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Date September 1984
37 Page Report

THE EFFECTS OF LONG TERM HIGH IDLE OPERATION ON DIESEL ENGINES

CONT: DAAK 70-81-D-0157 - T.O. 0018

FINAL REPORT

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PREFACE

This work was carried out with the assistance of personnel from a number of organizations identified in the report. Their efforts were largely responsible for making the timely completion of the program possible.

Particular thanks are due to Mr. James P. Lucas of the Belvoir Research and Development Center. His guidance and assistance were critical in directing the course and maintaining the progress of the investigation.

Finally, thanks are due to Mr. E. W. Spannhake for his technical review of this work, as well as for the diesel background information he provided. Mr. Spannhake began his career as a Diesel Injection Engineer for American Bosch, and progressed through assignments as Director of Engineering and Research for Le Tourneau-Westinghouse and Vice-President of Engineering for White Consolidated Industries. He is presently an independent consultant in Naples, Florida.

The views, opinions and findings contained in this report are those of the author. They should not be construed as an official Department of the Army position, policy or decision unless so identified by other documentation.

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SUMMARY

There is a common belief among users of DoD diesel-driven (DED) generators that extended operation of diesel engines at rated speeds and light loads (high idle) results in deterioration of performance and engine damage.

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SUMMARY

There is a common belief among users of DoD diesel driven (DED) generators that extended operation of diesel engines at rated speeds and light loads (high idle) results in deterioration of performance and engine damage.

This investigation was directed at defining the nature and extent of the damage potential. It included a comprehensive literature survey, and conferences with users and suppliers of diesel engines and DED generators. Quality Deficiency Reports and Equipment Improvement Recommendations concerning the DoD family of tactical DED generators were reviewed for the period from 1970 to the present.

Information developed indicates that the ill effect of high idle on most military diesel engines is limited to the nuisance of carbon buildup in the exhaust system and discharge of unburned fuel (wet stacking or slobbering) in the engine vicinity when operating at low temperatures. The 15 kW and 30 kW set engines are an exception in that some of these engines wet stack lubricating oil at moderate temperatures.

E.J. Kates (12) reaches the same conclusion in his standard text, "Diesel and High Compression Gas Engines", with the statement "no serious harm follows underloading, but it is uneconomical ... overloading causes combustion problems and overheating."

Techniques to avoid the nuisance effects of high idle operation are presented. Recommendations are made with the goal of improving operating efficiencies and reducing life cycle costs.

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1.0 INTRODUCTION

1.1 Background - There is some feeling among diesel engine driven (DED) generator users that sustained operation of lightly loaded diesel engines at rated operating speeds results in deterioration of performance, significantly increased maintenance requirements, and ultimately in damage to the engines. This concept is expressed both verbally and occasionally in engine generator literature.

Most engine driven generator sets function in a unique engine operating environment in that they usually run at speeds dependent only on the desired output frequency and virtually independent of the electrical load. Under the light loads frequently encountered in military service this condition may be described (approximately) as high idle.

This operating mode is somewhat exaggerated in DoD sets since they are powered for full performance at elevated temperatures and altitudes, as well as for emergency overload conditions. This results in excess engine power availability at low altitudes and moderate temperatures.

1.2 Scope of Investigation - This program is concerned with the extent and nature of the potential problems described above as they pertain to the DoD family of tactical DED generator sets from 5 kW to 200 kW.

The conclusions reached here are based on an extensive survey of the literature including documented user complaints. In addition personal and telephonic conferences were held with both users and suppliers of this equipment to determine the sources and the extent of any problems.

1.3 Sources of Information - Data bases were accessed at the National Technical Information Service (NTIS), Library of Congress, University of Central Florida, and the Society of Automotive Engineers (SAE). Additionally Quality Deficiency Report (QDR) and Equipment Improvement Recommendation (EIR) files were searched at TROSCOM, St Louis, MO for any failure mode patterns.

Other Government documents (standards, specfications, manuals, drawings and internal memoranda) were also examined and, where applicable, are identified in the bibliography section of this report.

A large number of references were retrieved by the data base search, and were reviewed for information relating to this program. Those considered applicable are discussed in this report and identified in the bibliography. In certain cases the authors were contacted for clarification of the published information. Any communications with authors that played a part in forming our opinions are also identified.

Technically oriented personnel from the following Government and Industrial organizations actively involved in diesel engine technology were contacted. They provided background and "state of the art" information as viewed by both suppliers and users.

DoD Project Manager (MEP)	Springfield, VA
AMC (AMCDE-SSV)	Alexandria, VA
Belvoir R & D Center (STRBE-EE)	Fort Belvoir, VA
Belvoir R & D Center (STRBE-TE)	Fort Belvoir, VA
Belvoir R & D Center (STRBE-VF)	Fort Belvoir, VA
TROSCOM (DRSTR-MES)	St. Louis, MO
Allis-Chalmers Engine Division	Harvey, IL
Caterpillar Tractor Company	Peoria, IL
Cummins Engine Company, Inc.	Columbus, IN
Deutz Corporation (Engine Div.)	Atlanta, GA
Lister Diesels, Inc.	Olathe, KA
Onan Corporation	Minneapolis, MN
Technology Research Corporation	Clearwater, FL
White Engines, Inc.	Canton, OH

The timely completion of this work was made possible in a large part by the excellent cooperation and information provided by personnel from all of the organizations identified above.

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2.0 DIESEL ENGINES - DESIGN VARIABLES

2.1 General - The diesel cycle is based on the atomization of a jet of fuel in a combustion chamber containing air heated by compression above the ignition temperature of the fuel-air mixture. All diesel engines share this basic concept. The methods of creating this scenario are widely diverse. The differences that exist among diesel engines are much more dramatic than those in spark ignition engines.

Considering the long history of diesel engine development and refinement, there are an incredible number of design permutations currently in production. There are major differences in the engine cycle, cooling, breathing, fuel systems, injector and nozzle design, combustion chamber design, lubrication systems, injection timing methods, and peripheral devices. These design differences exist not only between manufacturers, but also between different engines from the same manufacturer.

In 1953 C.C. Pounder (18) wrote that "no amount of theory can ever replace test bed development in the final stages of the evolution of a new diesel engine". Some 25 years later Lipkea (16) paraphrased that concept with the statement that "...regardless of the results of fundamental research and theoretical analysis, both engine manufacturers and fuel suppliers work largely by empiricism and experiment rather than by direct application of the fundamentals of combustion".

While it is true today that some use is made of computer simulation in diesel engine design and development, the final design of these engines is at best semi-empirical. Each successful engine is a workable combination of the above factors developed by "cut and try" techniques.

2.2 Military Diesel Engines - The military engines within the scope of this program are rated from 9 to 340 horsepower at 1800/2000 RPM and are the product of a number of different manufacturers. They include most of the inter-engine differences identified above. The design of each of the military engines is described briefly in appendix a.

The engines involved are all four cycle models currently procurable for the DoD family of DED generator sets. Also described for comparison purposes is the two cycle Detroit Diesel 4-71 engine used by the Air Force on a 72 kW generator set. The comparison is made because this Detroit Diesel engine is the subject of the most complete investigation of a high idle problem and solution reported in the literature.

* * * * * *

3.0 DIESEL ENGINES - COMBUSTION PROCESSES

3.1 General - While inter-engine differences dictate analysis of high idle operation on an engine by engine basis, the combustion processes are common to all of the engines. This applies to the rapid reactions within the combustion chamber as well as to the much slower combustion processes occurring in the exhaust system. Thus, the nature of combustion both in the combustion chamber and exhaust system affords a generalized basis for a consideration of high idle phenomena.

The effect on combustion processes of high load conditions will also be considered for two reasons. First, high load operation is currently used for engine "cleanup". Second, some of the effects of high load operation are occasionally attributed to high idle operation.

A brief (and simplified) review of diesel combustion and carbonization theory and processes is presented in appendix b. of this report. This theory serves as the basis for the following discussion.

3.2 Exhaust Composition - The diesel exhaust constituents important to this work are soot, bound carbon, and the various oxides of sulfur. The bound carbon consists of unburned fuel and lubricating oil, in addition to high molecular weight hydrocarbons formed during combustion.

3.2.1 Carbonization - Characteristics of the various forms of carbon generated during combustion may be summarized as follows.

Soot is essentially soft powdery carbon. When deposited in the combustion chamber, it normally migrates to the oil filter due to the detergent action of the oil. When deposited in a dry exhaust system, it is removed by high flow (high load) exhaust gases.

Tar formation is due to heat induced reactions of both fuels and lubricants, and is primarily a high temperature phenomenon. Extended exposure of tar to high temperatures in a combustion chamber can result in transformation to a "lacquer", with possible resultant ring sticking.

Vitreous carbon is a hard shiny black deposit that is formed most rapidly on surfaces in the active "coking range" of 500 to 700 degrees F. The phenomenon usually occurs in combustion chambers under heavy loads, and exhaust systems under light loads.

3.2.1.1 Fuel and Oil Effects on Carbonization - Carbon buildup is affected to some extent by both fuel and lubricating oil. Appendix b details the fuel and lubricant characteristics which promote or inhibit carbon formation.

It is important to note that carbon in all of its forms can be copiously generated in any engine and in any operating mode when improper fuels or lubricants are used. It should also be noted that combustion chamber carbonization and lacquer formation are characteristic of high combustion chamber wall and ring temperatures (high loads).

3.2.2 Wet Stacking - Diesel engines operating at colder than normal temperatures have always exhibited a characteristic commonly known as "slobbering". In recent years this term has been replaced in some quarters by the more euphemistic term, "wet stacking".

The phenomenon in a properly operating engine is attributable to the incomplete combustion of fuel and lubricating oil because of low combustion chamber temperatures. It is normally a characteristic of a cold operating diesel engine rather than a symptom of an engine problem . However, there are conditions under which it can be a symptom of potential trouble, as well as conditions under which the symptom itself is sufficiently severe to become a nuisance.

In most cases the liquid discharged through the exhaust system is primarily fuel oil mixed with some lubricating oil and condensed hydrocarbons. In certain cases the effluent is primarily lubricating oil. In any case the lubricating oil has a more significant impact on diesel exhaust than its relative proportion in the exhaust stream would indicate.

3.2.2.1 Lubricating Oil Effects on Wet Stacking - The properties of lubricating oil that make it a satisfactory cylinder lubricant also make it difficult to eliminate from diesel exhaust by combustion.

Lubricating oil will typically have a much higher flash point and molecular weight, and much poorer ignition quality than fuel oil. Additionally it is usually introduced into the combustion chamber in the form of a film or droplets rather than as an atomized spray. Thus any lubricating oil (and its combustion products) in the exhaust stream will tend to generate significantly more liquid and solid particulates than will the same quantity of fuel oil.

A recent General Motors Research Laboratories study (17) indicated that lubricating oil contributed from 50 to 280 times as much material to particulate emissions (solid and liquid) as would be expected on the basis of its consumption relative to fuel. The oil contribution to particulate exhaust was further shown to increase with increasing engine speed, and to decrease with increasing engine load.

3.2.2.2 Engine Cycle Effects on Wet Stacking - Two cycle engines appear more likely to exhibit wet stacking phenomena than 4 cycle engines. Oil consumption is inherently higher in a 2 cycle engine because of combustion chamber and exhaust port geometry. This is substantiated by emission data that indicate 2 cycle exhaust to be considerably higher in hydrocarbons than 4 cycle exhaust.

A test program at Southwest Research Institute (9) compared the exhaust of a Detroit Diesel 6L-71T (2 cycle) engine with that of a Cummins NTC-290 (4 cycle) engine. The investigators found the 2 cycle engine particulates to be primarily hydrocarbons with a small amount (17%) of excess carbon or soot. The 4 cycle engine showed hydrocarbon material with substantial (160 %) excess carbon.

This would indicate a tendency toward liquid rather than solid exhaust particulate for the 2 cycle engine, and a resultant tendency toward wet stacking.

A comparison of a Caterpillar 3208 with a Detroit Diesel 6V-71 (8) yielded similar results. It was observed that the 6V-71 engine exhaust was more "oily" than the 3208 exhaust, and that the hydrocarbon content of the 6V-71 engine exhaust particulate was about four times that of the 3208.

3.3.3 Combustion Under Light Loads - A desirable condition in operating diesel engines at light loads is the maintenance of combustion chamber temperatures adequate to support full combustion. This temperature is influenced by both engine design parameters (e.g. compression ratio) and by environmental parameters (e.g. intake air temperature).

A naturally aspirated diesel engine ingests a quantity of air that is independent of the amount of fuel being injected. Under light load conditions (low exhaust flow) this is also true of turbocharged engines.

Any diesel engine will exhibit wet stacking symptoms if the intake air is cold enough and if the fuel required for power is insufficient to maintain an appropriate combustion chamber temperature. Carried to an extreme, this condition can result in one or more cylinders ceasing to fire.

Another effect of light load operation is the deposition of particulates in the exhaust system because of relatively low exhaust gas flow. This phenomenon has been documented by Danielson (2) among others, who found that diesels exhibited lower than normal emission characteristics for some time after clearing the exhaust system by wide open throttle operation.

Thus, light load operation can be enhanced by maintaining moderate air and engine temperatures through the use of enclosures and cooling system modulation.

Overfuelling at light loads can also contribute to wet stacking and exhaust carbonization. This can be avoided by means of fuel injectors designed to operate properly over the entire engine load range.

3.3.4 High Idle vs. Low Idle - Engines used to drive military generator sets typically operate at idle speeds in the range of 1500 to 2000 RPM rather than at low idle speeds in the range of 800 to 1100 RPM. The effect of the idle speed increase on combustion adequacy will vary with engine design, and may be either detrimental or beneficial.

Atomization of fuel will improve at high idle since injection rate and chamber turbulence generally increase with engine speed. The combination of more finely dispersed fuel and faster injection (better preignition mixing) will lead to most of the fuel being consumed during the period of rapid combustion (see appendix b).

Further the tendency of fuel particles to overpenetrate and impinge on cylinder surfaces is reduced at high idle. Finally an engine will normally operate at a somewhat higher temperature at high idle than at low idle because of the added fuel requirement due to increased windage and friction.

On the other hand the total quantity of exhaust particulate generated per unit time at high idle will increase approximately in proportion to the increase in speed. Furthermore the time available for combustion at high idle is decreased approximately in proportion to the increase in speed (depending on ignition lag).

The relative effect of these factors are determined by the engine design, the operating conditions, and the nature of the exhaust effluent. There is some evidence that high idle in general may be a less severe operating condition than low idle with respect to wet stacking. However, it can be a more severe operating condition in the case of any specific engine.

3.3.5 Decarbonization - It has been stated that carbon formed as soft soot is easily removed from both the combustion chamber and exhaust system. A mixture of carbon and liquid hydrocarbons that has been exposed to coking temperatures is considerably more difficult to eliminate.

The dissipation of coked carbon can be accomplished by the same technique used in the modern self-cleaning oven. This requires heating the carbon deposits to a temperature above their ignition temperature in the presence of adequate oxygen for a sufficient period of time. The temperature and time will depend on the nature and ratio of carbon and hydrocarbon constituents in the coked material, and on the amount of material present.

The self-cleaning oven typically requires four hours at 800 degrees F to remove carbonaceous material. Ignition points of engine-formed hydrocarbons range from approximately 500 to 900 degrees F, and the ignition point of carbon is approximately 925 degrees F. A normally operating diesel engine ingests 15% or more excess air at maximum power.

The surfaces of the coked areas in the exhaust system of a four cycle diesel engine under load can easily reach temperatures in excess of 925 degrees F, due both to high exhaust temperatures and to the ignition of exhaust deposits. Thus, carbon removal by high load operation is feasible.

Removal of carbon based combustion chamber deposits by this technique is not possible. Unfortunately, the same load conditions that promote carbon removal from the exhaust system are those that tend to promote carbon formation in the combustion chamber. This occurs because some of the combustion chamber surfaces can reach coking temperatures at high loads, but will not normally reach the ignition temperatures of the deposits.

The heat transfer and combustion processes that occur in an exhaust cleaning operation are too complex to be treated on an analytical basis for determination of optimum cleaning times and (load-induced) temperatures. This can only be done empirically for each specific engine generator system, and will depend to a large extent on the condition of the system prior to cleaning.

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4.0 HIGH IDLE OPERATION - BACKGROUND SURVEY

4.1 General - The term high idle is used here to designate an operating mode for DED generator sets at rated (synchronous) speeds from no load to approximately 25% of rated load. There is a considerable difference of opinion with regard to the damage potential of this mode of operation. The origins and development of these opposing points of view are highlighted below.

4.2 Air Force DED Generator Sets - The concept of high idle as a problem operating mode was apparently first addressed in the military by the Air Force. The prime mover for most of the Air Force flight line DED generator sets is a Detroit Diesel 2 cycle engine in any one of a number of configurations.

We have seen earlier that this engine design is particularly prone to a wet exhaust. For some years these generator sets were operated with load banks to yield higher engine temperatures and decrease wet stacking tendencies.

The Air Force in 1981 and 1982 attempted to find an alternative to load banking in an evaluation of the Stewart and Stevenson DRYXAUST system. The work was performed by Stewart and Stevenson Services, Inc., and the results were reported in a 1983 Air Force report (24).

Wet stacking was indicated in that report to cause "increased fuel consumption, accelerated engine wear, and deterioration of exhaust system components". Air Force engineering and maintenance personnel identified in the report (5)(7) were contacted to determine the nature of the engine and exhaust system damage.

These personnel stated that the problem was not one of engine damage, but rather an unacceptable housekeeping and accident hazard situation involving ground surfaces covered with black oily liquids.

Stewart and Stevenson states (in the Air Force report) that when diesel engines are operated at high idle, "the fuel injectors supply more fuel than the engine is capable of burning.... This unburned fuel collects in the exhaust system and causes a fuel sludge buildup commonly referred to as slobbering or wet stacking".

The Stewart and Stevenson "fix" consisted of substantially reducing exhaust back pressure by means of a change in muffler design, slightly increasing back pressure by means of a gravity operated exhaust damper valve, and substituting injectors less likely to overfuel at low loads.

The theory of using an exhaust brake to increase back pressure and reduce wet stacking tendencies is valid and will be discussed later. However, based on the data presented by Stewart and Stevenson it would appear that the most significant change to the engine wet stacking tendency in this case was the result of installing injectors better suited to low load operation than the original injectors.

It would also appear (in the absence of more complete information) that the reportedly improved fuel consumption was primarily a result of better injection characteristics combined with lower exhaust back pressure from a more appropriate muffler design. It is not obvious from the information presented that the DRYXAUST valve played a significant role in the "fix".

4.3 DOD DED Generator Sets - User Assessment - As previously stated, there is a perception on the part of many users of these sets that high idle is a highly deleterious operating mode for all DED generators. The result has been a movement toward integral load banking of sets to avoid light load operation. It is useful to examine the background and development of this perception in order to assess its validity.

4.3.1. Documented User Reports - While much of the evidence of user dissatisfaction with high idle operation is verbal, there are several documents which fairly reflect that general position. Quality Deficiency Reports (QDR's) and Equipment Improvement Recommendations (EIR's) will be discussed separately since they refer to specific generator sets.

4.3.1.1 System Assessment Reports - The 1981 system assessment report (15) for the 30 kW 60 Hz generator sets makes the statement that "users are operating the generator sets under low-output load requirements ..... load bank kits would eliminate engine carbonization". The 1982 system assessment report (3) states that "use of load banks when the operational loads .... are low will contribute to a longer life for the generator engine".

No evidence was presented in either of these reports to substantiate the position that light loading caused engine "carbonization" or shortened engine life. An author of the 1982 report (4) was contacted to determine the basis for the high idle damage scenario.

It was stated that a thorough search of both military and civilian data bases by these authors had provided no data upon which to assume reduced engine life or decreased reliability. It would appear that these judgements either were based on intuition, or reflect opinions voiced by others during the field survey portion of that work.

4.3.1.2 Field Reports - Recent sample data collection activity summarizes in an unpublished trip report some of the feelings about high idle operation held by field personnel. That report essentially stated that all 10 kW sets in a tactical unit were inoperative. The problem was attributed to the system usually operating at less than 25% of maximum rated load (high idle).

It is significant that 7 out of 9 reported generator failures occurred in the period from November to January in a relatively cold climate. It is also significant that similarly equipped tactical units operating in the same area concurrently reported no major problems.

In light of these facts it is probable that a lack of familiarity with these air cooled units on the part of operating personnel rather than engine deficiency was the cause of the problem. Nevertheless supervisory personnel attributed the failures to extended high idle operation.

Another unpublished field report stated with regard to 30 kW DED generator sets that "it is evident that these sets must not be operated for any length of time without a load, or wet stacking will result". The writer evidently considered the wet stacking to be a problem rather than a symptom. Again no evidence was presented that any damage or deterioration of the engines had occurred.

4.3.2 Verbal Reports - Discussions were held with operating and maintenance personnel from a number of organizations varying both in location and function. A substantial proportion of these personnel expressed the opinion that high idle was a problem operating mode. Their position parallels that expressed in the previous documented reports.

In some few instances specific problem sets were identified as experiencing failures due to high idle operation. In fact, most of these failures were of a nature more likely to be the result of other circumstances than high idle. The units which reportedly failed due to high idle operation had been repaired, so that no first hand observations could be made.

<u>4.4 Diesel Manufacturers - High Idle Assessment</u> - Engine builders and those associated with the industry consistently express a viewpoint somewhat contrary to that evidenced by users. The concensus of builder opinion was that high idle operation dictated careful attention to specified routine service procedures, but caused no decrease in engine life or reliability. This proved to be true regardless of whether or not they were current suppliers of engines to the military.

All sources contacted provided some narrative to support their position, although once again documentation was lacking. The almost unanimous manufacturer perception of high idle as a (usually) non-problem operating mode is best exemplified by the following case histories.

Several manufacturers report that diesel construction equipment in very cold climates operates almost continuously at low idle during winter months because of the difficulty of low temperature starting.

The equipment is stopped only for routine maintenance, and never long enough for engines to cold soak. The only special provision recommended for this usage is the increase of low idle speed by 200 to 300 RPM in order to increase the engine idle operating temperature.

Two sources also report that cold climate diesel locomotives are started in round houses daily, and then moved outside. In the case of yard engines they are operated at idle almost continuously, and rarely experience high loads. The only detrimental effects reported were of a housekeeping nature, namely the spraying of unburned diesel fuel upon applying load.

One manufacturer reports the current use of a diesel generator engine in the 50 kW class which at present has operated without problem for over 12,000 hours. This engine is in marine service as a primary power unit and operates almost continuously at high idle. It has had no unscheduled service, and apparently does not exhibit any tendency to wet stack.

Finally, the almost continuous use of 100 kW primary power sets to meet a demand typically in the 5 to 15 kW range was reported. These sets were said to have operated for a number of years without any unusual engine service problems.

4.5 QDR's and EIR's - The TROSCOM DED generator maintenance files were examined for evidence of high idle problems experienced by any of the DoD standard family of tactical engine generators. The review included all problems reported for these sets from 1970 until the present.

With the exception of the 15 kW and 30 kW sets, there were two reports concerning problems that might be considered high idle associated. The first, EIR (control no. Y77992) referenced exhaust carbon buildup and incomplete combustion in 5 kW DED generator sets. The problem was finally traced to faulty fuel injection nozzles.

The second, QDR (control no. 670997) referenced a 100 kW DED generator set showing signs of oil leakage and "excessive slobbering" at the exhaust. This was eventually determined to be caused by faulty piston ring installation in a single piston of the problem engine.

All other complaints and recommendations were in reference to the 15 kW and 30 kW DED generator sets powered by the 198ER and 298ER engines described in appendix a.

4.5.1 198ER / 298ER Engines - High Idle Problems - These engines were the subject of a number of EIR's, QDR's and memoranda concerning reportedly unsatisfactory high idle operation. The "exhaust problem" correspondence for these engines begins in 1979, and continues to the present. They have recently been the subject of a review with regard to their application in both the Pershing and Patriot systems. The problems as perceived by operating personnel are best summarized by the following case histories.

Fort Stewart, GA reported in 1979 that one 30 kW and four 15 kW sets were "pumping fuel and oil, mostly oil, out the exhaust". They also reported oil leaking at the manifold to muffler flanged joint. The sets were run at 75% load for 16 hours without improvement. Teardown inspection, cylinder honing, and the addition of valve seals failed to solve the problem.

The Illinois National Guard reported in 1980 that when a 30 kW set was operated at "low power (10% of capacity), oil leakage was noted at the manifold gasket and the exhaust gases were very dirty". They also reported (but did not define) excessive oil consumption.

Replacing the manifold gasket solved the oil leakage problem. Load banking cleared up the "dirty exhaust" problem temporarily, but "exhaust gases continued dirty at low power".

Teardown inspection of the engine indicated the combustion chamber and associated components to be in "excellent visual condition".

The Pennsylvania National Guard reported in 1980 that a 15 kW generator set wet stacked and used excessive oil. It was stated that "the engine does not miss and seems to operate normally". Oil consumption from 14 to 93 hours (on the running time meter) averaged one quart of oil every seven hours.

Recently this writer had the opportunity to examine eight 30 kW sets at the Belvoir R an D Center in temperate weather. These sets were powered by 298ER engines manufactured between June 1981 and February 1982. The sets had between 10 and 15 hours of running time on the meters.

Four of the sets were dribbling oil at the flanged joint between the exhaust manifold and the muffler at high idle. The result was a coating of oil down the side of the engine and on the set structure.

The wet stacking and oil leakage was stopped by load banking at full load for about 15 minutes. When the load was dropped to high idle, oil dribbling and wet stacking resumed. After running the sets at full load overnight, return to high idle again resulted in oil dribbling after approximately one hour of operation.

4.6 Engine Oriented Problem Scenarios - It becomes apparent that we are concerned with the effects of two different syndromes generated by high idle operation of DED generator sets.

The first is characterized by the generic "slobbering" of unburned fuel in all diesel engines operating under light loads in a cold environment. The second is characterized by the "slobbering" of lubricating oil in some 198ER and 298ER engines under light loads regardless of environmental conditions.

The remainder of this report will treat these phenomena as two separate and distinct areas for consideration.

* * * * * *

5.0 HIGH IDLE - DAMAGE ANALYSIS

5.1 General - While there is no apparent evidence that high idle operation of diesel engines in general causes acute or catastrophic damage, there are some chronic "nuisance" effects which must be considered. It should be noted at this point that any of these chronic nuisances can also occur for reasons other than light load operation.

5.2 High Idle Problems - Most diesel engines in good repair exhibit undesirable symptoms attributable to a high idle operating mode only when conditions are such that the combustion chambers becomes too cold for good combustion to occur. This usually occurs only with a combination of light loads and low environmental temperatures. The noticeable effects are some carbon buildup in the exhaust system and occasional wet stacking.

While carbon buildup in the combustion chambers, valves, and injectors has occasionally been attributed to high idle operation, combustion theory and some experimental data indicate that this is not the case. We have previouly noted that teardown inspection of 198ER and 298ER engines in several cases after wet stack operation showed clean combustion chambers.

The Caterpillar Tractor Research Department (14) performed some experiments with their diesel engines at low temperatures because, they said, "many commercial users idle our engines continuously between working periods; and in some instances, the engines are not stopped long enough to get cold during the entire winter".

A D2 Caterpillar engine was operated continuously for 4 days (96 hours) at 700 RPM idle in an ambient temperature of -40 degrees F. The only engine protection consisted of paper in front of the radiator. Teardown inspection immediately after cold idle operation revealed no evidence of nozzle plugging, and showed an engine reported to be in excellent condition. The only effect noted was some soft carbon sludge in the exhaust valve ports.

5.2.1 Effects of Wet Stacking - Wet stacking (by fuel oil) tends to result in cylinder wall washing. This is usually accompanied by increased blow-by of combustion gases into the crankcase with resultant oil dilution and occasional sludging.

"Cold sludge" (crankcase sludge) is defined by Stinson (21) as a colloidal mixture of oil, water, and combustion products. He further states that "hot sludge" can be formed in the exhaust system as a result of continuous exposure of hydrocarbon and carbon mixtures to high temperatures during wet stacking. Hot sludge is reported to resemble coffee grounds in appearance.

It should be deposited in combustion chambers (with subsequent "lacquer" formation) only under the high wall and ring temperatures associated with heavy loads. Sludge formation in the combustion chamber is thus not a problem related to high idle operation.

Sludges can cause corrosion of crankcase and exhaust system components when high sulfur fuels and lubricants which decompose to form inorganic and organic acids are used. D.L. Raymond (19) states (with regard to cold weather operation of diesel engines) that prolonged idling causes condensation and sludging of crankcase oils, promotes crankcase corrosion, and interferes with lubrication. To avoid these problems he advises raising the idling speed to 1000 RPM to maintain higher engine temperatures.

Finally, severe wet stacking can create a housekeeping problem by coating surrounding equipment and ground surfaces with a fuel, oil, and carbon mixture. In the case of locations requiring personnel access, this can create a potential safety hazard in the form of slippery footing areas.

5.3 Alternate Problem Sources - The nuisance symptoms of low temperature high idle operation are also caused by a number of other more serious conditions. Among these are overfuelling due to improper injector sizing, after dribble caused by leaky or corroded injectors, low compression, improper timing, and poor quality fuel or lubricating oil.

When high idle type symptoms are found in certain individual engines rather than in a class of engines, it is probable that the cause is one of these engine specific problems rather than operation in the high idle mode.

Occasionally other problems such as the failure to accept load or rough running have been attributed to extended high idle operation. These kinds of failures are not typical of extended low temperature light load operation unless the temperatures are low enough to cause one or more cylinders to be inoperative. Again it is more likely to be peculiar to an individual engine not in good repair than to a class of engines.

5.4 Assessment - Military Diesel Engines - With the possible exception of the 198ER and the 298ER engines which will be discussed separately, there is no indication that high idle operation is a problem mode for any of the engines used as DoD tactical generator drivers. Occasional reports of heavy exhaust carbon or failure to accept load in these engines are probably due to poor engine condition, poor fuel, or poor lubricating oil.

The directed maintenance regimen for the military engines is conservative with regard to inspection, operation, and servicing. Adherence to the service guidelines and use of specified fuels and lubricants should prevent engine damage from any of the possible effects of high idle operation described above.

5.5 Idle Mode Symptom Alleviation - Several techniques other than load banking are available to reduce the symptoms of extended cold operation (in either the low or high idle mode) when the symptoms become an unacceptable nuisance. These techniques are all based on increasing the combustion chamber and exhaust temperatures.

They have been used primarily in cases where the spraying of unburned fuel has been unacceptable to the user. There are no reports of these techniques being used to enhance engine operation, extend engine life, or prevent engine damage.

5.5.1 Increased Exhaust Back Pressure - Three instances of avoiding unburned fuel discharge by increasing exhaust back pressure have been reported.

The Stewart and Stevenson DRYXAUST system apparently intends their gravity operated exhaust valve to serve this purpose. Cummins Engine Co. (21) reported the installation of an air operated "guillotine" valve in the exhaust of a locomotive diesel engine to increase back pressure and reduce spraying of fuel. Lister Diesels (6) reported that unmuffled air cooled diesel engines in irrigation service discharged unburned fuel until back pressure was increased by the installation of mufflers.

Increasing exhaust back pressure (exhaust braking) acts to increase engine temperatures by increasing the fraction of residual gas in the combustion chamber at the start of the intake cycle. It also requires additional fuel (and thus higher cylinder temperatures) to discharge the exhaust against the higher pressure.

On the negative side, increasing exhaust back pressure will tend to increase crankcase oil dilution, and may increase soot formation.

5.5.2 Capacity Modulation - This technique involves cutting off fuel to one or more cylinders in either V or in-line engines. This is generally feasible only in cases where low pressure fuel distribution is used e.g. the Cummins PT system. The result of this procedure is to cause the working cylinders to carry more load, use more fuel, and thus operate hotter. It is reported that engines operating in this mode do not run noticeably rougher than with all cylinders firing.

While this approach is not suitable for the current line of military diesels, it does point out the possibility of DoD DED generators appearing to run normally while in fact there are one or more inoperative cylinders. This would provide a likely scenario for a set in apparent good repair "failing to pick up load".

5.5.3 Intake Air Preheat - Absolute air temperature at the end of the compression cycle (without combustion) varies almost linearly with absolute intake air temperature. It also varies as a fractional power of the compression ratio, the power being typically of the order of 0.33 (22).

If we assume an intake air temperature of 0 degrees F (460 degrees absolute), a compression ratio of 15 to 1, and a compression ratio factor of 0.33, we would arrive at a compression temperature of 664 degrees F (1124 degrees absolute). Intake air temperature of 100 degrees F would result in a compression temperature of 909 degrees F. Thus an increase of 100 degrees F in intake air temperature would result in an increase of 245 degrees F in compression temperature.

This indicates that increasing of intake air temperature would result in an amplified increase in compression temperature. Thus intake air preheat would appear to be a promising avenue for extending the non-symptomatic temperature range for high idle operation.

Intake air heating might also be accomplished by electrical heating of the intake manifold. This would have the dual effect of preheating intake air and increasing generator load. Alternately, heating could be provided by exhaust gas heat exchange, or (under some conditions) by engine intercoolers, aftercoolers, or radiators.

5.5.4 Exhaust Gas Recirculation - The technique of exhaust gas recirculation (EGR) consists of mixing some of the exhaust with the intake air at light loads through the application of waste gate technology. The effect of this technique is to increase intake gas temperature, and thus combustion chamber and exhaust temperature.

On the negative side oil dilution will be somewhat increased as in the case of the exhaust brake. Additionally there is some evidence (10)(22) that EGR increases soot formation by extending combustion duration (decreasing flame speed). This could result in less complete soot combustion at the time of exhaust valve opening.

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6.0 The 198ER and 298ER Engines

6.1 General - Some of the 198ER and 298ER engines have a tendency to wet stack at high idle regardless of ambient temperature. Contrary to the ususal wet stacking phenomenon, the effluent appears to be primarily lubricating oil.

This might indicate combustion chamber temperatures high enough to permit essentially complete combustion of the finely dispersed fuel, but not high enough for combustion of the less dispersed and lower cetane value lubricating oil. Alternately, it might result from an excessive amount of lubricating oil reaching the cylinders.

No information concerning lube oil consumption specifically under high idle conditions has been found for these engines. There is an indication from field reports that high idle oil consumption in some cases may be more than one quart every eight hours. It would seem on the basis of available information that this may not be typical of this design, but may be limited to certain sets.

6.2 Manufacturer Assessment - White Engines, Inc. (1) essentially states with regard to the 198ER and 298ER engines that:

1. continuous operation at light or no load will not affect engine reliability, or shorten engine life.

2. lubricating oil wet stacking will not cause injector fouling, or cause failure of the engine to respond to sudden full load application.

3. oil consumption will not be appreciably different at high idle than at the same speed under load.

4. excessive cylinder oil in these engines is primarily a problem of the state of repair of the engine, or the absence of valve guide seals.

5. oil leakage from manifold gasketing is not an abnormal condition, and oil discharge from the exhaust stack or manifold gasketing is a purely "cosmetic" problem.

<u>6.3 Analysis - Manufacturer's Position</u> - Based on information previously reported, the assessment by the manufacturer seems valid with several reservations.

There is an indication in the field literature that some of these engines consume excessive oil when operating at light loads. It has been reported previously that in at least one case the installation of oil seals in accordance with the manufacturer's recommendations did not correct the oil throwing problem. It is possible that oil in excess of that required for good lubrication is reaching the cylinders through the valve guides or through faulty oil ring action in some of the 198ER and 298ER engines.

Oil leakage past the exhaust manifold gasketing results in an oil covered engine and enclosure. This causes the collection of dirt on the engine and requires a cleanup operation before maintenance is performed. In addition the slobbering of oil down the sides of the engine creates a question in the mind of the user about the possibility of engine damage through continued use.

Since keeping oil contained in the engine envelope is within the state of the art, it would be desirable to correct this problem once its scope and cause are determined.

Finally, whether the problem of oil discharge is cosmetic or safety related depends on the application. In those cases where the generators are mounted on trailers or other structures, and where personnel access to these areas is required, the presence of oily surfaces can be a personnel hazard. This is particularly true in high stress situations such as might occur in a combat scenario.

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7.0 SUMMARY OF FINDINGS

7.1 The Effects of High Idle - This investigation has revealed no instances in which reduced engine life, reduced reliability, engine damage, or failure to accept load could be directly traced to high idle operation. Under most conditions for most engines no unusual symptoms result.

There is no indication that high idle is in general a more severe operating mode for diesel engines than low idle, and some indication that it may be less severe. This may be deduced from the typical recommendation to increase low idle speed by several hundred RPM for extended low temperature idle. Whether or not the recommendation can be safely extrapolated to high idle is problematical.

The wet stacking symptoms exhibited by the 198ER and 298ER engines do appear to be aggravated by an increase in speed, as might be expected in the case of excessive lube oil reaching the cylinders. Some of the 198ER and 298ER engines have a tendency to slobber oil out of the exhaust stack as well as out of exhaust manifold gasketed joints. It may be characteristic of the engine design, or may be a quality problem with part of the production.

This trait may cause excessive oil consumption, housekeeping, and safety problems, but it is not likely to produce engine damage. In fact, excessive cylinder oiling should not create the oil dilution problems occurring in the overfuelling situation more typical of diesel wet stacking.

7.2 Military Engines - Except as noted, the military engines as a class do not exhibit any unusual tendency toward high idle problems. Reported excessive carbon buildup in the exhaust at certain geographical locations is probably attributable to fuel, oil or filter problems.

Carbonized or wet exhaust can be eliminated (if considered necessary) by the occasional load banking of sets in accordance with the provisions of the 1983 TSARCOM directive (25). This document recommends load banking lightly loaded sets at full load for 6 hours every 30 days, checking oil weekly for signs of oil dilution, and using smaller sets where possible to provide operation at a higher percentage of rated load.

There is no information available upon which to improve the above schedule in terms of frequency, duration, or level of load application. In the absence of hard data that might permit some reduction in these factors, this empirically specified procedure appears effective.

The recommendation to use sets well sized to their application to minimize the nuisance factors of high idle operation is well taken for several reasons.

First, initial set cost is reduced for smaller sets. Second, brake specific fuel consumption decreases and efficiency increases dramatically with load for diesel engines until approximately the 50% load point is reached. Third there is evidence (11) that combustion quality with regard to total exhaust particulates (carbonizing and wet stacking contributors) is optimum at about 50% load.

Thus it appears that sets sized to operate at generator loads of 50% to 100% will operate more efficiently and cleanly than lightly loaded sets. Additionally sets thus sized can undergo exhaust clearing by the occasional application of their operating load rather than by load banking.

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8.0 ENGINE SCREENING - HIGH IDLE OPERATION

8.1 General - It has been shown that problems associated with high idle operation are primarily related to exhaust system reactions, and secondarily to crankcase oil contamination. If it is desired to screen new engine types to assure satisfactory operation in this mode, these two areas can be evaluated by the following techniques.

8.2 Test Methods - Exhaust analysis can be performed under no load and rated speed conditions for the test engine using U.S. Environmental Protection Agency procedures for diesel engine exhaust testing (26). Analysis should be made for dry soot and soluble organic fraction (SOF). The dry soot value will indicate exhaust carbonizing tendencies, and the SOF will indicate the wet stacking propensities of the engine.

Crankcase oil can be examined for viscosity, total base number (TBN), and insolubles. These tests will serve to measure the extent of the lubricating oil deterioration.

In order to establish pass fail criteria, a baseline study would be required using engines now in service that are considered acceptable. Appropriate values for all of the above parameters could be established by the application of reasonable tolerances to the performance of the currently acceptable engines.

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9.0 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions - Based on the foregoing analysis the following conclusions may be drawn.

a. Diesel engines designed in accordance with good commercial practice, in good repair, and properly serviced can operate at high idle speeds indefinitely without suffering decreased life, decreased reliability, or engine damage. The primary potential source of damage from high idle operation as contrasted to high load operation involves possible excessive crankcase oil dilution and contamination.

The military specification for diesel fuels and lubricants together with conservative servicing procedures are sufficient to insure safe operation of military diesels with regard to oil dilution.

b. The nuisance effects of high idle operation are some carbon buildup in the exhaust, and occasional slobbering of a primarily diesel fuel effluent at low temperatures. There is no significant effect on the combustion chamber from extended high idle operation, and consequently no effect on the engine's ability to respond to load application.

These effects can be ameliorated (if desired) by proper orientation of the exhaust system, and by occasional load banking in accordance with the previously cited 1983 TSARCOM directive.

c. The 198ER and 298ER engines are exceptions to this conclusion to the extent that at least some of these engines slobber lubricating oil rather than fuel oil, and the slobbering is relatively independent of ambient temperature.

No damage to the 198ER and 298ER engines is expected from this mode of operation, although continuous housekeeping and occasional safety problems are created by the ejection of lubricating oil.

9.2 Recommendations - The following suggestions are intended to help answer some unresolved questions, to decrease maintenance costs, and ultimately to help provide more reliable tactical power with lower life cycle costs.

a. The DoD DED tactical generator drivers in general are adequate for extended high idle operation. The concept of monthly clearing of the systems by high load operation, and weekly oil inspection in accordance with the 1983 TSARCOM directive should be maintained until improved procedures can be developed.

b. A refinement of the TSARCOM procedures should be developed to optimize the load and operating time requirements for high load clearing operation. This should be done as a function of set design, operating hours, service application, and climatic conditions. Where possible load clearing of the system should be by normal operating load rather than by load banking.

c. The 198ER and 298ER engines should be tested and evaluated to determine whether lube oil slobbering is a design or production quality characteristic. Worst case engines should be tested for lubricating oil consumption under high idle and full load conditions.

The leakage of oil at exhaust manifold gaskets on some 198ER and 298ER engines is not typical of good design and workmanship. It presents an unacceptable housekeeping problem and should be corrected.

Where the 198ER and 298ER engines are used in a field application such that the oil discharge presents a personnel safety hazard, it is suggested that the exhaust systems be reoriented to minimize the problem.

d. The future selection of engines for DED generator application should include screening for fuel and lubricating oil control by application of tests similar to those outlined in paragraph 8.2 of this report.

e. An effort should be made to properly size tactical generator sets for particular applications to increase efficiency and mobility, to decrease the need for load banking, and to reduce life cycle costs.

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11.0 APPENDIX

Appendix a.

TACTICAL GENERATOR DRIVERS

2.2.1 Onan Model 100-1344 - This engine is two cylinder air cooled, displaces 70 cubic inches, and develops 9 brake horsepower (BHP) at 1800 RPM. It is naturally aspirated (non-turbocharged) with a compression ratio of 19 to 1. It has an AMBAC fuel system with indirect injection into a precombustion chamber equipped with glow plugs. Cold weather starting is also aided by electrical induction-air heaters in the intake air manifold. It powers the 5 kW 60 Hz DED generator set.

2.2.2 Onan Model 100-1345 - This engine is a four cylinder version of the Onan 100-1344, displacing 140 cubic inches and developing 18 BHP at 1800 RPM. It drives the 10 kW 60 Hz DED generator set and (with minor modifications) the 10 kW 400 Hz DED set.

2.2.3 White Engines, Inc. Model 198ER - This engine is four cylinder, liquid cooled, and naturally aspirated. It has a displacement of 198 cubic inches based on a bore of 3.75 inches and a stroke of 4.50 inches. It has a compression ratio of 17.5 to 1, and is rated 41 BHP at 1800 RPM. It uses a Stanadyne/Hartford fuel system in a direct injection combustion chamber. It powers the current production of 15 kW 50/60 Hz and 400 Hz DED generator sets.

2.2.4 White Engines, Inc. Model 298ER - This engine is a six cylinder version of the White 198ER, displacing 298 cubic inches and developing 57 BHP at 1800 RPM. It has a compression ratio of 17 to 1, and drives the 30 kW 50/60 Hz and 400 Hz DED generator sets.

2.2.5 Allis-Chalmers Model 3500 - This engine is six cylinder, liquid cooled with a displacement of 426 cubic inches. It is turbocharged and rated 120 BHP at 1800 RPM. It uses a Stanadyne/Hartford fuel system with direct injection of fuel into the combustion chamber. It has a compression ratio of 16 to 1, and drives the 60 kW 50/60 Hz and 400 Hz DED generator sets.

2.2.6 Caterpillar Model D-333T - This engine is six cylinder, liquid cooled with a displacement of 638 cubic inches (bore 4.75 inches, stroke 6.0 inches). It is turbocharged , rated 221 BHP at 1800 RPM, and has a 17.5 to 1 compression ratio. It uses a Caterpillar designed fuel system, and a precombustion chamber with a single hole nozzle delivering a fairly coarse spray. It drives the 100 kW 50/60 Hz and 400 Hz DED generator sets.

2.2.7 Caterpillar Model D-343T - This engine is similar to the Caterpillar D333T except that the bore is increased to 5.4" and the stroke to 6.5". The compression ratio is lowered to 16 to 1. This provides a six cylinder displacement of 893 cubic inches and a continuous power rating of 344 BHP at 1800 RPM. It powers the 200 kW 50/60 Hz DED generator set.

2.2.8 Detroit Diesel 4-71 - This engine is two cycle, four cylinder, naturally aspirated (Roots pump scavenged) with a displacement of 284 cubic inches. It has a compression ratio of 17 to 1, and is rated 118 BHP at 1800 RPM. It is a direct injection engine using General Motors unit injectors. It powers an Air Force version of the 72 kW Hobart engine generator set used by the commercial airlines.

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Appendix b.

DIESEL COMBUSTION - THEORY AND EFFECTS

Combustion Theory - The three stage combustion theory postulated by Ricardo (20) in 1930 still governs diesel combustion research. Taylor (23) states that stage one (the delay period or ignition lag) is long enough so that, at ignition, there is a considerable quantity of gaseous and finely divided liquid fuel well mixed with the air.

The ignition lag will depend on the temperatures and pressures in the combustion chamber as well as the wall temperatures on which the injected spray impinges. These factors are a function of the engine design and operating conditions

The second Ricardo stage is the period of rapid combustion. This results from multiple ignition points combined with high combustion chamber temperatures at the start of ignition. The rapid combustion period consumes fuel which has had a chance to evaporate and form a combustible mixture with air during the period of ignition lag.

Taylor further points out that the nature of fuel injection in diesel engines is such that there will be fuel/air ratios in the chamber from zero (no fuel) to infinity (no air in fuel droplets) until the fuel is completely evaporated. It follows from this that the quantity of fuel consumed in stage two is a function of the duration of ignition lag, of injection spray characteristics, and of chamber turbulence.

During the third Ricardo stage unburned fuel from stage two together with any fuel still being injected burns at a rate controlled by the local availability of air. This final stage begins approximately at the time of maximum cylinder pressure. It ends when combustion is essentially complete or is interrupted by the action of the exhaust cycle.

When stage three combustion extends into the exhaust cycle, incomplete combustion results, with effects that include wet stacking and exhaust carbonization.

Carbonization - Accepted theory is that exhaust soot is the net result of soot formation during combustion, and the partial combustion of the soot so formed during the remainder of the combustion cycle. Factors affecting soot formation are detailed by I.M. Khan (13) and restated in the later work by Lipkea. Khan indicates that soot formation is partially engine design related, depending essentially on injection timing, injection rate, and nozzle design.

Tar results primarily from liquid phase pyrolysis, and is a semisolid form of high polymeric carbonaceous material. When deposited in the combustion chamber and exposed to high cylinder wall and ring temperatures it can become a source of the "lacquer" occasionally found in those areas.

Vitreous carbon is a hard shiny black deposit that is formed on hot surfaces. When found in the combustion chamber, it is most likely the result of mixtures of carbon, high molecular weight hydrocarbons, and lubricating oil being exposed for extended periods of time to surface temperatures in the active coking range of 500 to 600 degrees F. These temperatures are typical of ring and liner temperatures found in small and medium 4 cycle engines under heavy loads according to Stinson.

The same material and temperature considerations apply to hard carbon formation in the exhaust system. However, in the exhaust system temperatures in excess of 500 degrees F occur at low load as well as high load conditions

Fuel and Oil Effects on Carbonization - Carbon buildup is significantly affected by both fuel and lubricating oil as well as engine operating loads. Taylor indicates that carbon-based deposits tend to increase with increasing viscosity, decreasing volatility, and decreasing cetane rating (fuel ignition quality). He also notes that sulfur in fuel promotes both deposits and corrosion.

Stinson states that oils vary in their wall and piston temperature reactions. Naphthenic based mineral oils tend to form soft soot which (by means of oil detergent action) is picked up by the oil filter or escapes through the exhaust system. Paraffin based oils form harder deposits which are more likely to lead to ring sticking.

He further points out that even the naphthenic based oils will cause abnormal deposits in the combustion chambers and valves when engines are run at high loads for long periods of time. These deposits take the form of piston lacquers and sticky ring deposits. This condition increases blow-by of combustion gases to the crankcase, and may result in oil sludging where the oil has insufficient oxidation stability.

Kates (12) notes that the (Conradson) test for carbon residue in oils does not indicate whether the oil will form soft fluffy carbon which will be blown out, or the hard deposits that cause sticking rings.

It is noteworthy that combustion chamber carbonization, sludging and lacquer deposition depend to a large extent on the quality of fuels and lubricants. It is also significant that these effects are typical of heavy rather than light load operation.

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