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SMOKE ABATEMENT FOR DOD TEST CELLS

AIR QUALITY RESEARCH DIVISION
TYNDALL AIR FORCE BASE, FLA. 32403

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CIVIL AND ENVIRONMENTAL ENGINEERING DEVELOPMENT OFFICE

(AIR FORCE SYSTEMS COMMAND)
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The Department of Defense owns and operates nearly 200 jet engine test cells. Occasionally, visible exhaust smoke is emitted from these structures. Several pollution control agencies, most notably the State of California, have expressed interest in limiting test cell smoke emissions. A review committee composed of various Air Force and Navy representatives recommended further study of fuel additives as a means of achieving this goal. They recognized additives as the most promising near term solution to the test cell smoke problem. Ferrocene →

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20. Abstract (continued)

appeared to be the best of existing additives. Studies were undertaken to determine the environmental impact, toxicological hazards and engine effects associated with routine ferrocene use. Four types of Navy turbine engines were tested for ten hours each using ferrocene. These tests indicated that engines suffered no harm attributable to ferrocene, but that the additive must be certified for each engine type on an individual basis. Emission measurements made during the tests showed that most pollutants are virtually unchanged in quantity and character by ferrocene use and that particulate matter is actually reduced. Additionally, ferrocene is actually less toxic and hazardous than the fuels and solvents in which it is dissolved. Ferrocene is, then, environmentally acceptable for routine test cell use, but additional testing to certify its acceptability for certain types of Air Force engines is required and will be accomplished.

PREFACE

This report summarizes recent Air Force and Navy R&D efforts to find an environmentally and economically acceptable method of controlling visible emissions from turbine engine test facilities. The task of coordinating the efforts of several Air Force and Navy units was assigned to the Air Force Civil Engineering Center, Environics Directorate, which subsequently became Det 1,(Civil and Environmental Engineering Development Office (CEEDO)) HQ Armament Development and Test Center. This report was written by CEEDO personnel under JON 21037A29 based on a literature search and experimental data provided by other DOD agencies.

Thanks are extended to Mr Anthony Klarman of the Naval Air Propulsion Test Center (NAPTC), Mr L. E. Michalec and Dr John Krimmel of the Naval Aircraft Environmental Support Office (AESO), Lt Col Harry Suggs of the Air Force School of Aerospace Medicine (USAFSAM), Col V. L. Carter of the Air Force Aerospace Medical Research Laboratory (AMRL), and Mr C. R. Martel of the Air Force Aero Propulsion Laboratory (AFAPL) for their contributions of data and analysis.

This technical report has been reviewed and is approved for publication.

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SMOKE ABATEMENT FOR DOD TEST CELLS

I. EXECUTIVE SUMMARY

Various air pollution control authorities are focusing considerable attention on DOD turbine engine test cell visible smoke emissions. Currently, the DOD believes there is no legal requirement for test cells to comply with stationary source emission standards, but this issue is being contested in Federal court. It is appropriate, however, that all technologically and economically feasible means of reducing test cell smoke to acceptable levels be assessed to provide information on alternatives to meet possible compliance schedules.

Fuel additives are the most economical known method of smoke abatement. Ferrocene is currently the most desirable additive. While ferrocene is essentially non-toxic and environmentally acceptable, it leaves iron oxide deposits in the engine hot section. The Navy has tested four engine types for up to ten hours each with ferrocene under typical acceptance testing conditions with no adverse effects. However, the Director of Production and Technology, HQ AFLC/DCS Maintenance, has concluded that metallurgical analysis and tests of Navy engines are not sufficient to determine the acceptability of ferrocene for use in other engines. He expressed his concerns in a letter to the Environics Directorate, Air Force Civil Engineering Center, on 31 Mar 77. Personnel of the Turbine Engine Division of the Air Force Aeropropulsion Laboratory also stated concern over extrapolating test data to form conclusions related to engines of another type. The Navy is also testing a fuel-water emulsion which is capable of reducing smoke and may be a better alternative than ferrocene.

In view of the current legal problems and DOD's commitment to leadership in compliance with environmental regulations, further development of a test cell smoke abatement system is recommended. The first step should be installation of an engineering prototype fuel additive system at an Air Logistics Center (ALC) test cell to determine the compatibility of ferrocene with Air Force engines. Water emulsion equipment could be added and the performance of the two systems compared. To firmly establish the system capabilities, electronic smoke monitoring should be an integral part of the program.

Attrition of older, "smokier" engines may partially alleviate the test cell smoke problem, while a major change in turbine engine fuel and consequent increases in smoke emissions might render a system designed to meet today's situation inadequate. The timing of such events must be considered in a cost-benefit analysis of all alternatives. Routine use of a smoke abatement system of any kind is not recommended until the legal issues are resolved.

II. INTRODUCTION

For several years some state and local air pollution regulatory agencies have expressed interest in visible smoke from DOD turbine engine test facilities. DOD holds that turbine engine test cells are not stationary sources and are not subject to regulation by state or local authorities since the engine is the source of emissions. The responsibility to set emission standards for aircraft and aircraft engines has been given to the Environmental Protection Agency (EPA) through the Clean Air Act. Although the issue has not yet been finally decided, it is submitted that this EPA authority to set emission standards does not apply to military aircraft.[1] The most significant recent development is a suit brought by the State of California against the Navy for alleged violations of visible emission standards. The outcome of this lawsuit notwithstanding, the DOD has been, and continues to investigate methods of smoke reduction.

The objective of current research is to determine if an economically and environmentally acceptable method exists to control visible emissions from Department of Defense (DOD) turbine engine test facilities. Based on the results of previous research and economic studies, a review committee comprised of Air Force Logistics Command, Air Force Systems Command and US Navy representatives determined that fuel additives, and specifically ferrocene, merited further investigation (Reference 1). Ferrocene is an organometallic compound which is effective in reducing visible smoke from numerous combustion sources. Previous testing by the Navy proved ferrocene's ability to reduce visible smoke from turbine engines to acceptable levels (Reference 2). Questions which remained were:

1. Do the products of combustion of ferrocene in jet fuel change engine pollutant emission levels?

2. Does ferrocene or ferrocene in solvents present any additional occupational safety or health hazards?

3. Does the use of ferrocene in normal engine acceptance testing degrade engine performance, damage components, or reduce engine life?

The first two questions are resolved by this report, while the answer to the third requires further testing. In light of the un-

[1] The Clean Air Act definition of aircraft is tied to FAA airworthiness certification, a requirement not applicable to military or government aircraft. This is not to suggest that by Executive Order or other authority, military aircraft could not be made subject to EPA emission standards.

certainty of the acceptability of ferrocene, alternatives were also considered. Most were eliminated for economic reasons, but several of the more promising alternatives will be described in Part IV.

With cost effectiveness a foremost consideration, the Air Force joined the Navy's ongoing research program in test cell smoke abatement. The first joint product was a report addressing the technological and air quality issues of test cell smoke abatement and entitled Joint Navy-Air Force Study on Air Emissions from Aircraft Engine Test Facilities (Reference 3). The report concludes that acceptable techniques are not available to immediately eliminate emissions without creating an adverse impact on aircraft readiness and national defense and that test cell emissions have little impact on ambient air quality.

Two control projects which have reached the hardware stage are exhaust scrubbers and fuel additives. Full scale scrubbers are being evaluated at Naval Air Stations at Jacksonville and Norfolk. The Navy also took the lead in fuel additives research. The Air Force is currently participating in several joint smoke suppression projects with the Navy, including evaluation of ferrocene and a fuel-water emulsion system. Fuel additives in general are the cheapest method of reducing visible smoke, and ferrocene is currently the most acceptable. The water emulsion approach has significant potential and may be superior to ferrocene.

The cost effectiveness of any system depends to a great extent on its useful life. Since newer engines are essentially smokeless, attrition of older engine types will gradually alleviate the smoke problem. On the other hand, fuels of the future will probably have a lower hydrogen content than JP-4 and could aggravate the smoke problem. Appendix E and Reference 4 describe the effects of fuel characteristics on visible smoke. Changes in the characteristics of jet fuel, engine attrition, possible engine retrofit, and the ability to develop smokeless engines which meet military requirements in the future will determine the useful life of a smoke abatement system and will significantly influence the cost-benefit analysis.

III. RESULTS

A. Potential Emission Standards Violations

The frequency of potential emission violations depends on the engine overhaul schedule, the mix of engines tested, the power settings of each test, the condition of the engines, the configuration of the test cell and the standards which are applied. The standards which most agencies apply are written with reference to the Ringelmann scale. Ringelmann numbers represent the fraction of incident light obscured by a smoke plume, with 20 percent obscuration corresponding with a Ringelmann 1, (R1), 40 percent obscuration a Ringelmann 2, etc. R1 is the prevailing standard at most Air Force locations. The Ringelmann scale has been widely criticized in the technical literature (for example, Reference 5). As many as fourteen variables have been identified which cumulatively can cause the apparent smoke density to vary by a factor of five or more. These variables are all beyond the control of the operator and in most cases the observer. Latitude of the site, time of day, color of the plume, color of the sky, relative position of the observer, time of year and relative humidity are some of the more significant factors which make it impossible to accurately predict when a test cell will exceed a Ringelmann standard.

Two factors resulting from this variability have prevented a meaningful analysis of the potential for violations of standards. First, observations of the same type engines at different locations varied so widely that there was no readily identifiable trend. Second, the alleged violations cited by regulatory agencies were not specific enough as to the conditions surrounding the observations to be able to reconstruct the circumstances. Until more consistent observations are available, prediction of potential to violate standards must be based on extrapolation of engine test results and records of the location and frequency of engine tests.

The engines which produce the most concentrated smoke emissions using JP-4 fuel (in descending order) are the J-79, J-75, J-57, TF-33, and TF-41. These engines all produce highly visible smoke at cruise power and above. Violation of standards would depend on the conditions of the observation. Under most conditions these engines can produce visible plumes exceeding a Ringelmann 1 and, under some conditions, Ringelmann 2.

The TF-30 engine family seldom exceeds a Ringelmann 1 except under unusual conditions. The T-56 might exceed standards if no augmentation air were present in the test cell exhaust flow. The remaining Air Force engine types should meet plume visibility standards under all conditions with the rare exception of defective engines.

Without a compensating engine design change, a switch to a lower hydrogen fuel, such as that derived from shale or coal, would significantly increase exhaust smoke from these engines (Reference 4). Such a fuel conversion might require smoke abatement in the future for some engines which are presently smokeless.

Tinker AFB is the Air Force location which has received the most interest from air pollution control authorities. It is the major overhaul facility for most of the Air Force's smokiest engines. J-79 testing is primarily conducted at Kelly AFB. A certified visible emissions reader from the Air Force Civil Engineering Center observed numerous engine tests at Kelly AFB and Tinker AFB. He reported emissions exceeding R1 only at high power settings. Even these emissions were only slightly in excess of R1 and constituted less than half of the total engine testing at these locations. However, observations of these same engine types by other Air Force observers at Tinker, Kelly, and other locations were not consistent with this finding. The range of observations typically ran from less than Ringelmann ¼ to Ringelmann 2 or higher. Even though some variation would be expected due to the subjective nature of the standard, observer tolerance alone is not likely to account for the wide range of observations; therefore other factors must be responsible.

In addition to the influence of the prevailing conditions under which the observations were made, one factor has been identified which may be partially controlled. At some test cells, cooling water is sprayed into the exhaust stream to protect the structure from the high exhaust gas temperatures. Experiments conducted by personnel of the USAF Occupational and Environmental Health Laboratory (OEHL) at McClellan AFB, California have proven that under some conditions a significant portion of plume visibility can be attributed to particle growth and water droplets resulting from use of these cooling systems. For example, a TF-30 running at military power had an electronically measured plume opacity of 10 percent or R½. When the cooling water system was activated the visibility rose to slightly over R1. (A 10 percent opacity differential was also noted with a J-75 engine, but the baseline was R1½ or 30 percent opacity.) Most standards specify that any visibility attributable to water or water vapor does not constitute a violation. However, the portion of the plume visibility attributable to wat · or water vapor in these specific cases was not discernible by a tr. .ned observer. The plumes with cooling water were dirty gray in color and appeared identical to gray smoke. Therefore, these plumes would be cited by observers as violations of the emission standards, even though the actual visibility without cooling water might meet standards.

Minimizing the use of cooling water, then, could certainly be beneficial to those engine/cell combinations which marginally exceed standards during cooling water application. Associated utilities conservation would be an additional benefit of considerable value at locations with critical water supplies. The basic procedure to minimize water use would be to use no water until the temperature of the critical components reaches the maximum allowable, and after that restrict the flow rate to the minimum level required to maintain the maximum allowable temperature. This will also be the most efficient use of water because the latent heat of vaporization provides the greatest cooling effect per unit of water. If the vapor condenses, it will usually form a visible white steam plume which can be readily discerned by observers. The results should be reduced water consumption and less visible emissions.

B. Toxicology

The Navy Toxicology Unit at the National Naval Medical Center, Bethesda, Maryland, performed a study to determine the toxicity characteristics of ferrocene and solutions of ferrocene in JP-5, tolulene and xylene (Reference 2). The results indicate that ferrocene will not present an occupational health hazard if used as a smoke suppressant in turbine engine test cells. The USAF 6570th Aerospace Medical Research Laboratory has determined that the Navy's ferrocene toxicology studies and information available in the biomedical literature (Reference 6) have adequately verified the relatively non-toxic response of this compound in mammalian systems. Any toxic response resulting from a mixture of ferrocene in fuel or solvents would result from the jet fuel or solvent itself and not from the presence of ferrocene. No direct information is available on the effects of ferrocene on lower terrestrial and aquatic life forms. However, the relatively small amounts used in test cell operations coupled with the known innocuous nature of this compound to mammalian species would indicate that the possible introduction into the environment from such test cell operations would not adversely affect the environment.[2]

Iron pentacarbonyl ($Fe(CO)_5$) is a possible combustion product when ferrocene is used in turbine engines. The recommended threshold limit value of ($Fe(CO)_5$) is 0.01 ppm (Reference 7). This is based on the known carcinogenicity of $Ni(CO)_4$ and the implication of iron as a co-carcinogen. The highest expected concentration of ($Fe(CO)_5$) in a jet engine test cell exhaust plume should never exceed 10^{-19} ppm (Reference 2). This concentration of ($Fe(CO)_5$) is judged to be so dilute as to pose no hazard.

[2]USAF 6570th Aerospace Medical Research Laboratory letter, "Fuel Additives for Test Cell Smoke Suppression", 10 May 1977.

C. Emission Measurements

Three factors were considered in determining the environmental acceptability of ferrocene from an emissions standpoint. They were:

- Does ferrocene cause a significant change in the mass of pollutants emitted?

- Does it change the characteristics of those pollutants in any manner which would increase their adverse health effects?

- Are any new pollutants emitted which would have a detrimental effect on ambient air quality?

Emissions measurements have been an integral part of the ferrocene evaluation procedure since it began. Early samples indicated trends, but were not conclusive (Reference 2). Previously, there were no data at all concerning particle size distribution, although it appeared that ferrocene produced an overall reduction in the total mass of particulate emissions. Additional samples were taken in conjunction with a test program intended to certify the acceptability of ferrocene for testing certain Navy engines. Appendices A and B report the results of some of those emission measurements.

1. Particulate Matter

Appendix A deals with particulate emissions from Navy J-52, J-57, TF-30, TF-41 and J-79 engines, with and without ferrocene added to JP-5 fuel. In each case only the minimum amount of ferrocene required to reduce plume visibility to less than R1 was used. These samples generally supported earlier findings that ferrocene caused a reduction in particulate emissions of 40 percent to 60 percent by weight. This occurred at all power settings for most of the engines sampled. There were some exceptions to this trend, but it is believed that some factor external to the use of ferrocene was responsible.

A change in the particle size distribution could have either adverse or beneficial health effects. A significant increase in the number of particles of 0.5 to 5 microns in diameter is generally considered to be an increased respiratory hazard. A net shift away from this size range would have a beneficial effect. Measurements shown in Appendix A were limited to particles less than 1.0 micron in diameter. This was the upper size limit of the aerosol sampling system. (Sampling by another method at the test cell exhaust plane indicated that 60 percent to 95 percent of the particulate mass is constituted by particles less than 1.0 micron in diameter.) Data presented in Appendix A indicates that the number of particles less than one micron in diameter is only slightly changed by the addition of ferrocene. (See Appendix A, figures 3 through 6, 11 and 12 and 16 and 17). Furthermore, the differences between particle size distributions with and without ferrocene are no greater than the difference between two separate measurements of the same engine, both without ferrocene, shown in Figure 2, Appendix A. The reported mass emission reduction coupled with an essentially constant submicron particle count implies that the mass reduction is due to fewer particles in the 1 to 10 micron range when the additive is used. Hurley and Hersh conducted a thorough study of the effects of fuel additives on the emissions from stationary power turbines (Reference 8). Their data included electron mobility analyzer measurements (like those of Appendix A) which were limited to particles less than one micron in diameter, and low pressure impactor samples to characterize larger particles. Hurley and Hersh concluded that no change in size distribution can be attributed to additive use, even though some differences in distribution were observed for different test cases.

The bulk of available data, therefore, supports the conclusion that the size distribution of particulate emissions from engines burning ferrocene doped fuel are not significantly different than emissions from untreated fuel, and the total particulate mass is substantially reduced by the use of ferrocene. The health hazard from particulate emissions associated with the use of ferrocene appears to be less than that associated with present test cell emissions.

An undetermined fraction of the effluent from engines burning ferrocene-doped fuel consists of iron oxide (Fe_2O_3). Although this constitutes the introduction of a new exhaust product, iron oxide appears to have a lower potential for adverse health effects than carbon, the primary form of exhaust particulate matter. The threshold limit value (TLV) for iron oxide fumes is 5 mg/m_3 while the TLV for carbon is 3.4 mg/m_3 (Reference 9). The higher TLV for Fe_2O_3 and the reduction in particulate mass associated with the use of ferrocene indicates that the immediate health hazard is proportionally reduced. The long term effects of introducing submicron iron particles into the environment is not known, however. This does not imply that further testing of the additive should be curtailed. A test program would only produce limited exposure for which the effects are well documented. However, before ferrocene is used on a broad scale, the possible long term effects of exposure to submicron particles of Fe_2O_3 should be considered.

2. Hydrocarbons

Appendix B reports results of the most recent hydrocarbon sampling from the exhaust of several engines and test cells, both with and without ferrocene. These samples were taken in conjunction with tests to determine the effects of ferrocene on engine performance. Earlier testing of a T-56 engine with ferrocene indicated a slight increase in hydrocarbon emissions at lower power settings, while J-52 hydrocarbon emissions were unchanged (Reference 2).

Hydrocarbon emissions from turbine engines are highest at idle power and decrease significantly as power is increased. Ferrocene will normally be used only at high power. In order to remain within the operating range of the sampling apparatus, all sampling described in Appendix B was performed at the lowest power settings at which ferrocene would be required. Even though more ferrocene would be required at higher power settings, the baseline hydrocarbon emissions are so low that any change due to the addition of ferrocene would not be discernible from systematic or instrument error.

Total hydrocarbon emissions from a J57P-10 engine with ferrocene (as reported in Appendix B), averaged 35 percent less than emissions from the same engine without ferrocene. The actual concentrations were at the lower limit of the instrument's range in both cases and the measured difference is considered within the range of experimental error. A sample from a TF-41 engine showed a marked decrease in hydrocarbon emissions when ferrocene was used, while results of another test were mixed. Generally, hydrocarbon concentrations both with and without ferrocene were in the range of 2 to 4 parts per million (ppm) as carbon.

Hurley and Hersh concluded that total unburned hydrocarbon emissions at a fixed high power setting did not vary with additive concentration, and that the levels were insignificant (Reference 8). Since ferrocene is only required at relatively high power settings where hydrocarbon emissions are minimal, variability between samples with and without ferrocene is considered insignificant.

The hydrocarbon species which are part of the photochemical smog reaction chain are important, since they can be related to health effects. One of the objectives of sampling exhaust emissions in conjunction with recent Navy engine testing was to quantify any observed changes in the quantity of these species when ferrocene is used. Sampling was conducted by the Crew Environment Branch of the USAF School of Aerospace Medicine (USAFSAM/VNL). Unfortunately the results of these measurements are not conclusive. At the power settings where ferrocene was required to control visible smoke, the concentration of total hydrocarbons in the exhaust was so low that reliable measurements of individual hydrocarbon species was not possible. (The previously cited EPRI study (Reference 8) was also inconclusive due to inconsistent results.) A rough comparison of the relative fractions of major hydrocarbon groups is presented in Figure 1. No numerical values are assigned, for to do so would imply an accuracy not warranted by the data. The most apparent change in composition with the addition of ferrocene was the increase in ketones and aldehydes. These increases appear to be at the expense of alkenes and acetylene, although the actual change in alkenes was somewhat obscured by erratic results and the absence of data on C_1-C_3 hydrocarbons not collected.

Ketones, aldehydes, aromatics, alkanes, alkenes and acetylene were found to comprise significant fractions of the total hydrocarbons in exhaust samples reported in USAFSAM/VNL report Effects of Ferrocene Smoke Abatement Additive on Hydrocarbon Emissions of Turbine Engine (unpublished). These fractions were computed for exhaust samples with and without ferrocene. The computations were based on averages of all reported samples. The differences between samples collected at the engine exhaust plane and those at the test cell exhaust stack were considered insignificant, supporting the rationale for averaging them. When ferrocene was used, alkenes appeared to decrease from approximately 10 percent of the total hydrocarbons present to 5 percent, while acetylene had an apparent decrease from 8 percent to 2 percent, aldehydes increased from about 14 percent to 19 percent and ketones increased from 12 percent to 18 percent. The percentage of aromatics and alkanes was essentially unchanged. These results appear consistent with the possibility that ferrocene promotes the oxidation of unsaturated hydrocarbons. The composite photochemical reactivity of the two averaged samples was estimated using the technique of Trijonis, Dimitriades and Arledge (Reference 10). The estimated reactivity without ferrocene is 0.79 and 0.81 with ferrocene. The difference is negligible and both figures agree fairly well with the estimate of 0.88 for reactivity of jet aircraft emissions presented in Reference 10. In summary, the overall effect of ferrocene addition on the reactivity of test cell emissions appears to be negligible.

The available data indicate, but do not prove conclusively, that hydrocarbon reactivity is not affected by the use of ferrocene. However, even if the reactivity were significantly increased, it is unlikely that there would be a detectable change in ambient smog levels. This is because test cell hydrocarbon emissions at high-power modes (where ferrocene would normally be used) are not sufficient to influence ambient air quality (Reference 3).

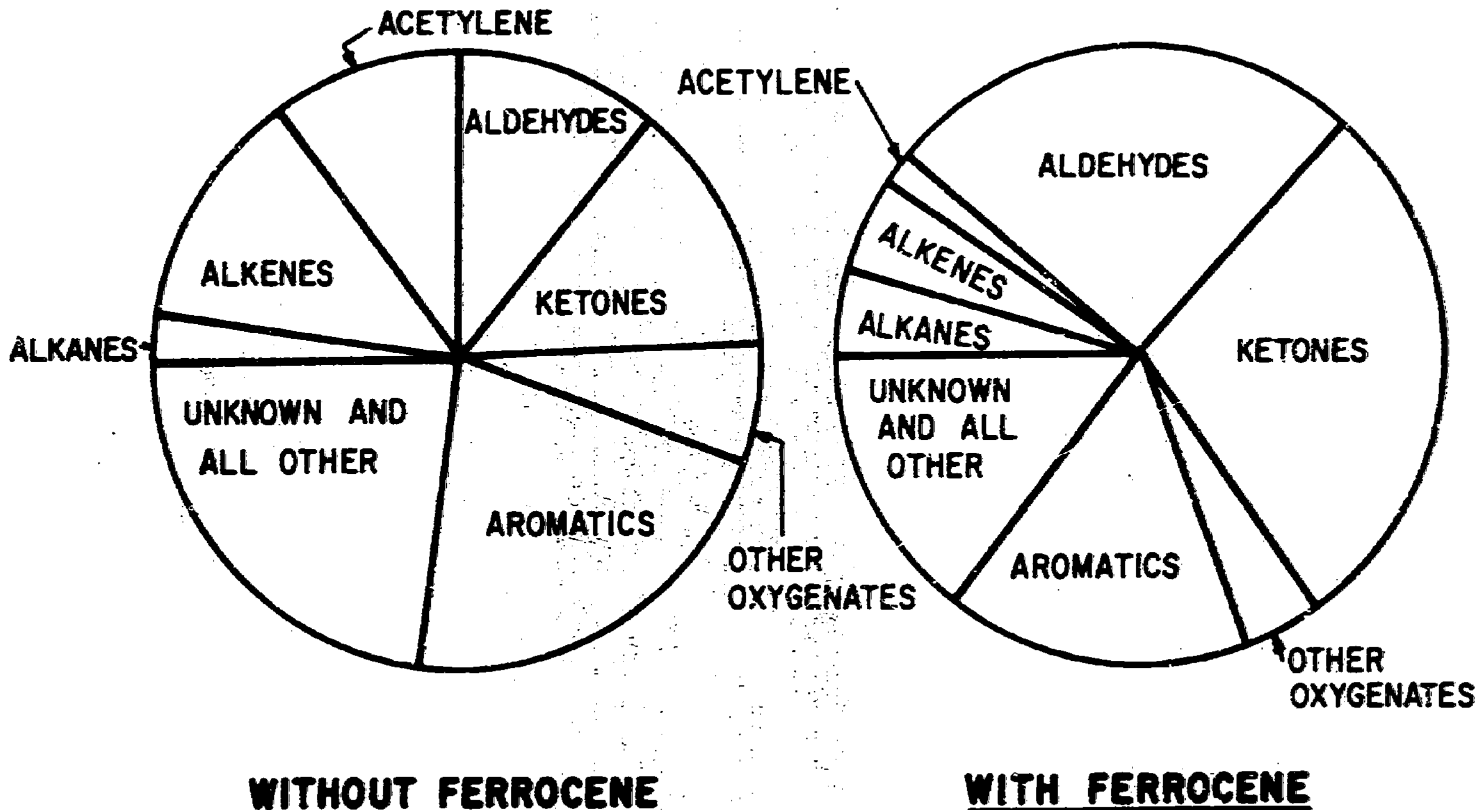

Figure 1. Effect of Ferrocene on Exhaust Gas Hydrocarbons

(From USAFSAM Report; Effects of Ferrocene Smoke Abatement Additive on Hydrocarbon Emissions of Turbine Engines)

3. Gaseous Pollutants Other Than Hydrocarbons

There has been little change reported in non-hydrocarbon gaseous pollutant emissions due to use of ferrocene. Oxides of nitrogen (NO_x) were unchanged in almost every sample studied (References 2 and 8). The carbon monoxide (CO) concentration in the exhaust increased as much as 20 percent at high power settings in some tests (Reference 2). Otherwise, it was unchanged. In test cell exhaust measurements performed by the Aircraft Environmental Support Office of the Naval Environmental Protection Support Service subsequent to those reported in Appendices A and B, ferrocene addition at high power settings caused slightly increased carbon monoxide levels and slightly decreased oxides of nitrogen. The net change in both areas were approximately 10 percent or less.[3] Since CO emissions are minimal at high power settings, the increases noted are not considered significant. Oxides of sulfur were unchanged and the SO_2 and SO_3 ratio was not affected (Reference 8).

[3] Private communication with Dr John Krimmel, Aircraft Environmental Support Office, Naval Air Rework Facility, NAS North Island CA.

D. Engine Effects

The primary purpose of current Navy ferrocene testing is to determine ferrocene's effects on engine performance, maintainability and reliability. There are three areas of concern. First, can ferrocene be used during acceptance testing without degrading engine performance beyond acceptable limits? Second, will deposits cause any immediate engine damage such as clogging of turbine blade cooling passages? And last, will the additive cause any changes which might lead to premature failure or reduced time between overhauls?

The Navy has certified some of its engines for limited use of ferrocene (Reference 2). There were problems with excess iron deposits in the engine hot section during early tests. It is felt that the deposits can be reduced to acceptable levels by minimizing ferrocene use. For this reason an electronic ferrocene feed system, or automated smoke abatement system (ASAS), was developed under contract and tested by the Navy. A description of this system is found in Reference 2. The ASAS uses a light sensing device (transmissometer) to measure the smoke plume and control a pump which injects additive in the fuel at the minimum rate required to maintain plume visibility standards. It is hoped that using this system will permit routine testing of all engine types and extend test periods to complete virtually all testing without engine degradation. Personnel of the Naval Air Propulsion Center estimate that the cost of ASAS equipment would be $25K per test cell if purchased on a large scale.

The Navy is currently engaged in a testing program to certify the acceptability of ferrocene for up to 10 hours of engine testing on five of its engines. One test program involving J-57, J-52, TF-41, TF-30 and J-79 engines has been completed. It involved repeating the performance cycle for each engine until ten hours had accumulated using the ASAS. The results have not yet been published, but the project manager has related that the J-79, J-57, and J-52 suffered no measurable performance degradation. A slight power loss was noted for the TF-30, but it still fell within the acceptable range of exhaust pressure ratio versus engine speed (rpm). An analysis of engine records is being performed to determine what fraction (if any) of the TF-30 engines tested might be degraded to an unacceptable level by ferrocene, assuming the same change would occur as on the test engine. Power loss of the TF-41 was out of tolerance by the end of the test cycle. The TF-41 is scheduled for retesting to determine if ferrocene was the cause, since other variables may have been introduced.

As part of the Navy testing program, each engine was partially disassembled, inspected and reassembled. Normal acceptance runs were then made without ferrocene and the engines put into service. So far, there is not enough data to determine if the time between overhauls will be affected. There are, however, no indications that it will be. In fact, observations of a T-56 turboprop engine indicate that as the engine is run with regular jet fuel, the iron oxide deposits are dissipated (Reference 2). Four Navy J-79s have been run with ferrocene from four to ten hours and placed in service. The J-79 was chosen since it required the most ferrocene and suffered the densest deposits. This limited fleet test of the J-79 should aid in determining if the deposits accumulated during acceptance testing have any long term detrimental effects. The results should be applicable to other engine types as well.

Visual and metallurgical examinations of J-79 hot section parts subjected to 10 hours of running with ferrocene are included as Appendices C and D.[4] These reports conclude that: (1) the parts were structurally sound, and no metallurgical changes attributable to ferrocene were observed, (2) the only physical evidence that ferrocene was used was iron oxide deposits, and these deposits would probably cause no future damage, especially if they were removed during subsequent operation, and (3) the fuel nozzle had a substantial carbon deposit buildup, but it is not known whether this is a normal deposit for ten hours of operation or if it is due to the ferrocene. Further ground tests without ferrocene were recommended to determine if the deposits on any of the components are dissipated under normal operating conditions. TF-41 turbine inlet guide vanes subjected to ten hours of running with ferrocene had similar iron oxide deposits and were also considered structurally sound.

[4] The figures in these appendices are not included in this report.

IV. ALTERNATIVES

State-of-the-art particulate removal methods are analyzed in Reference 3. Both capital and operating costs of other alternatives are as much as a hundred times as high as fuel additive costs. Fuel additives other than ferrocene are either not as effective or have toxicological properties which make them dangerous to handle or store (Reference 2). Three additional alternatives are in various stages of analysis. They are special high hydrogen fuel for test cell use, water emulsified in the normal fuel, and a fabric filter or "bag house" for particulate removal.

A feasibility and economic analysis of using a special, high hydrogen fuel for test cells is included as Appendix E. There has been no full scale testing of this fuel, but it appears to be significantly more costly than ferrocene. Also, because the specific gravity of this fuel is different from standard jet fuel, it might require modified calibration runs or adjustments to the engine fuel control unit to make performance tests meaningful. This might be an unacceptable maintenance burden. Still, if ferrocene proves unsatisfactory for some engines, a special fuel may be a satisfactory alternative. It appears less expensive than any of the mechanical removal systems proposed so far.

A water-fuel emulsion is a very promising technique. It is presently being tested by the Navy with partial Air Force funding. It has proven effective in reducing visible emissions below R1. It has the additional benefit of reducing NOX emissions. Preliminary tests caused some scale deposits. These could be eliminated by using demineralized water, if necessary. Further tests are scheduled to determine if visible emission standards can be met without significantly affecting engine performance.

The third alternative, a fabric filtration system or "bag house' is in the feasibility study stage. Among the design obstacles are the pressure drop and large physical size of these devices. Availability of a fabric which will withstand the test cell environment, and size, weight and cost of the system are important considerations. The use of test cell cooling water may also add unacceptable complications and cost.

In addition to reducing the plume visibility, the "bag house" removes virtually all of the particulate matter from the exhaust Since most engines don't exceed any current particulate mass emission standards, this is not a significant advantage. The possibility of switching to synthetic or shale derived fuels in the future might, however, make the fabric filter the best long run solution. The fuels of the future are potentially much smokier than current JP-4 or even JP-5, so much so that smoke could be beyond the control capability of fuel additives. The cost effectiveness of any system must be evaluated on the basis of its useful life. The useful life of a smoke abatement system depends to a great extent on the timing of any significant fuel changes.

V. CONCLUSIONS

1. The fuel additive ferrocene, used to control visible smoke from jet engine test cells, creates no greater adverse air quality impact than does the operation of test cells without the additive. There is generally a reduction in the mass of total suspended particulate matter emitted during testing with ferrocene use. There was no significant change in the emissions of other pollutants.

2. Ferrocene presents less of a toxicological hazard than do the solvents and fuels in which it is mixed for test cell use. There is no significant occupational health or safety hazard associated with handling or storage of ferrocene.

3. It is impossible to predict the frequency of potential violations of stationary source visible emissions standards with currently available data. Uncontrolled variables appear to preclude a useful correlation of engine/test cell combinations and their emissions with reference to the Ringelmann scale.

4. The use of water for test cell structural cooling can substantially increase exhaust plume visibility. The addition of cooling water alone may cause apparent violations of standards at some test cells at certain power settings. More careful use of water will aid in utility conservation as well as in reduction of smoke.

5. Ferrocene leaves iron oxide deposits on engine hot section parts. These deposits have caused unacceptable degradation of T-56 thermocouples (Reference 2). The deposits appear to dissipate during engine use without ferrocene. Ferrocene may be responsible for carbon deposits on J-79 fuel nozzles. Four engine types (including the J-79) have been successfully run for up to ten hours with ferrocene with no significant performance loss or structural damage. Ferrocene must be certified for each engine type individually, however.

6. A fuel-water emulsion system appears capable of controlling test cell visible emissions over a broad range of conditions. It has the added benefit of reduced NO_X emissions. It is potentially more desirable than ferrocene.

7. If the DOD switches to a shale derived or other synthetic fuel with a lower hydrogen content, fuel additives may not be capable of controlling smoke. The useful life of additive systems, then, might be unacceptably short.

VI. RECOMMENDATIONS

1. The DOD should continue research in test cell smoke abatement. Ferrocene and a water-f ~l emulsion are the most desirable alternatives for the near future. .. ooperative Air Force-Navy effort should be continued to avoid duplication. The first specific project should be installation of an automated smoke abatement system (ASAS) at an AFLC engine overhaul facility. This would enable AFLC engine managers to determine the acceptability of ferrocene for Air Force use. The second phase of this program could be the addition of fuel-water emulsion hardware if the results of present studies indicate it is warranted. An economic analysis should be included.

2. An immediate action which may be within the capability of the test cell users is to minimize the use of cooling water. This could reduce exhaust plume visibility at some locations and may save substantial quantities of water.

3. An analysis of the DOD's future needs for test cell smoke abatement systems should be performed. The future composition of the engine inventory, the time phasing of any fuel changes, and their interrelationship should be considered. Applicability of current and possible future emission standards will be the controlling factor. As the Air Force's engine manager, AFLC may be best qualified to perform this task for the Air Force.

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REPORT NO. AESO 111-77-2
FEBRUARY 1977

APPENDIX A

PARTICULATE EMISSIONS FROM J79, J52, J57, TF30, AND TF41 ENGINES DURING TEST CELL FERROCENE EVALUATIONS

NAVAL ENVIRONMENTAL PROTECTION SUPPORT SERVICE
NAVAL AIR SYSTEMS COMMAND
AIRCRAFT ENVIRONMENTAL SUPPORT OFFICE
NAVAL AIR REWORK FACILITY
SAN DIEGO, CALIFORNIA 92135

Enclosure (1)

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LIST OF ABBREVIATIONS

AESO	Aircraft Environmental Support Office
EPA	Environmental Protection Agency
NAVAIRPROPTESTCEN	Naval Air Propulsion Test Center
NAVAIREWORKFAC	Naval Air Rework Facility
RPM	Revolutions Per Minute
USAFSAM	United States Air Force School of Aerospace Medicine

I. INTRODUCTION

A. Special tests to determine the effect of ferrocene-containing fuel on the operational characteristics and the components of gas turbine engines were initiated at NAVAIREWORKFAC, North Island on 8 November 1976, and at NAVIAREWORKFAC, Alameda on 29 November 1976. These tests were coordinated by the NAVAIRPROPTESTCEN. The main purpose of these tests was to evaluate the engine after 10-hour operations using ferrocene-containing fuel. In other testing, the AESO measured gaseous, smoke, and particulate emissions at NAVAIREWORKFAC, North Island and total hydrocarbons and particulate emissions at NAVAIREWORKFAC, Alameda. The USAFSAM collected hydrocarbon samples at NAVAIREWORKFAC, Alameda.

B. This report gives the results of the particulate emission measurements taken by the AESO at NAVAIREWORKFAC's, North Island and Alameda.

II. EXPERIMENTAL

A. Equipment

1. An Aerotherm High Volume Stack Sampler (HVSS) was used to take samples at the test cell stack exhaust plane. The HVSS allows samples of up to six cubic feet per minute to be taken while following EPA Method 5.

2. The Aerotherm Automatic Jet Engine Particulate Sampler was used to sample particulate emissions isokinetically at the engine exhaust plane. The mass loading samples were taken according to EPA Method 5. The sampler takes particle size distributions using a Thermo Systems Model 3030 Electrical Aerosol Analyzer simultaneously with total particle loading. The Model 3030 was detached from the automatic sampler and used to take the top of stack size distributions.

B. Sampling Procedure

1. Top of Stack

a. The stacks for the test cells at NAVAIREWORKFAC, North Island and Alameda are externally identical. They are 60 feet high and 22 feet square with one-foot thick walls. Both stacks contain sound baffles to reduce the emission of noise. At NAVAIREWORKFAC, North Island these sound baffles are at the stack rim. At NAVAIREWORKFAC, Alameda the sound baffles are approximately 10 feet below the stack rim.

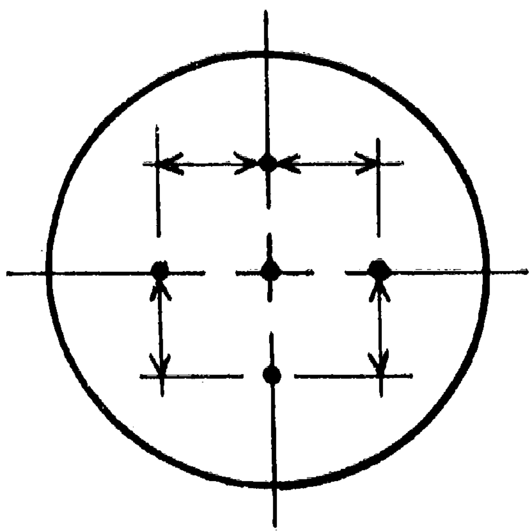
b. The placement of the sound baffles produced two distinct flow regimes which required two separate sample traverse schemes. At

NAVAIREWORKFAC, North Island a five-point traverse was used. The points were chosen to represent the widely varying exit velocities across the baffles. Each point was sampled for three minutes. At NAVAIREWORKFAC, Alameda the flow was divided into two regimes. The upstream (west) side of the stack showed exit velocities from -2 to +2 feet per second (fps). The downstream (east) side of the stack showed much higher velocities from 30 to 50 fps in an almost homogeneous flow. The flow pattern plus sample platform physical limitations, limited traversing to three points for five minutes each. The three points were taken at nine, six, and three feet from the east wall of the stack approximately eight feet from the south wall.

2. Engine Exhaust Plane

The gas turbine engine exhausts are circular and vary from 12 to 30 inches in diameter. For each engine mode, a total of five traverse points were sampled (Figure 1). Each point was sampled for three minutes.

FIGURE A-1



Engine Exhaust Plane Traverse Points
All indicated distances are one-quarter diameter.

C. Collection and Analysis of Data

1. The J79 engine was sampled at NAVAIREWORKFAC, North Island on 6 November 1976, with ferrocene and 12 November 1976, without ferrocene. Samples were taken at the top of the stack only. Figures 2-6 give the size distribution of the particles emitted. Table I gives the results of the Method 5 samples.

TABLE I PARTICULATE EMISSIONS FROM A J79-GE-8D GAS TURBINE AT NAVAIREWORKFAC, NORTH ISLAND

Mode	Without Ferrocene		With Ferrocene	
	mg/m^3	gr/scf	mg/m^3	gr/scf
Idle	11.2	0.0049	61.5*	0.0269
30% (thrust)	-		49.4	0.0216
85% (RPM)	31.7	0.0138	27.1	0.0118
Normal Rated	26.5	0.0116	20.5	0.0090
Military	27.1	0.0118	64.7	0.0282

*Ferrocene is not used at idle, but this data point was taken during the ferrocene run.

2. The J52-P-6B engine was sampled at NAVAIREWORKFAC, Alameda on 4 December 1976, and 15 January 1977. Samples taken on 15 January were size distribution and duplicate total mass emissions without ferrocene at the top of the stack. No engine exhaust plane samples were taken because of the excess probe to engine distance. Figures 7-9 give the size distribution of the particles emitted.

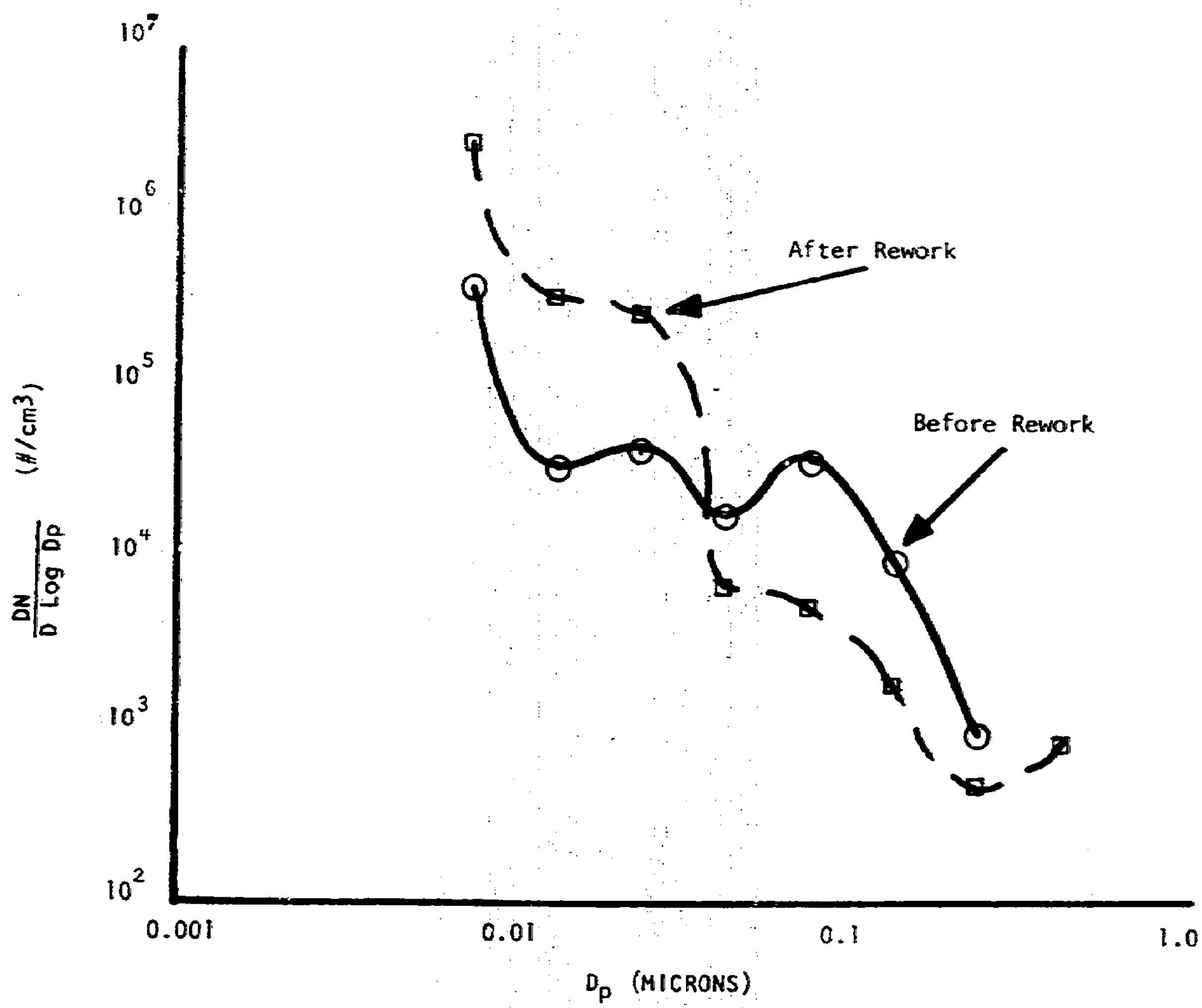


Figure A-2. Size Distribution of Aerosol Emitted From Test Cell by J79 Engine at Idle Power Before and After Ferrocene Test

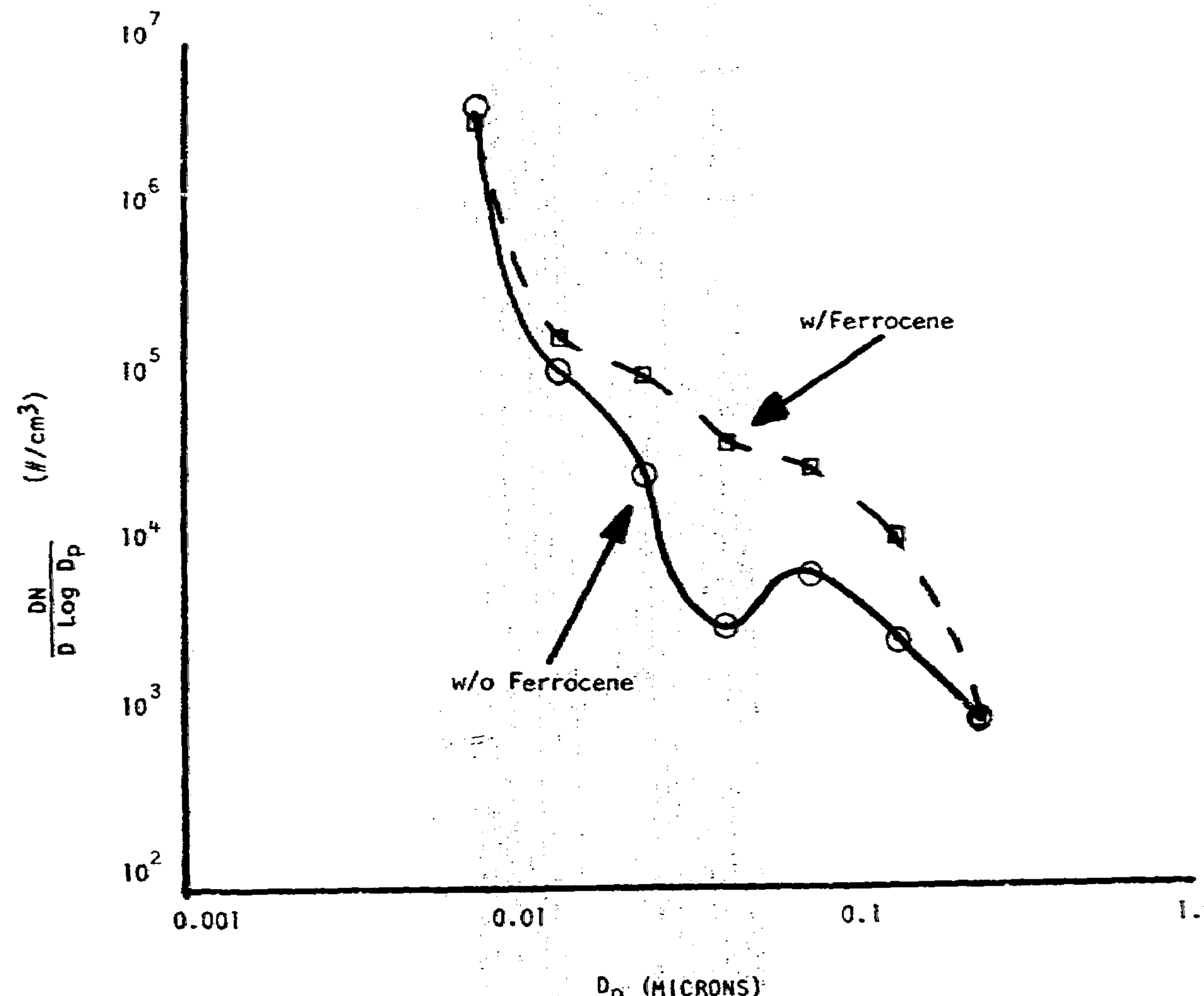


Figure A-3. Size Distribution of Aerosol Emitted From Test Cell by J79 Engine at 30% (Thrust) Power With and Without Ferrocene

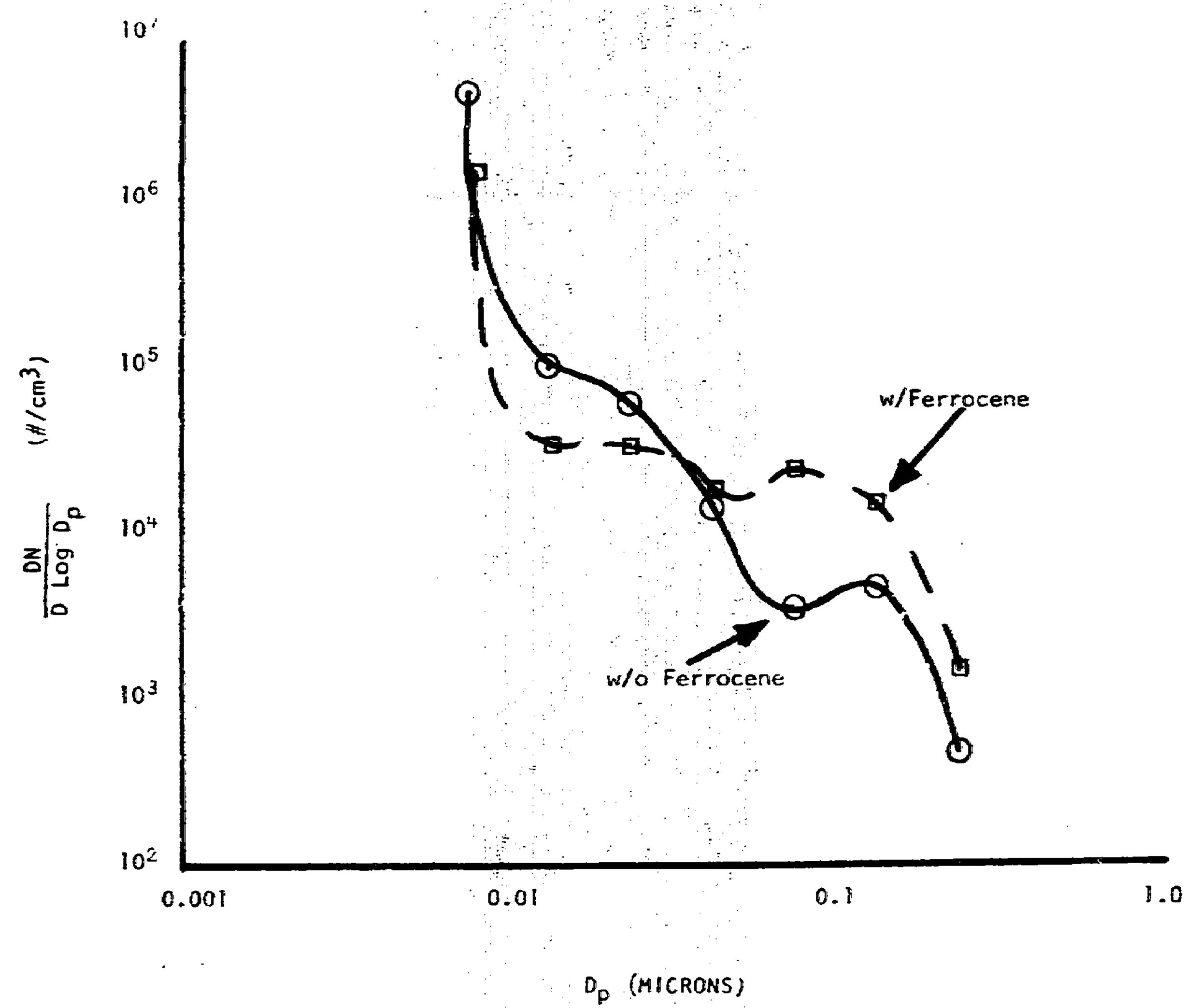


Figure A-4. Size Distribution of Aerosol Emitted From Test by J79 Engine at 85% (RPM) Power With and Without Ferrocene

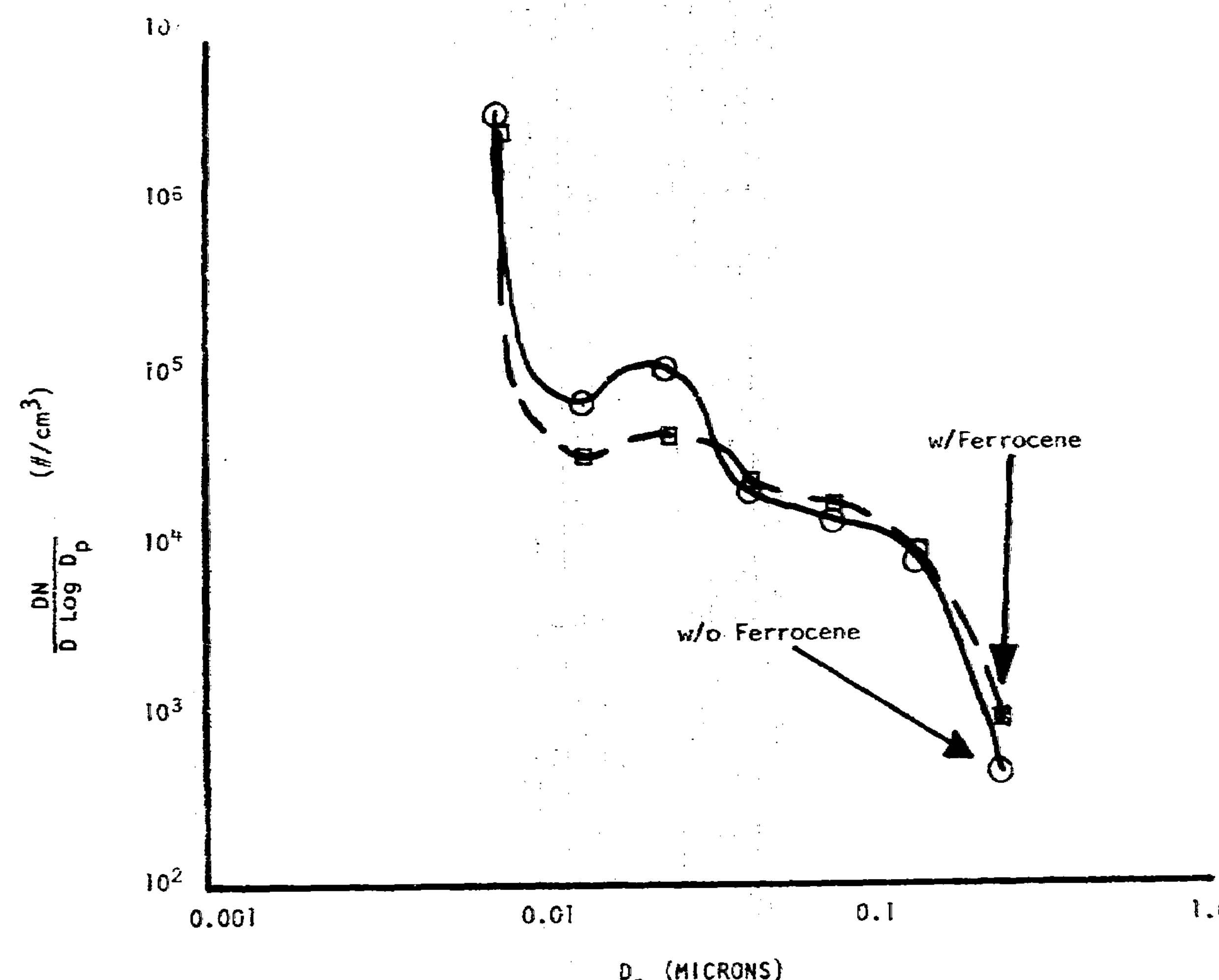


Figure A-5. Size Distribution of Aerosol Emitted From Test Cell by J79 Engine at Normal Rated Power With and Without Ferrocene

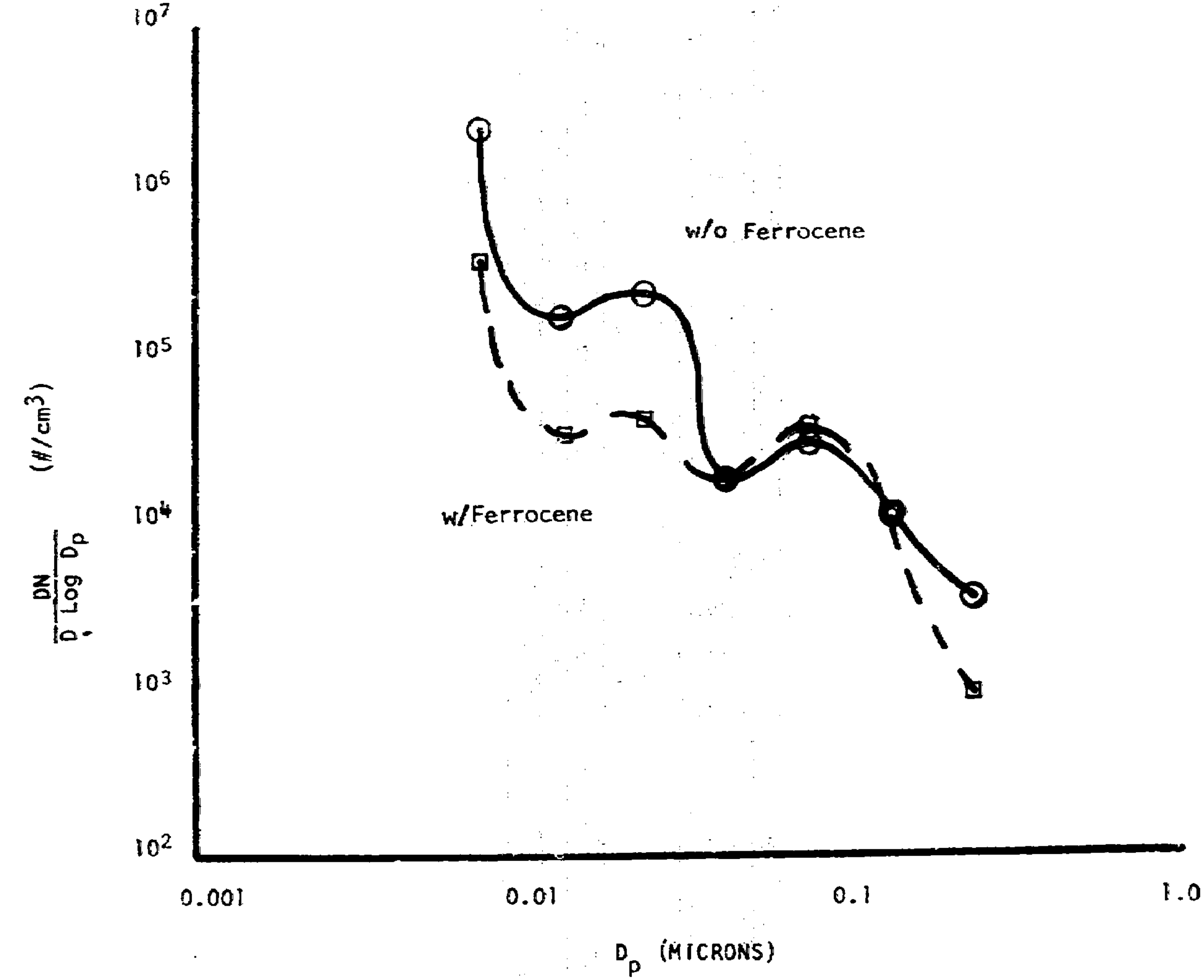


Figure A-6. Size Distribution of Aerosol Emitted From Test Cell by J79 Engine at Military Power With and Without Ferrocene

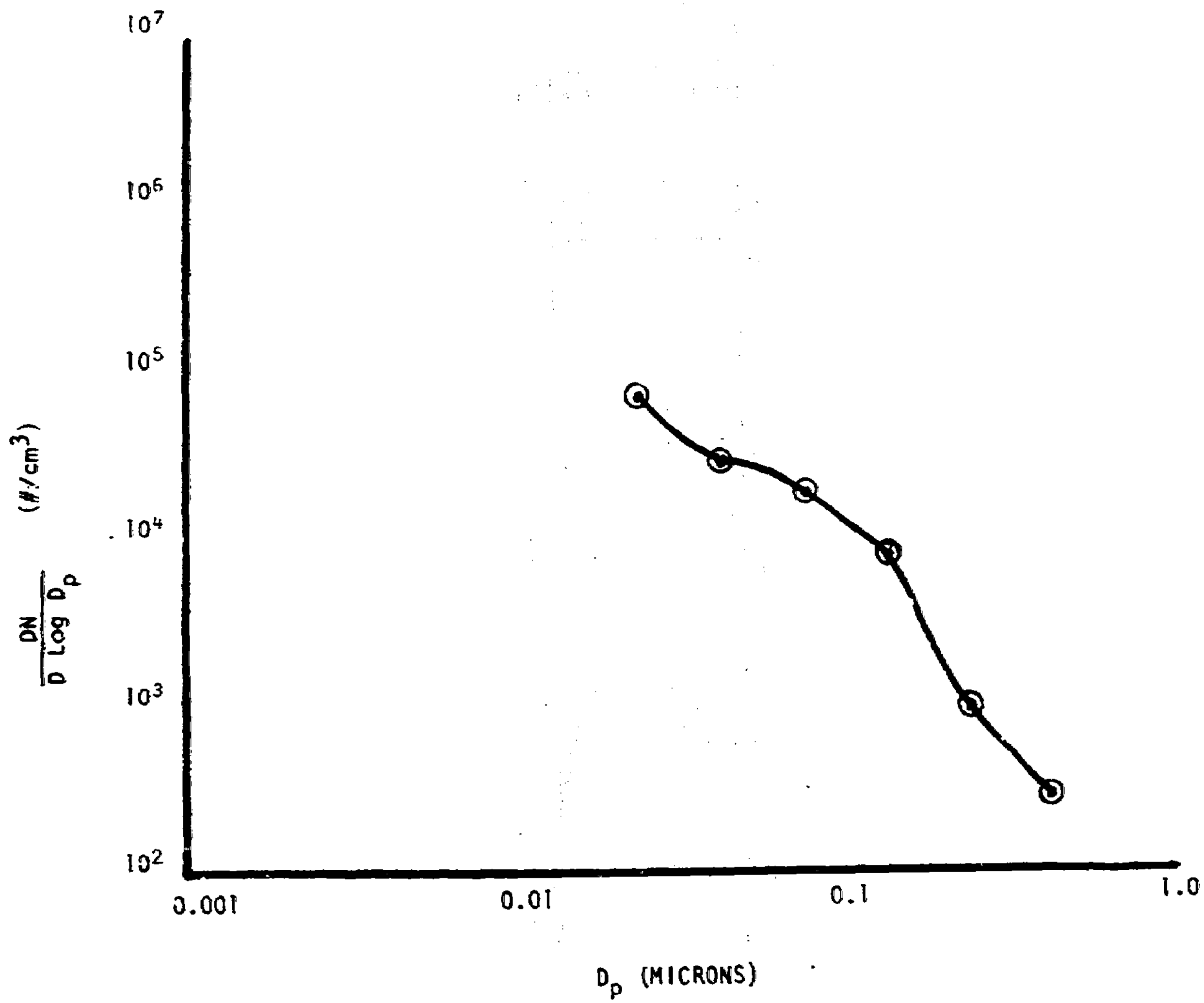


Figure A-7. Size Distribution of Aerosol Emitted From Test Cell by J52 Engine at Idle Power Without Ferrocene

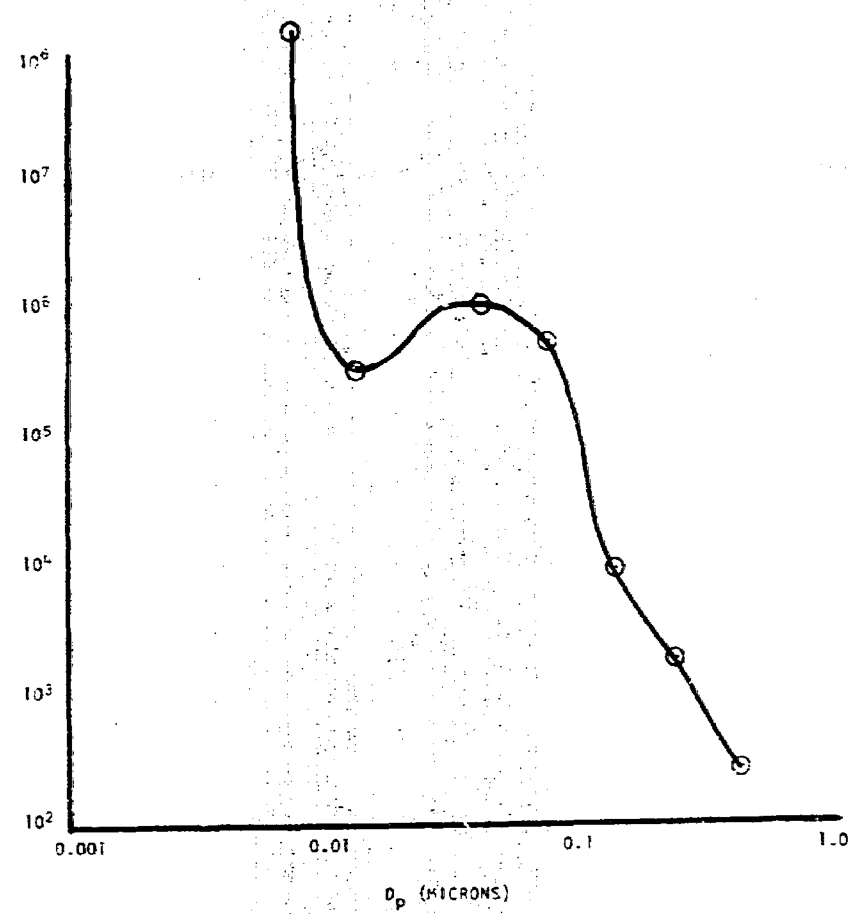


Figure A-8. Size Distribution of Aerosol Emitted From Test Cell by J52 Engine at Normal Rated Power Without Ferrocene

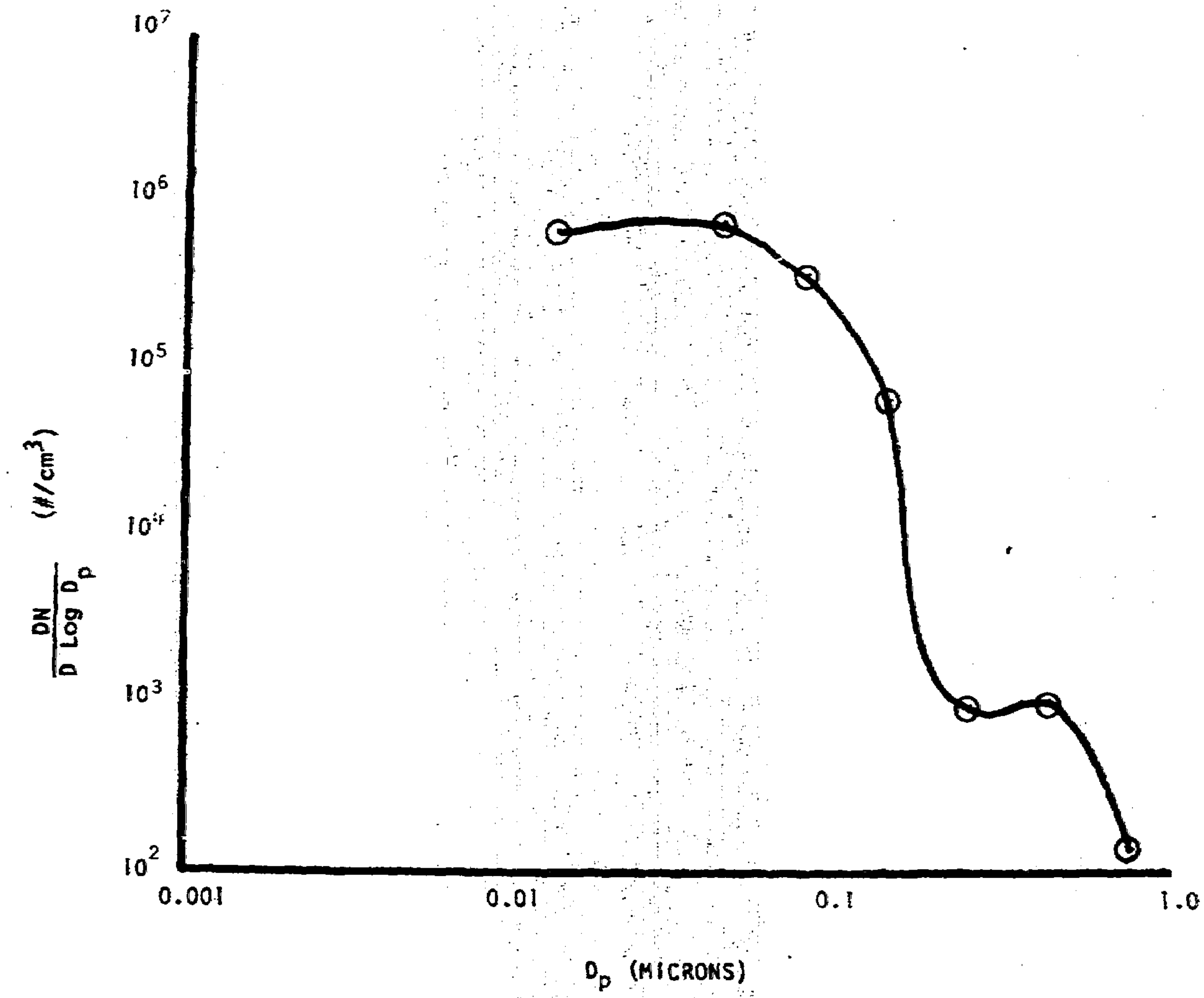


Figure A-9. Size Distribution of Aerosol Emitted From Test Cell by J52 Engine at Military Power Without Ferrocene

Table II gives the results of the Method 5 samples.

TABLE II PARTICULATE EMISSIONS FROM A J52-P-6B GAS TURBINE AT NAVAIREWORKFAC, ALAMEDA

Mode	Without Ferrocene		With Ferrocene	
	mg/m^3	gr/scf	mg/m^3	gr/scf
Idle	1.8	0.0008	-	-
Normal Rated	13.2	0.0058	3.5	0.0015
Military	11.0	0.0048	3.0	0.0013

3. The J57-P-10 engine was sampled at NAVAIREWORKFAC, Alameda on 3 December 1976, and 12 January 1977. Samples taken on 12 January 1977, were size distribution and duplicate total mass emissions without ferrocene at the top of the stack. Figures 10-14 give the size distribution of the particles emitted. Table III gives the results of the Method 5 samples.

TABLE III PARTICULATE EMISSIONS FROM A J57-P-10 GAS TURBINE AT NAVAIREWORKFAC, ALAMEDA

Mode	Engine Exhaust Plane				Top of Stack			
	W/O Ferrocene		W/Ferrocene		W/O Ferrocene		W/Ferrocene	
	mg/m^3	gr/scf	mg/m^3	gr/scf	mg/m^3	gr/scf	mg/m^3	gr/scf
Idle	11.6	0.0051	-		5.2	0.0023	-	
Normal Rated	28.9	0.0126	10.9	0.0048	14.6	0.0064	9.3	0.0041
Military	25.4	0.0111	9.7	0.0042	21.8	0.0095	10.3	0.0045

4. The TF30-P-6C engine was sampled at NAVAIREWORKFAC, Alameda on 6 December 1976, and 14 January 1977. Samples taken on 14 January were size distribution and duplicate total mass samples at the top of the

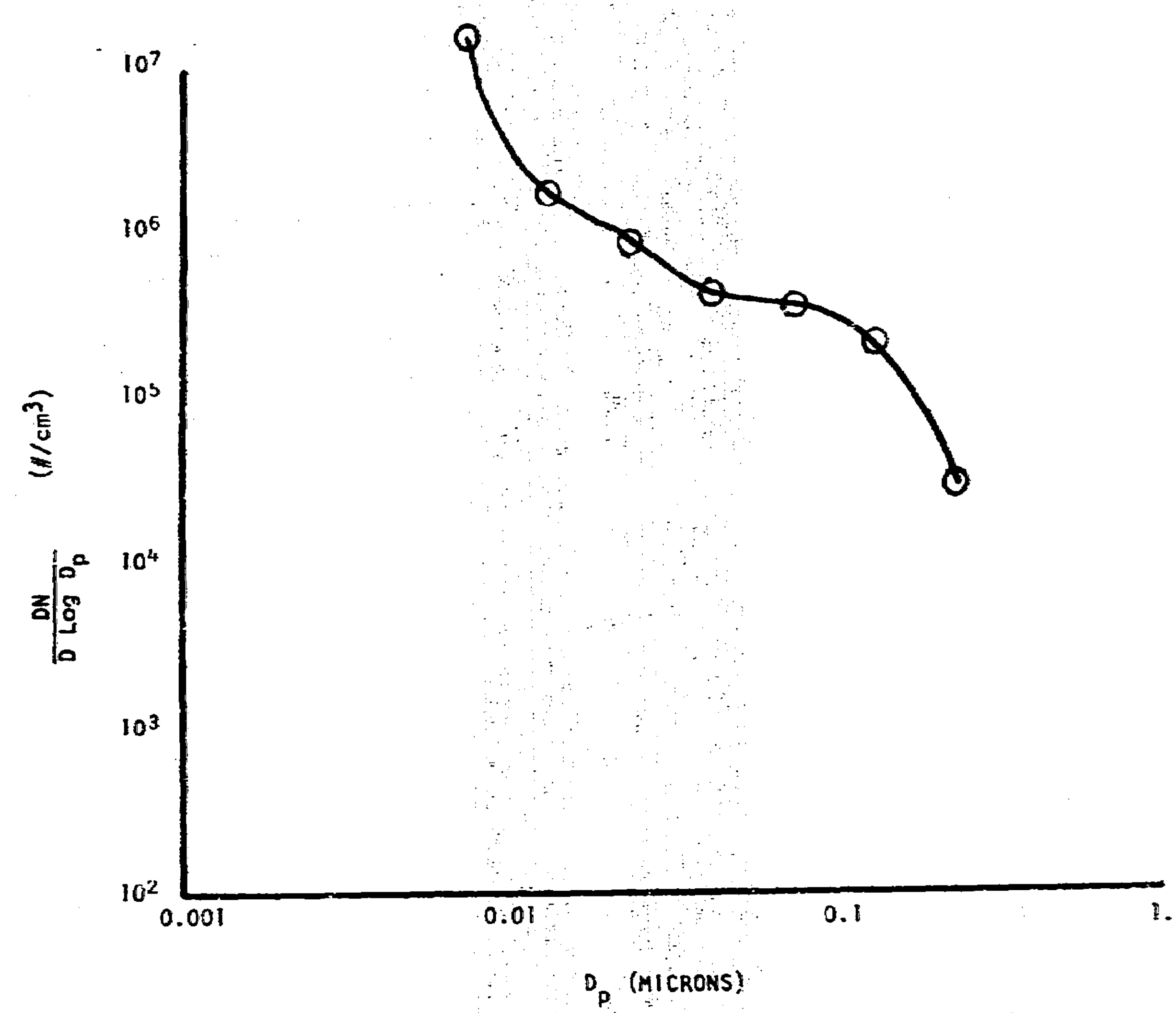


Figure A-10. Size Distribution of Aerosol Emitted From J57 Engine at Idle Power Without Ferrocene

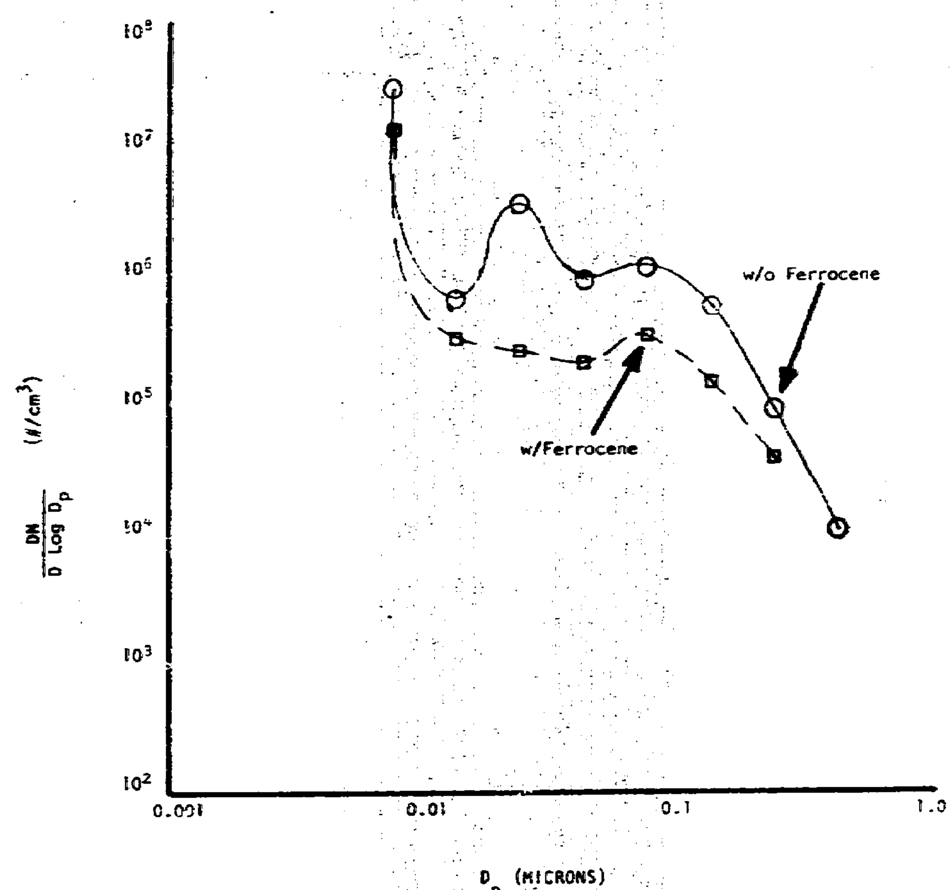


Figure A-11. Size Distribution of Aerosol Emitted From J57 Engine at Normal Rated Power With and Without Ferrocene

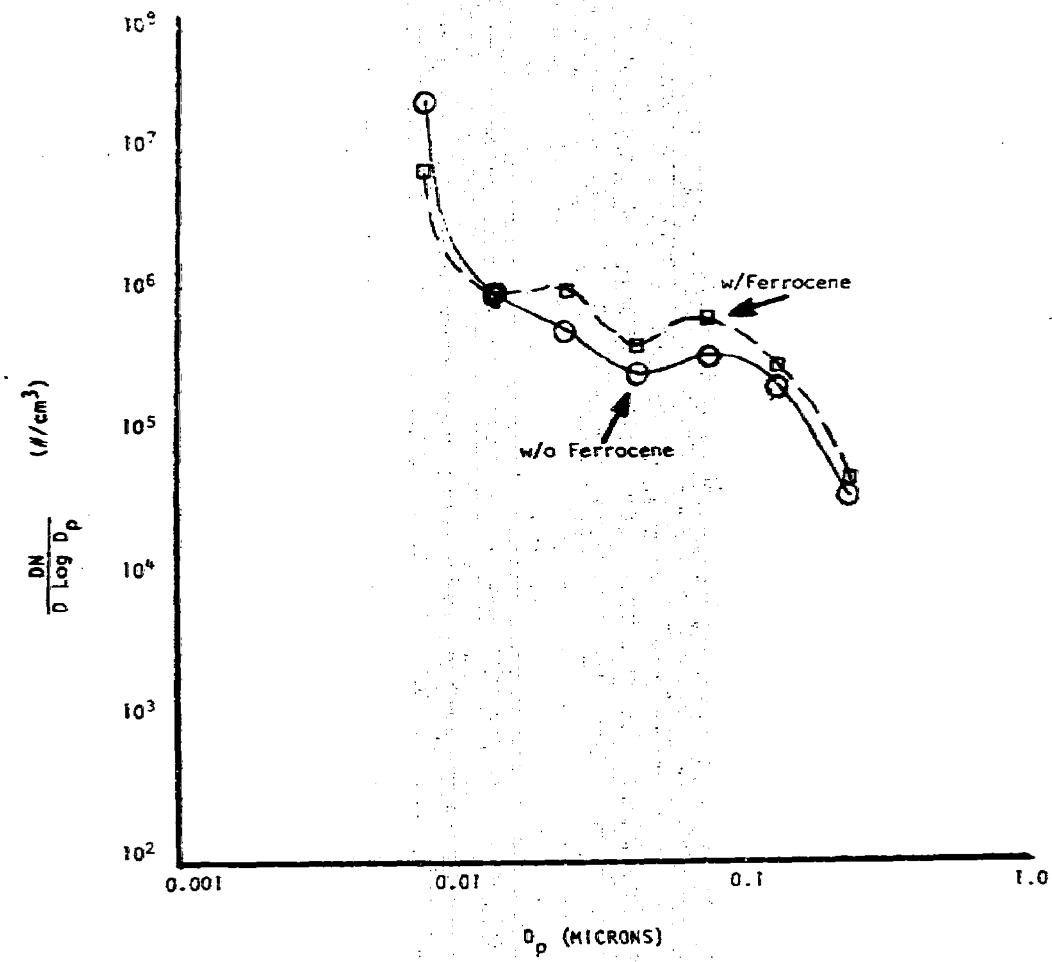


Figure A-12. Size Distribution of Aerosol Emitted From J57 Engine at Military Power With and Without Ferrocene

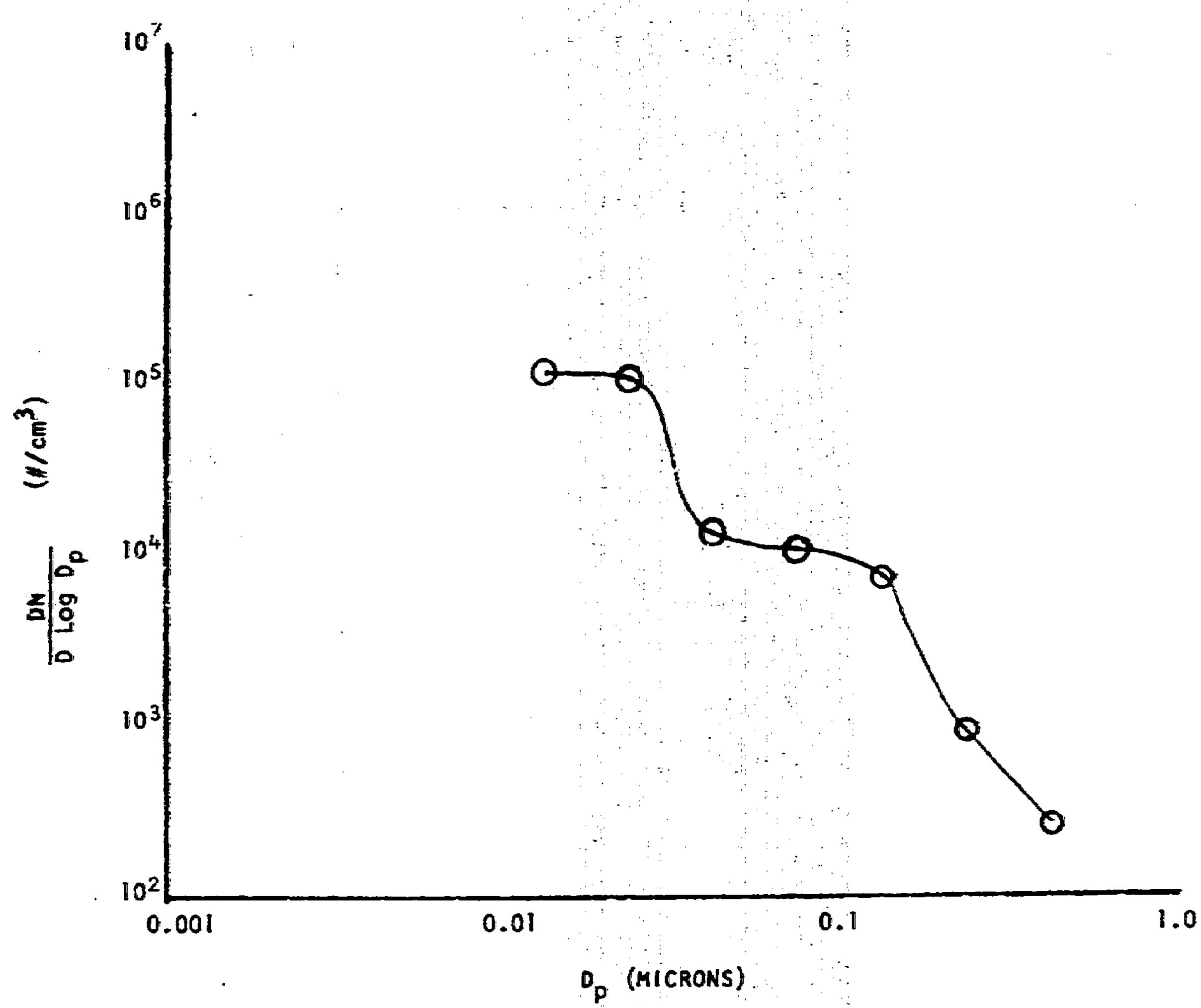


Figure A-13. Size Distribution of Aerosol Emitted From Test Cell by J57 Engine at Normal Rated Power Without Ferrocene

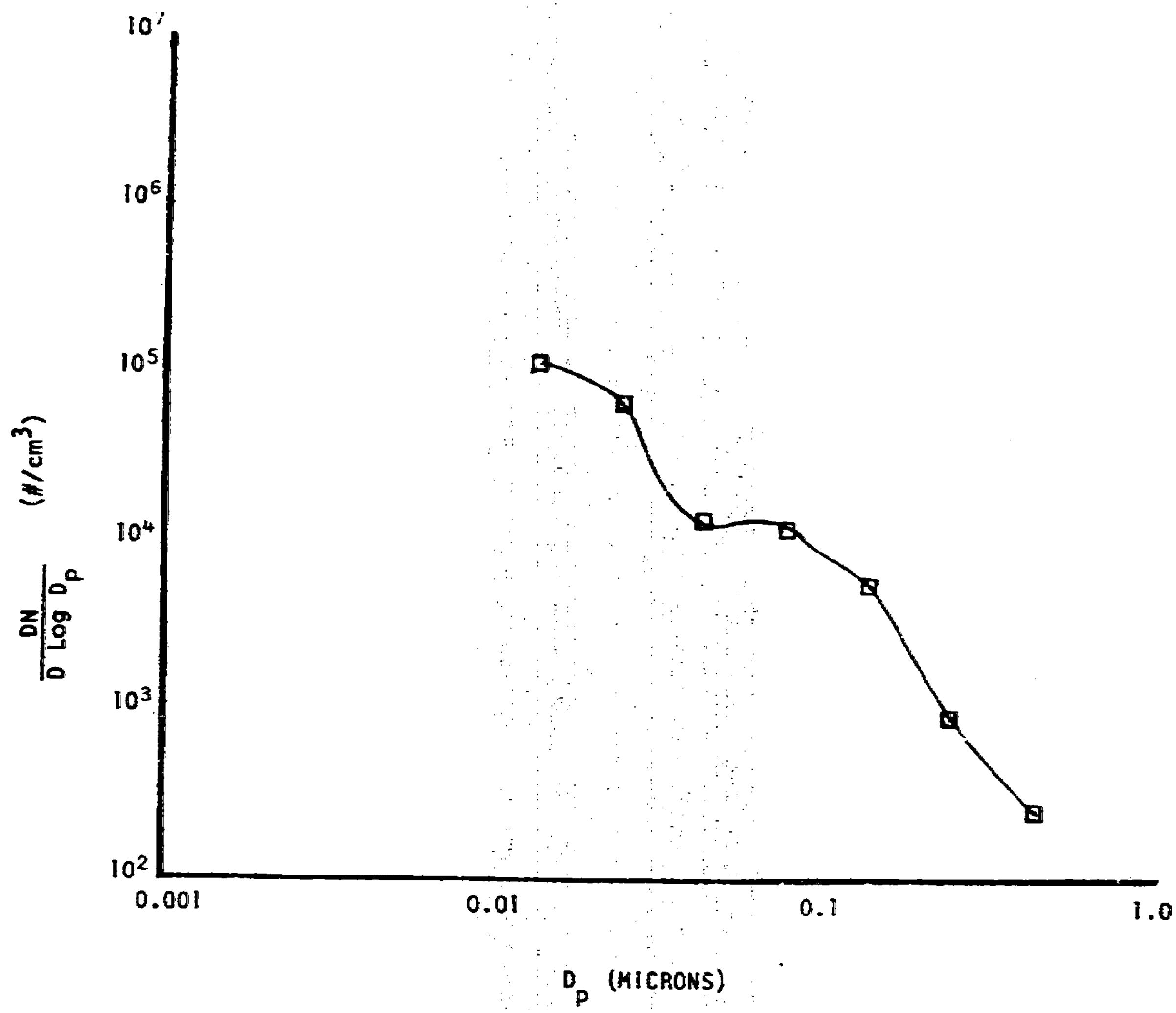


Figure A-14. Size Distribution of Aerosol Emitted From Test Cell by J57 Engine at Military Power Without Ferrocene stack only. Figures 15-18 give the size distribution of the particles emitted. Table IV gives the results of the Method 5 samples.

TABLE IV PARTICULATE EMISSIONS FROM A TF30-P-6C GAS TURBINE ENGINE AT NAVAIREWORKFAC, ALAMEDA

Mode	Engine Exhaust Plane W/O Ferrocene mg/m^3	Engine Exhaust Plane W/O Ferrocene gr/scf	Engine Exhaust Plane W/Ferrocene mg/m^3	Engine Exhaust Plane W/Ferrocene gr/scf	Top of Stack W/O Ferrocene mg/m^3	Top of Stack W/O Ferrocene gr/scf	Top of Stack W/Ferrocene mg/m^3	Top of Stack W/Ferrocene gr/scf
Idle	13.3	0.0058	-	-	3.5	0.0015	-	-
Normal Rated	66.5	0.0290	32.5	0.0142	18.6	0.0081	8.6	0.0038
Military	76.8	0.0335	29.7	0.0130	28.7	0.0125	9.7	0.0042

5. The TF41-A-2 engine was sampled at NAVAIRWWORKFAC, Alameda on 1 and 2 December 1976, and 10 January 1977. Samples taken on 10 January were size distribution and duplicate total mass samples at the top of the stack only. Figures 19-21 give the measured size distribution of the particles emitted. Table V gives the results of the Method 5 samples.

TABLE V PARTICULATE EMISSIONS FROM A TF41-A-2 GAS TURBINE ENGINE AT NAVAIREWORKFAC, ALAMEDA

Mode	Engine Exhaust Plane W/O Ferrocene mg/m^3	Engine Exhaust Plane W/O Ferrocene gr/scf	Engine Exhaust Plane W/Ferrocene mg/mg^3	Engine Exhaust Plane W/Ferrocene gr/scf	Top of Stack W/O Ferrocene mg/m^3	Top of Stack W/O Ferrocene gr/scf	Top of Stack W/Ferrocene mg/m^3	Top of Stack W/Ferrocene gr/scf
Idle	53.0	0.0231	-	-	4.8	0.0021	-	-
Normal Rated	-	-	21.1	0.0092	21.7	0.0095	5.1	0.0022
Military	-	-	20.5	0.0090	12.4	0.0054	32.4	0.0142

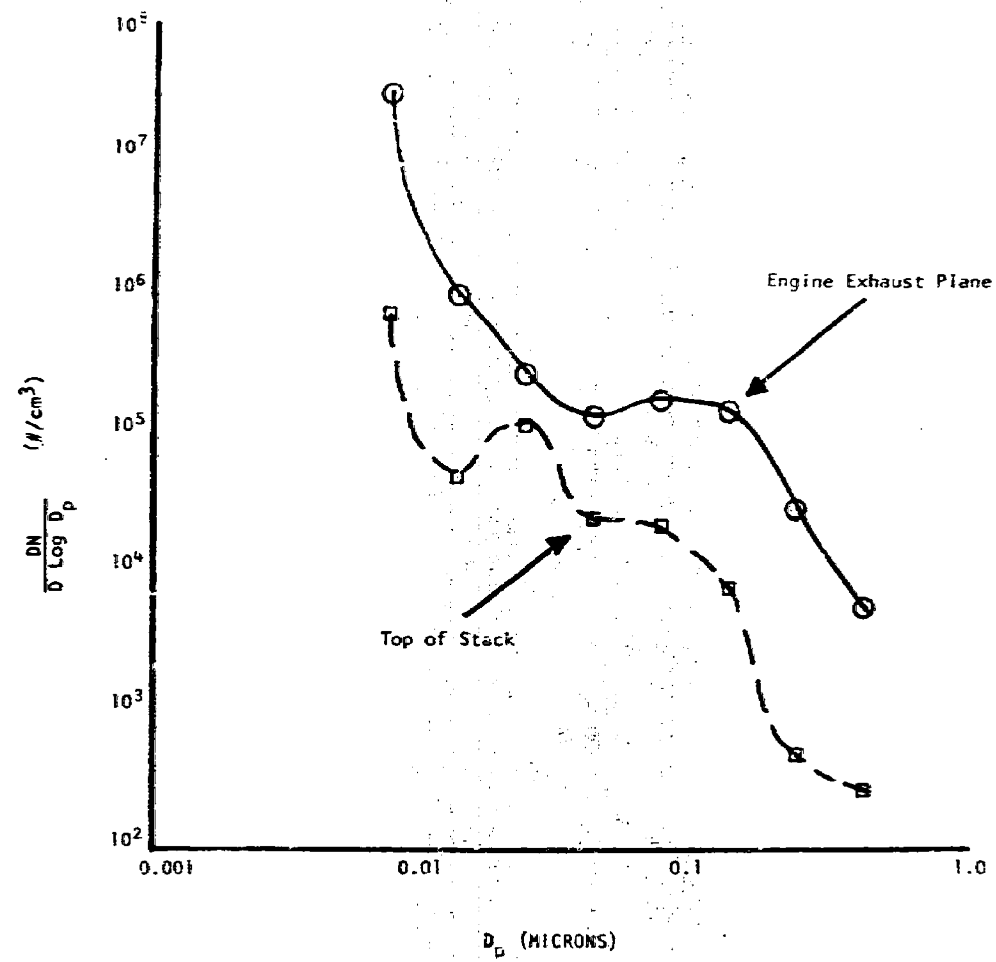


Figure A-15. Size Distribution of Aerosol Emitted From Test Cell Stack and TF30 Engine at Idle Power Without Ferrocene

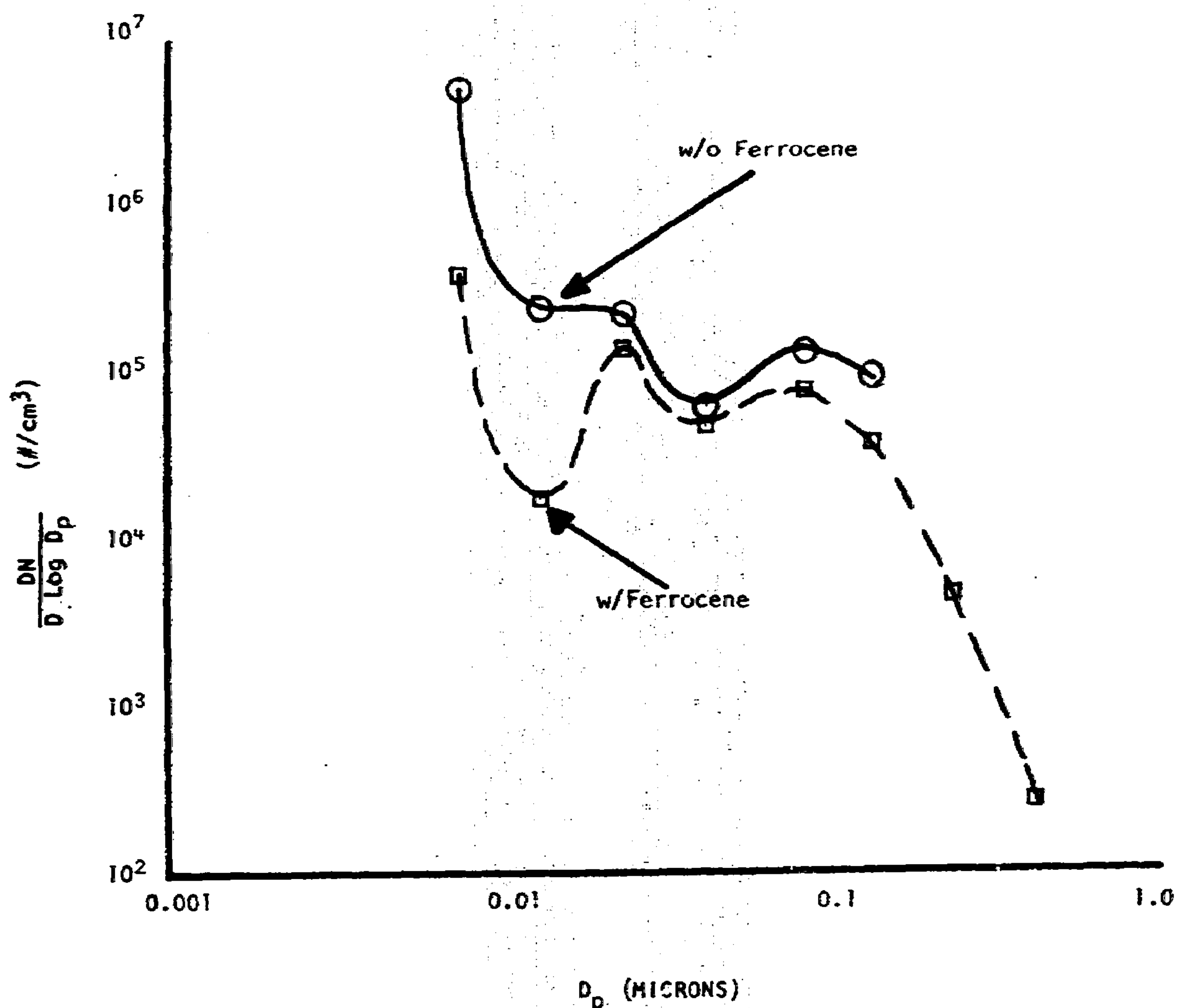


Figure A-16. Size Distribution of Aerosol Emitted From TF30 Engine at Normal Rated Power With and Without Ferrocene

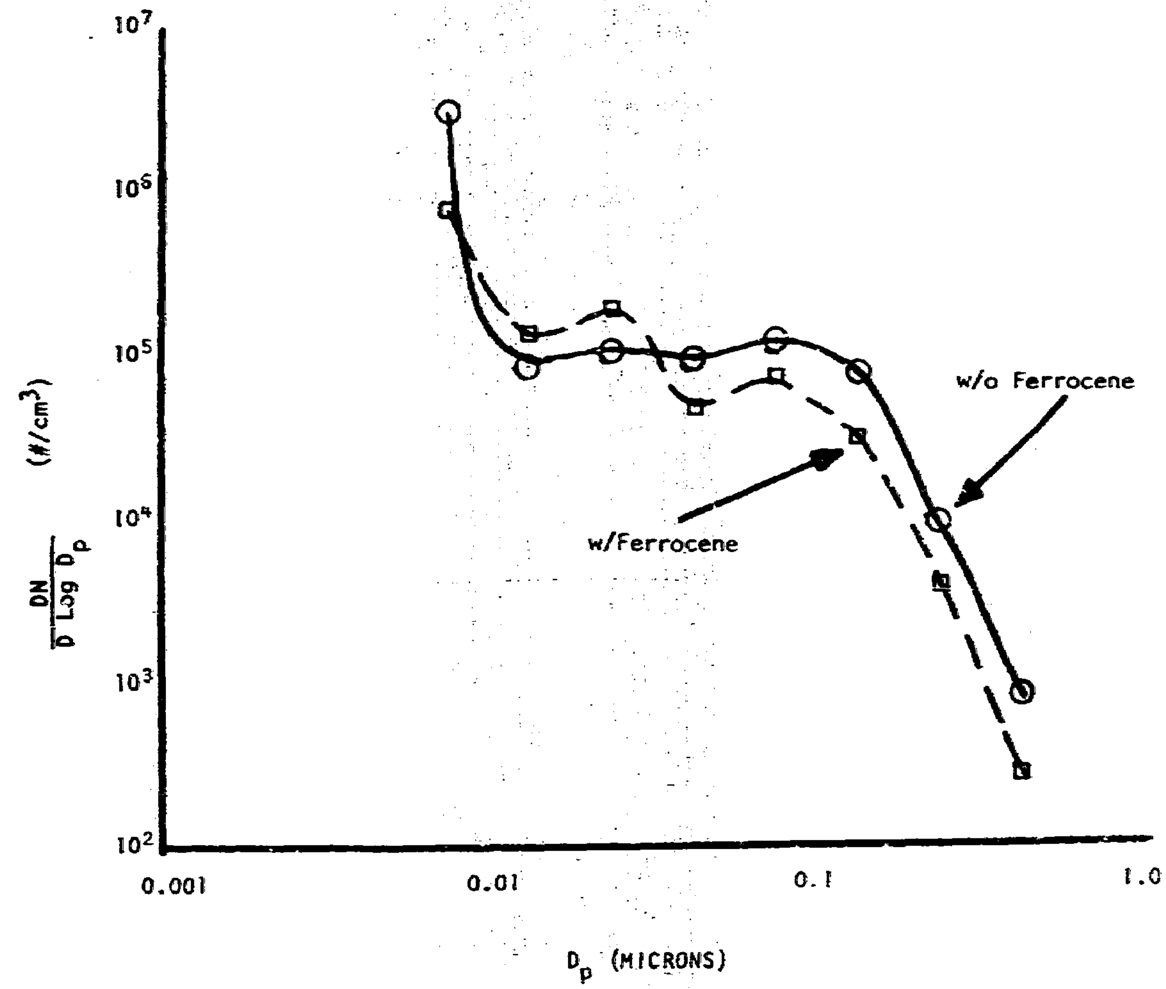


Figure A-17. Size Distribution of Aerosol Emitted From TF30 Engine at Military Power With and Without Ferrocene

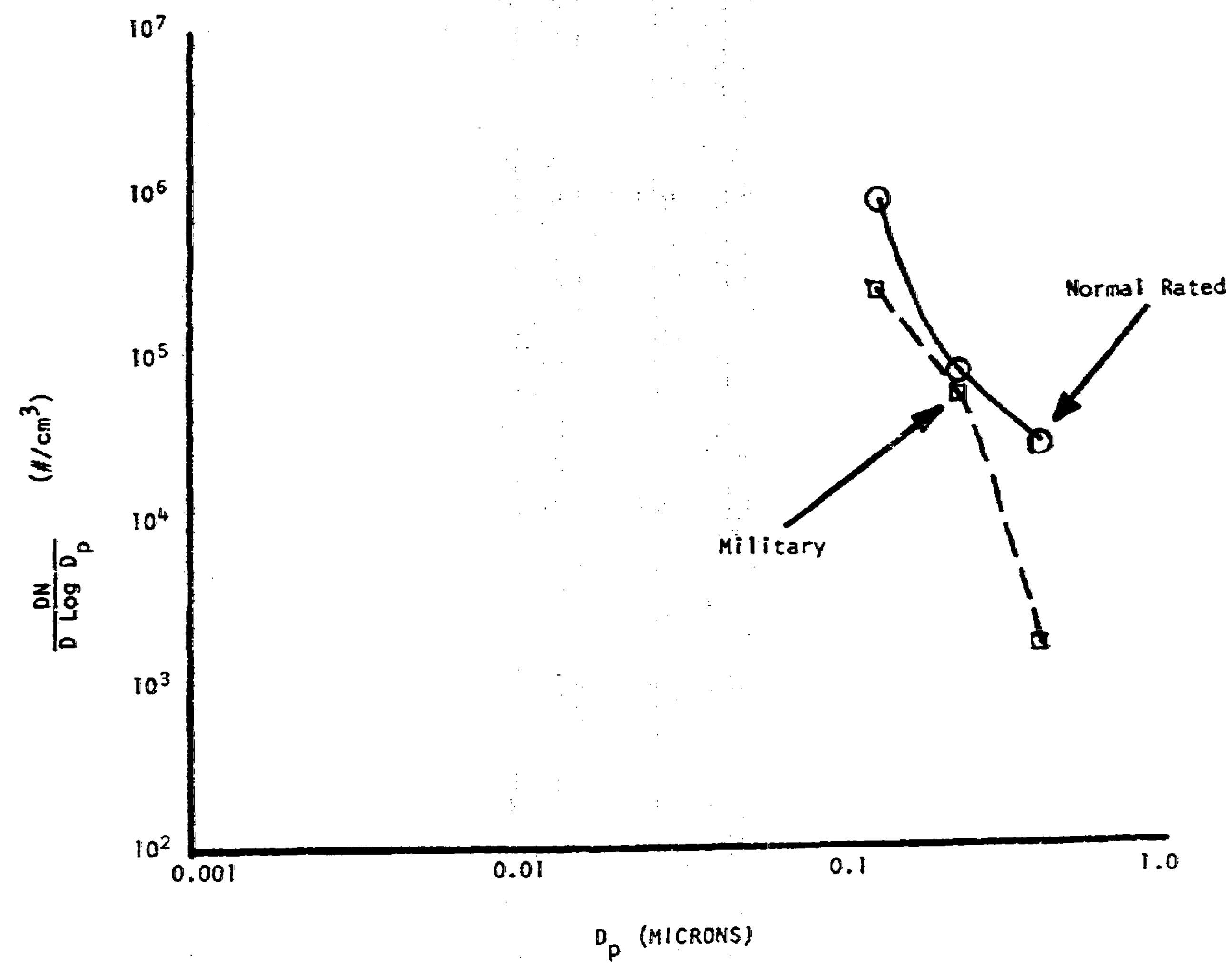


Figure A-18. Size Distribution of Aerosol Emitted From Test Cell by TF30 Engine at Normal Rated and Military Power Without Ferrocene

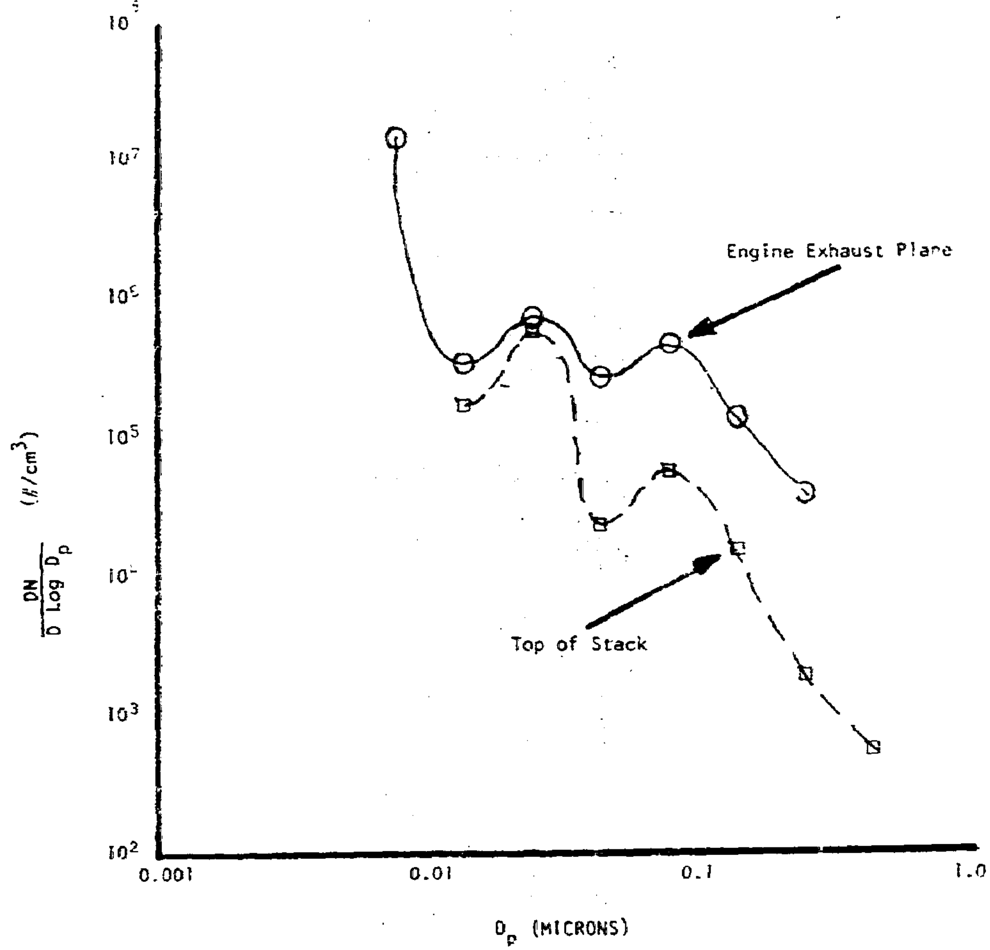


Figure A-19. Size Distribution of Aerosol Emitted From Test Cell Stack and TF41 Engine at Idle Power Without Ferrocene

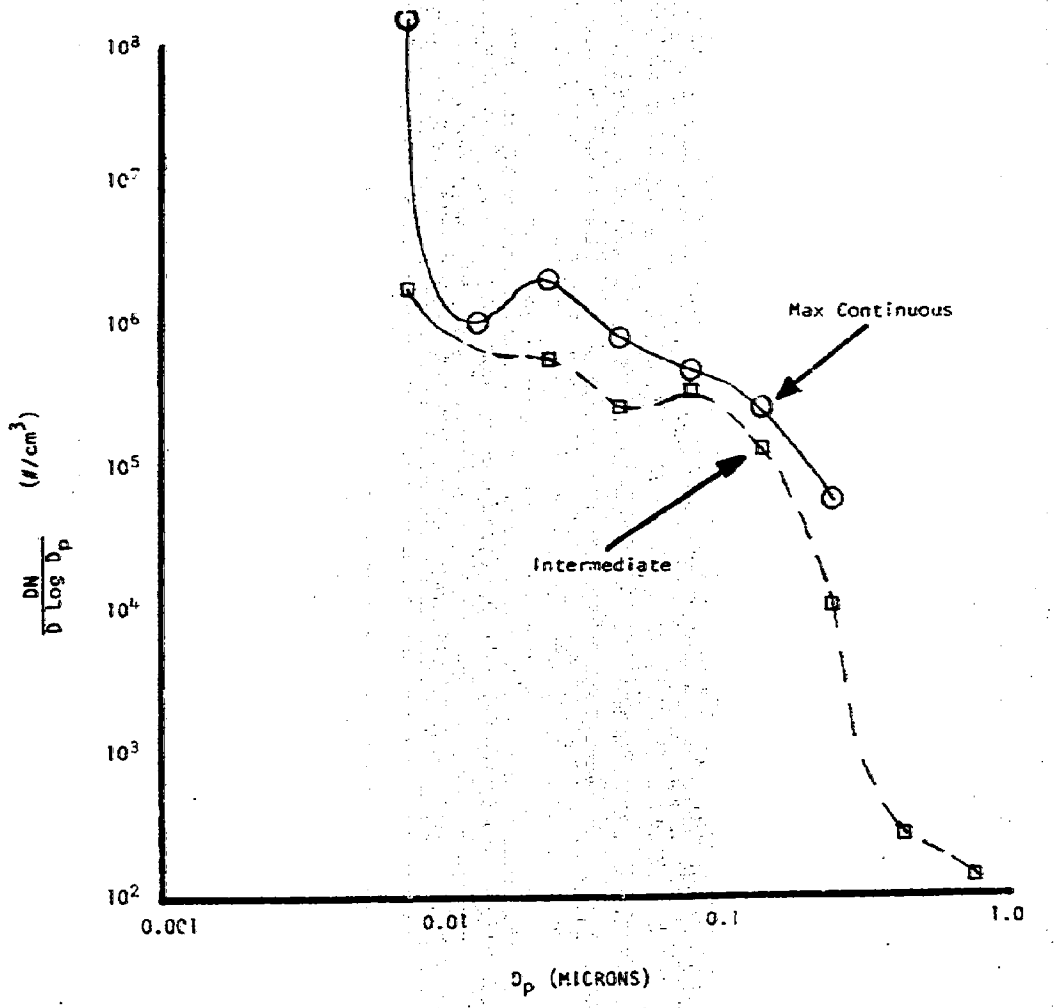


Figure A-20. Size Distribution of Aerosol Emitted by TF41 Engine at Normal Rated and Military Power With Ferrocene

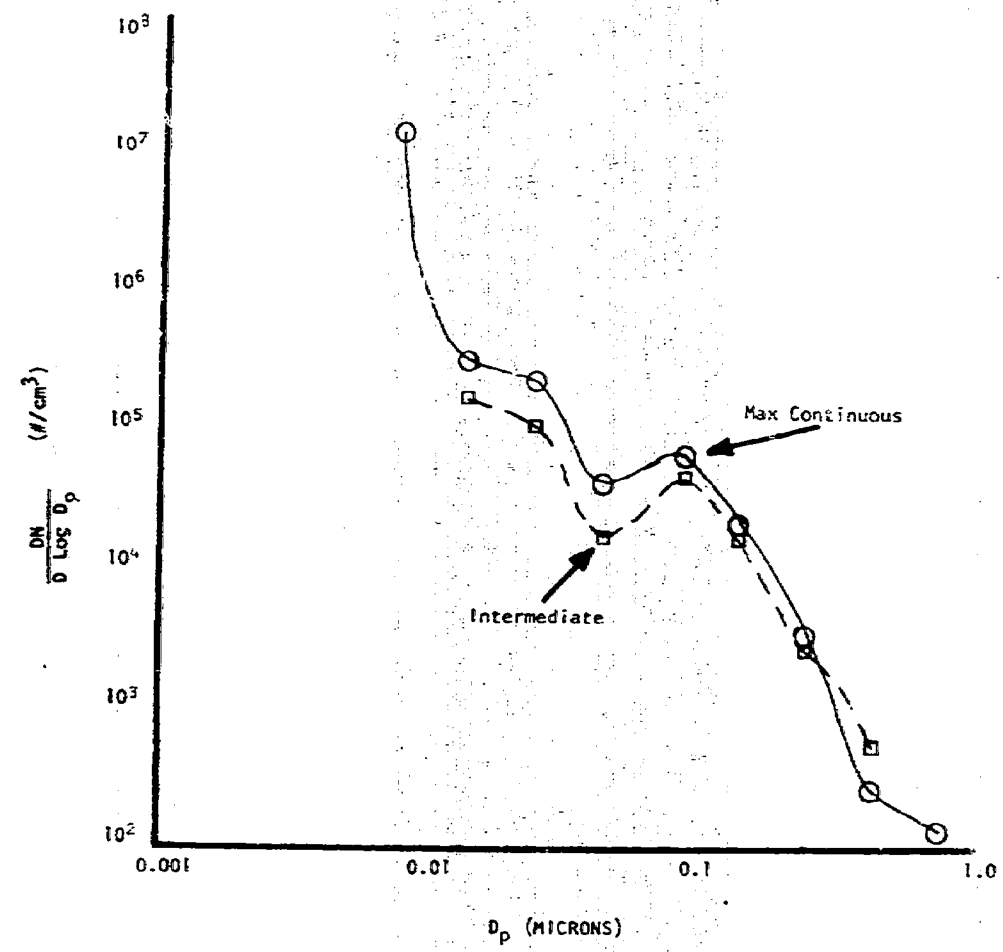


Figure A-21. Size Distribution of Aerosol Emitted From Test Cell by TF41 Engine at Normal Rated and Military Power Without Ferrocene

III. CONCLUSIONS

A. Total Mass Emissions

1. Ferrocene reduced particulate emissions from the J52, J57, and TF30 by approximately 50%. The reduction is evident at both the engine exhaust plane and the top of the stack for the J57 and TF30. No engine exhaust plane samples were taken from the J52 due to excess engine nozzle to probe distance.

2. The data for the J79 and TF41 are mixed. Ferrocene reduced emissions from the J79 at 85% RPM and normal rated, but increased them at military power. The TF41 data shows a similar anomaly. More samples from the J79 and TF41 need to be taken to determine the true effect of ferrocene on these engines.

B. Size Distribution

1. Direct comparison of the effect of ferrocene on the aerosol size distribution is possible in Figures 3, 4, 5, 6, 11, 12, 16, and 17. Figures 6, 11, and 16 show a reduction in all aerosol sizes. Figures 4, 5, and 12 show fewer smaller and more larger particles. Figure 17 shows a reduction of the very small and larger sizes. Figure 3 shows an increase in all aerosol sizes.

2. In six of the cases investigated, ferrocene seemed to reduce the number of particles $<0.03\mu$ in diameter. In three of the cases, all particle sizes were reduced. In one case the number of particles actually increased. Unfortunately, it is not possible to compare total mass loadings for this case (Figure 3) due to the loss of one of the samples.

C. Overall Conclusions

1. Ferrocene has been shown to reduce total particulate emissions and visible emissions for three of the gas turbine engines tested. There are indications such reductions will be shown for the remaining two engines (TF41 and J79) with further testing.

2. Figure 22 is a plot of percent mass emissions reduction/percent Ferrocene by weight versus percent Ferrocene by weight for all samples using ferrocene except TF41 and J79 at military. The data points were fitted to an expoential curve using a least squares regression method. The correlation coefficient (r^2) was 0.90.

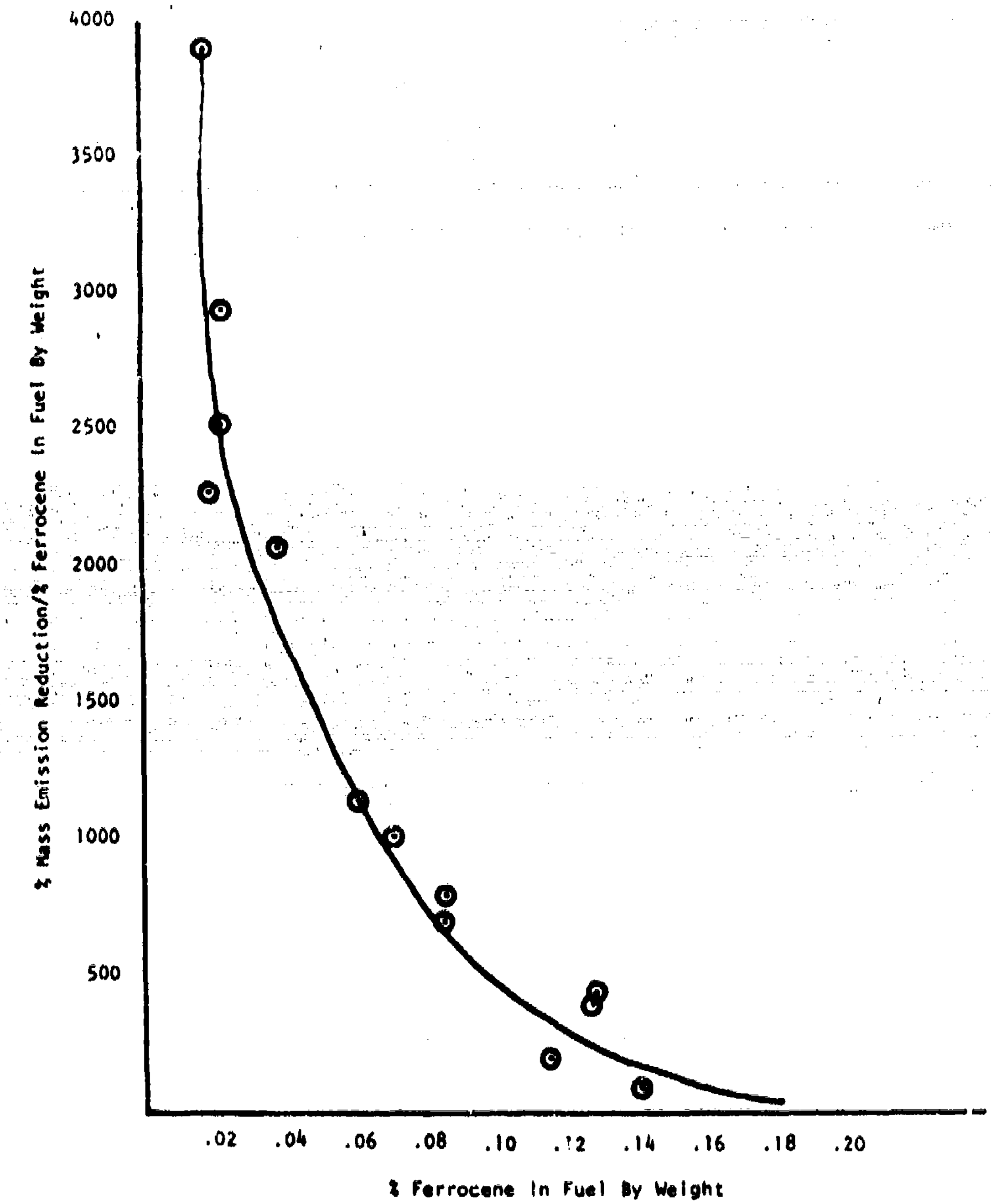


Figure A-22. Change in Mass Emissions as a Function of Ferrocene Concentration

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APPENDIX B

TOTAL HYDROCARBON EMISSIONS FROM J57 AND TF41 ENGINES DURING FERROCENE-CONTAINING FUEL EVALUATIONS

NAVAL ENVIRONMENTAL PROTECTION SUPPORT SYSTEM
NAVAL AIR SYSTEMS COMMAND
AIRCRAFT ENVIRONMENTAL SUPPORT OFFICE
NAVAL AIR REWORK FACILITY
NORTH ISLAND, CALIFORNIA 92135

ABSTRACT

The total hydrocarbon content of the exhaust gas from a J57 and a TF41 engine was measured as part of testing to determine the effect of ferrocene-containing fuel on the operation of the engine. Measurements were made at the exhaust plane of the engine. Most hydrocarbon concentrations were in the range of 2-4 ppmC.

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I. INTRODUCTION

Special tests to determine the effect of ferrocene-containing fuel on the operational characteristics and the components of gas turbine engines were initiated at the Naval Air Rework Facility (NAVAIREWORKFAC), North Island on 8 November 1976 and at NAVAIREWORKFAC, Alameda on 29 November 1976. These tests were coordinated by Naval Air Propulsion Test Center (NAVAIRPROPTESTCEN). The main purpose of these tests was to evaluate the engine after 10-hour operation using ferrocene-containing fuel. In related testing, the Aircraft Environmental Support Office (AESO) measured gaseous, smoke and particulate emissions at NAVAIREWORKFAC, North Island and total hydrocarbon and particulate emissions at NAVAIREWORKFAC, Alameda. The United States Air Force School of Aerospace Medicine (USAFSAM) collected hydrocarbon samples at NAVAIREWORKFAC, Alameda.

This report gives the results of the total hydrocarbon measurement by AESO at NAVAIREWORKFAC, Alameda.

II. EXPERIMENTAL

A. EQUIPMENT

1. Hydrocarbon Analyzer

A Beckman Model 402 Hydrocarbon Analyzer was used for the determination of total hydrocarbons. The zero reference was "zero" air. The span calibration gas was 50.8 ppm propane referenced to National Bureau of Standards "Standard Reference Material 1667" (Propane in Air, 46.3 ± 0.5 ppm by volume.)

2. Sampling Probes

Twelve-hole-cruciform probes were used to collect gaseous emission samples at the exhaust plane of the engine. Each arm of the probe contained three holes of the sizes and at the locations specified in Table II-1

TABLE II-1

Sizes and Locations of Holes in Cruciform Probes

Engine	Hole diameter inches	Location of holes from the center of the probe inches		
J57	1/4	4 7/8	8	10 1/4
TF41	1/8	5 1/4	9	11 1/2

Samples from all twelve holes were combined into a single stream before being put in the sample line.

3. Sample Line

The sample line between the probe and the instruments was a 50-foot-insulated-Teflon-core line (3/8" O.D.) maintained at

$300 \pm 10^{\circ}F$. The sample line was pressure tested both before and after use to verify that there were no leaks during the sampling. The sample line was divided at the instrument end. One branch went to the AESO hydrocarbon analyzer and the other to the USAFSAM three-stage cryogenic sampler.

b. When an engine was in operation, the pressure in the sample line was higher than could be regulated to operational range by the flow control system of the hydrocarbon analyzer. The pressure was adjusted to the operational range of the instrument by adding an adjustable flow-restricting valve between the sample line and the hydrocarbon analyzer.

B. COLLECTION AND ANALYSIS OF DATA

1. Total Hydrocarbon Analysis of Exhaust Gas Stream

AESO made continuous measurements of the total hydrocarbon content of the gas stream at the engine exhaust plane during the collection of cryogenic samples by USAFSAM. Each sample was collected for about one hour. Except for one run in which the probe broke, cryogenic samples were collected at the exhaust plane for both the TF41 and the J57 engines each operating with either regular JP-5 fuel or JP-5 fuel containing ferrocene. Cyrogenic samples of the exhaust stream at the top of the stack were collected during some of these runs. The continuous recorder traces from the AESO hydrocarbon analyzer output show every little deviation throughout the sampling periods. Zero and span references were recorded at arbitrary intervals. Tables II-2 through II-5 report representative total hydrocarbon values. For best accuracy, each reported reading was made either just before or just after the recording of the zero and span references.

TABLE II-2

Hydrocarbon Emissions from TF41-A-2A engine, JP-5 Fuel Containing Ferrocene

Engine	TF41-A-2A
Serial number	141479
Fuel	JP-5 Containing ferrocene
Power setting	75% Thrust
Test cell	Alameda 15
Probe	TF41
Date	1 December 1976

Sample	Elapsed time Minutes	Total hydrocarbons ppmC
1	7	3.5
2	12	2.3
3	41	1.9
4	46	1.9
5	62	2.1
6	72	1.9

TABLE II-3

Hydrocarbon Emissions from a TF41-A-2A Engine, JP-5 Fuel

Engine	TF41-A-2A
Serial number	141479
Fuel	JP-5, no ferrocene
Power setting	75% Thrust
Test cell	Alameda 15
Probe	J57[a]
Date	2 December 1976

Sample	Elapsed time	Total hydrocarbons
	Minutes	ppmC
1	16[b]	8.8

a. The J57 probe was used in this run because the TF41 probe broke during a prior endurance test.

b. The total time of the sample collection at the exhaust plane was limited to about 20 minutes. The probe broke during this run. A repetition of this run could not be scheduled.

TABLE II-4

Hydrocarbon Emissions From A J57-P-10 Engine, JP-5 Fuel

Engine	J57-P-10
Serial number	627207
Fuel	JP-5, no ferrocene
Power setting	75% Thrust
Test cell	Alameda 15
Probe	J57
Date	3 December 1976

Sample	Elapsed time Minutes	Total hydrocarbons ppmC
1	2	4.4
2	17	2.6
3	32	2.6
4	50	2.2

TABLE II-5

Hydrocarbon Emissions from a J57-P-10 Engine, JP-5 Fuel Containing Ferrocene

Engine	J57-P-10
Serial number	627207
Fuel	JP-5 containing ferrocene
Power setting	75% Thrust
Test cell	Alameda 15
Probe	J57
Data	3 December 1976

Sample	Elapsed time Minutes	Total hydrocarbons ppmC
1	2	1.6
2	15	2.3
3	45	1.8
4	60	1.5

2. Analysis Of Bag Samples.

USAFSAM collected bag samples from the exhaust stream before and after it passed through the three stage cryogenic sampler. The sample collected before the cryogenic sampler passed through a water trap and a Tenax trap before entering the sample bag. Tenax is an adsorbent marketed by Applied Science Labs., State College, PA. This sample is referred to as the "Tenax" bag sample. The sample collected after the cryogenic sampler passed through a Tenax trap and then into the sample bag. This sample is referred to as the "Cryogenic" bag sample. Each bag sample was collected for about one hour. Bag samples from measurements at the exhaust plane of the engine were analyzed by AESO for total hydrocarbon content immediately after each run. Bag samples from the top-of-the-stack sampling position were analyzed at the conclusion of the J57 run with ferrocene-containing fuel.

The total hydrocarbon concentration for each bag is reported in Table II-6. AESO measurements were made on each bag by drawing a sample through the hydrocarbon analyzer for about 20 seconds.

3. Related Measurements

At arbitrary times during the testing, AESO measured the total hydrocarbon content of the ambient air in the test cell and in the service room betweem cells 15 and 16 in which the AESO and USAFSAM instruments were located. Measurements on test cell air were made when the engine was not in operation. Total hydrocarbon concentration in the test cell ranged from 5.9 to 11.8 ppmC and in the service room, usually from 5.2 to 9.6 ppmC. On one occasion, due to leakage in the ferrocene injection system the total hydrocarbon concentration in the service room reached 40 ppmC.

TABLE II-6

Total Hydrocarbons Content of Bag Samples

Engine	Ferrocene in fuel	Probe location	Bag number	Bag sampling location	Flow rate l/min	Total hydrocarbons ppmC
TF41-A-2A	yes	Engine	1	a	a	2.4
	yes	exhaust	2	a	a	1.4
	yes	plane	3	a	a	3.2
J57-P-10	no	Engine	1	Tenax	1.0	2.7
	no	exhaust	2	"	0.5	2.2
		plane	3	Cryogenic	-	3.0
J57-P-10	yes	Engine	1	Tenax	1.0	4.4
	yes	exhaust	2	"	0.5	3.4
	yes	plane	3	Cryogenic	-	5.6
J57-P-10	no	Top of	1	Cryogenic	-	4.7
	no	stack	2	Tenax	1.0	4.9
J57-P-10	yes	Top of	3	Tenax	1.0	5.9
	yes	stack	4	Cyrogenic	-	3.1

[a] Not known

III. CONCLUSION

For a J57-P-10 and a TF41-A-2A engine operating at 75 percent thrust and using either JP-5 fuel or JP-5 fuel containing ferrocene, the total hydrocarbon concentration of the gas stream at the exhaust nozzle of the engine usually was in the range of 2-4 ppmC.

APPENDIX C

VISUAL REPORT, J79-GE8 HOT SECTION PARTS

BY: KEN HOPKINS/AFAPL/TBC/55421

TO: CHARLES R. MARTEL/AFAPL/SFF

DATE: 2 MARCH 1977

1. BACKGROUND:

Several hot section parts from a J79-GE8 were brought to the Air Force Aero-Propulsion Laboratory, Components Branch, Combustion Technical Area (AFAPL/TBC) for visual inspection and report. The engine had been run for about 10 hours in a Naval Air Propulsion Test Center (NAPTC) test cell using JP-5 containing ferrocene. The object of the test was to determine whether the introduction of ferrocene, a smoke abatement agent, during relatively short test cell operations would have any adverse affects on the life and health of the engine. This report is based on observation.

2. OBSERVATIONS:

The reviewed parts were one (1) combustor liner (Figures 1 through 5), two (2) first-stage turbine blades (Figure 6) and one (1) fuel nozzle (Figure 7).

The inside of the combustor liner was orange in color (Figures 1 through 5). This orange film was loosely attached as it could be wiped off. This can be seen in the fingerprint smears in Figure 1 at the 3 o'clock position near the liner exit. However, some of the orange film seems to be attached firmly.

The liner showed some evidence of warm streaking but only one streak stood out (Figure 2 at the 4 o'clock position near the liner exit and seen also in Figure 3 at the 1 o'clock position.

Liner cracking was non-existent.

There was some discoloration on the outside of the liner but this was not a deposit but rather caused by temperature. The warm streak mentioned above, when viewed from the outside seems to be a cool area.

In Figure 4, the warm streak appears at 10 o'clock where there is no metal discoloration. Note, however, the 8 o'clock position has obviously been operating at a higher temperature as shown by the discolored louvers.

The first-stage turbine blades were orange to red in color (Figure 6). This coating is apparently the same as that on the combustor liner. There was no evidence of cracking, oxidation or other distress.

The fuel nozzle appeared to have a limited thickness of orange coating on the radiation shield (or cooling shroud). The build-up of carbon seemed to be thicker than the orange coating (Figure 7).

3. CONCLUSIONS AND RECOMMENDATIONS

The orange coating on the liner should not shorten its life unless it metallurgically weakens the liner (to be determined by others) or it dramatically increases the liner surface emissivity. Since most coatings and oxides possess emissivities of at least 0.8 with none above 0.9, the increase in emissivity is not expected. If the emissivity increases significantly, the liner temperature increases which could shorten its life and also could lead to combustor case burn-through. Although this is not expected, it cannot be rejected. However, if the orange coating is removed by operating the engine with pure JP5, this potential problem would be solved. A ground test would be sufficient to determine this if the ambient air does not contain impurities that are commonly called "iron oxide" by ground test personnel.

The warm streak is not unusual. The J79 usually possesses warm streaks and hot streaks. However, this reviewer is not accustomed to inspecting parts that were subjected to only 10 operating hours.

The build-up on the fuel nozzle shroud appears to be thicker than on the other parts. Build-up can be serious because it distorts the fuel spray. The build-up should be investigated to determine if it is predominantly ferrocene or of hydrocarbon origin. If it is ferrocene, it could affect the life of the engine if: (1) it is unusually thick compared with normal carbon deposits after 10 hours operating time, and (2) it persists after operation with pure JP5.

KENNETH N. HOPKINS
Aerospace Engineer
Components Branch
Turbine Engine Division

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Figures
(attachments deleted from this report)

SYSTEMS SUPPORT DIVISION
AIR FORCE MATERIALS LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

APPENDIX D

EVALUATION REPORT

J-79-8 ENGINE HOT SECTION PARTS

REPORT NR: AFML/MX 77-[illegible]5

DATE: 17 February 1977

PROJECT NR: 327Z

TYPE EVALUATION: Metallurgical

MANUFACTURER:

SPEC NR:

SUBMITTED BY: AFAPL/SFF (Mr. C. R. Martel)
WPAFB, OH 45422

ITEM SERIAL NR:

I. PURPOSE:

To conduct a metallurgical examination of J-79-8 engine hot section parts to identify bright orange colored deposits on the components and determine the effect of the deposits on the metal microstructures.

II. FACTUAL DATA:

1. A combustor can, a fuel nozzle and two high pressure first stage turbine blades from a J-79-8 engine were submitted to AFML/MXA for metallurgical analysis.

2. The parts came from an engine which had been used in a program to suppress smoke at jet engine test stands. The engine had been subjected to 10 hours of operation using JP-5 fuel containing an anti-smoke additive, ferrocene. The introduction of ferrocene resulted in bright orange deposits on the parts examined. A photograph of the parts submitted is shown in Figure 1. The orange deposit can be readily seen on the turbine blades. The combustor can has the deposits on the inside and there is very little on the nozzle. The nozzle does exhibit some black deposits which are not readily seen in the photograph.

3. The orange deposits were analyzed and found to be iron oxide (Fe_2O_3). The black deposits on the nozzle turned out to be carbon.

4. Cross sections of metal containing iron oxide coatings were examined metallographically. The microstructures observed showed no effects which could be attributed to the presence of the oxide coating. A section of a turbine blade, Figure 2, shows a typical cast microstructure for Udimet 500 which is the base material. The nozzle is stainless steel and the combustor can is Hastelloy X. Figure 2 also shows that the blades were coated. This coating is proprietary and is applied during fabrication of the blade and is not related to the iron oxide deposits.

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5. In addition to microscopic examination, all the parts were X-rayed and dye penetrant inspected. These examinations showed that the components were all structurally sound. There were no defects and no evidence that the oxide deposits had in any way had an adverse effect on the base metal.

III. CONCLUSIONS:

1. The bright orange deposit on the combustor, nozzle and turbine blades is iron oxide (Fe_2O_3).

2. The oxide deposits had no effect on the metal microstructure and nondestructive examination (NDE) showed all parts were structually sound.

IV. RECOMMENDATIONS:

None, data merely submitted.

COORDINATION:

LENNIE COHEN, AFML/MXA

PREPARED BY:

PAUL L. HENDRICKS, AFML/MXA

PUBLICATION REVIEW

This report has been reviewed and is approved.

T. D. COOPER, Chief
Materials Integrity Branch
Systems Support Division

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AFAPL-SFF-TM-77-16

APPENDIX E

SPECIAL FUELS FOR SMOKE ABATEMENT OF AIRCRAFT TURBINE ENGINES DURING TEST CELL OPERATION

Charles R. Martel

Technical Memorandum AFAPL-SSF-TM-77-16

April 1977

AIR FORCE AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

FOREWORD

This report was prepared by the Fuels Branch of the Fuels and Lubrication Division of the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The work was performed in response to a request from the Air Force Logistics Command, through the Air Force Systems Command, to assist the AFLC in finding solutions to the engine exhaust smoke problem during test stand operation.

This report documents the available information on the use of low smoke producing fuels that might be a solution to the test stand smoke problem.

This Technical Memorandum has been reviewed and approved.

Arthur V. Churchill

ARTHUR V. CHURCHILL
Chief, Fuels Branch
Fuels and Lubrication Division

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SPECIAL FUELS FOR SMOKE ABATEMENT OF AIRCRAFT TURBINE ENGINES DURING TEST CELL OPERATION

SECTION I
INTRODUCTION

The Air Force and Navy operate several jet engine overhaul facilities including the ones at Tinker AFB, OK, Kelly AFB, TX, Naval Air Rework Facility, Alameda, CA, and others. During the Viet Nam conflict up to 6000 jet engines were overhauled per year at a single overhaul facility. Following overhaul, each engine is run on a test stand to check its performance and for calibration and trimming. Between two and three hours of operation are required for each test stand test, but many of the engines must be reworked and retested before they meet minimum operating standards. As many as 10 hours of test stand operation may be required for some engines before the newly overhauled engine meets acceptance limits.

The Air Force and Navy are currently investigating means for reducing the visible smoke plume from stationary gas turbine engine test cells. The State of California has recently filed a suit against the Navy for operating jet engine test stands in violation of visible smoke emission laws. This case hinges upon the definition of jet engine test stands as "stationary sources", as a "stationary source" must meet different exhaust emission requirements than Mobil sources.

The environmental laws governing "stationary sources" normally require that the visible smoke emitted have less than a Ringleman 1 rating. A Ringleman 1 rating is equivalent to an opacity of 20% with no smoke giving 0% opacity and 100% opacity equivalent to smoke so thick that light will not pass through the cloud. Unfortunately, many Air Force and Navy engines emit smoke that is in excess of a Ringleman 1 rating when operated in test stands. To reduce the test stand visible emissions to less than a Ringleman Number 1 rating, the Navy has examined various methods for removing the smoke downstream of the engine. One device tested was a mechanical scrubber that directed the exhaust gases through a torturous path with surfaces wetted with water. A full scale scrubber was successfully built and tested, but was very expensive in both initial and operating cost.

The use of fuel additives to reduce smoke is an attractive approach from both a cost and simplicity standpoint. Ferrocene (cyclopentadienyl iron) appears to be the most attractive additive presently available in terms of cost, effectiveness, and minimal toxicity. The Ethyl Corporation's CI-2 additive (methyl cyclopentadienyl manganese tricarbonyl) has also been successfully used and is equally effective in reducing smoke. However, it is considerably more toxic than ferrocene. Both CI-2 and ferrocene leave deposits within the engine that may be detrimental to engine life and performance (Ref. 1,2).

The Navy has conducted many tests using different engines to determine the effects of ferrocene on jet engines. Currently, the Navy has approved the use of ferrocene with all smoky engines except for the J-79 and the T56-A-10 for up to two hours of operation (Ref. 2). Tests are scheduled to requalify all engines for up to 10 hours of operation using ferrocene-doped JP-5 fuel. If these tests are successful, a cheap solution to the test cell smoke problem will be available.

If legally required to suppress smoke from jet engine test stands, the Air Force will likely follow the Navy approach; i.e., the use of the fuel additive, ferrocene. However, for some engines such as the J-79, where ferrocene may cause engine problems, a different solution may be required. One solution would be to retrofit all J-79 engines with smoke-less combustors; a straight-forward solution but an expensive one.

As an alternate to the use of ferrocene, a special fuel for use only at test stands is proposed to reduce smoke to acceptable levels. This report documents available information on the use of special fuels for use in test stands to reduce smoke.

SECTION II
FUEL COMPOSITION EFFECTS ON SMOKE EMISSIONS

Various researchers have documented effects of fuel composition on smoke emissions from aircraft turbine engines (References 1, 3, 4, 5, 6, 7). In general, smoke emissions increase as the hydrogen content of the fuel decreases. In terms of hydrocarbon species, normal paraffins (straight-chain) give minimum smoke followed by iso-paraffins (branched-chain), cyclic paraffins, and aromatics in order of increasing smoke emissions (Ref. 5). The difference in smoking tendency between normal paraffins and iso-paraffins occurs in diffusion flames, and may be unimportant for the turbulent combustion that occurs in jet engine combustors.

Early jet engines were especially noted for being affected by the volatility of fuels, with volatile fuels giving less smoke than lower volatile fuels. This observation agrees with the conclusion reached by Gaganidze and Wagner (Ref. 4), that smoke emissions tend to increase with an increase in the molecular weight of the fuel. They attribute this to the increasing ignition delay and the reduced vaporization of the heavier fuels. However, hydrogen content tends to decrease with increasing molecular weight, although in a non-linear manner for cycloparaffins and aromatics.

For the more modern aircraft turbine engines, major advances in combustor design and the increased temperatures and pressures within the combustors have tended to eliminate fuel composition and volatility as primary smoke emission variables (Ref. 7). However, the Air Force has thousands of older engines in service, and these older engines, such as the J-57, J-75, and J-79, as well as newer engines such as the TF-30 and TF-41, are noted as "smokers" and are anticipated to remain in service for many more years.

SECTION III
PREVIOUS TESTS WITH SPECIAL FUELS

1. Pratt and Whitney Tests:

Pratt and Whitney Aircraft Division tested the effect of fuel type on the smoke emitted from the JT-8D engine (Ref. 3). A naphtha fuel was tested that reduced the smoke density[1] to about 15 even though JP-4 and JP-5 fuels gave smoke densities of 46 and 48, respectively. Figure 1 is a graph showing the smoke density emitted by the JT-8D engine versus the estimated hydrogen content of the five fuels tested. The hydrogen contents for the fuels were calculated using ASTM D 3343 which requires the measured API gravity, the aromatics content in volume percent, and the volumetric average boiling point, °F (see Table 1). As the volumetric average boiling points for the five fuels were not available, they were estimated. For the aviation gasoline the aromatics content was also estimated.

2. Naval Air Propulsion Test Center J57-P8 Test:

The Naval Air Propulsion Test Center (NAPTC) operated a J57-P8 engine as part of their anti-smoke investigation. As part of their test program they experimented with different fuels including a JP-4, a JP-5, a commercial solvent (Soltrol 130), and normal heptane (Ref. 1). The smoke emitted from the engine-test cell combination was measured in photovolt reflectance ratings, but these have been converted to SAE Smoke Numbers using the correlation given in Reference 8. Table 2 is the reduced data for the NAPTC tests

The hydrogen content has been estimated using ASTM D 3343 for the JP-4, JP-5 and Soltrol 130. For the normal heptane the hydrogen content was calculated from its molecular composition. Table 3 documents the properties of the four test fuels.

Figure 2 is the plot of the SAE Smoke Number versus the hydrogen content of the fuel for the J57-P8 turbojet engine at four engine power settings. As seen in Figure 2, the correlation between the smoke number and the hydrogen content of the fuel is excellent. For this particular engine, a maximum SAE Smoke Number of 42 is considered to give an acceptable low smoke emission (assumed to mean that the smoke is essentially invisible). Referring to Figure 2, the maximum allowable hydrogen content of a fuel to give a maximum Smoke Number of 42 under all engine operating conditions is 15.7 weight percent. At lower engine power settings the hydrogen content required to give a maximum smoke number of 42 decreases greatly.

[1] Smoke density - Believed to be the smoke number determined using the filtration method.

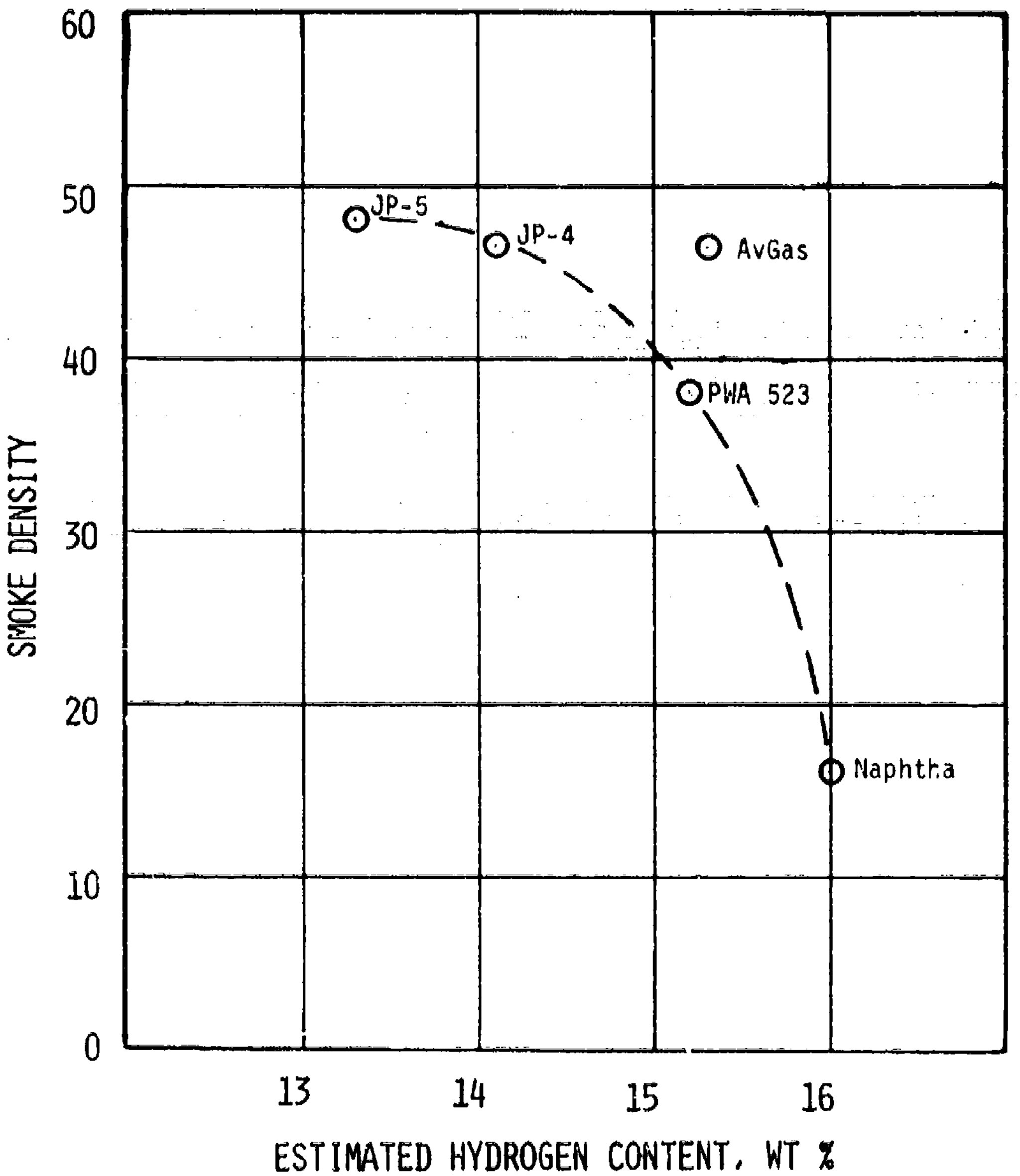

Figure E-1. Fuel Type Effects on Smoke Emitted by JT-8D

TABLE E-1 . Properties of Fuels Used in JT-8D Tests

Fuel Property	JP-5	JP-4	AvGas	PWA 523	Naphtha
Gravity, °API	39.0	54.6	69.4	52.3	80.8
Distillation (°F)					
Initial Boiling Pt	350	147	100	394	103
End Point	540	436	314	491	287
Aromatics, Vol %	22.6	16.8	---	2.3	12.4
Smoke Point, mm	19	25	---	---	---
Luminometer Nr.	40	60	100	109	140
Btu/lb	18,475	18,660	18,945	18,945	19,120
Est. Volumetric Ave. Boiling Pt, °F	429(1)	290(1)	205(2)	474(1)	240(1)
Est. Hydrogen Content, Wt %	13.3(3)	14.1(3)	15.3(2)	15.2(3)	16.0(3)

(1) Back calculated using ASTM D 3338 knowing the heat of combustion, the aromatic content, and gravity.

(2) Best estimate based on limited data available and average aviation gasoline properties.

(3) Calculated using ASTM D 3343 using known aromatics content and gravity and estimated volumetric average boiling point.

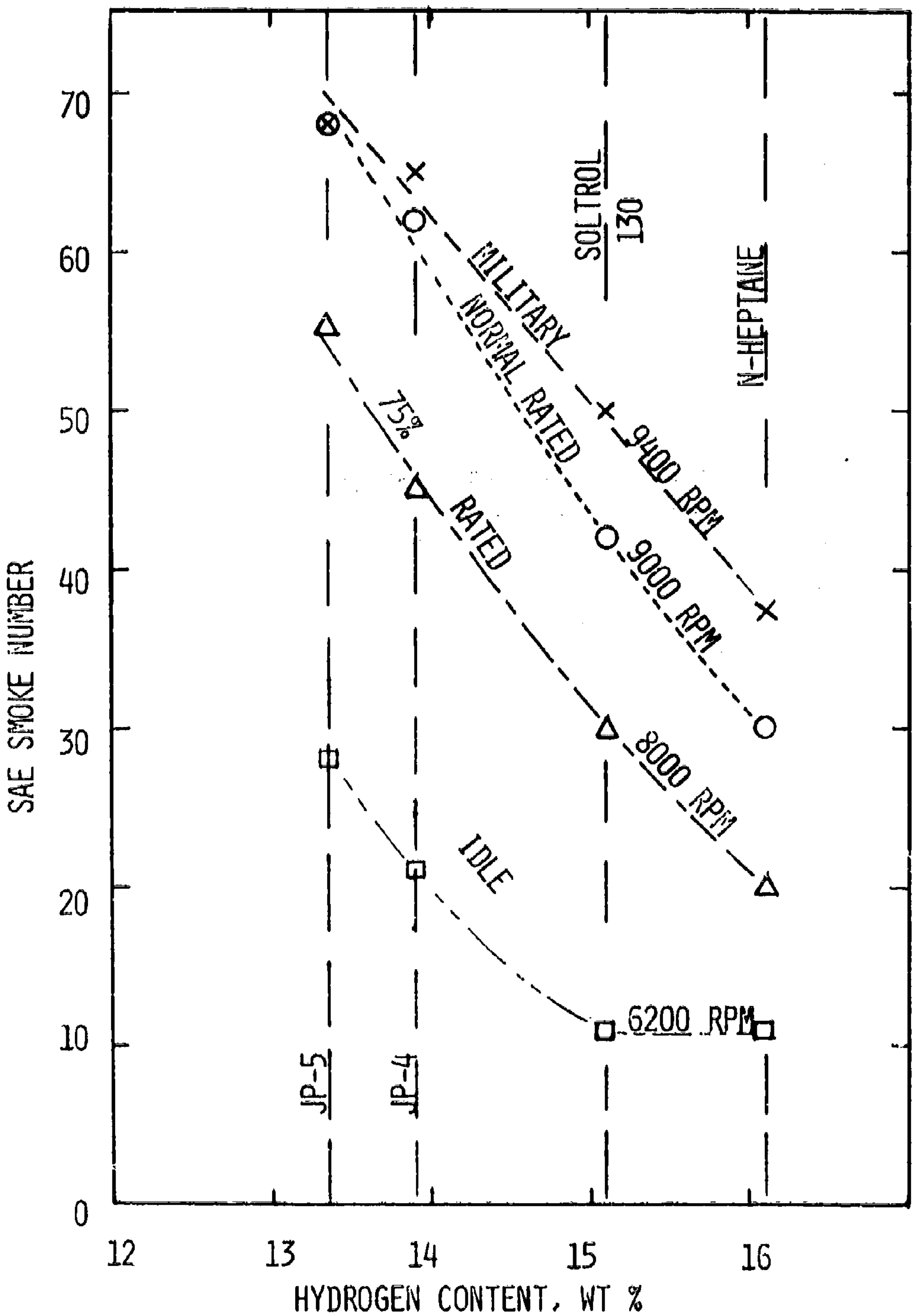

Figure E-2. Fuel Type Effects on Smoke Emitted by J57-P8

TABLE E-2. J-57-P8 Engine Test Data With Different Fuels

RPM	JP-5	JP-4	Soltrol 130	n-Heptane
	Photovolt Reflectance			
6200	80	84	92	92
8000	55	62.5	78	86.5
9000	43	48	67.5	78
9400	43	46	61	72
	SAE SMOKE NUMBER*			
6200	28	21	10	10
8000	56	45	30	20
9000	68	62	42	30
9400	68	65	50	37.5

* SAE Smoke Number estimated from Navy Reflectance Rating Using Reference 8.

TABLE E-3. Properties of Test Fuels Used by NAPTC

Fuel Property	Soltrol 130	JP-4	JP-5	N-Heptane
Gravity, °API	55.2	54.1	39.0	62.1
Distillation, °F				
IBP	354	152	335	200
10% Recovered	360	202	381	203
20% Recovered	360	219	399	---
50% Recovered	366	264	435	205
90% Recovered	382	356	484	207
End Point	422	385	513	210
Est. VABP, °F	369	274	433	205
Aromatics, Vol. %	0.84	18.9	21.8	0
Aniline Point, °F	184	---	---	---
Flash Point, °F	128 (D 56)	---	---	---
Hydrogen Content Est. Weight %	15.1	13.91	13.35	16.1
Smoke Point	40	26	19	---
Composition	99+% Isoparaffins			

3. Air Force Aero Propulsion Laboratory Test:

Late in May 1976, a short test was conducted using the T-56 combustor test rig available in the in-house facilities of the Air Force Aero Propulsion Laboratory. These tests were run using two different fuels; a JP-4 and isooctane. Table 4 gives the specification data for these two fuels. The T-56 combustor was operated using three air inlet conditions, 500, 700, and 900°F with a constant exhaust gas temperature of 1700°F. At each test point a minimum of three data points were taken and the resulting test data, Table 5, is the average of these three or four data points at each test condition. Exhaust emissions measured included total hydrocarbons, carbon monoxide, carbon dioxide, nitrogen oxides, and smoke number. Figure 3 is a plot of the Smoke Number test data of Table 5 versus the hydrogen content of the two fuels.

The test data show that increasing the hydrogen content of a fuel will decrease exhaust smoke. As seen in Table 5, the effect of fuel type on other exhaust emissions was less noticeable; only the nitrogen oxides were also decreased by increasing hydrogen content.

4. Low Luminosity Fuel:

In the 1950-1960 time period, considerable development work on low luminosity fuels was accomplished. As low luminosity fuels radiate less heat during their combustion than conventional fuels, reduced engine hot-section maintenance should result. These fuels also result in decreased exhaust smoke and a range increase for weight-limited aircraft. In general, a low luminosity fuel is highly paraffinic, giving a high energy content per unit weight, a high hydrogen/carbon ratio, and excellent chemical stability.

The unofficial designation for the low luminosity fuel was JP-150, the "150" pertained to the Luminometer Number (ASTM D 1740) which was to be in the 150 range. According to an article in Aviation Week (Ref. 9), Texaco Incorporated and Pratt & Whitney Aircraft Division led in the development of JP-150. Texaco claimed the virtual elimination of exhaust smoke on take-off while Pratt and Whitney claimed a 50 to 60% reduction in engine exhaust smoke during take-off for the J-57 engine.

Navy tests with a JP-150 fuel indicated a significant improvement in engine combustion efficiency at idle RPM for a J-57 engine as compared to JP-4 and JP-5 fuels. However, trimming of the engine was required to compensate for the low specific gravity of the JP-150 as compared to JP-4 and JP-5 fuels.

TABLE E-4. JP-4 and Isooctane Fuel Properties

	JP-4	ISOOCTANE
Gravity °API	54.5	71.7
Distillation (°F)		
IBP	156	204
10%	196	206
20%	217	206
50%	304	206
90%	433	206
EP	474	292
Aromatics, Vol %	11.6	NIL
Hydrogen, Wt %	14.44	15.93

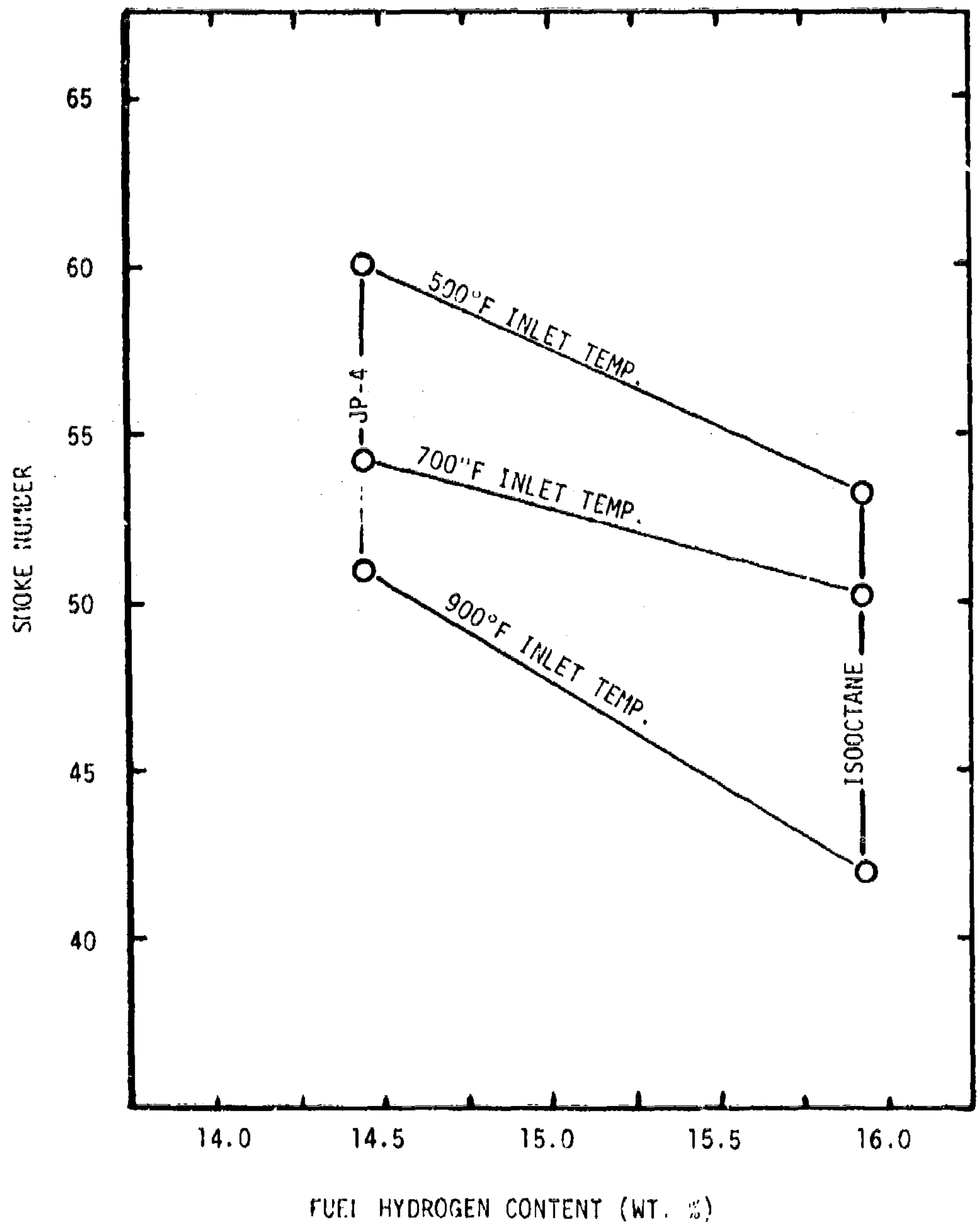

Figure 3. J-56 Combustor Tests Comparing JP-4 and Isooctane

TABLE E-5: T-56 Combustor Tests Using JP-4 and Isooctane Fuels

Fuel Type	T_3 (°F)	EGT (°F)	HC (PPMC)	CO (PPMV)	CO_2 (%)	NO_x (PPMV)	Ave. Smoke Number	Smoke Nr. %of Baseline
JP-4	507	1700	22.3	72	3.55	80.3	60	100
ISO	502	1700	22.3	53	3.47	73.7	53.3	88.8
JP-4	703	1700	17.1	40.3	2.89	111	54.3	100
ISO	705	1700	21.7	31.7	2.93	109	50.3	92.6
JP-4	904	1700	15.3	30	2.51	150.5	51	100
ISO	902	1700	17	32.7	2.43	141.3	42	82.4

In the 1959 time period the JP-150 fuel was estimated to cost an additional 2¢/gallon as compared to a base price for delivered fuel of about 14¢/gallon. Texaco revealed that the JP-150 was basically a by-product of a solvent extraction process used in the manufacture of highly aromatic motor gasolines.

Table 6 gives the measured specification properties for a JP-150. The estimated hydrogen content was added by the author using ASTM D 3343 to calculate the hydrogen content. Table 7 gives the proposed specification limits for JP-150, but a formal specification was never developed.

5. Summary of Previous Tests with Low Smoke Producing Fuels:

The Pratt and Whitney tests and the NAPTC tests measured the emitted smoke at the exhaust of the engine. No tests results using high hydrogen content fuels in engines mounted in test stands have been found. As test stand design and operating parameters (such as water injection and auxiliary air flow rates) significantly affect the visible smoke emitted from the test stand, there appears to be no way to estimate the minimum hydrogen content of a fuel required to reduce smoke to below a Ringleman rating of one. Actual tests using engines and test stands of concern will have to be conducted to determine the minimum hydrogen content of the special test stand fuel.

TABLE E-6

Analyses of JP-150 Fuel Sample Shipped from Port Arthur, Texas

TESTS	JP-150 SPECIFICATIONS	RESULTS
Gravity °API	60-69	66.5
Gravity, Specific at 60/60°F	0.706-0.759	0.715
Distillation: °F		
IBP	170 Min	198
50%	270 Max	250
90%	285 Min	300
E.P.	370 Max	342
Residue, Vol %	1 1/2 Max	1
Distillation Loss %	1 1/2 Max	1
Existent Gum mb/100 ml.	7 Max	1
Potential Gum mg/100 ml.	14 Max	1
Corr. Cu Strip ASTM Classifications	No. 1 Max	1A
Sulfur, Total %	0.4 Max	0.002
Mercaptan Sulfur, %	0.001 Max	None
Doctor	Negative	Negative
Aromatics, Vol %	25.0 Max	1.6
Olefins, Vol %	5.0 Max	1.6
Reid Vapor Pressure, psi	2.0 Max	1.2
Smoke Point, mm	Report	50+
Smoke Volatility Index	52.0 Min	92+
Aniline-Gravity Product	5,250 Min	10,520
Freezing Point °F	-76 Max	Below -76
Water Reaction	1B Max	1B
Inhibitors		
Gum, Pounds/1000 bbls	8.4 Max	None
Type		
Corrosion, Pounds/1000 bbls		None
Type		
Metal De-activator lbs/1000 bbls	2 Max	None
Thermal Stability at 400°F/500°F		
Change in pressure drop in 5 hr in. Hg.	13 Max	0.6
Preheater Deposit	Less than 3	Code 2
Luminometer No.	135 Min	138.3
BTU's per lb	18,900 Min	19,070
EST. Hydrogen Content, wt. % (ASTM D 3343)		15.6

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CHEMICAL AND PHYSICAL REQUIREMENTS OF JP-150

Distillation	
Initial Boiling Point	170°F min
50% Fuel Evaporated	270°F max
90% Fuel Evaporated	285°F min
End Point	370°F max
Residue, Vol %	1.5 max
Loss, Vol %	1.5 max
Gravity °API - min.	60
Gravity °API - max.	69
Existent Gum, mg/100 ml	7.0 max
Total Potential Residue 16 hr. aging, mg/100 ml	14.0 max
Reid Vapor Pressure, 100°F ps max. (gm/om^2, max.)	2.0
Freezing Point, °F, max.	-76
Thermal Value, Heat of Combustion (Net BTU/lb)	19,000 min
Water Reaction, Interface Rating	1B max
Copper Strip Corrosion at 122°F	1A max
Thermal Stability, D1660 at 400/400/6	
Change in Pressure Drop in 5 hr., in. Hg	13 max
Preheater Deposit, max.	3
Luminometer Number (Sometimes designated Luminosity Number)	135 min

SECTION IV
PROPOSED TEST STAND FUEL

1. Fuel Characteristics:

For the purpose of preparing an economic estimate of the costs of using a special low-smoke-producing test stand fuel, it has been assumed that the fuel must contain a minimum of 15.7 weight percent hydrogen. This assumption is based on the fact that in both the Pratt & Whitney and NAPTC tests, a fuel with a hydrogen content of about 15.7 weight percent apparently reduced smoke to an essentially invisible amount at the engine exhaust. Also, jet engines that do not emit visible smoke in flight or during ground operation do not create smoke problems when mounted in test stands.

Table 8 gives a proposed specification for the 15.7% minimum hydrogen content test stand fuel. To obtain such a high hydrogen content, a fuel composed primarily of normal paraffins and iso-paraffins must be used, and the molecular makeup of the fuel must be composed primarily of heptanes, octanes, and nonanes. More volatile liquids such as hexanes would result in a high vapor pressure and excessive losses through evaporation. Higher molecular weight compounds such as decanes have a hydrogen content of less than 15.7 weight percent.

The presence of aromatics, cycloparaffins, and olefins must be reduced to quite small concentrations, as these molecular species have lower hydrogen contents than desired.

The volatility of the special fuel as proposed in Table 8 would range between that of JP-4 and motor gasoline, so no unique fuel storage or handling system would be required. However, a separate system in addition to the existing JP-4 fuel system would be required.

The use of a fuel such as that proposed in Table 8 would require that the test engine be operated for a few minutes on regular JP-4 after the completion of the test. This would flush out the special test stand fuel and expose the elastomer seals and gaskets to JP-4, which contains about 15% aromatic compounds on the average. Aromatics cause elastomers to swell, and this swelling is counted on to insure that the seals and gaskets do not leak. Although the flushing operation could be performed at engine idle where smoke formation is normally not a problem, this would dictate that an additional fuel handling system be available for the special test stand fuel.

TABLE E-8 Preliminary Specification for a Low-Smoke Test Stand Fuel.

Fuel Property	Limits Min	Max	Test Method
Total Acid Number, mg KOH/g		0.015	D 3242
Aromatics, Volume %		5	D 1319
Olefins, Volume %		5	D 1319
Mercaptan Sulfur, Weight %		0.001	D 1323
Sulfur, Total, Weight %		0.40	D 1266, D 1552, D 2622
Distillation, Temperature °C			
Initial Boiling Point	35		
10% Recovered, Temperature	80		
50% Recovered, Temperature		Report	
90% Recovered, Temperature		150	
End Point, Temperature		170	
Density, kg/m^3 OR	669	755	D 1298
Gravity, °API	56	80	D 1298
Vapor Pressure, 37.8°C, kPa (psi)		41.3 (6)	D 323, D 2551
Freezing Point, °C		-30	D 2386
Heating Value, KJ/kg (Btu/lb)	44.2 (19,000)		D 240, D 2382, D 3338
Hydrogen Content, Weight %	15.7		D 1018, D 3343
Copper Strip Corrosion, 2 hr at 100°C		1b	D 130
Thermal Stability; Test Temp = 260°C			D 3241
Change in Pressure drop, mm of Hg		25	
Preheater Deposit code, less than		3	
Existent gum, mg/100 ml		7	D 381
Water Separation Index, Modified	70		D 2550
Fuel System Corrosion Inhibitor Per QPL-25017	REC	MAC	None

2. Cost Estimates:

The following cost estimates have been made on the basis of anticipated use of the special test stand fuel at Tinker AFB, Oklahoma. This Air Force Logistic Center is the largest engine overhaul base in the Air Force. As seen in Table 9, Tinker AFB performs overhauls and subsequently tests all five of the major "smoker" engines in the Air Force; the J-57, J-75, J-79, TF-30, and TF-41. Also listed in Table 9 are the estimated number of engines of each type overhauled per month, the length of the tests, and the estimated gallons of fuel used per month based on one engine test per engine overhauled. It is reported, however, that many engines must be reworked after the initial test following overhaul to meet minimum performance specification. Thus, the actual number of engine tests per month may be 50 to 75% higher than indicated in Table 9.

To test the engines overhauled at Tinker AFB, two buildings housing several test stands each are in use. Building 3234 contains several test stands, four of which are used for testing the J-75, TF-30, and TF-41 engines, among others. Building 214 also houses several test stands, six of which are used for testing the J-57, J-79, and TF-41 engines. Thus, at Tinker AFB, two buildings with a total of 10 test stands must be modified to incorporate the additional fuel system for the special test fuel.

From Table 9 it is seen that the estimated quantity of fuel used for these 10 test stands at Tinker AFB is about 1,200,000 gallons/mo. Assuming that 60% of the engines must be retested once each, this would increase the fuel required to about 2,000,000 gallons/mo. For a 30 day fuel supply one 50,000 Bbl storage tank would be needed at an estimated cost of $1,000,000 including pumps, piping, and installation. Each test stand complex (i.e., buildings 214 and 3234) should have about two each 50,000 gallon underground tanks located nearby. These tanks, plus pumps, filters, controls, and pipelines would cost an additional $350,000 (Ref. 11). This gives a total cost of about $1,350,000 to equip the 10 test stands at Tinker AFB with the special fuel system.

Special fuels, solvents, and other low-production hydrocarbons products are usually made at only a few refineries. This reduces the manufacturing cost of the product through minimization of the invested capital in manufacturing equipment. For a special test stand fuel to be delivered

TABLE E-9 Fuel Used for Overhauled Engine Tests at AFLC Bases

AF Base	Engine Type	No. Per Month	Length of Test (Min)	Fuel Per Test (Lb)	Total Fuel Per Mo. (Lb)	Total Fuel Per Mo. (Gal)
Hill	J-75	5	63	12,000	60,000	9,200
	J-79	15	56	8,000	120,000	18,500
					Hill Total	27,700 Gal/Mo
Kelly	J-79	60	147	19,000	1,140,000	175,400
					Kelly Total	175,400 Gal/Mo
McClellan	J-57	9	76	16,000	144,000	22,200
	J-75	2	76	28,000	56,000	8,600
					McClellan Total	30,800 Gal/Mo
Tinker	J-57	116	125	9,000	1,044,000	161,000
	J-75	37	121	21,000	777,000	120,000
	J-79	29	102	14,000	406,000	63,000
	TF-30	92	158	33,000	3,036,000	467,000
	TF-41	87	287	32,000	2,784,000	428,000
					Tinker Total	1,239,000 Gal/Mo

to Tinker AFB, Oklahoma, it is likely that the necessary product would be manufactured for the Air Force somewhere along the Gulf Coast. The freight cost from Houston, TX to Oklahoma City, OK is about 8 to 11¢/gallon.

The average cost of JP-4 world-wide is about 43.3¢/gallon, delivered. A speciality fuel, purchased by the Air Force in limited quantities, costs about 43¢/gallon FOB. Thus, the difference in price between JP-4 and a special test stand fuel would probably be equal to the transportation cost of about 10¢/gallon.

For an estimated consumption rate of 2,000,000 gallons/month, the increased fuel costs for using the special test stand fuel at Tinker AFB will be about $200,000/month.

In summary, the cost of using the special test stand fuel at Tinker AFB would be about $1,350,000 for facility modifications and about $200,000/month additional fuel cost.

The special test fuel costs could be reduced significantly by using various mixtures of the special test fuel with JP-4 at different engine operating conditions. As noted above, smoke is normally not a problem at idle, and only at high power operation does smoke become a problem for some engines. Thus, for idle and low power operation only JP-4 would be used. As power is increased (and as smoke production would tend to increase) a mixture of JP-4 and special test fuel would be used, with increasing concentrations of the special test fuel at increased power levels. A simple proportioning system has already been developed for the injection of an anti-smoke additive, taking a signal from a light transmissometer mounted on top of the exhaust stack of the test cell. Such a system can be obtained for about $25,000 per test cell (Ref. 10).

Through the use of the automatic JP-4/special test fuel blending system, the special test fuel requirement could be reduced by about 50%; i.e., from $200,000/month to $100,000/month. The reduced fuel requirement would also reduce the special test fuel system costs from an estimated $1,350,000 to about $760,000. However, the automatic JP-4/special test fuel blending system costs for the 10 test cells at Tinker AFB would cost an estimated $250,000, bringing the total facility costs to about $1,000,000.

The use of the automatic JP-4/special test fuel mixing system may not be compatible with the post-overhaul engine testing program. As the JP-4/special test fuel mixture changes, the fuel density changes requiring an adjustment to the engine fuel control trim. As the post-overhaul engine tests include engine fuel control trim calibration and adjustment, this constantly varying fuel density would greatly complicate this trimming procedure and could substantially increase engine test time and associated costs.

3. AVAILABILITY - Information received from Shell Oil Company indicates that special solvents similar to or meeting the proposed specification limits for a low-smoke fuel (Table 8) are widely available. Firms producing such products are stated to include: Shell Oil Company, EXXON Company, Phillips Petroleum Company, Skelly Oil Company, Standard Oil of California, and others.

One promising candidate is the raffinate by-product from the production of toluene. Depending upon the crude oil source, such a raffinate should meet all of the Table 8 specification requirements.

SECTION V
CONCLUSIONS

1. The use of a special test stand fuel, having a minimum hydrogen content by weight of about 15.7%, appears to be an acceptable method for reducing test stand smoke emissions to environmentally acceptable levels.

2. The additional cost for such a fuel would cost about $240 to $480 per 2 hour test, aside from any iniital costs to provide an additional fuel system. This is about 5 to 10 times more expensive than the use of ferrocene.

3. Engine effects from using the special test stand fuel would be restricted to possible temporary seal leakage caused by slight shrinkage of seals exposed to the high hydrogen content (low aromatics) fuel. This possible problem could be avoided by flushing the engine with a regular JP-4 or JP-8 fuel at the conclusion of the test.

SECTION VI
RECOMMENDATIONS

1. The facility modification costs and the added fuel costs involved in the use of a special test stand fuel for smoke abatement at Tinker AFB, OK appear to be excessive. Further consideration of this approach is not recommended unless other, less expensive, approaches are found to be unsatisfactory.
2. If the high costs of using a special test stand fuel appear to be justified, a special test program should be initiated as soon as practical to verify the effectiveness of the approach and to better define the specification limits for the special fuel. This testing should be done in a representative test stand using all engines of concern (i.e., J-57, J-75, J-79, TF-30, and TF-41). The special test program should also determine: (1) the magnitude of special fuel savings possible by the blending of JP-4 with the special test stand fuel at part-power engine operation, as permitted by the Ringleman rating of the exhaust smoke; and (2) the problems that would be encountered in the calibration and adjustment of the engine fuel control trim as the density of the JP-4/special test fuel mixture varies.

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