_3 Addition (ppm)	NH_3 Slip (ppm)	Avg. NOx Removal (%)
10" Vermiculite with 12" Zeolite A				
167	1.5	0	0	0
330	1.7	0	0	25
504	1.5	0	0	58
542	1.4	0	0	66
590	1.7	0	0	72
637	1.7	120	0	92
661	1.7	60	0	86
10" Vermiculite with 12" Zeolite C				
250	1.6	0	0	0
402	1.4	180	10	19
537	1.4	140	2	75
577	1.9	140	2	82
608	1.5	140	0	80
647	2.0	0	10	84
645	2.4	0	8	82

TABLE 17. SELECTED DATA COLLECTED DURING A LONG CYCLING RUN

Time After Start (Min)	Exhaust Gas Velocity (fps)	Exhaust Gas Temperature (°F)			ΔP, Bed (in W.G.)
		Entering Filter	In Filter	Exiting Filter	
30	0.9	550	413	310	0.6
60	1.1	506	417	323	0.7
90	1.1	502	413	315	0.7
120	0.9	523	425	318	0.9
150	1.4	549	446	336	0.9
180	1.4	554	455	346	0.9
210	1.6	550	453	346	0.9
240	1.5	547	440	339	0.9
270	1.5	538	432	329	0.9
300	1.2	538	432	329	1.0
330	1.4	536	437	329	1.0
360	1.8	564	500	409	1.9
390	1.7	563	508	408	1.7
420	2.2	554	492	390	2.1
450	1.9	539	470	367	2.1
480	2.1	545	484	385	2.0
510	2.1	556	479	379	2.1
540	1.9	550	471	384	2.0
570	2.3	561	482	391	1.9
600	2.2	559	480	382	1.9
630	1.2	464	378	306	1.2
660	1.3	464	400	327	1.1
690	1.4	456	397	328	1.2
720	1.3	443	377	308	1.2
750	1.2	464	378	306	1.2
780	1.3	490	409	339	1.4
810	1.7	535	453	368	1.9
840	1.5	566	469	375	1.7
870	1.8	547	480	402	2.0
900	1.8	559	489	400	1.7
930	1.6	567	486	397	1.9
960	2.0	560	475	383	2.0

TABLE 17. SELECTED DATA COLLECTED DURING A LONG CYCLING RUN (CONTINUED)

Time After Start (Min)	Incoming Gas Composition					Outgoing Gas Composition					
	NOx (ppm)	CO (ppm)	O_2 (%)	CO_2 (%)	NH_3 (ppm)	NOx (ppm)	CO (ppm)	O_2 (%)	CO_2 (%)	NH_3 (ppm)	% NOx Removal
30	31	817	17.9	1.8	0	26	790	17.9	1.8	0	16
60	90	810	18.9	1.2	0	57	824	18.9	1.2	0	37
90	93	776	18.9	1.1	0	70	793	18.9	1.1	0	25
120	87	662	18.3	1.4	0	75	660	18.4	1.3	0	14
150	87	663	18.3	1.4	0	75	660	18.2	1.3	0	14
180	83	669	18.4	1.3	0	76	666	18.5	1.3	0	9
210	76	688	18.6	1.4	115	17	700	18.7	1.3	16	78
240	76	669	18.8	1.3	0	23	670	18.8	1.3	0	70
270	76	660	18.8	1.3	0	27	690	18.8	1.3	0	64
300	78	692	18.7	1.3	0	37	674	18.8	1.2	0	53
330	75	677	18.8	1.2	0	64	650	18.9	1.2	0	15
360	70	52	17.9	1.8	0	64	47	18.2	1.5	0	9
390	70	54	18.1	1.6	0	68	52	18.2	1.6	0	3
420	69	39	18.3	1.6	0	68	37	18.3	1.5	0	1
450	71	42	18.5	1.4	115	23	34	18.5	1.4	20	68
480	64	39	18.3	1.5	115	13	34	18.3	1.5	20	80
510	67	30	18.4	1.5	0	15	27	18.4	1.5	10	78
540	65	22	18.5	1.4	0	19	27	18.5	1.5	13	71
570	67	25	18.3	1.5	0	25	27	18.4	1.5	13	63
600	67	25	18.4	1.5	0	48	25	18.5	1.5	0	28
630	36	20	18.2	1.6	0	36	30	18.5	1.4	0	0
660	26	15	18.6	1.4	50	20	18	18.6	1.4	0	23
690	26	72	18.9	1.2	50	7	67	18.9	1.1	10	73
720	26	74	19.0	1.1	0	13	76	19.0	1.1	0	50
750	24	81	19.0	1.2	0	13	84	19.0	1.1	0	46
780	49	0	18.1	1.6	0	36	0	18.1	1.6	0	27
810	46	0	17.4	2.0	0	40	0	17.4	2.0	0	13
840	46	0	17.6	1.9	0	44	0	17.5	2.0	0	4
870	72	76	18.1	1.7	0	69	59	18.1	1.7	0	4
900	72	3	18.1	1.6	400	16	5	18.1	1.6	0	78
930	69	0	18.2	1.6	400	11	0	18.2	1.5	100	84
960	70	0	18.3	1.6	0	15	0	18.3	1.6	0	79

TABLE 17. SELECTED DATA COLLECTED DURING A LONG CYCLING RUN (CONTINUED)

Time After Start (Min)	Exhaust Gas Velocity (fps)	Exhaust Gas Temperature (°F)			ΔP, Bed (in W.G.)
		Entering Filter	In Filter	Exiting Filter	
990	1.7	558	472	383	1.8
1020	1.8	545	463	376	2.0
1050	1.0	400	304	233	0.3
1080	1.0	396	291	220	0.2
1110	0.8	396	275	204	0.2
1140	1.0	391	282	211	0.3
1170	1.0	391	284	209	0.3
1200	1.1	394	284	209	0.3
1230	0.9	483	413	341	1.6
1260	1.5	463	424	353	1.6
1290	1.5	449	414	338	1.6
1320	1.7	450	406	324	1.7
1350	1.5	448	406	323	1.8
1380	1.7	449	401	321	1.9
1410	1.9	443	394	314	1.6
1440	2.3	501	436	353	1.9
1470	2.4	497	434	347	2.4
1500	2.4	501	429	342	1.9
1530	2.2	499	430	343	2.3
1560	2.3	497	425	340	2.0

TABLE 17. SELECTED DATA COLLECTED DURING A LONG CYCLING RUN (CONCLUDED)

Time After Start (Min)	Incoming Gas Composition					Outgoing Gas Composition					% NOx Removal
	NOx (ppm)	CO (ppm)	O_2 (%)	CO_2 (%)	NH_3 (ppm)	NOx (ppm)	CO (ppm)	O_2 (%)	CO_2 (%)	NH_3 (ppm)	
990	69	0	18.3	1.5	0	19	0	18.3	1.5	30	72
1020	69	0	18.5	1.5	0	62	0	18.5	1.5	0	10
1050	170	301	19.8	0.7	0	170	284	19.8	0.7	0	0
1080	163	223	19.7	0.8	400	130	231	19.7	0.8	150	20
1110	159	219	19.6	0.8	28	81	216	19.6	0.8	3	49
1140	116	214	19.6	0.8	600	48	197	19.6	0.7	200	59
1170	112	211	19.7	0.7	0	42	214	19.7	0.7	0	63
1200	112	211	19.7	0.7	0	54	197	19.7	0.7	15	52
1230	47	311	18.3	1.6	0	14	306	18.3	1.6	0	70
1260	55	325	18.8	1.3	0	20	322	18.8	1.2	0	63
1290	45	292	19.0	1.1	0	26	294	19.0	1.1	0	42
1320	45	271	19.1	1.1	115	30	266	19.1	1.1	0	33
1350	45	264	19.1	1.1	200	13	254	19.1	1.0	40	71
1380	42	261	19.1	1.1	0	15	256	19.2	1.0	40	64
1410	38	260	19.2	1.0	0	23	257	19.2	1.0	0	40
1440	80	0	18.7	1.3	180	19	0	18.7	1.3	6	76
1470	75	0	18.7	1.3	10	21	0	18.7	1.3	2	72
1500	72	0	18.8	1.2	0	39	0	18.8	1.3	0	46
1530	74	0	18.8	1.3	0	66	0	18.8	1.3	0	11
1560	72	0	19.0	1.1	0	72	0	19.0	1.1	0	0

TABLE 18. RESULTS OF REGENERATION TRIALS ON EXPOSED VERMICULITE MATERIALS

Regeneration Temperature (°C)	Weight Loss (%) After 10 Min	Weight Loss (%) After 30 Min	Physical Appearance After 30 Min
100 (212°F)	1.34	1.50	Similar to exposed material; many black particles of a wide range of sizes.
200 (392°F)	1.40	2.72	Half to two-thirds of the particles gone; signs of a new crystalline phase forming on the surface.
300 (572°F)	4.44	5.08	Nearly all black particles gone; gray phase formed.
400 (752°F)	5.69	6.13	Essentially all particles gone; gray surface phase.
500 (932°F)	6.58	7.29	Completely changes appearance; clean surfaces and golden yellow in color.

Regeneration Atmosphere - Air

TABLE 19. SUMMARY DATA ON LONG-TERM CYCLING EXPERIMENTS INVOLVING REGENERATED VERMICULITES

	Total Sorption Run Time	Avg. NOx in Gas	Avg. NH_3 Consumed	Avg. NH_3 Slip	Avg. NOx Removal
Fresh Bed	26 hr.	70.8 ppm	40.2 ppm	13.2 ppm	42.1%
Regenerated Bed	19 hr.	54.1 ppm	38.0 ppm	27.7 ppm	45.7%
Re-regenerated Bed	5 hr.	100.6 ppm	33.8 ppm	1.5 ppm	25.9%

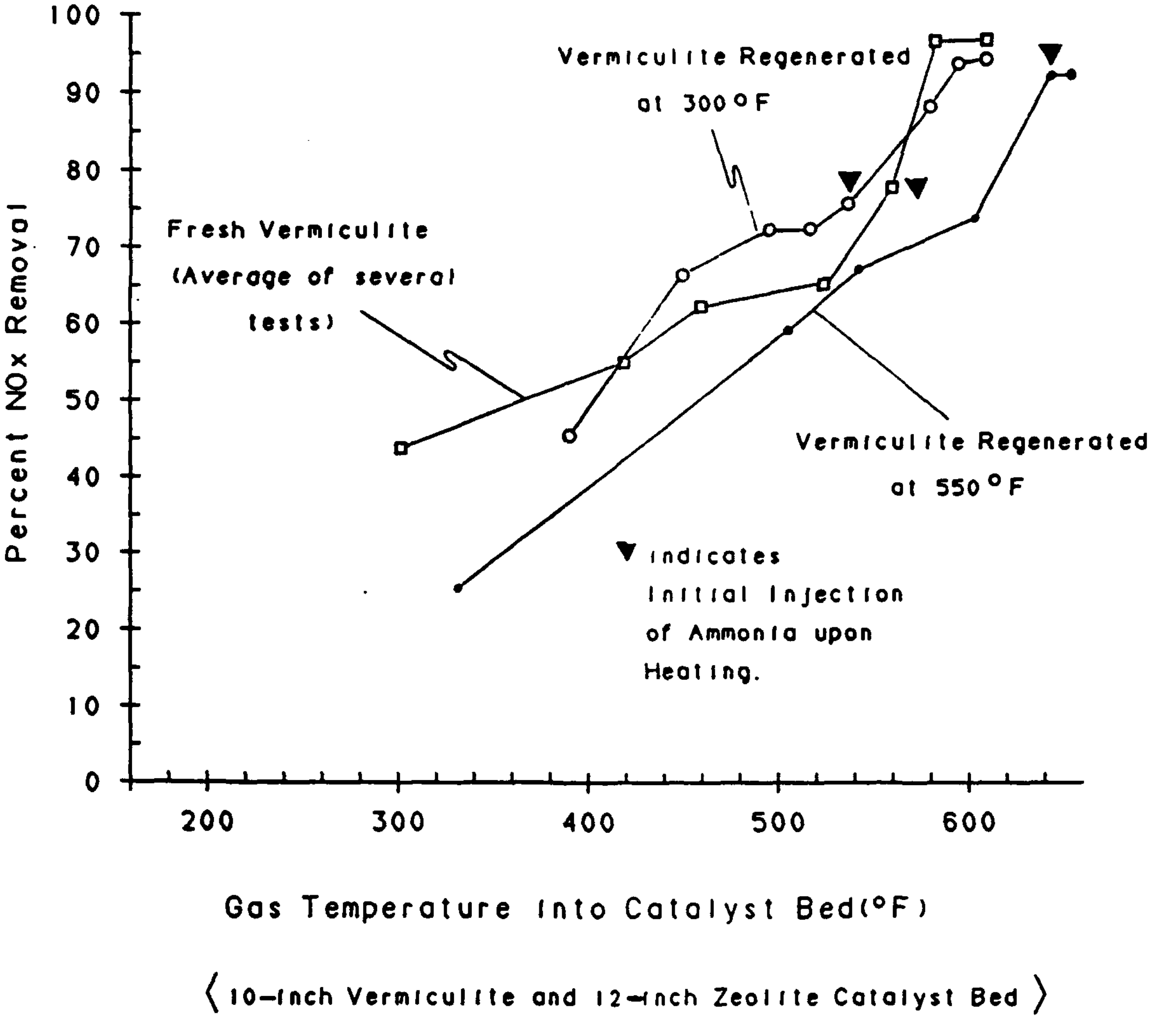


Figure 7. NOx Removal Performance as a Function of Temperature for Systems Containing Fresh and Regenerated Vermiculite

3. Particulate-Capture Studies

The ability of catalyst/sorbent beds to capture particulates from exhaust gases was evaluated by measuring the particulate levels of gases entering and leaving the beds during runs. A special unit was designed and built to collect samples. The units were designed on the assumption that filters having a specific pore size will allow particles smaller than that size to pass through and particles larger to be held back. Figure 8 shows the particulate-sampling device in assembled and disassembled forms.

The collector units were placed immediately before and immediately after the beds. Each unit captured particles in two nominal size ranges, greater than 2.7 μm and between 0.3 and 2.7 μm. Particles smaller than 0.3 μm were assumed to pass through the units. A two-headed pump was employed to draw gas samples simultaneously into the two units. The flow rate of gas into the sampling systems was balanced with the flow rate of the gas in the exhaust gas duct so gas velocities in the units and in the duct were the same. Filters inside the units were weighed carefully before and after a test run. The differences in the weights of particulates in the incoming-gas unit and in the outgoing-gas unit were used to indicate the net particle removal rate of the beds. Because fresh catalyst/sorbent beds invariably lost some small particles to the exhaust gas stream, the net capture rate measured was always smaller than the actual rate.

Vermiculite beds were observed to be excellent filters for particles greater than 0.3 μm. Data collected during a typical run, in which the exhaust gas was produced by burning jet fuel, are given in Table 20.

TABLE 20. PARTICULATE-CAPTURE STUDY RESULTS

	Filter Location	
	In Front of Vermiculite Bed	Behind Vermiculite Bed
2.7 μm Filter		
Disc Wt. Before Run (g)	0.1176	0.1189
Disc Wt. After Run (g)	0.1243	0.1191
Δ Wt. During Run (g)	0.0067	0.0002
0.3 μm Filter		
Disc Wt. Before Run (g)	0.0817	0.0828
Disc Wt. After Run (g)	0.0816	0.0828
Δ Wt. During Run (g)	0.0001	0.0000

Each Δ Wt. value above represents the quantity of particulates collected on each filter during a run.

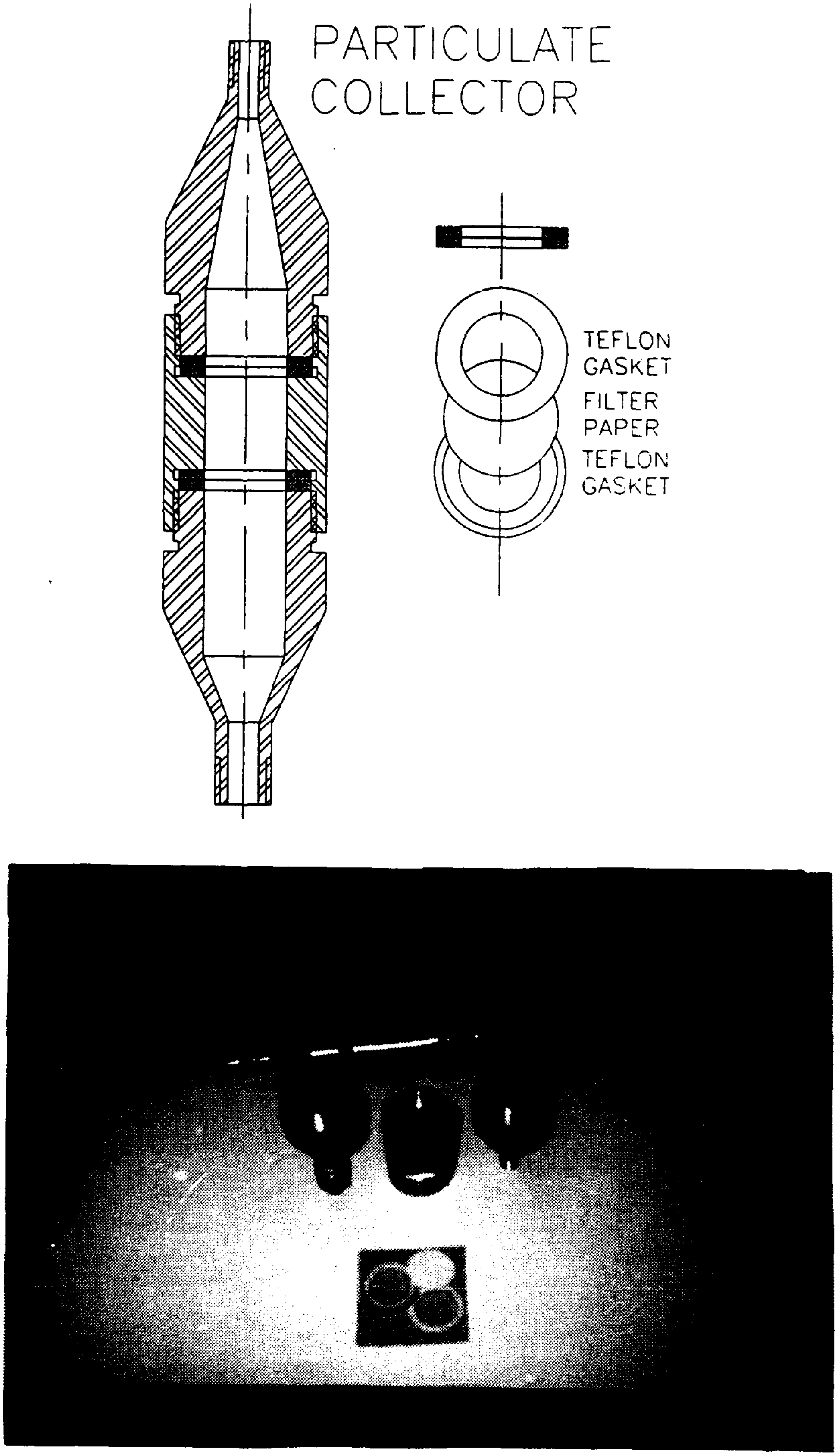


Figure 8. Special Particulate Collection Device
–Assembled and Disassembled

4. Environmental Studies

The leachability of vermiculite and of MgO–vermiculite was examined. More specifically, a modified EP Toxicity Test (EP-Tox) was performed on samples of the following materials:

(1) As-received expanded vermiculite (Coarse grade).
(2) Fresh 45 wt percent MgO–55 wt percent vermiculite.
(3) Vermiculite exposed for three hours to a hot, high-NOx exhaust gas stream.
(4) MgO (45 wt percent) coated onto 55 wt percent vermiculite and exposed for 6 hours to a hot, high-NOx exhaust gas stream.

The Modified EP Toxicity (EP-Tox) Test employed by Sorbtech followed closely the Toxicity Characteristic Leachate Procedures (TCLP) defined by the U.S. Environmental Protection Agency. Because the constituents being tested were non-volatile, a cage-type extractor was used for the extraction. Although many of the vermiculite-based particles were greater than 1 centimeter in size, no milling was required owing to the open structure of the particles.

In EP-Tox testing, 20-gram samples of the solids were agitated in distilled water for 20 hours at a pH of 5.0; the mixtures were adjusted every 15 minutes with additions of acetic acid to maintain the pH level. The mixtures were then vacuum filtered through 0.6-μm mesh papers, and the supernatant leachates were analyzed by standard wet chemistry methods for the targeted ions.

The quantities of nitrites, nitrates and heavy metals detected in leachates are listed in Table 21. The results indicate that (1) nitrates are the principal species that can be expected to leach from the materials upon exposure in soil applications and (2) heavy metal contamination should not be a problem.

5. Bench-Scale Work–Summary of Observations

Important observations made during bench-scale testing include the following:

a. Two systems emerged as showing most promise for controlling NOx and particulates emissions. These systems were: (1) a two-bed system consisting of vermiculite (front bed) and zeolite (back bed) with direct ammonia additions to the exhaust gas; and (2) a bed of vermiculite coated with magnesia (MgO).

b. With the two-bed vermiculite–zeolite system, NOx removals at times approached 100 percent, although in long-term runs, average NOx removals were in the range of 40 to 50 percent. Very high NOx removals were not possible without some ammonia slip. The vermiculite bed (which was placed in front of the zeolite bed) effectively captured fine particulates and protected the zeolite catalyst from degradation.

c. With the vermiculite–zeolite system, the vermiculite bed, which was placed in front of the zeolite bed, appeared to serve several functions: (1) it removed some NOx from the exhaust gas; (2) it removed a significant amount of the particulates (including smoke particles) that were present in the gas; (3) it protected the zeolite catalyst from degradation; and (4) it reduced the CO levels of the exhaust gas. Zeolite beds, when employed alone, did not remove CO.

TABLE 21. CONTAMINANT CONCENTRATIONS IN LEACHATES

Constituent	EP Toxicity Regulation Level* (mg/L)	Fresh Vermiculite (mg/L)	Vermiculite Exposed for 3 hours (mg/L)	Fresh MgO-Vermiculite (mg/L)	MgO–Vermiculite Exposed for 6 hours (mg/L)
Aluminum	-	5	3	22	15
Cadmium	1.0	N/D	N/D	N/D	N/D
Chromium	5.0	N/D	N/D	N/D	N/D
Copper	-	20	22	N/D	60
Iron	-	38	17	185	170
Lead	5.0	N/D	N/D	N/D	N/D
Mercury	0.2	N/D	N/D	N/D	N/D
Nickel	-	N/D	N/D	N/D	
Nitrates	-	N/D	30	N/D	650
Nitrites	-	<1	30	<1	<1
Zinc	-	N/D	20	N/D	4

N/D - None Detected

*New regulation levels enacted on 25 September 1990; Reference: Federal Register, Volume 55, No. 61, 29 March 1990 (p. 11804).

d. The vermiculite–zeolite system was effective with exhaust gases having temperatures within the range 475° to 800°F. It was not effective with lower-temperature exhaust gases. The system demonstrated the somewhat unusual ability to remove NOx from a waste gas well after ammonia additions to the gas were stopped. The vermiculite bed appeared to be able to hold ammonia and to release it slowly.

e. Both vermiculite alone and vermiculite modified with MgO removed NOx from waste gases, although the best removals with vermiculite alone were limited to about 30 percent. Vermiculite modified with MgO systems demonstrated high NOx removals, about 60 to 90 percent, at temperatures below 150°F with low gas face velocities. NOx removal efficiency decreased with increases in temperature and in gas velocity.

f. The pressure drops across both candidate systems were relatively low, but varied significantly with the face velocity of the gas. For the vermiculite–zeolite system, for example, a gas face velocity of 3 feet per second caused a pressure drop of about 2 inches W.G.

g. Activated carbon and several patented compounds, all reported to remove NOx effectively from waste gases, were examined. Activated carbon was found to be effective at low space velocities, as long as the temperature of the gas did not exceed 150°F. Other materials, such as CuO, Co_2O_3 and sodium formate, all coated on vermiculite, were found to be not particularly effective.

SECTION IV

SLIPSTREAM TESTS AT WRIGHT-PATTERSON AFB

A. BACKGROUND

The goal of this phase of the project was to determine if the two systems designed by Sorbtech for combined NOx and particulate control would work as well on actual exhaust gases from Air Force test cells as they did on simulated gases in the laboratory.

In consultation with Dr. Joseph D. Wander, the Air Force project officer, several possible test sites were evaluated. Criteria for site selection included: (1) access to an undisturbed exhaust gas stream; (2) the extent of alteration required to the site; (3) the extent of alteration required to Sorbtech's test equipment; (4) the similarity of the engines being tested at the site to Air Force engines expected to be tested in the future; (5) the proximity to Sorbtech's laboratory facility to the site; and (6) the frequency of engine runs during the proposed testing period.

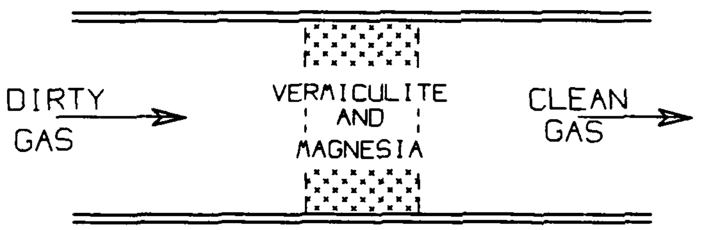
Of several possible sites, the hush house operated at Wright-Patterson AFB was found to be most workable. This hush house is devoted primarily to the testing of jet engines from F-16s after maintenance and repair. The facility is also large enough to test full planes. The personnel at 906 TFG/AMF (headed by Capt. Robert Eardley) displayed both a willingness to assist in this effort and an interest in the experimental results.

Of the two systems for NOx–particulate control developed by Sorbtech, one system involves a single panel bed and the second involves two beds in series. The single-bed system employs a bed of vermiculite modified with magnesia (MgO) that operates on exhaust gases at temperatures below 300°F. This system reduces the NOx levels in exhaust gases in the laboratory typically by 30 to 60 percent. The second system involves a vermiculite bed followed by a zeolite bed, and employs small periodic injections of ammonia. This system typically removes 90 percent of the NOx present in an exhaust gas, but requires exhaust gas temperatures in the 450°F to 800°F range. Both systems demonstrate good removal of small particulates. Sketches of the two systems are given in Figure 9.

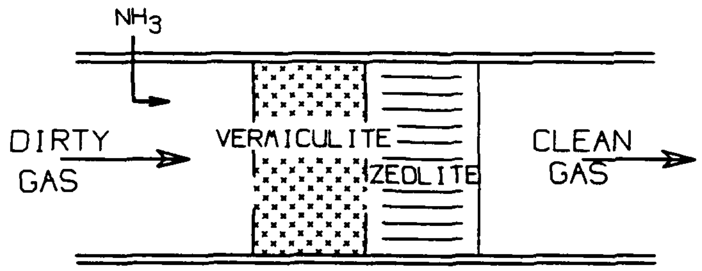
B. EXPERIMENTAL WORK

1. Facilities and Equipment

The 906 hush house is laid out as shown in Figure 10. Engines or complete planes are taken into a large hanger-like building for testing. The sides of the building contain louvers that allow air to be drawn into the building during engine testing. Connected to the building is a long, oval-shaped tubular augmentor structure into which the jet-engine exhaust gases are expelled during testing. The augmentor structure is approximately 80 feet long, 12 feet high and 18 feet wide. The double-walled augmentor tube is lined with stainless steel sound-suppression panels, and sound deadening chambers exist between the two walls. At the end of the augmentor tube is a room-like chimney structure that is open at the top and contains a deflector that changes the direction of the exhaust gas (directs it upward) as it exits the augmentor tube. The deflector is constructed of concrete with a stainless-steel sound-suppression face.



VERMICULITE + MgO SYSTEM



VERMICULITE--ZEOLITE SYSTEM

Figure 9. Two Systems Tested for Simultaneous Removal of NOx and Particulates

The easiest and most attractive location for removal of exhaust gases from the jet-engine test cell is near the end of the test-cell structure (i.e., in or at the end of the chimney area). This location is well away from the engine being tested, and, as such, should least affect the engine's performance during testing.

Much of the bench-scale sorption/catalyst test system employed in the laboratory was taken into the field for tests at Wright-Patterson AFB. The test train consisted of piping, the ammonia-injection system, an induced draft fan, sampling ports and analysis equipment, and two sorbent chambers. Additional piping was installed to connect this train to the gas collection system. The temperature, pressure, and flow measurement equipment required modification for manual data recording. The gas analyzers were already equipped for manual readings. A schematic drawing of the test train is given in Figure 11.

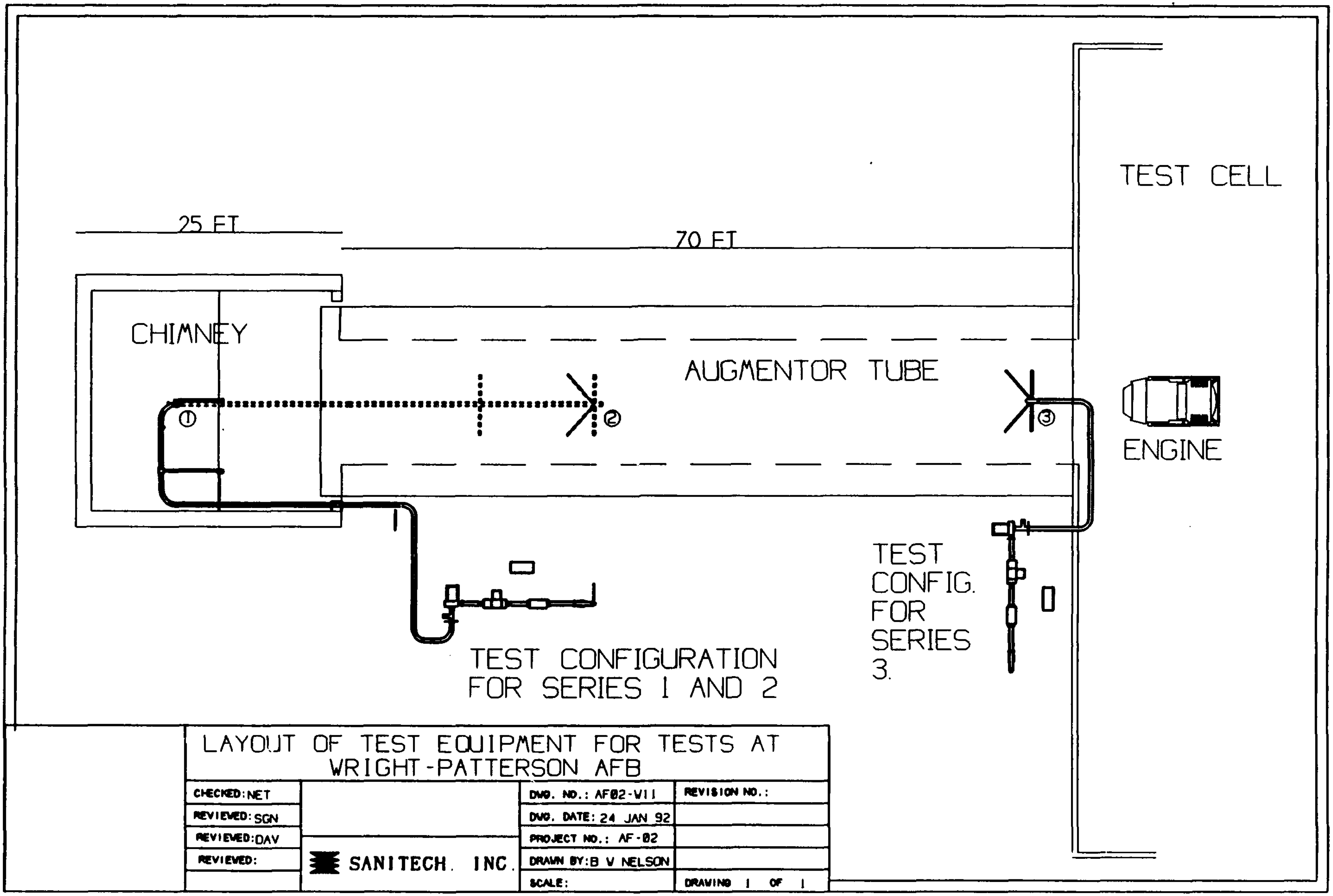


Figure 10. Layout of Hush House and Test Equipment

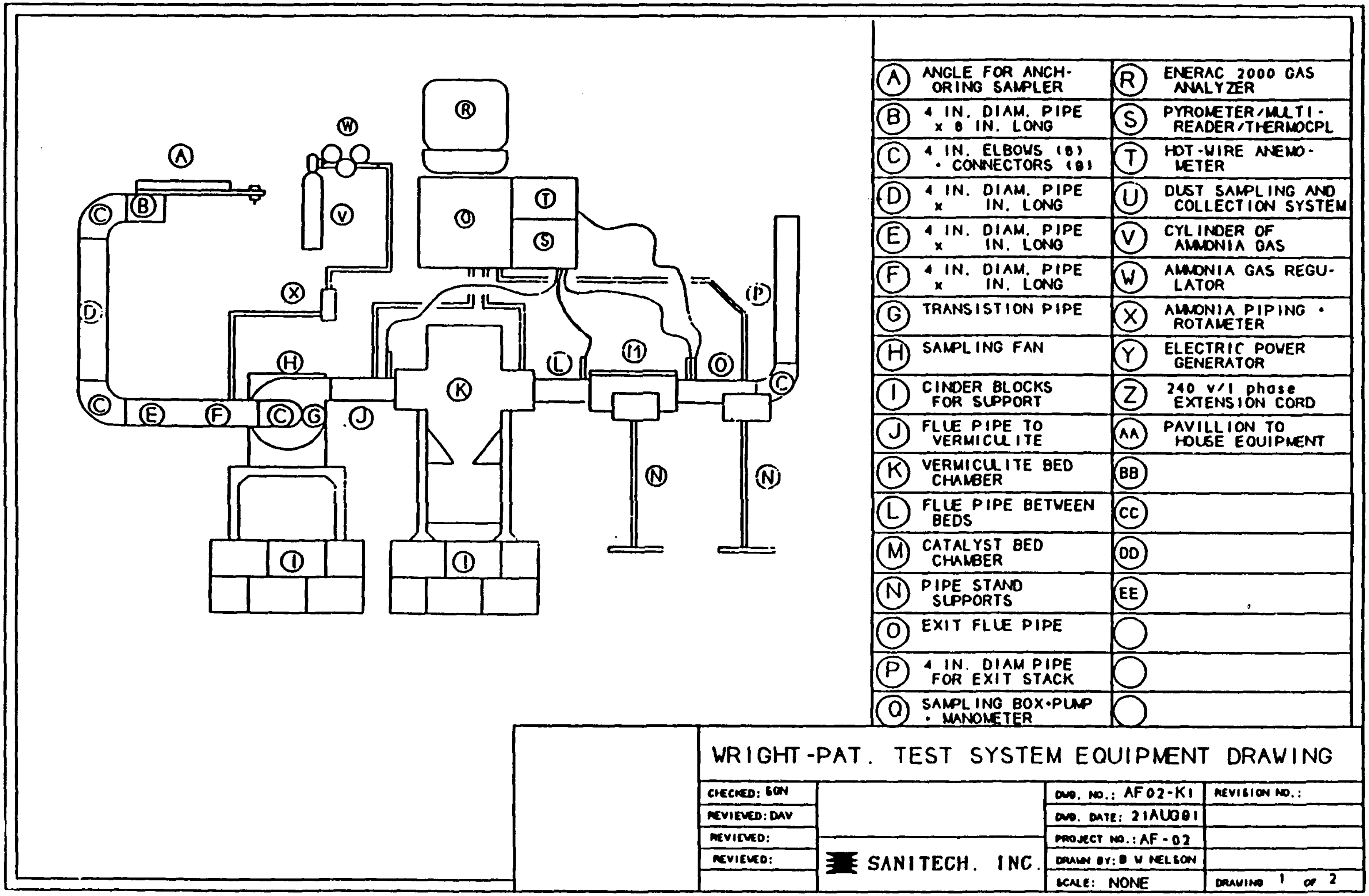


Figure 11. Schematic Drawing of Test Train

2. Procedures and Results

a. Week 1

The first series of tests was designed to determine the potential for using the vermiculite–zeolite catalyst system at the back end of the augmentor tube. A gas collection/diverter pipe with a 4-inch inside diameter was installed against the gas deflector to capture and remove a slipstream of exhaust gas opposite to the center line of the augmentor tube. (See Figure 12.) The catalyst train, which was disassembled and brought from Sorbtech's laboratories in Twinsburg, was connected to the pipe. A fan was installed to draw the gas through the system, if such a procedure was necessary. During the engine test cycles, the hush house operators maintained the engine at different levels corresponding to typical test conditions for extended time periods so that steady-state readings could be taken.

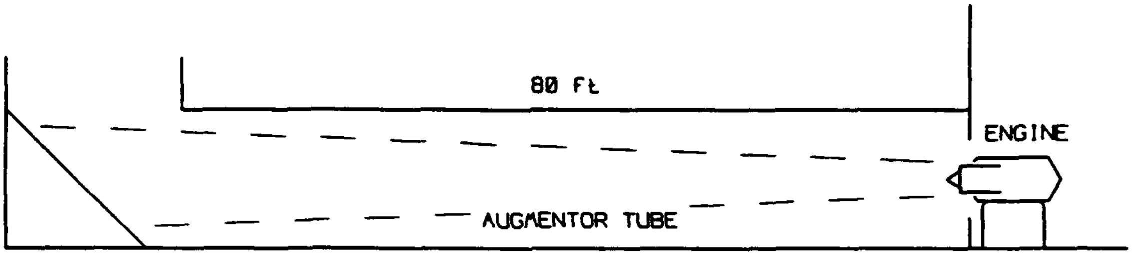
The first tests were run without ammonia additions, using Stronglite vermiculite and the catalyst supplied by Engelhard Industries. These tests indicated several important facts. First, the maximum temperature at the end of the augmentor tube reached only 180°F. (See Table 22 for the temperature data that were collected.) Next, the average exhaust-gas velocity through the augmentor tube was approximately 250 feet per second at 100 percent (military) power. Also, as expected, the zeolite catalyst was ineffective in reducing the NOx in the exhaust gas at temperatures between 100° and 170°F. Finally, it was observed that the vermiculite was sorbing minimal levels of NOx from the gas.

A second series of tests were conducted using the same procedures as before, only with ammonia injection into the gas stream prior to the vermiculite bed. The ammonia was injected at approximately a 2:1 ammonia–NOx ratio. The results mirrored the first test series, although about half the ammonia was adsorbed by the vermiculite bed.

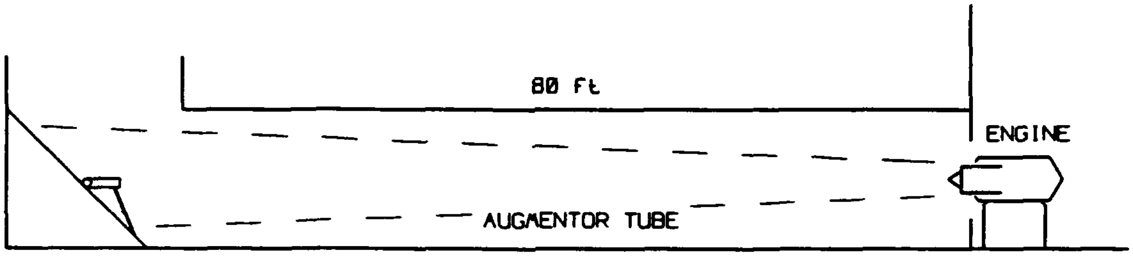
b. Week 2

During the second week of testing, two series were run. The first series of experiments was performed to determine the effectiveness of using magnesia-coated vermiculite to sorb NOx from a split of the exhaust gas stream removed from the end of the augmentor tube. Magnesia (MgO) was found to be an effective alternative to SCR for removing NOx in previous laboratory tests. The setup for these tests was similar to that employed during the first week, except the vermiculite and zeolite beds were removed from the previously installed equipment, and a bed of magnesia-coated vermiculite was placed in the vermiculite chamber. During these runs, the temperature ranged from 100° to 160°F when the engine was running during its normal testing sequence, and up to 195°F when the engine went into the maximum afterburner mode. The slipstream take-off system performed well, even though the entire augmentor tube vibrated heavily with the higher thrust settings.

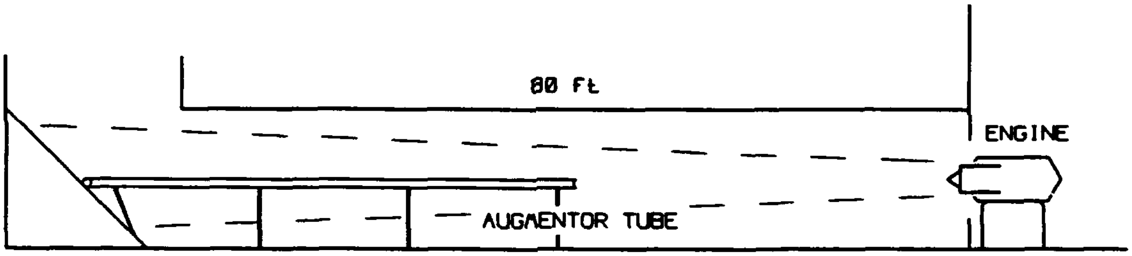
The magnesia-based filter system removed from 45 to 70 percent of the NOx present in the exhaust gases (with an average removal rate of 55 percent). Fine particulate removals by the bed were approximately 85 percent for particles in the 0.3-μm to 2.7 μm range and 65 percent for particles larger than 2.7 μm. Typical particulate collection data are provided in Table 23. The procedures followed in particulate sampling and analyses were similar to those employed in bench-scale testing (See Particulate-Capture Studies in Section III, Bench-Scale Testing).



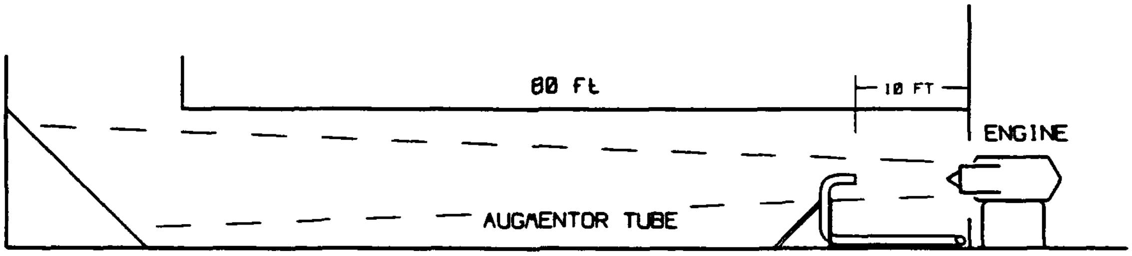
WPAFB 906TFG HUSH HOUSE - Normal Arrangement



(1) Sampling Design During Week 1 and 2



(2) Sampling Design During Week 2



(3) Sampling Design During Week 3

Figure 12. Sampling Arrangements During Testing at Wright Patterson AFB

TABLE 22. AVERAGE TEMPERATURES DURING SLIPSTREAM RUNS

	At Inlet to Pipe (°F)	At Vermiculite Bed (°F)	At Catalyst Bed (°F)
Week 1 - 30% Power	120	110	90
Week 1 - 100% Power	127	118	105
Week 1 - Afterburner	180	160	132
Verm.–Magnesia Test (80% Power)	123	95	85
Week 2 - 50% Power	160	136	118
Week 3 - 50% Power	320	293	276
Week 3 - 100% Power	370	319	294

TABLE 23. PARTICULATE SAMPLING RESULTS FROM WRIGHT-PATTERSON AFB TESTS

Flow Rate - 8.0 liter/min
Collection Time - 50 min
Volume of Gas Sampled - 0.4 m^3

<u>Before Bed</u>	<u>0.3 µm</u>	<u>2.7 µm</u>
Before Test	0.0810 g	0.1164 g
After Test	0.0833 g	0.1170 g
Accumulated	0.0023 g	0.0006 g
Particle Loading	0.0058 g/m^3	0.0015 g/m^3
<u>After Bed</u>		
Before Test	0.0803 g	0.1144 g
After Test	0.0807 g	0.1146 g
Accumulated	0.0004 g	0.0002 g
Particle Loading	0.0010 g/m^3	0.0005 g/m^3
<u>Percentage Removed</u>	83	70

The second test series in week 2 involved extending the slipstream diverter pipe halfway (40 feet) up the augmentor tube (See Figure 11) in efforts to achieve a higher temperature at the gas intake and subsequently at the catalyst beds. We determined that the gas temperature at this location was not significantly higher than at the end of the augmentor tube. The typical temperature observed during normal testing was 200°F, and the maximum temperature was 210°F. Additionally, the thrust and vibration present inside the augmentor tube at this location threatened to detach the pipe from the augmentor tube when power settings above 80 percent were employed.

c. Week 3

Before the third week of testing, all filter test equipment was moved to a location near the entrance to the augmentor tube, and special piping was fabricated to take a gas slipstream from the exhaust gas directly behind the jet engine. Tests similar to those performed during week 1 were then run on this hotter gas stream. Several observations were made during these tests. One, temperatures at the intake and catalyst bed increased to 350°F and 325°F, respectively (significantly higher than before, but still not in the satisfactory temperature range for NOx removal). Two, the vibration of the slipstream pipe was significantly worsened, although the sturdy anchoring of the pipe against the walls and the floor of the augmentor tube allowed us to proceed. Three, the thrust experienced in the slipstream pipe was so great, even with the booster fan running backwards, that diffusion plates were required to decrease the gas velocity to measurable levels. And, four, the NOx removal levels with the vermiculite and zeolite beds at these temperatures never exceeded 20 percent, even with the addition of ammonia.

Data on pressure drops across the vermiculite and catalyst beds were collected during most runs during the three weeks of testing. These data are summarized in Table 24.

TABLE 24. AVERAGE LINEAR VELOCITIES AND PRESSURE DROPS DURING RUNS

	Linear Velocity (fpm)	Pressure Drop Across Bed (in H_2O)
Week 1 - 30% Power	450	4
Week 1 - 100% Power	550	5
Week 1 - Afterburner	700	6
Verm.–MgO Test (80% Power)	850	2
Week 2 - 50% Power	800	7.5
Week 3 - 50% Power	1350	16
Week 3 - 100% Power	1300	15

d. Environmental Tests

EP toxicity tests were performed on vermiculite samples exposed to exhaust gases to determine their potential to contaminate soils or waters if the materials were disposed of in a landfill. The procedures followed in EP toxicity tests were described earlier in Section III. The results of the EP toxicity tests, shown in Table 25, suggest no leaching problems from accumulated cadmium, chromium, copper, cyanide, lead, mercury, silver and zinc.

3. WPAFB Tests--Summary of Observations

a. The exhaust gas temperatures observed during all runs at WPAFB were lower than expected. Gas temperatures at the exhaust-gas deflector at the end of the augmentor tube were in the range 120° to 180°F during all stages of testing. The temperature of gas removed from the augmentor tube 40 feet from the engine was approximately 200°F. The temperature of gas removed from the augmentor tube 10 feet from the engine was 350°F.

b. The systems for removal of NOx and particulates developed by Sorbtech and evaluated at WPAFB performed essentially the same in the field as in the laboratory earlier.

c. All structures placed inside the augmentor tube were exposed to extensive vibrations and horizontal loading during engine testing. The conditions became more severe as one approached closer to the engine and at increasing power settings.

d. It does not appear feasible to place a device to control NOx and particulates inside the augmentor tube itself without (1) eventually sustaining damage to the device and (2) affecting the performance of the engine being tested.

e. It does appear feasible, however, to place a device to control NOx and particulates at the exit of the augmentor tube or at points away from the augmentor tube. At these locations, the exhaust gas temperatures are relatively low, below 180°F, and the likelihood of influencing the engine's performance is minimized.

f. For applications to Air Force hush houses, the use of MgO-modified vermiculite merits further consideration. The use of vermiculite in combination with zeolites, on the other hand, does not.

The use of a replaceable bed of vermiculite in combination with a stationary bed of zeolite for NOx removal makes good sense when the exhaust gases are hot (above 500°F) and are reasonably constant in flow rate and composition. This may generally be the case with most utility and conventional gas-turbine applications. However, with jet-engine test cells, these conditions are not normally seen, and use of a MgO--vermiculite bed appears to be more appropriate.

TABLE 25. EP TOXICITY TEST RESULTS FROM THREE VERMICULITE SAMPLES

Sample 1: Exposed to Exhaust Gas at Wright-Patterson AFB During Bench-Scale Testing.

Sample 2: Exposed to Exhaust Gas in the Laboratory During Runs with Jet Fuel (Heavy Deposition of Carbon) in Bench-Scale Testing.

Sample 3: Fresh Vermiculite Standard.

	Sample 1 (mg/L)	Sample 2 (mg/L)	Sample 3 (mg/L)	EPA Toxicity Regulation Level (mg/L)
Cadmium	0.03	0.43	0.43	1.0
Chromium	0.4	0.3	0.2	5.0
Copper	< 0.05	0.1	< 0.05	-
Cyanide	0.016	0.013	0.017	-
Lead	0.50	0.27	0.90	5.0
Mercury	< 0.01	< 0.01	< 0.01	0.2
Silver	< 0.1	< 0.1	< 0.1	5.0
Zinc	0.06	0.03	0.04	-

SECTION V

PROTOTYPE TESTS AT TYNDALL AFB

A. BACKGROUND

Given the encouraging results at Wright-Patterson AFB, a small-scale test of the new control technology was conducted on a complete exhaust stream. The test cell in Building 239 at Tyndall AFB in Panama City, Florida, was selected as a host site (See Figure 13). This facility, once employed to test large aircraft engines, today is used exclusively to test smaller engines on a regular basis. Typically, subscale drone aircraft with engines attached are brought into the building and tested. A drone aircraft being readied for a test is shown in Figure 14.

B. TYNDALL AFB PROGRAM

The overall objective of prototype tests was to scale up and demonstrate the new technology on a complete exhaust steam by applying the knowledge gained in earlier laboratory and field tests. The specific objective was to design, construct, install, and evaluate a prototype system that would handle the total exhaust gas stream during tests at Building 239. The goal of the program was to demonstrate performances similar to those observed in earlier laboratory and slipstream runs. Specific goals were 50 percent NOx removal and 50 percent particulates removal over all ranges of engine testing, and a pressure drop (ΔP) across the bed of 2 inches W.G. or less.

C. PROTOTYPE DESIGN, CONSTRUCTION AND INSTALLATION

Sorbtech engineers visited Building 239 at Tyndall AFB in early 1992 and measured exhaust-gas temperatures, flow rates, and compositions during typical engine-test runs. On the basis of these measurements and of the results of earlier laboratory and Wright-Patterson AFB trials, the following design parameters for a prototype system were established:

1) Location of filter: At the end of the chimney.
2) Expected exhaust gas temperatures: 150° - 200°F.
3) Expected exhaust gas NOx levels: 2 - 5 ppm.
4) Expected exhaust gas flow rates: around 100,000 cfm.
5) Filter bed composition: Vermiculite modified with MgO.
6) Filter bed thickness: 8 to 12 inches.

In addition to these design parameters, other considerations were incorporated into the design. For example, the filter system should permit some or all of the exhaust gas to exit the chimney without going through the filter, if such a situation were desired. Also, if the pressure across the filter (back pressure) became excessive or if more gas were generated than was planned, the system should allow automatic by-pass around the filter. The filter beds should be easily replaceable. The prototype should also include sampling and access ports.

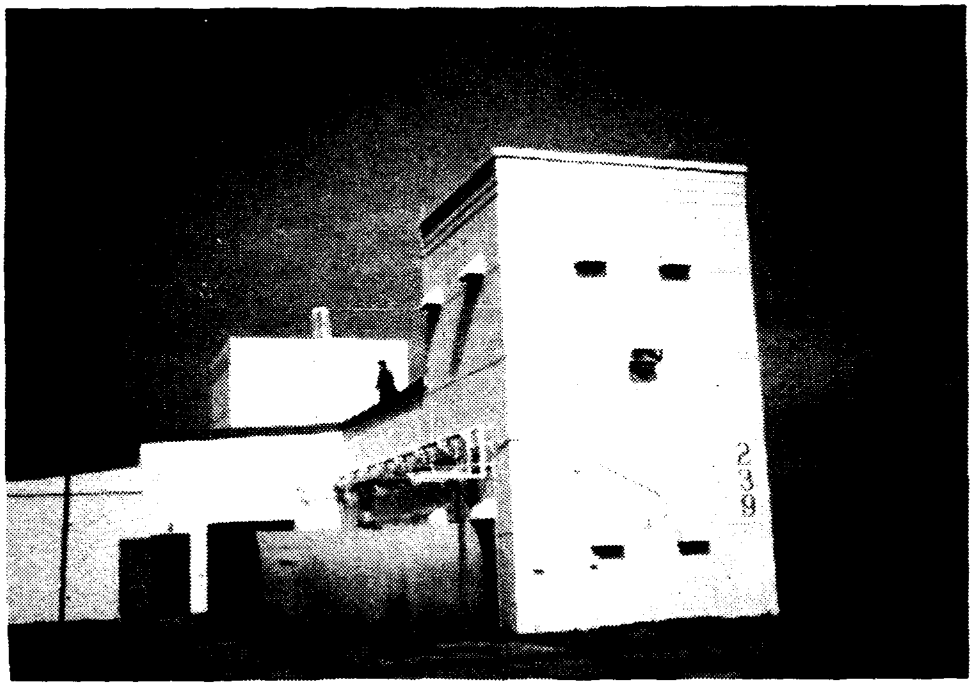


Figure 13. Building 239, Tyndall AFB.
The Exhaust Stack is in the foreground.

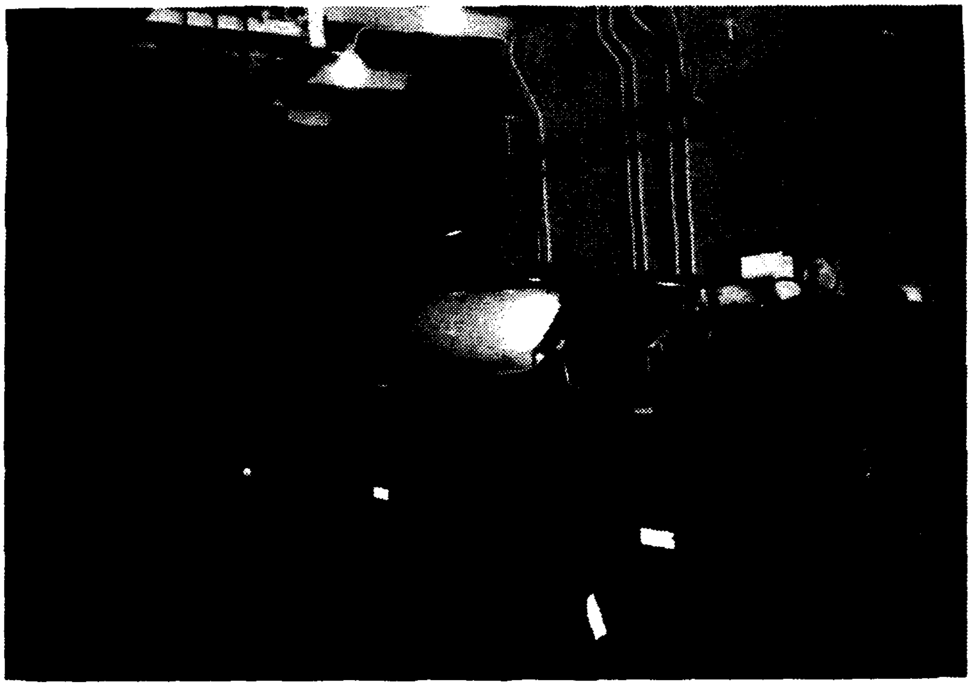


Figure 14. A Drone Aircraft Positioned for an Engine Test.

1. Prototype Design

The prototype design shown in Figure 15 was developed by implementing the above considerations. The prototype filter was engineered to sit atop and be fastened to the existing exhaust-gas chimney. With this unit in place, exhaust gases moving vertically upward are deflected by the top of the unit and pass horizontally through the filter bed. The filter bed consisted of four separate vertical sections joined together as one unit. The top of the filter chamber contained 12 elongated slat doors that are closed during normal operation, but can be opened manually or will open automatically, if significant overpressure develops inside the chimney and filter chamber.

Doors at the top of the filter bed sections opened to introduce sorbent, and an exit at the bottom allowed the removal of sorbent. Each filter section consisted of three screens, an outside 10-mesh steel screen, an inside 14-mesh stainless steel screen, and an intermediate 10-mesh steel screen. Four inches separated the inside and intermediate screens; eight inches separated the intermediate and outside screens. Threaded rods and washers backed by nuts preserved this spacing in the center of the screen faces.

The overall prototype unit was 14.7 feet by 15.2 feet at the base and 10 feet high. A special platform and railing network was designed to sit upon the top of the chimney surrounding the filter unit, allowing easy, secure access to all parts of the unit. Figure 16 shows this network.

Exhaust-gas sampling systems were placed on the entrance and exit sides of the filter beds. Each sampling system consisted of multiple sampling ports placed within an inch of the sorbent beds. A special enclosure was placed over and down the sides of the filter sections to reduce the possibility of dilution of the exhaust gas exiting the filters during monitoring runs and to provide some degree of weather protection. However, rain was not expected to influence the performance of the sorbent significantly.

2. Prototype Construction and Installation

The main parts of the prototype filter were fabricated by L & L Fab Company of Streetsboro, Ohio. The filter was prepared in seven major parts (four filter-bed sections and three filter chamber sections). The sampling system was constructed separately by Sorbtech engineers. The vermiculite sorbent materials were prepared at Sorbtech's facilities in Twinsburg, Ohio. All components and materials were delivered by truck to Tyndall AFB.

At Tyndall AFB, the various components were removed from the truck (Figure 17) and pre-assembled on the ground (Figure 18) before being placed on the chimney top. The platform/railing section was completed first and was lifted and attached by welding to the top of the chimney. The main filter section was assembled next by bolting together the four major components, then adding the outside special filter enclosure. After fresh sorbent materials were introduced into the filter sections, the complete filter structure was lifted and attached to the top of the chimney. Once the platform railing assembly and sorber were in place, Sorbtech engineers installed the sampling systems.

Various Tyndall AFB personnel–crane operators, welders and the Project Technical Officer–contributed significantly to the success in assembling and installing the facilities.

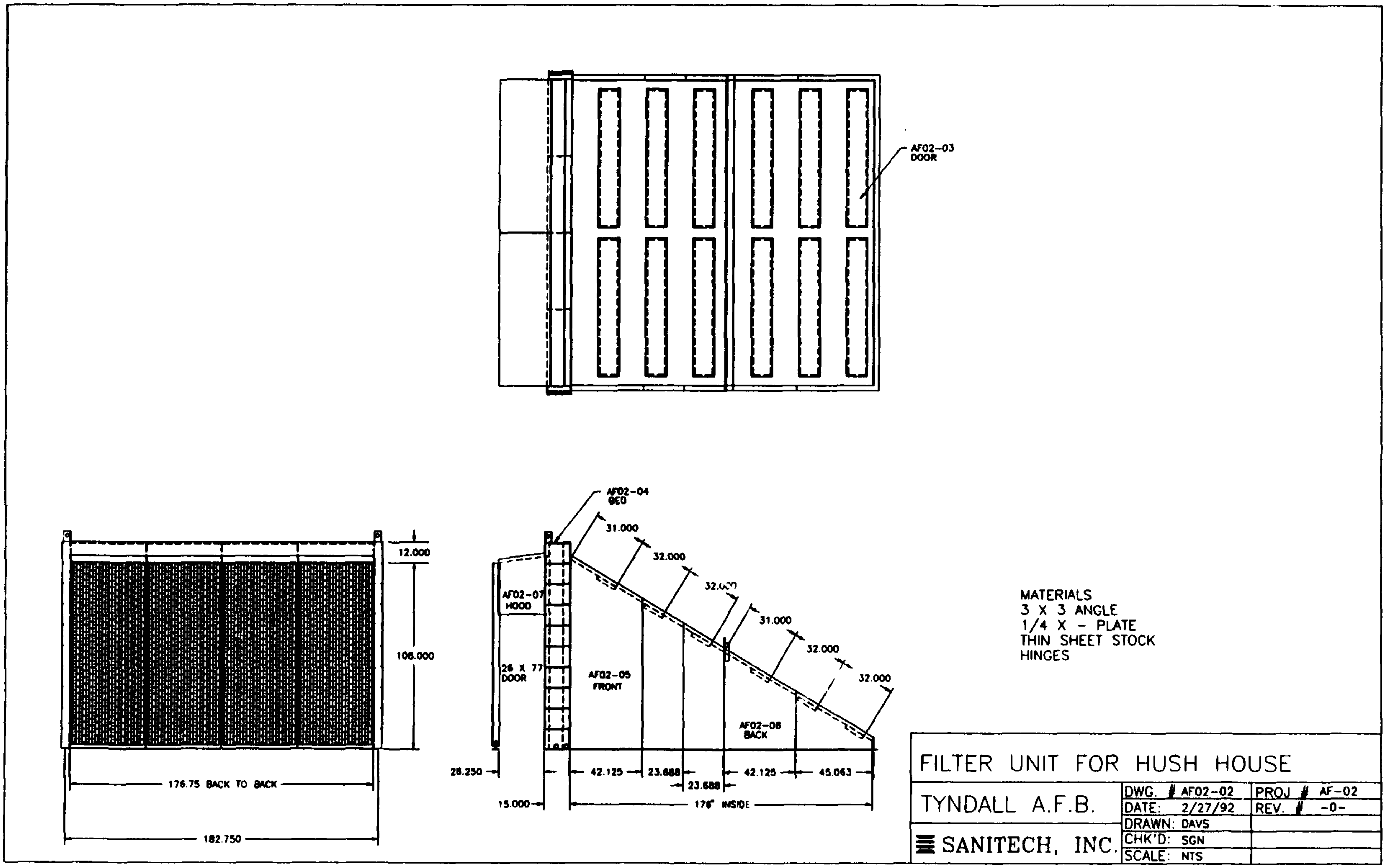


Figure 15. Filter Unit Design.

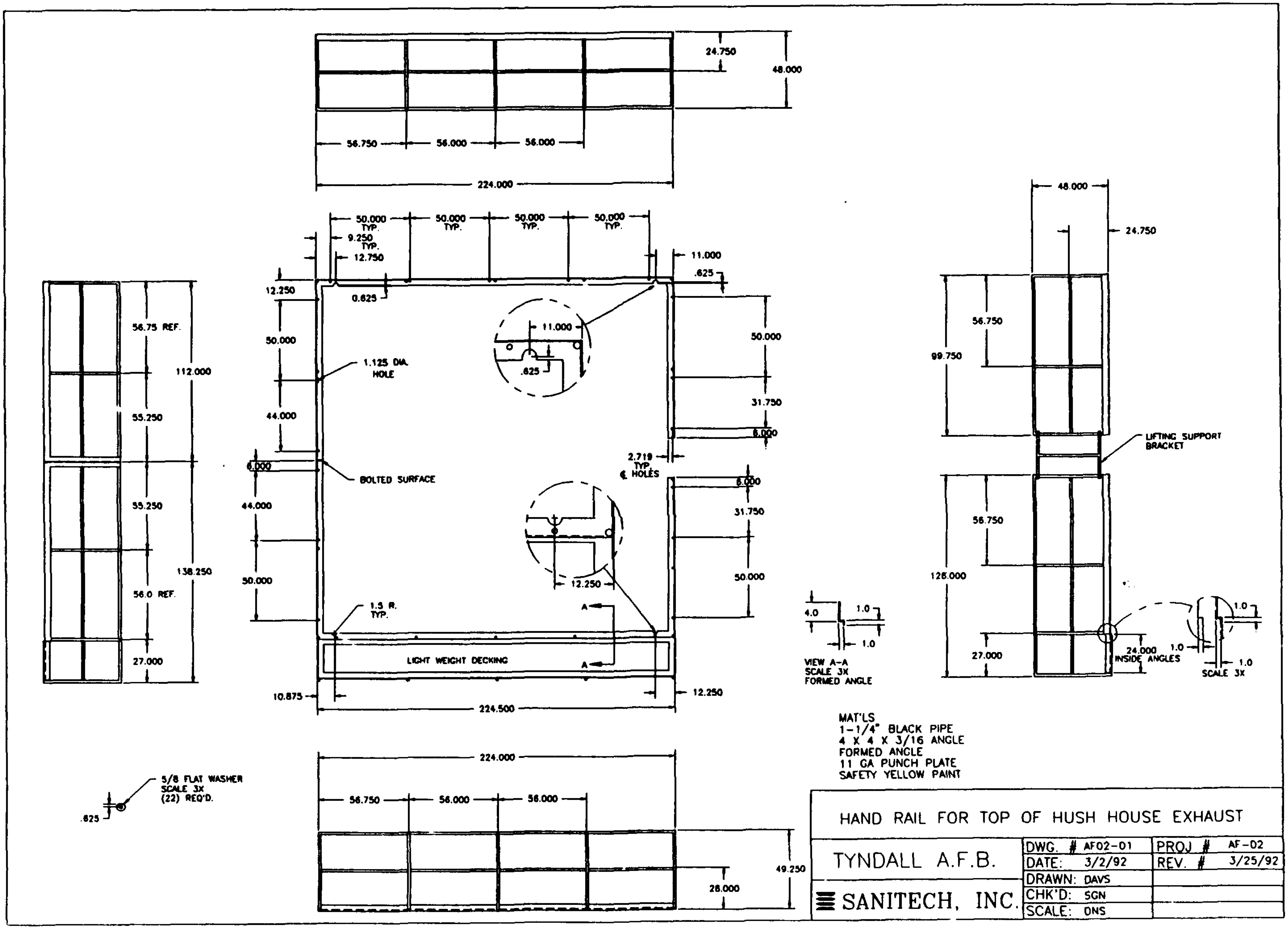


Figure 16. Platform and Railing Design.

Figure 17. Filter Components Upon Arrival at Tyndall AFB.

Figure 18. Assembly of Filter Components.

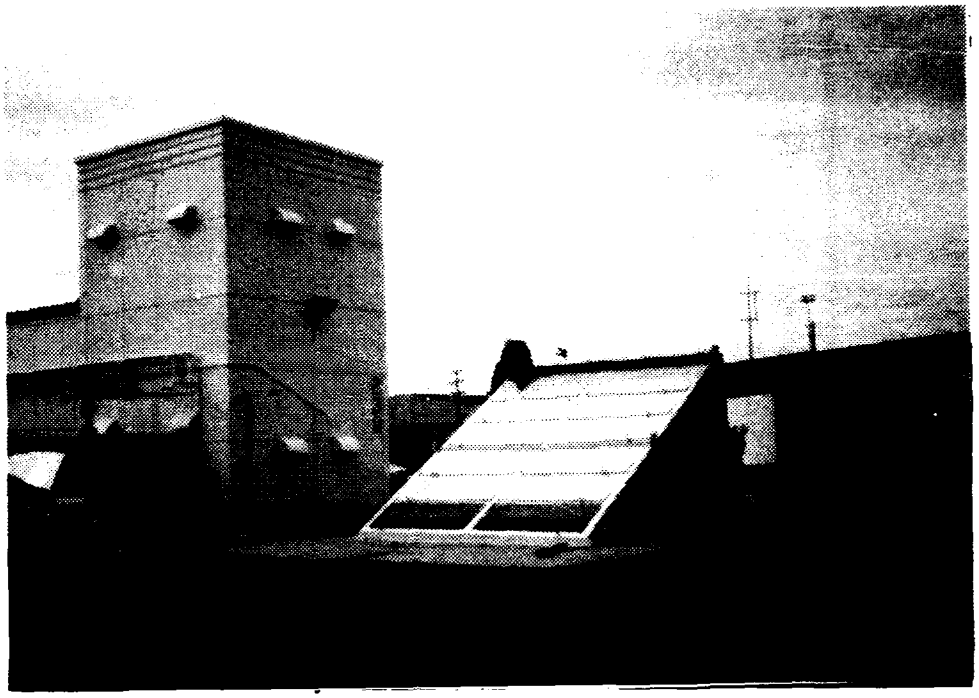


Figure 19. Completing the Filter Assembly.

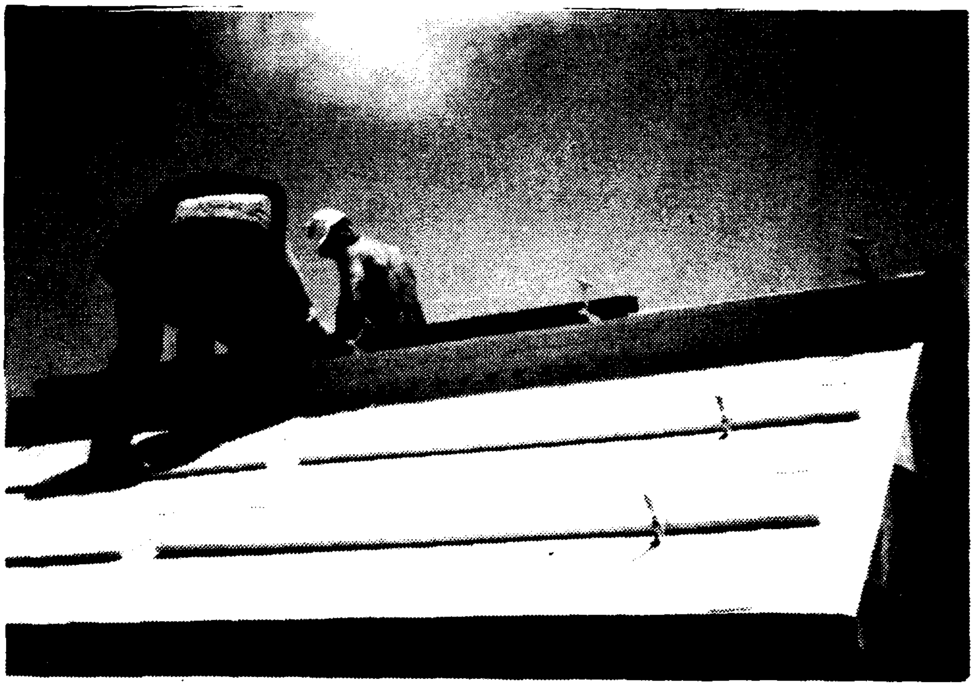


Figure 20. Filling of the Sorbent Beds.

Additional photographs show the steps of installation and the final assembly. Figure 19 shows work activities on the main filter section carried out next to the test cell; Figure 20 shows the adding of sorbent to the filter. The lifting of the platform/railing section and the lifting of the main filter section are shown in Figures 21 and 22. The completed installation is shown in Figures 23 and 24.

D. PROTOTYPE TESTS

During the time period 9-11 June 1992, the performance of the prototype filter system was monitored continuously during five engine-test runs. The first and fourth runs were performed on small (Teledyne-CAE J-402-CA-702, 930 pounds thrust) drone engines; the remaining three runs involved large (GE J-79, 2200 pounds thrust) drone engines.

The following variables were recorded as a function of time during each run:

1) Average gas temperature before the bed.
2) Average gas temperature after the bed.
3) Velocity of gas at exit of bed.
4) NOx level of gas into the bed.
5) NOx level of gas out from the bed.
6) Pressure drop (ΔP) across the bed.
7) Power level of the engine tested.

Also obtained during most runs were separate gas samples and particulate samples collected from gases entering and leaving the filters. Figure 25 shows sampling and measurement points that were employed.

Gas temperatures were measured with thermocouples placed at several locations at the front and back of the filter beds. Velocities were measured with two different instruments: a Kurz hot-wire anemometer and a pitot-tube unit. NOx levels were continuously monitored with a chemiluminescent NO/NOx analyzer (Thermo Environmental Instruments, Inc., Model 10). NOx levels were also checked periodically with Matheson–Kitagawa length-of-stain titration tubes. The pressures in the system and across the beds were monitored with manometers. Cascade impactors were employed to collect particulate samples. Gas samples for later analysis were collected in Teflon® bags and in stainless steel spheres. The levels of certain gaseous organic compounds in the exhaust gases were determined by Matheson–Kitagawa tubes.

1. Test-Cell Conditions

During a typical drone-engine testing exercise at Tyndall AFB, the engines are tested first at increasing power levels and then during a smoke phase. During the smoke phase, the drone aircraft releases a lubricating oil into the exhaust to produce man-made smoke, as is done in actual use to facilitate observation. The total testing time, including the smoke-release phase, is typically 10 to 15 minutes. For the monitoring runs, test-cell personnel agreed to extend the testing times to 20 or more minutes. In all runs, the drone engines were taken through their normal testing sequence, which was completed in less than 10 minutes, and were then held at 80 to 90 percent power (which normally produces the highest NOx levels) for the remaining time.

For safety and mechanical reasons, the test cell operators require a small flow of air around the engines and into the augmentor tube before the engines are started up. A small flow of air

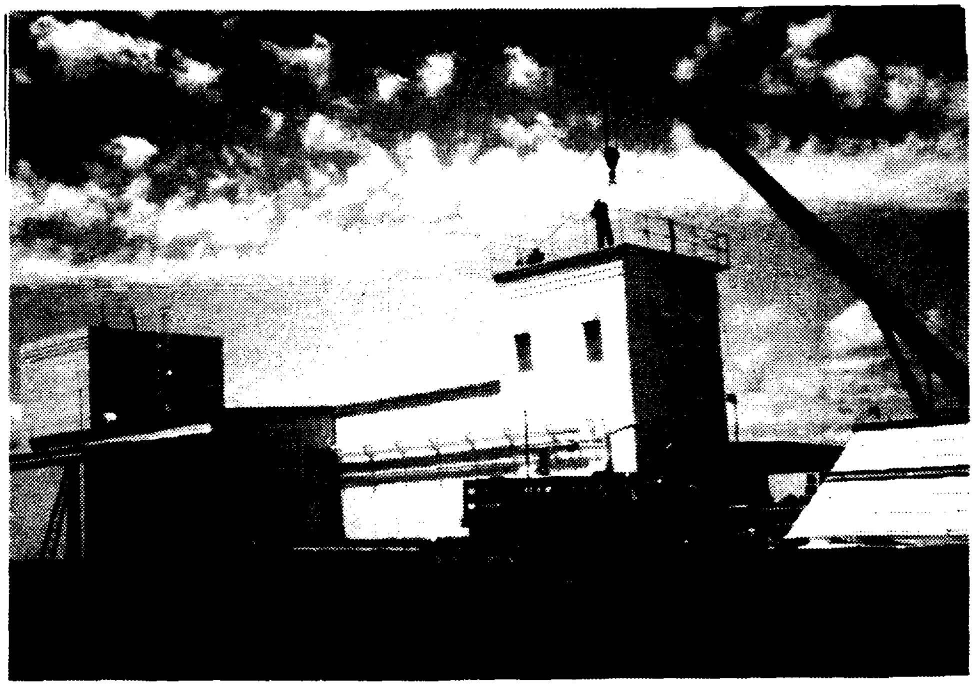


Figure 21. Placement of the Platform and Railing Section.

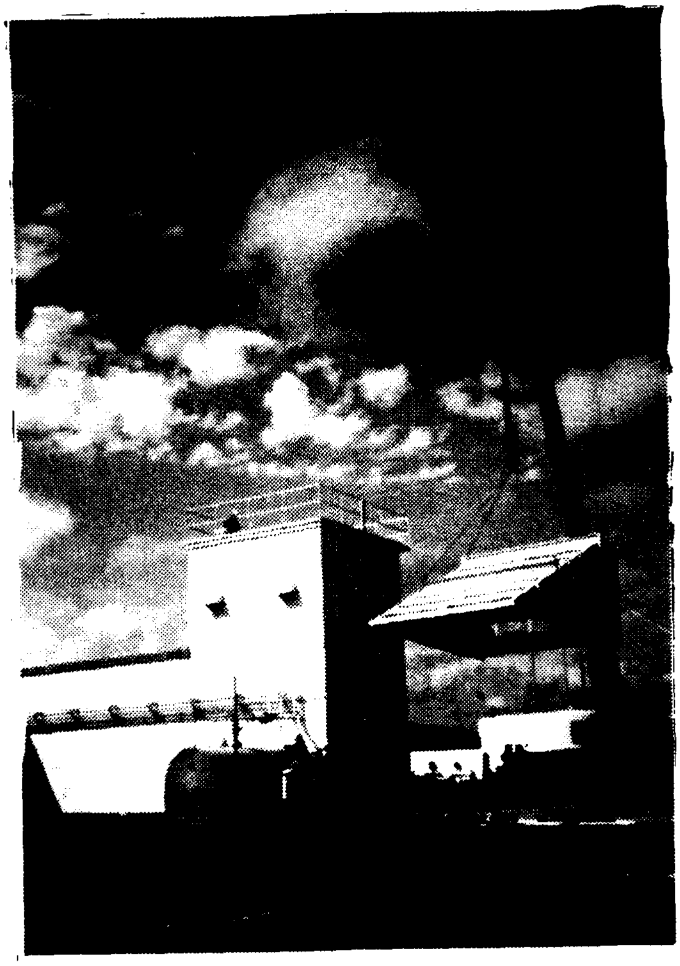


Figure 22. Transporting the Filter Assembly to the Top of the Chimney.

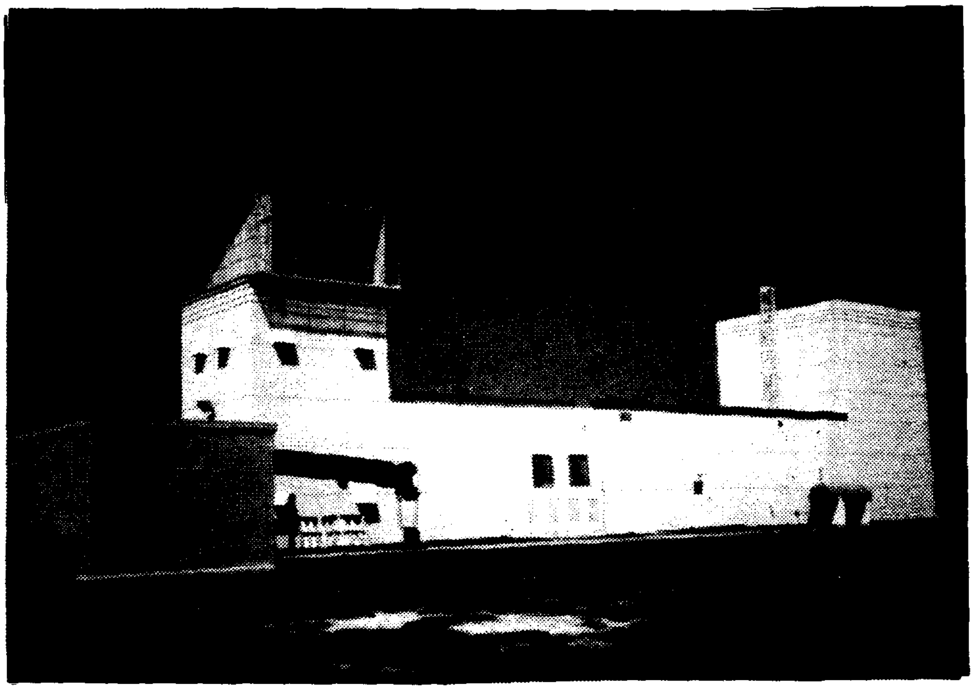
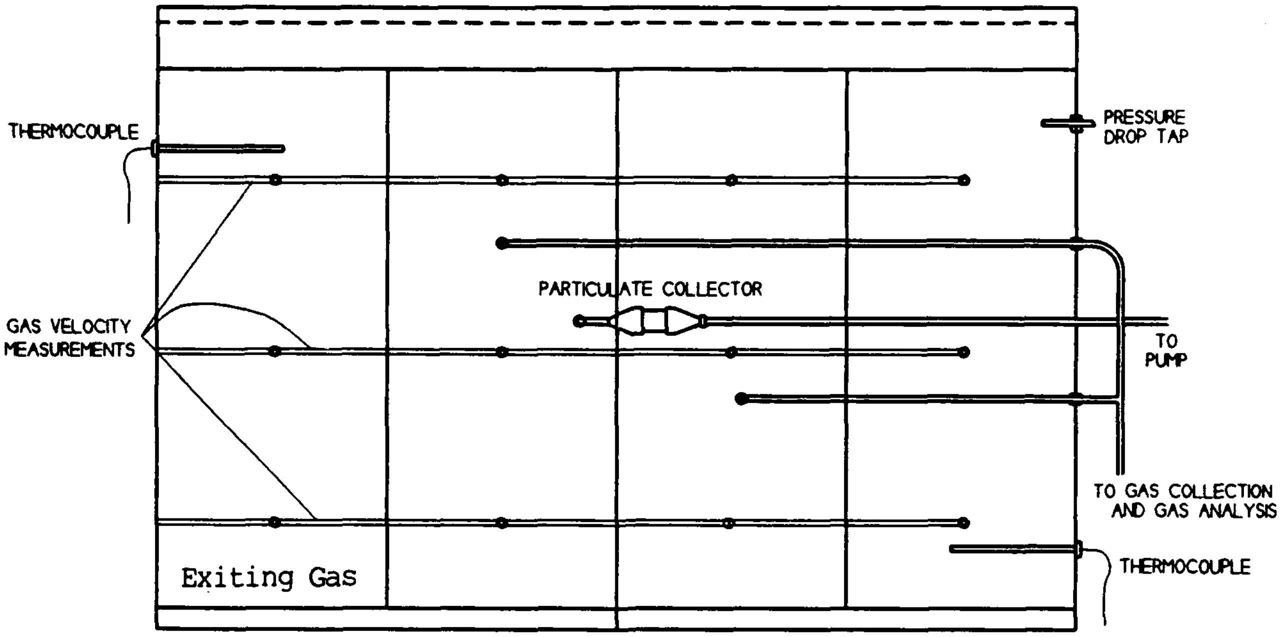
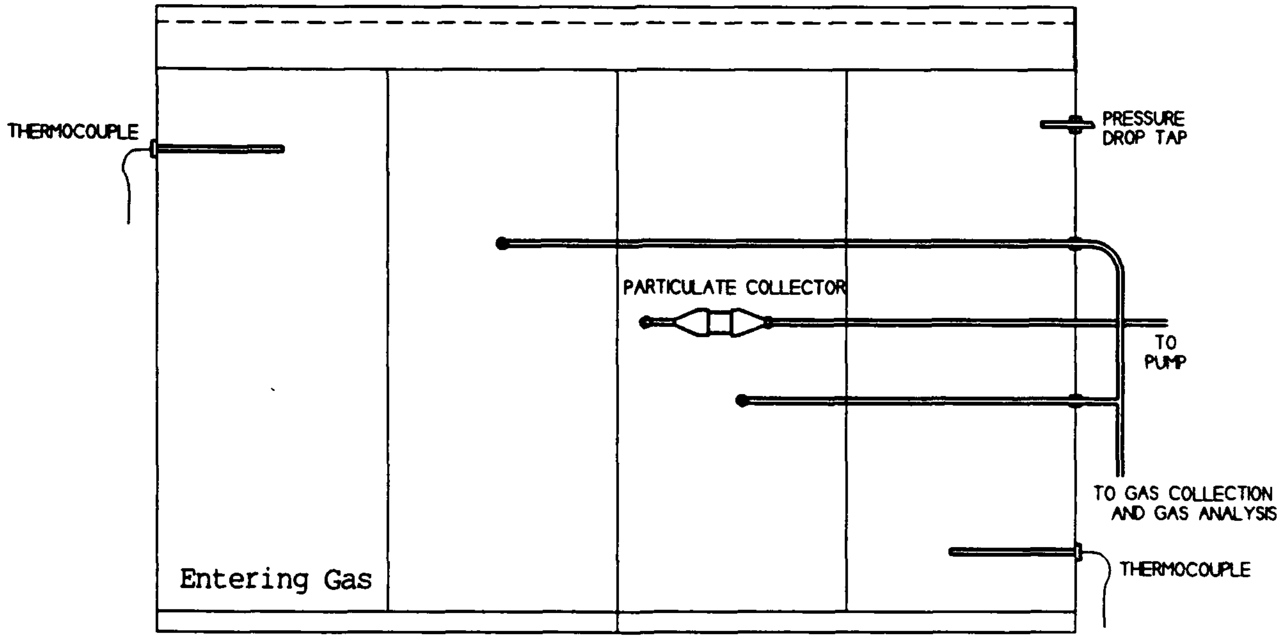


Figure 23. The Filter in Place on Building 239.

Figure 24. View of the Filter.



SAMPLING SYSTEM POINTS AT BACK OF SORBENT BED.



SAMPLING SYSTEM POINTS AT FRONT OF SORBENT BED.

Figure 25. Sampling and Measurement Locations.

generally occurs naturally as a result of the draw of the chimney. However, placing a closed filter-system over the top of the chimney eliminated the natural draft. To recover this natural draft, it was found possible to simply open some of the slat doors on the top of the unit. Once the engine was running, all or some of these doors were then closed.

During the full-power testing of the large drone engines, larger than expected volumes of exhaust gases were delivered. To handle the larger gas volumes while minimizing any effect on engine testing, it was found desirable to leave some of the slat doors open during the runs. Velocity measurements indicated that during some runs, one-half to three-quarters of the exhaust gases actually by-passed the filter and exited the filter through the slat doors.

During the normal testing of drone engines in this test cell, as much as 30 volumes of augmentation air are employed, much larger than commonly seen at large-engine facilities. As a consequence, NOx levels in the exhaust gases are low, several parts per million NOx being common. During the testing of drone engines in this project, the presence of the filter system drastically decreased the amount of dilution air in the exhaust gas, especially for the small engines. As a result, the total volumes of exhaust gases that were produced decreased and the NOx levels increased significantly. Nevertheless, gas velocity measurements indicated that, at near full power, typically about 100,000 cfm of exhaust gases were delivered to the chimney. This volume of gas is equivalent to that produced by a 30-MW power-plant boiler.

2. Filter Bed Design

In earlier tests, a two-layer filter-bed design consisting of four inches of expanded, virgin vermiculite in front of 8 inches of MgO-coated vermiculite gave promising results, in terms of combined NOx and particulate capture. This was the principal filter-bed design adopted for the project. Although that combination effectively removed NOx and particulates, it did not remove significant amounts of volatile hydrocarbons in laboratory tests. Replacement of the virgin vermiculite with activated carbon appeared to add the capacity to adsorb hydrocarbon vapors and also to improve NOx-removal performance. A second design consisting of 4 inches of activated carbon in front of eight inches of MgO-coated vermiculite was therefore also selected for examination in the project.

3. Test Results

Run 1

Objective:	To evaluate the performance of the filter system during the testing of a small drone engine with normal dilution air.
Sorbent Bed:	4-in vermiculite and 8-in vermiculite--MgO
Engine Tested:	Teledyne-CAE J-402-CA-702
Total Run Time:	18 minutes
Number of Slat Doors Open:	Eight of 12 were open during the first six minutes; all were closed for the remainder of the test.
Discussion of Results:	Data collected during Run 1 are given on the next page.

TABLE 26. RUN 1 TEST RESULTS

Time (Min)	Power Level (%)	NOx IN (ppm)	NOx Out (ppm)	NOx Removal (%)	ΔP Filter (in W.G.)	Gas Temp. In (°F)	Gas Temp. Out (°F)	Gas Velocity Thru Bed (fpm)
2	Increasing	1-2	0-1	>50	0.8	148	—	450
4	"	—	—	—	0.8	155	—	—
6	"	—	—	—	0.9	167	98	450
8	80	1-2	0-1	>50	1.0	174	105	—
10	80	—	—	—	—	180	113	450
12	80	—	—	—	—	188	123	—
14	80	1-2	0-1	>50	—	197	146	—
16	80	—	—	—	0.8	207	160	—
18	80	—	—	—	—	215	167	—

The NOx level of the exhaust gas was very low and varied widely over the range 1 to 2 ppm; the NOx level of the gas passing out from the filter likewise varied widely. On an average, the NOx removals were greater than 50 percent.

As the power level of the engine was increased, the pressure drop across the filter increased from 0.8- to 1.0-inch W.G., although the gas velocity through the bed remained fairly constant at 450 fpm (7.5 fps) throughout the run. As the test run progressed, the average temperature of the exhaust gas increased from 148°F to 215°F. The filter bed significantly cooled the exhaust gas during the run, dropping its temperature nearly 70°F initially and about 50°F at the end.

Run 2

Objective:	To evaluate the performance of the filter system during the testing of a large drone engine.
Sorbent Bed:	4-in vermiculite and 8-in vermiculite–MgO
Engine Tested:	GE J-79
Total Run Time:	21 minutes
Number of Slat Doors Open:	Four were open and eight were closed (four locked down).
Discussion of Results:	Data collected during Run 2 are given in Table 27. Particulate collection data are provided in Table 28.

TABLE 27. RUN 2 TEST RESULTS

Time (Min)	Power Level (%)	NOx IN (ppm)	NOx Out (ppm)	NOx Removal (%)	ΔP Filter (in W.G.)	Gas Temp. In (°F)	Gas Temp. Out (°F)	Gas Velocity Thru Bed (fpm)
1	Increasing	—	—	—	—	—	—	350
3	"	20	5	75	—	—	—	—
5	80	55	16	71	0.5	180	113	400
8	80	54	20	63	—	198	112	—
10	80	55	33	40	1.0	208	132	400
12	80	55	33	40	1.1	212	154	—
14	80	52	28	46	1.1	214	161	450
17	80	53	29	45	—	216	167	—
19	80	52	28	46	1.1	219	170	300
21	80	51	26	49	1.0	224	173	—

With the filter system in place, the large drone engine produced an exhaust gas with about 20 ppm NOx when it was operated at about 50 percent power. However, when the power level was increased to 80 percent, the NOx level exceeded 50 ppm. The filter was effective in removing an average of 53 percent of the NOx during the run. The pressure drop across the bed was 1.1 inch W.G. or less, and the gas velocities varied from 300 fpm (5.0 fps) to 450 fpm (7.5 fps), values similar to those observed with the smaller drone engine.

During the run, samples of gas were removed simultaneously from the exhaust gas directly in front of and directly behind the filter. Solid particulates 0.3 μm or greater in size were collected. Collected samples indicated a net removal of about 50 percent for large particles (greater than 2.7 μm) and 85.7 percent for smaller particles. Actual removals of particles from the gas stream were probably higher, because some small particles from the sorbent bed undoubtedly entered the exiting gas, and these particles entered into the removal calculations.

The nature of the particles collected during the run contrasted significantly with that of particles collected during earlier Wright-Patterson AFB runs. The vast majority of particles collected during the run were white in color. The particles collected at Wright-Patterson AFB were black.

It should be noted that during the smoke test phase of engine testing, a large white plume is normally discharged from the test-cell chimney. With the filter unit in place and some of the slat doors of the filter unit open, this plume is divided into two streams. As indicated by velocity and flow measurements, one stream passes through the filter beds and a second of somewhat larger size flows out through the open slat doors and other openings during the smoke tests. The filter beds appeared to be effective in eliminating or reducing the plume. Figure 26 shows the facility during a smoke test in Run 2.

TABLE 28. PARTICULATE-COLLECTION DATA

Particle Size: 0.3 to 2.7 μm

	Wt. of Particles Collected from Gas			% Wt.
Run No.	Into Filter (g)	Out from Filter (g)	Δ Wt.(g)	Removed
2	0.0007	0.0001	0.0006	85.7
3	0.0008	0.0001	0.0007	87.5
4 and 5	0.0010	0.0006	0.0004	40.0
			Average % Removal	68.0

Particle Size: Greater than 2.7 μm

	Wt. of Particles Collected from Gas			% Wt.
Run No.	Into Filter (g)	Out from Filter (g)	Δ Wt.(g)	Removed
2	0.0070	0.0035	0.0035	50.0
3	0.0007	0.0007	0.0000	0.0
4 and 5	0.0009	0.0007	0.0002	22.2
			Average % Removal	43.8

Dust Removal (Particles Collected on 0.3-μm and 2.7-μm Filters)

Run No.	Gas Flow (cu ft)	Avg. Dust IN (mg/m^3)	Avg. Dust OUT (mg/m^3)	% Dust Removed
2	4.00	70.56	32.99	53.2
3	3.91	14.06	7.50	46.7
4 and 5	8.70	8.01	5.48	31.6

NOTE: During Run 2, multiple smoke tests were performed. The collection units were left in place during Runs 4 and 5 and the results indicate the totals for these test runs.

Figure 26. The Test Cell During a Smoke Test

Run 3

Objective:	To repeat the conditions of Run 2, except for a longer time period. This run was originally designed to investigate an exhaust gas with 50 ppm or more NOx. Additional NOx was to be introduced into the exhaust gas from a cylinder of pure NOx. Because it was discovered that the exhaust gas often already contained more than 50 ppm NOx, supplementation was deemed unnecessary.
Sorbent Bed:	4-in vermiculite and 8-in vermiculite–MgO
Engine Tested:	GE J-79
Total Run Time:	30 minutes
Number of Slat Doors Open:	Four were open (80 percent) and eight were closed (four locked down). Eight were open during start-up and at the end of the test.
Discussion of Results:	Data collected during Run 3 are given on the next page.

TABLE 29. RUN 3 TEST RESULTS

Time (Min)	Power Level (%)	NOx IN (ppm)	NOx Out (ppm)	NOx Removal (%)	ΔP Filter (in W.G.)	Gas Temp. In (°F)	Gas Temp. Out (°F)	Gas Velocity Thru Bed (fpm)
8	Low	38	23	40	0.8	172	90	—
10	80	—	—	—	0.8	188	95	450
17	80	50	30	40	1.0	204	120	—
18	80	52	29	44	1.0	205	129	500
19	80	52	27	48	1.0	207	133	—
20	80	54	27	50	1.2	210	138	—
23	80	53	26	51	1.1	212	142	—
24	80	55	27	51	1.0	214	147	500
25	80	56	26	54	1.1	216	144	—
27	80	53	26	51	1.1	217	136	550
29	80	50	22	56	1.1	217	141	—
30	80	53	23	57	—	216	144	—

The results of this run were similar to those seen in Run 2. The only exception was the removal rate of particles larger than 2.7 μm. Although there was excellent (87.5 percent) removal of small particles, there was no measurable net removal of particles larger than 2.7 μm. The velocity of the exhaust gas passing through the filter bed was somewhat higher, up to 550 fpm (or 9.2 fps), during this run; the higher velocities did not significantly increase the ΔP across the bed, but the amount of by-pass gas was not determined. The average NOx removal was 49.3 percent.

Run 4

Objective:	To evaluate the performance of a smaller filter bed (8 inches) consisting solely of vermiculite–MgO.
Sorbent Bed:	8-in vermiculite–MgO
Engine Tested:	Teledyne-CAE J-402-CA-702
Total Run Time:	32 minutes
Number of Slat Doors Open:	None were open during the run. Before and after the run, eight were opened 80 percent.
Discussion of Results:	Data obtained during Run 4 are provided on the next page and in Table 28.

TABLE 30. RUN 4 TEST RESULTS

Time (Min)	Power Level (%)	NOx IN (ppm)	NOx Out (ppm)	NOx Removal (%)	ΔP Filter (in W.G.)	Gas Temp. In (°F)	Gas Temp. Out (°F)	Gas Velocity Thru Bed (fpm)
7	Increasing	53	—	—	0.5	134	88	250
15	80	58	31	47	0.5	139	90	—
17	80	56	31	—	0.6	141	94	200
18	80	58	34	41	0.6	143	99	—
19	90	74	44	41	0.7	153	103	—
20	90	72	43	40	0.6	157	100	150
22	90	76	43	43	0.6	159	104	—
23	90	72	43	40	0.6	161	112	250
25	90	75	41	45	0.6	162	113	—
26	90	72	40	44	0.6	163	112	—
28	90	73	42	42	0.6	164	112	250
30	90	73	43	41	0.6	167	116	—
32	80	55	27	51	0.6	155	103	—

The NOx levels of the exhaust gas generated during this small-engine test run were surprisingly high (as much as 76 ppm). The eight-inch filter removed approximately 44 percent of the NOx. The temperatures of the exhaust gas and its velocity through the bed were slightly lower than the levels observed in earlier runs. The pressure drops across the bed were very low, averaging less than 0.6 inch W.G.

The particle collectors were left in place during Runs 4 and 5, and therefore they collected composite samples. The data obtained, however, indicated that omitting the vermiculite front bed or substituting activated carbon for this bed reduces the overall particulate-collecting ability of the filter. Similar observations were made earlier in laboratory tests.

Run 5

Objective:	To evaluate the effects of adding activated carbon to the filter bed.
Sorbent Bed:	4-in activated carbon and 8-in vermiculite–MgO
Engine Tested:	GE J-79
Total Run Time:	26 minutes
Number of Slat Doors Open:	Four were open (at 80 percent power) and eight were closed (four locked down). Eight were open during start-up and during the smoke phase of the test.
Discussion of Results:	Data obtained during Run 5 are given in Table 31 and in Table 28.

TABLE 31. TEST 5 TEST RESULTS

Time (Min)	Power Level (%)	NOx IN (ppm)	NOx Out (ppm)	NOx Removal (%)	ΔP Filter (in W.G.)	Gas Temp. In (°F)	Gas Temp. Out (°F)	Gas Velocity Thru Bed (fpm)
4	—	68	—	—	0.8	134	92	—
9	80	68	20	71	1.0	189	99	—
11	80	58	10	83	0.9	199	103	—
12	80	58	18	69	0.9	203	102	—
13	80	53	10	81	0.8	203	107	—
14	80	58	14	76	0.8	204	108	—
15	80	56	10	82	0.8	205	115	—
18	80	63	14	78	0.8	209	115	—
19	80	60	10	83	0.8	212	111	—
21	80	63	14	78	0.8	214	120	—
23	80	60	10	83	0.8	215	115	300
25	80	64	14	78	0.8	217	113	—
26	80	60	12	80	0.8	218	112	—

The addition of a separate 4-inch activated carbon bed in front of the vermiculite–MgO bed resulted in an average NOx removal rate of 78.5 percent. NOx removals during the run, unlike during the earlier runs, were not constant, but fluctuated between removals of 69 percent and 83 percent. The velocity of the gas through the filter beds was 300 fpm (5.0 fps) and the resulting pressure drop was 0.8 to 1.0 inch W.G.

The particles collected on the entrance side of the filter were white in color; particles collected on the exit side were both white and black, providing an overall light gray color. The black particles appeared to be primarily activated carbon.

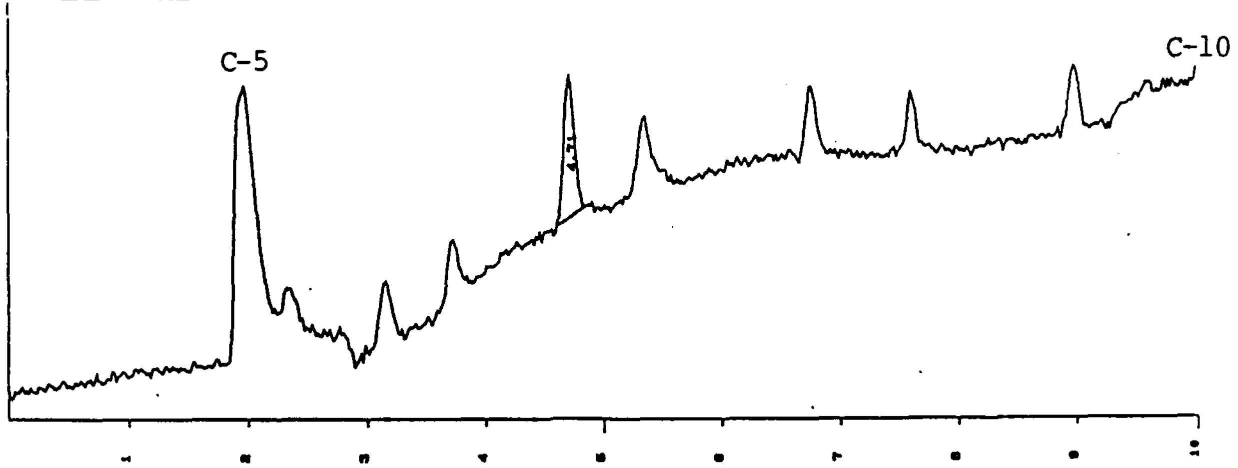
Gas samples collected in front of and behind the filter during the run were analyzed for benzene, toluene, ethylene, and formaldehyde. The results of these analyses are tabulated in Table 32, along with the results of analyses of similar samples collected during Run 2. The activated carbon/vermiculite–MgO combination appeared to be reasonably effective in removing benzene and toluene and, to a lesser degree, the other gases. The vermiculite/vermiculite–MgO combination, on the other hand, did not appear to be effective in removing any of these species. It should be noted that the analysis method employed with these samples was not quantitative.

TABLE 32. FILTER EFFECTIVENESS IN REMOVING SELECTED HYDROCARBON GASES

	Vermiculite/ Vermiculite–MgO Filter - Run 2			Activated Carbon/ Vermiculite–MgO Filter - Run 5		
Gas Species	Before Bed (ppm)	After Bed (ppm)	Removal (%)	Before Bed (ppm)	After Bed (ppm)	Removal (%)
Benzene	20	20	0.0	35	15	57.1
Toluene	40	35	12.5	30	15	50.0
Ethylene	200	190	5.0	200	170	15.0
Formaldehyde	5	5	0.0	7	6	14.3

Additional gas samples were taken in front of and behind the filters during these same runs, and, these samples were stored in stainless steel sampling spheres. Prior to sampling, the spheres had been cleansed, heated at 392°F for 1 hour, purged with nitrogen, and evacuated. The gas samples were delivered to the Chemistry Department of Kent State University for gas chromatography (GC). Typical chromatograms for gas entering and leaving the vermiculite/vermiculite–MgO filter are shown in Figure 27. These curves indicate clearly that the levels of a number of hydrocarbons in the gas were decreased in passing through the filter. No mass-spectrometric or other studies were performed to identify the specific compounds represented by the peaks, except that C-5 and C-10 compounds were run as standards (the locations of these compounds are indicated on the curves) and the compounds observed in the exhaust gas fall between these compounds. Similar curves were seen for the activated carbon/vermiculite–MgO filter.

GAS SAMPLE BEFORE FILTER



GAS SAMPLE AFTER FILTER

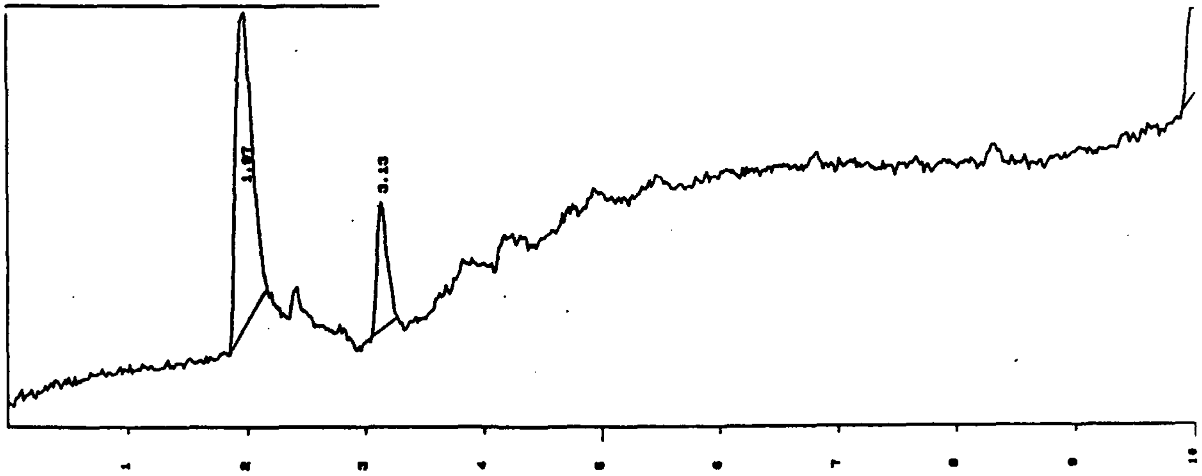


Figure 27. Chromatograms for Gas Entering and Leaving a Vermiculite/Vermiculite–MgO Filter

4. Follow-Up Monitoring

On 17 September 1992, Sorbtech engineers returned to the test cell site to remonitor the performance of the filter system. After the June runs, the prototype filter system was left in place atop the test-cell chimney with half the slat doors open. Approximately one month later, the remaining slat doors were opened to improve the natural draft in the chimney. During the time period 7 June through 17 September, approximately 150 drone-engine tests were performed. With the slat doors opened or partially opened, it is estimated that an average of about 10 percent or less of the exhaust gases passed through the filter beds during the period. The results of remonitoring are presented in Table 33.

Remonitoring Run

Objective: To evaluate the performance of the filter bed after three months.

Sorbent Bed: 4-in activated carbon and 8-in vermiculite–MgO.

Engine Tested: Teledyne-CAE J-402-CA-702

Total Run Time: 17 minutes

Number of Slat Doors Open: Four were open and eight were closed (four locked down). Ten were open during start-up.

TABLE 33. RESULTS OF SECOND MONITORING RUN

Time (Min)	Power Level (%)	NOx In (ppm)	NOx Out (ppm)	NOx Removal (%)	ΔP Filter (in W.G.)	Gas Temp. In (°F)	Gas Temp. Out (°F)	Gas Velocity Thru Bed (fpm)
3	Increasing	—	—	—	1.0	89	86	50
6	—	15	5	67	1.0	131	88	60
7	—	10	3	70	1.0	135	88	60
9	—	11	4	64	0.9	141	88	75
11	—	11	4	64	0.8	144	99	100
12	—	—	3	—	—	—	—	100
13	—	12	4	67	0.8	148	94	100
15	—	—	2	—	—	165	95	100

	CO In (ppm)	CO Out (ppm)	CO Removal (%)
15	150	25	83

<u>Discussion of Results</u>: The average NOx level of the exhaust gas produced by the small engine in this run was 12 ppm. This level is between the levels noted in Runs 1 and 4, which were performed earlier. NOx removals with the filter during this run averaged about 66 percent. This removal rate is typical of what was observed three months earlier.

The CO levels of the exhaust gas were monitored with Draeger tubes. Typical results on gas samples taken during the run showed that the filter was very effective in reducing the CO concentration of the exhaust gas.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the experimental work leading up to the prototype tests at Tyndall AFB, the following conclusions can be made:

1. Two fixed-bed filter systems show promise as approaches for controlling NOx and fine particulates in exhaust gas streams in general. These systems are (a) a modified selective catalytic reduction (SCR) approach consisting of a bed of virgin vermiculite followed by a honeycomb zeolite bed, with ammonia injection into the gas stream in front of the vermiculite bed; and (b) a vermiculite–MgO bed approach, which employs no ammonia injection.

2. Both systems demonstrate the ability to remove significant quantities of NOx, small particulates, and CO from exhaust-gas streams.

3. Both systems exhibit limitations in their use. The modified SCR system, for example, is effective only with gases within the temperature range 475-800°F. The vermiculite–MgO system, on the other hand, is most effective on gases at temperatures below about 150°F.

4. Locations near the aircraft engine exhaust or along the augmentor tube appear to be inappropriate for a NOx and particulates control system. At these locations, load and vibration conditions are severe, gas temperatures and velocities vary widely and rapidly, and any control system would invariably affect engine performance. The most favorable location appears to be at the end of the exhaust-gas chimney, where conditions are less severe and variable.

5. Of the two promising systems, only one, vermiculite–MgO, is suitable for possible use at the end of the chimney in test cells.

6. The use of a thin bed of virgin vermiculite or activated carbon in front of a vermiculite–MgO bed should be considered to improve the overall performance of the filter in removing NOx and protecting the vermiculite–MgO bed from particulate contamination.

On the basis of the data collected during evaluations of the new prototype filter system, the following conclusions can be made:

1. The placement of a static-bed vermiculite/vermiculite–MgO filter at the very end of the exhaust gas stream appears to be a workable approach for treating jet engine exhaust gases. With such an approach, the temperatures of the exhaust gases are relatively low, the range of temperatures encountered is tolerable, the effects of the control system on the engines being tested are acceptable, and retrofitting of existing hush houses can be simple and cost effective.

2. A static filter consisting of thin beds of vermiculite and vermiculite–MgO can effectively remove NOx and small particulates (smoke particles) from exhaust gases generated during the testing of jet engines. NOx removals of 50 to 60 percent and particulate removals of 50 percent or more can be expected.

3. A vermiculite/vermiculite–MgO filter placed at the end of the exhaust gas stream appeared to be effective over the entire range of jet-engine testing conditions and was not affected by rapid changes in conditions.

4. The pressure drop across the 12-inch filter bed was about 1.0-inch W.G. for an exhaust gas having a face velocity of 500 feet per minute through the bed.

5. Although the vermiculite/vermiculite–MgO filter appeared to remove small amounts of gaseous hydrocarbon compounds, the addition of activated carbon appeared to result in improved removal of these compounds, while also improving NOx removals to 80 percent or more.

6. Slat doors or shutters can be employed effectively in the filter system to provide a bypass for exhaust gases during engine start-ups and during times when back pressures become excessive. Open slat doors, however, can result in reduced overall removal performances. The installation of an in-line fan should be considered to compensate for the pressure drop across the filter.

Recommendations. It is recommended that a full-scale application of the new technology now be demonstrated. More specifically, we recommend that (1) alternative configurations of the sorbent bed be examined as a possible means of decreasing flow resistance, and (2) the vermiculite–MgO filter be scaled up to a full-scale, permanent system to treat the total exhaust gas stream of a jet-engine test facility.

REFERENCES

1. Directorate of Environics, The Effect of Navy and Air Force Engine Test Facilities on Ambient Air Quality, AFCEC-TR-76-36, October, 1976.

2. Seitchek, G.D., Aircraft Engine Emissions Estimator, ESL-TR-85-14, Tyndall AFB, FL, November, 1985.

3. Goodger, E.M., Hydrocarbon Fuels: Production, Properties, and Performance of Liquids and Gases, pp. 212-213, John Wiley & Sons, 1975.

4. Geiger, J.R. and Daley, P.S., The Feasibility of Controlling Turbine Engine Test Cell Particulate Emissions with a Baghouse, Civil and Environmental Engineering Development Office, Tyndall AFB, FL, Final Report, September, 1978.

5. Blake, D.E., Jet Engine Test Cells--Emissions and Control Measured: Phase I, EPA-340/1-75-006a, October, 1976.

6. Spicer, C.W., Aircraft Emissions Characterization: TF 41-A2, TF 30-P103, and TF 30-F109 Engines, ESL-TR-87-27, Tyndall AFB, FL, December, 1987.

7. May, P.A., Design and Costing of Alternative Selective Catalytic Reduction Systems for Existing Augmentor Tube Designs, DCN No. 86-203-023-35-09, Radian Corporation (for U.S. EPA), April, 1986.

8. Nelson, B.W., A New Catalyst for NOx Control, ESL-TR-89-11, Tyndall AFB, FL, June, 1989.

9. Behrens, C.K., An Experimental Investigation into NOx Control of a Gas Turbine Combustor and Augmentor Tube Incorporating a Catalytic Reduction System, M.S. Thesis, Naval Postgraduate School, Monterey, CA, March, 1990.

10. Ruch, R.J., The Physical Nature and Chemical Reactivity of a Heterogeneous MgO/Vermiculite Flue-Gas Sorbent, ACS National Meeting, Symposium on Clean Coal Technology: Control of SO_2 and NOx Emissions in Coal Combustion, Washington, DC, August, 1990.

11. Dwyer, R.E., U.S. Patent 3,162,516, December 22, 1964.

12. Hansford, R. C., U.S. Patent 3,842,158, October 15, 1974, assigned to Union Oil Company of California.

13. Nelson, S. G., U.S. Patent 4,721,582, January 26, 1988, assigned to Sanitech, Inc.