

THE EVALUATION OF A ONE-CYLINDER DELCO GASOLINE
ENGINE AS AN ACCELERATED LUBRICATING OIL TEST UNIT

by

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I. INTRODUCTION

To fulfill its purpose, a lubricant must do two things: (1) effectively reduce friction between adjacent surfaces; and (2) aid in carrying away heat generated by the shear that occurs within itself. It must accomplish these ends without being too viscous for use at low temperatures, without forming sufficient acid through oxidation to cause corrosion of metal parts, and without producing harmful deposits, such as "varnish," sludge, or carbon.

Lubricating oils are catalogued according to definite specifications on viscosity, flash and fire point, neutralization number, sludge and carbon residue, color, etc. These specifications are based on the results of laboratory tests on the above mentioned items. Numerous investigators, however, have decisively determined that the stability, or resistance of oxidation, resistance to bearing corrosion, resistance to ring sticking, and extent of carbon deposits of a lubricating oil under definite conditions of service cannot be predicted from the previously mentioned laboratory tests. The evaluation of these lubricating properties of an oil, therefore, must come from actual service tests.

Much progress has been made from the early era of lubrication in meeting the above conditions. Solvent refining of lubricating oils has removed many of the undesirable qualities of the oil. However, the selective extraction also removes some constituents which have provided resistance to oxidation or to the formation of acids, sludges, and other decomposition products. This shortcoming has been corrected by adding, after solvent refining, chemical inhibitors of oxidation. In some instances chemical detergents have been added; these detergents have the ability to maintain finely divided carbon particles in suspension, permitting their removal on drainage of the oil. The field of additives also embraces the aiding of other chemical and physical properties of the lubricating oil. These include viscosity-index improvers, pour-point depressants, extreme pressure lubricants, and bearing-corrosion inhibitors.

The road service tests are accurate, but are time-consuming and costly. Much work has been performed on lubricating oil tests conducted on stationary engines. These tests range from a running period of $3\frac{1}{2}$ hours to 500 hours, and from temperatures of 140°F . to 280°F . Many types of engines are used, varying from one-cylinder

gasoline or Diesel engines to multicylinder gasoline or Diesel engines. The results are at variance, so that many different tests are required to reach a decision on any one oil.

It is desirable to build a single one-cylinder testing engine capable of manipulation so that it can test lubricating oils for wear, corrosion, and tendency to oxidation and detergency, and give reproducible results.

The purpose of this investigation is three-fold:

(1) to install the control accessories required for control of the engine test conditions, and assemble the one-cylinder, two-stroke cycle engine as a unit to be used in conducting the tests, (2) to determine the breakdown characteristics of a solvent refined, asphalt base oil at varying conditions of temperature and load in the test engine, and (3) to correlate the breakdown characteristics of the oil with the performance of the test engine so as to rate the engine as a possible test unit for evaluation of lubricating oils.

II LITERATURE REVIEW

THEORY OF LUBRICATION

Lubrication is concerned with the science of reducing effectively the frictional resistance occurring at the surface of two solids when they are forced to slide or roll over each other⁽²³⁾⁽³⁹⁾⁽⁶⁸⁾. Corse⁽²⁵⁾ defines a bearing as a mechanism devised to provide for rotation or for sliding of two solid surfaces in contact with minimum friction. In 1835, Tower⁽⁸⁵⁾ initiated the present day theory of lubrication by proving that an actual fluid pressure was created within the oil film of a bearing and a journal. In 1886, Reynolds⁽⁷⁶⁾⁽⁷⁷⁾ verified Tower's discovery and described the lubrication process in which the lubricant was considered to be drawn into a convergent or wedge-shaped passage between the two solid surfaces (of a bearing and a journal) where, owing to its viscosity, the lubricant produces forces which account for the load carrying capacity and frictional reduction of the surfaces. Reynolds also verified the application of the laws of hydrodynamics to the oil films of bearing and journals. According to Genant⁽³⁹⁾ the fluid film may exist with any viscous fluid, such as mineral or vegetable oils; but even air, for example, possesses the required properties to

lubricate bearings. It is generally accepted that two different types of fluid film may exist between a bearing and a journal, namely; thick films and thin films, although both films will not exist at the same time.

Thick Film Lubrication. According to Corse⁽²⁵⁾, friction of a bearing and journal depends upon an interaction but not an interlocking of the roughness of the two surfaces, and above all, upon an interlocking of the electro-magnetic fields of force which radiate from the surface. If the introduction of a suitable viscous fluid between a bearing and a journal results in a film thick enough to suppress the effect of the attracting forces, and to allow the action of the film to be explained by the laws of hydrodynamics, then the film is called a thick film⁽⁶³⁾. Norton⁽⁶³⁾ stated that thick film lubrication has been maintained with films as thin as 1/40,000 of an inch.

Viscosity. Reynolds⁽⁷⁷⁾ proved that viscosity is the controlling characteristic of a lubricant under thick film conditions. Viscosity is defined as the internal resistance offered by a fluid to change of shape or relative motion of its parts⁽⁵⁾.

Sir Isaac Newton⁽⁶⁷⁾ discovered the fundamental principles of viscosity as a specific property of a lubricant. He postulated the law of viscous flow which may be summarized as follows: the shear stress is uniform in all parts of the film, and the rate of shear is proportional directly to the stress and inversely to the internal friction of the fluid. Reynolds⁽⁷⁷⁾ based his theoretical study of the manner in which oil could flow in a space between a bearing and a shaft upon this law.

Investigators⁽³⁷⁾⁽³⁹⁾⁽⁶⁸⁾ state that the viscosity of a mineral lubricating oil decreases with increase in temperature. Therefore, one of the criteria of a satisfactory lubricant for thick film lubrication is that the viscosity of the oil at low starting temperatures of an engine must be high enough to maintain the film thickness between bearings and shaft. Also the viscosity of the oil at the high temperature developed after normal running speed has been attained should not decrease below the point required to maintain the necessary film thickness⁽¹⁾⁽³⁷⁾.

Thin Film Lubrication. The existence of thick film lubrication of engine bearings and journals requires high speeds and light loads. Any engine at the moment of stopping, or starting, or when subject to heavy loads will

fail to meet the above requirement(1)(25)(68). During such a starting interval the coefficient of friction becomes progressively less until a minimum point is reached. Beyond this minimum point any increased speed results in an increased coefficient of friction which is a function of the speed of the shaft. This transition from a decreasing to an increasing coefficient of friction marks the advent of thin film or incomplete film lubrication(23)(25). Norton(68) states that thin film lubrication occurs when the film is so thin that its action cannot be wholly explained by the hydrodynamic theory. Thin film friction is not definitely understood, but it does involve the chemical nature not only of the lubricant but also of the surfaces separated by it (39)(48)(51)(68). Boundary lubrication is a limited case of thin film lubrication(67)(68). It exists in oil films under 10^{-5} cm. in thickness(39). Genant(39) states that no mathematical theory exists for boundary lubrication and that it is in the experimental stage.

Oiliness. Corse(25) states that the oil film, be it ever so thin, must constantly cover the solid surfaces and offer sufficient resistance to the forces trying to destroy it. Moreover, the molecules of the lubricant

require special properties to reduce the friction of the surfaces. The sum of these two phenomena is what Corse⁽²⁵⁾ calls the oiliness of the lubricant. Herschel⁽⁴⁵⁾ defines oiliness as the property which causes a difference in the friction when two lubricants of the same viscosity at the temperature of the film are used under identical conditions. In thin film lubrication the coefficient of friction depends upon the oiliness of the lubricant. Oiliness implies the comparison of either two lubricants with the same bearing or two different bearings with the same lubricant. No unit or standard scale for oiliness has been adopted⁽⁶³⁾. Attempts have been made to measure dipole moments as a guage of oiliness, but Kadmer⁽⁴⁷⁾ reports after extensive experimental work that no practical relationship exists between dipole moment and oiliness effect.

Two theories of oiliness have been mentioned. Langmuir⁽⁵²⁾ and Clower⁽²³⁾ list the hypothesis of stratification which states that oil molecules are oriented according to their dipolar nature for a number of layers out from the metal surfaces and that planes of easy slip are formed between the molecular layers adjacent to the metal surfaces. Experiments⁽⁵⁷⁾ have shown that the oiliness effect exists even when there are only two layers of molecular thickness between the metal surfaces. According

to Norton⁽⁶⁸⁾ and Foote⁽³⁷⁾ another hypothesis, one of absorption, suggests that bearing metals have a higher degree of attraction for certain types of oil molecules than for others, and that molecules of these types will separate out of the oil to form a tenacious, concentrated film which will cling long after a hydrodynamic film has been squeezed out. Both hypotheses have been supported by experiment and are based upon the dipolar nature of molecules, notably the (OH) or (COOH) grouping, found in organic alcohols, modified esters, and acids⁽¹⁾⁽³⁹⁾⁽⁵⁷⁾⁽⁶⁸⁾. These organic compounds possess greater oiliness characteristics than straight mineral oil and are added to the oils to improve their oiliness. The resulting oil is called a compounded oil⁽²³⁾⁽⁶⁸⁾.

Mechanism of Engine Lubrication. An oil in an internal combustion engine has three distinct functions: (1) to lubricate moving parts, (2) to form a seal around the piston rings, and (3) to conduct away heat generated by the shear it suffers in itself⁽⁶⁸⁾. Clower⁽²³⁾ states that the lubrication problems associated with the engine divide into two groups: (1) lubrication of the cylinder, and (2) lubrication of the bearings. The ideal situation

is to provide a complete unbroken oil film over the entire cylinder wall capable of acting as a lubricant for the piston rings and as a seal to prevent the passage of gaseous combustion blow-by products to the crankcase. Piston rings serve to maintain engine compression, control lubrication, and conduct heat away from the combustion chamber to the cylinder walls⁽⁷⁾. Clower⁽²³⁾ further states that both thick and thin type lubrication prevail between the rings and cylinder walls, and that sufficient oil must be furnished to the cylinder during each stroke of the piston so as to prevent the rings from making metal-to-metal contact with the cylinder walls. In addition, ring belt temperatures are considerably higher than the critical temperature of the oil, so the oil must be stable enough to prevent excessive carbon formation by thermal decomposition⁽¹⁶⁾⁽⁵⁰⁾.

Bearings. Composition of bearing metals and proper design of bearings for load and lubrication aids, such as oil grooves, are also functions of effective lubrication⁽⁸⁾. Experimenters⁽⁹⁾⁽⁵²⁾ have shown that the nature of the bearing metal to which the oil is attached in thin film lubrication plays an important part in the phenomenon of oiliness. Load capacity, wear, and corrosion also depend upon the nature of the metal. The bearing in general should

have high compressive strength, good wearing qualities, low coefficient of friction, and sufficient plasticity to compensate for any inequalities of alignment⁽²⁵⁾.

Babbitt bearings (alloy of tin, copper, and anti-mony⁽²⁵⁾) have been accepted generally as the preferred metal due to their low friction characteristics, conformability, and corrosion resistance. However, under conditions of increased load and high lubricant temperatures, Babbitt bearings are susceptible to fatigue failure. When such conditions are encountered, bearings of copper, lead, or cadmium-nickel alloys are used. These two types, however, are subject to extensive corrosion at normal lubricating oil operating temperatures⁽⁷⁴⁾.

Thin film lubrication is not as effective as thick film for the majority of present day bearings. Wear of metal surfaces is expected and found in the thin-film type. Operating conditions of a bearing may make thin films unavoidable however. Norton⁽⁶⁸⁾ lists such causes as excessive load; insufficient, intermittent motion; low viscosity; improper supply of lubricant; and roughness of the bearing surfaces. However, with improved surface finishings of bearings, thin film lubrication will become a reality⁽⁸⁾. This will permit lower clearances for

surfaces, and will allow the use of lower viscosity oils in which internal friction would be less, for the heat transfer is an important item. The lower the generated heat, the less the load on the oil film⁽⁸⁾.

CHEMICAL COMPOSITION OF LUBRICATING OILS

Kalichevsky and Stagner⁽⁴⁹⁾ list many types of classifications of petroleum oils, the most important classification being the separation of crude petroleum into three divisions, namely:

Paraffin-base petroleum oils

Mixed-base petroleum oils

Asphalt-base petroleum oils

Paraffin base, such as those of the Pennsylvania oil fields, contain large amounts of paraffin wax and practically no asphalt. Mixed-base, such as those of the Mid-Continent, contain both paraffin wax and asphalt. The asphalt-base petroleums, such as those of California and the Gulf Coast, contain asphalt but almost no wax.

Kalichevsky and Stagner⁽⁴⁹⁾ and Nelson⁽⁶⁶⁾ state that the principal constituents of petroleum are carbon (83-87%) and hydrogen (11-14%). Crude petroleums, furthermore, are composed of various percentages of the following compounds:

paraffins (C_nH_{2n+2}); naphthenes (C_nH_{2n}); aromatics (C_nH_{2n-6}); olefins (C_nH_{2n}); diolefins (C_nH_{2n-2}); a large number of miscellaneous hydrocarbons whose chemical formulas range from C_nH_{2n+2} to C_nH_{2n-20} ; and oxygenated compounds such as acids, aldehydes, alcohols, phenols, and many of undetermined chemical structure; and generally a high percentage of asphaltic matter, which is composed of hydrocarbon substances containing a relatively small percentage of hydrogen. The chemical structure of the asphalt is not known. The crude petroleum may consist not only of a mutual solution of these series of compounds but of combinations of radicals from two or more different hydrocarbon series. A molecule may be made up of a naphthene or aromatic nucleus with side chains belonging to the paraffin series, or, as is generally assumed, different types of ring nuclei may be grouped together in the same molecule.

Inorganic compounds present are nitrogen compounds whose structure is unknown, numerous sulfur compounds, and minute amounts of sodium, potassium, lithium, iron, copper, lead, cobalt, and calcium.

Mikeska⁽⁶⁾ reports that with regard to the higher boiling fractions falling in the lubricating oil range, practically nothing is known beyond the fact that they

consist of a mixture of aliphatic, naphthenic, and aromatic hydrocarbons in various proportions. Sachanen and Wirabianz⁽⁷⁸⁾ concluded that the aromatic content of the higher boiling fractions of crude petroleum oils varies from 10 to 40%, the naphthenic from 25 to 80%, and the isoparaffinic from 15 to 75%, depending upon the nature and source of the oil. Hicks-Bruun and Bruun⁽⁴⁵⁾ obtained open chain hydrocarbons and a series of polysubstituted cyclopentanes from low-boiling fractions of American petroleum oils. Marcusson⁽⁶⁰⁾ observed that saturated naphthenic compounds are the essential lubricating constituents of the oil. Dunstan and Thole⁽³²⁾ claim, however, that unsaturated compounds are responsible for the lubricating qualities of the oil. Mabery⁽⁵⁹⁾ concluded that paraffin-base oils contain a small number of rings in the molecule, and that corresponding fractions derived from asphaltic bases consist of molecules with highly condensed cyclic nuclei.

Separation of individual compounds from the petroleum oil has been impossible to date, thus preventing the securing of direct information as to their chemical structure and properties⁽⁶⁵⁾. Fenske and Hersh⁽³⁵⁾ have succeeded in segregating components into groups ranging from monocyclic naphthenes to polycyclic aromatics. Mikeska⁽⁶¹⁾ in work performed on structure of lubricating oil fractions

found that for hydrocarbons of a given molecular weight, the greater complexity of the ring, the higher the viscosity. He also reported that the viscosity index of a given aromatic or naphthenic hydrocarbon increases as the ratio of paraffinic to naphthenic carbon atoms is increased. In addition, the viscosity increases with the number of side chains if the number of paraffinic carbon atoms attached to a given nucleus remains unchanged, and olefinic linkage in the side chain invariably decreases the viscosity.

Brozyna⁽¹⁶⁾ states that in general asphaltic base oils are good for low pour point and low coke value; bad for chemical stability, viscosity, and low flash point. Paraffinic base oils are good for stability, viscosity, and high flash point; bad for pour point and coke value.

REFINING OF LUBRICATING OILS

Many of the constituents contained in crude petroleum such as the unstable hydrocarbons; the resinous, wax, and asphaltic substances; and some of the oxygen, sulfur, and nitrogen compounds are undesirable when the petroleum oil is used as a lubricant. Chemical refining includes the use of sulfuric acid, caustic alkalies, and adsorptive clays; and solvent refining includes the use of various solvents to remove these undesirable constituents⁽³⁾⁽²³⁾⁽⁴⁹⁾.

Chemical Refining. (3)(23)(49)(66). The old, conventional refining method employing sulfuric acid, sodium hydroxide, and clay as the principal reagents is quite capable of removing the asphaltic and resin compounds and the chemically unstable hydrocarbons from the lubricating oil stock. However, the action of sulfuric acid on the oil stock is both chemical and physical. As a result, acid refined oils may contain certain undesirable substances, produced during the refining period, such as products of polymerization and condensation, and sulfonated bodies. The problem of disposing of the acid sludge, and the loss of oil in the sludge are also undesirable features of the acid-refining process.

Sodium hydroxide is added to the acid-treated oil after the acid sludge has been removed. Action of the caustic is to neutralize the acid constituents present in the oil. Frequently such neutralization will cause the formation of emulsions. These emulsions are of such stability that only a repeated acid treatment will cause a separation. As a result, loss of oil in the acid sludge becomes even more pronounced. The treated oil may also contain small quantities of oil soluble soaps formed by the reaction of the neutralizing caustic with organic acids present in the oil.

The removal of the above impurities and such suspended, colloidal, and dissolved impurities as carbon, coke, resinous and asphaltic substances, and coloring matter, can be accomplished by the use of adsorptive clays, such as fullers earth and bauxite. The use of such clays in conjunction with the acid and alkali treatment results in refined oils of greater chemical stability, resistance to oxidation, and less acidity.

Kalichevsky and Stagner⁽⁴⁹⁾ sum up the results of chemical refining as follows: The color is improved, the odor is lessened, and the sulfur content is reduced. The amount of unsaturated, asphaltic, and aromatic constituents is decreased, resulting in a lower specific gravity of the oil. Highly refined oils may oxidize in use more readily under certain conditions than the less refined oils, although they are superior in many other respects. The viscosity of the refined oil decreases considerably, but an increase in viscosity index results.

In general, asphalt base oils require treatment with the acid, caustic, and clay. Paraffin base oils, however, can usually be refined by clay treatment without utilizing acid or caustic⁽⁶⁶⁾.

Solvent Refining⁽³⁾⁽²³⁾⁽⁴⁹⁾⁽⁶⁶⁾. The shortcomings of the chemical refining process has led to the solvent-

extraction process, which is purely physical in action and permits the recovery of both the desirable and undesirable constituents in their original form. The solvent extraction refining is based on the differences in the solubilities of the various hydrocarbons and other constituents of the petroleum oil in certain types of solvents. The solvents selectively extract the sulfur compounds, nitrogen, some of the unsaturated hydrocarbons, and oxygenated compounds. The saturated hydrocarbons remain out of solution. This results in a two-phase system, consisting of refined oil as one phase and solvent plus dissolved undesirable constituents as the other phase. The solvent has a much higher specific gravity than the oil so that the two phases are readily separated by gravity settling. Several solvents employed are furfural, Duo Sol, phenol, and nitrobenzene.

The solvent method, however, is not effective in removing the asphaltic and the wax compounds present in lubricating oil stocks. As a result, lubricating oils must be dewaxed, deasphalted, and extracted with solvents when of asphaltic base stock; and they must be dewaxed when of paraffin base stock. In some cases, paraffin base crudes may undergo light solvent extraction, but it is not generally required. Dewaxing is performed to remove waxes

found in petroleum distillates, so that the oil will have high fluidity at low operating temperatures. It can be performed by filtering, centrifuging, filter acids, electrical precipitation, and solvents. Deasphaltization is generally accomplished by employing propane to precipitate the asphaltic material from solution.

Solvent refining tends to remove aromatic constituents which are believed to contribute poor viscosity-temperature characteristics, low oxidation stability, and a tendency to form carbon residues to the oil. The viscosity index of a solvent refined oil is much higher than the viscosity index for a corresponding acid refined oil⁽⁴⁹⁾. Wolf⁽⁹⁰⁾ states that the objectional sludge-forming materials are removed, but that the natural oxidation inhibitors are also removed in solvent refined oils. Davis and co-workers⁽²⁷⁾ conducted tests using furfural as a solvent to check the effect of the degree of refining on the oil. Four different degrees of refining were employed ranging from light to heavy. Viscosity index measurements showed that light extracted oils removed the more easily oxidized materials and left the natural inhibitors. As the severity of the extraction increased, a larger portion of the natural inhibitors were removed. Burwell⁽¹⁸⁾ concludes that solvent refined oils are not as good lubricants as chemical refined oils, but they are much more stable than the chemical refined oils.

ADDITIVES

With the increasing demands on engines, gasoline and Diesel, during the past decade as to speed and normal load, higher operating temperature, reduction of bearing area, and application of new bearing alloys, the necessity arose of improving the quality of refined mineral lubricating oils by adding a small amount of definite chemicals to a mineral base oil. These chemicals are given the general name of additives⁽⁴⁾⁽²³⁾⁽⁸⁰⁾. A lubricating oil additive may be defined as a chemical compound or mixture added to the oil which either imparts new properties to the oil or else improves the existing properties of the oil⁽⁴⁾. As a rule, rather low concentrations of additives, ranging from 0.01 to 5.0 per cent, are sufficient to achieve the desired results⁽⁴⁾.

All lubricating oil additives may be divided into two major classes⁽⁴⁾⁽²³⁾⁽⁴⁹⁾:

(1) Those which are concerned with the phenomenon of crankcase oil oxidation, such as anti-oxidants, anti-corrosives, and detergents.

(2) Those which are added to an oil to improve some physical property of the oil, such as pour point, viscosity index, film strength, oiliness, and rust-protection characteristics.

Kalichevsky and Savage⁽⁴⁸⁾ state that refining of lubricating oils is carried out with the purpose of securing maximum additive response rather than optimum performance in the absence of additives. Basically, oxygen, nitrogen, phosphorus, halogen, and sulfur-containing organic compounds constitute the bulk of the oil additives. Pritzker⁽⁷¹⁾⁽⁷²⁾⁽⁷³⁾ reviews over 300 patents that have been granted for organic and inorganic oil additives. Reiff⁽⁷⁵⁾ reveals that metal salt addition agents have been developed from alkylated phenolic compounds resulting in multifunctional agents capable of imparting combined properties such as pour point depressant action, improved viscosity, and anti-oxidant value to the lubricating oil.

Anti-Oxidants. The general subject of lubricating oil oxidation is considered on page 28. It is sufficient to say here that any lubricating oil which is exposed to air at any temperature will eventually oxidize. The length of time before this takes place and the rate with which it occurs depends on a number of factors, including amount of oxygen, temperature, catalytic agents present, and the ability of the oil to withstand oxidation⁽⁴⁾. The results of oxidation include the formation of corrosive acids, sludges, and lacquers. Additives which increase the resis-

tance of an oil to oxidation are called anti-oxidants⁽⁴⁾, Schnurmann⁽⁸⁰⁾, Kalichevsky and Savage⁽⁴⁸⁾, and Davis and co-workers⁽²⁷⁾ conclude that the additive greatly decreases the amount of oxygen taken up by the oil, thereby furthering the life of the oil and decreasing the formation of oxidation products. Davis⁽²⁷⁾ further proposes that a second action of the inhibitor may be a chemical reaction between the inhibitor and the metal of metallic accelerators present in the engine crankcase. The reaction results in the precipitation of an oil-insoluble inert compound. Schnurmann⁽⁸⁰⁾ states that the mechanism by which the anti-oxidants function is not known, not even whether they react with molecular oxygen or with peroxides. Clower⁽²³⁾ lists phenolic derivatives, naphthols, aniline derivatives, and arsenic and antimony compounds as further sources of oxidation inhibitors.

Anti-Corrosive Additives. Constant improvements in Diesel and gasoline engines permitting the development of more power for the equivalent size and weight engine, necessitated the use of materials better able to withstand the higher stresses imposed. Chief among these was the demand for bearings with higher load-carrying capacity and higher fatigue resistance than normally found in babbitt bearing metals. New bearing alloys resulted such as copper-lead, cadmium-silver, and cadmium-nickel⁽⁴⁾. At the same time development of new and more efficient refining processes

resulted in drastically refined oils, which produced harmful oxidation products in engine crankcases⁽⁸⁰⁾. It was soon found that these oxidation products, especially organic acids, of such oils were very corrosive to the new alloy bearings, particularly at the high temperatures obtained in the high-speed Diesel and gasoline engines. To remove this problem, numerous corrosion inhibitors have been recommended for addition to crankcase oils. Kalichevsky and Savage⁽⁴⁸⁾ and Davis and co-workers⁽²⁷⁾ report that the added corrosive inhibitor forms a protective coating or film in the form of an oxide of the inhibitor material on the surface of the bearing, so as to prevent the acids from reaching the metal. Schnurmann⁽⁸⁰⁾ however, reports that in experiments conducted on corrosive inhibitors possessing either phosphorus, sulfur, nitrogen, or oxygen containing compounds, that the protective film formed on the iron surface was not a phosphide, sulphide, nitride, or oxide, but rather it consisted of amorphous iron oxide.

Detergents⁽²⁾⁽⁴⁾⁽⁸⁴⁾⁽⁸⁸⁾. Webster⁽⁸⁸⁾ defines the action of detergency as the cleansing or purging away of foul or offending matter. The use of detergents just came into being approximately ten years ago when Diesel engines began to be used in high speed work. Difficulties

such as ring sticking and piston scuffing were remedied by the use of additives called detergents in the lubricating oil. Since that time the term detergent has been applied to all additives which have the property of preventing the build up of any crankcase deposits, or removing the already formed sludge, lacquer or carbonaceous products which prevent efficient operation of internal combustion engines. These materials may originate from combustion chamber blow-by such as soot or other detritus, as well as from oil deterioration or decomposition in the crankcase. Mougey and Moller⁽⁶⁴⁾ state that the amount of material which the detergent properties of the oil must handle depends on the amount present at any time, and the rate of formation of newly oxidized material, plus the amount of material in, and the rate of, the blow-by gases.

Watkins⁽⁸⁷⁾ concluded that uninhibited naphthenic oils dissolve more sludge than paraffinic oils, but oxidize more readily to form oil-insoluble materials. As a result, the naphthenic base oils appear to have greater detergency under mild running conditions but less detergency under severe running conditions. Watkins⁽⁸⁷⁾ further postulates that the action of a detergent additive is chemical as well as physical (cleansing action). A reaction takes place between the polar detergent molecules

and the polar molecules of the carbon or metal particles which prevents such particles from becoming insoluble materials to be deposited on various engine parts.

Various metallo-organic compounds such as phosphates, phenolates, alcoholates, naphthenates, sulfonates, and high molecular weight soaps or organic salts of tin and cobalt possess the property of detergency⁽⁴⁾. Talley and Larsen⁽³⁴⁾ have conducted extensive experiments on detergency and concluded that lack of uniform laboratory tests have hampered the development of new detergents.

Pour-Point Depressants. The pour-point of an oil is the lowest temperature at which the oil flows under conditions established by A.S.T.M. procedure⁽¹¹⁾. On chilling wax containing lubricants, wax crystals form and reduce the flow properties of the oil⁽⁴⁾⁽⁴⁸⁾⁽⁸⁰⁾. The development of addition agents such as benzyl chloride, aluminum stearate, Paraflow (condensation product of chlorinated wax and naphthalene), and Santopour (condensation product of phenol and chlorinated wax) which reduce the pour-point by hindering the formation of large wax crystals has resulted. Kalichevsky and Savage⁽⁴⁸⁾ theorize that the additive coats the surface of the minute wax crystals, thus preventing the formation of the usual large complicated crystal structure at low temperatures.

Viscosity Index Improvers(4)(10)(49)(80). The importance of viscosity of a lubricating oil in thick film lubrication has been stressed as the oil's essential physical property(77). Viscosity is dependent upon temperature, but to enable complete performance of an engine at varying temperatures, this dependence should be small. In an attempt to express the viscosity-temperature relationship in one figure, Dean and Davis(28) introduced the Viscosity-Index which indicates the rate of change of the viscosity of a lubricating oil with temperature. The higher the viscosity index, the less the viscosity of the oil changes with temperature.

In order to extend the usable temperature range of low viscosity index oils to low temperatures of starting and operating internal combustion engines, it has been found necessary to develop viscosity-index improvers. These materials usually consist of high molecular weight compounds or highly polymerized materials such as products of unsaturated hydrocarbons and fatty acids.

Conclusions on Additives. Wolf(90) and Georgi(40) state that in general oxidation inhibitors and detergent agents are by far the most important of the addition agents. Wolf lists the relative importance of oxidation inhibitors and detergents in different types of service as follows:

	Inhibitor	Detergent
Diesel Engine	xxx	xxx
Gasoline Engine		
Truck and coach	xxx	xx
Passenger car		
Average	xx	
Severe	xxx	x

DETERIORATION AND BREAKDOWN
OF LUBRICATING OILS

Definition. Webster⁽⁸⁸⁾ defines "deteriorate" as "to make or grow worse, to impair, degenerate. Deterioration implies the impairment of quality, character, or value." The word deterioration aptly describes the state of a lubricating oil which has been impaired in lubricating value⁽⁶⁾. Breakdown is defined as "chemical decomposition." Chemical decomposition in turn is defined as the resolving of a chemical compound into two or more different compounds or elements. It has been stated⁽⁶⁾ that lubricants can be chemically decomposed, but not at the temperatures and pressures which exist ordinarily in lubricated mechanisms. However, lubricants do deteriorate in service. Investigators⁽⁶⁾⁽¹²⁾⁽⁷⁰⁾⁽⁷⁶⁾ conclude that deterioration in service results from oil oxidation

and other intrinsic contaminants within the lubrication system, and from lubricant dilution and contamination by extrinsic materials. Davis⁽²⁶⁾ and Rescoral and co-workers⁽⁷⁶⁾ state that deterioration will be evidenced by variation in one or more of the following properties: viscosity, carbon residue, sludge content and acidity.

Oxidation. Mougey and Moller⁽⁶⁴⁾ state that if a petroleum lubricant is subjected to high temperature and oxygen, it will eventually oxidize. The length of time before it occurs and the extent to which it occurs depends on the temperature and extent of exposure to oxygen and catalytic substances, and the ability of the lubricant to withstand oxidation⁽⁶⁾. Pomeroy⁽⁷⁰⁾ and Fenske and co-workers⁽³⁶⁾ opine that the exact mechanism of oxidation is not clearly understood because of the complex structure of the oil hydrocarbons; and because of the secondary reactions such as polymerization, condensation, cracking, and volatilization which take place during the process. Davis and co-workers⁽²⁷⁾, Foote⁽³⁷⁾, Dornte⁽²⁹⁾, and Fenske and co-workers⁽³⁶⁾ consider oxidation to be autocatalytic and that a chain mechanism is involved. Oxidation can occur in two ways: (1) burning of the hydrocarbons to H₂O and CO₂. In this case the hydrocarbon actually decomposes as is evidenced by the progressive

oxidation of methane, the simplest hydrocarbon molecule, to H_2O and CO_2 ; (2) When the temperatures are not high enough to cause burning, the oxygen generally adds itself directly to the original molecule, and as this step proceeds the molecule becomes oxidized to a greater degree and complexity. As time goes on, more and more lubricant molecules start the oxidation process. The oxidized materials formed appear to promote further oxidation at an accelerated rate. This second method is the theory of the autocatalytic and chain reaction as originally propounded by Bodenstein⁽¹⁴⁾ and as verified by Dornte⁽²⁹⁾ and Fenske and co-workers⁽³⁶⁾. Davis and co-workers⁽²⁷⁾ further explain the autocatalytic type of reaction in actual engine lubrication service as the reaction of acidic oxidation products with the metals of the system to form secondary products which accelerate oxidation at a much faster rate than the primary oxidation products of the oil.

Laboratory experiments conducted by Davis⁽²⁶⁾ and Dornte⁽²⁹⁾ indicated that oxidation of the lubricant has three periods: (1) an initial or induction period of slow oxidation, (2) a second or transition period in which oxidation accelerates rapidly, and (3) a period in which oxidation continues at a relatively high rate. They

further concluded that measurement of the rate of oxygen absorption during these periods by moderately and highly refined oils can be used as a laboratory method of determining the resistance to oxidation of the oil.

Products of Oxidation. Pomeroy⁽⁷⁰⁾ states that the recognized products of oxidation of lubricating oils are known as peroxides, alcohols, ketones, aldehydes, and organic acids. The organic acids include small amounts of volatile acids. Kalichevsky and Stagner⁽⁴⁹⁾ conclude that the type of the above products formed depends upon the complexity of the lubricant molecules undergoing oxidation. The more complex molecules oxidize to some degree and then combine or link together by condensation or polymerization to form soluble and insoluble resins, varnishes, lacquers, and sludges⁽²⁶⁾⁽⁷⁰⁾. Haslam and Frolich⁽⁴⁴⁾ report that even the simple aldehydes and ketones will condense to higher molecular oxygenated compounds. Soluble organic acids attack the metal oxides of the lubricating mechanism and produce metal soaps insoluble in the oil⁽⁶⁾. In addition, if temperatures are high enough, pyrolysis of the lubricating oil hydrocarbons may occur and cause the formation of carbon particles and deposits, or resinous, gummy or asphaltic materials⁽⁷⁰⁾. All of the products of the process of oxidation are classified as

oil insolubles or oil solubles at the operating temperature of the lubricating mechanism. Kalichevsky and Stagner(49) state that oil sludges are difficult to analyze. Chermolzhukov(21) has made a rough classification of the sludges formed during oxidation of heavy petroleum products as follows: (1) sludges which are formed by polymerization and oxidation of tarry substances; (2) distinctly acid sludges which are formed by oxidation, condensation, and polymerization of the more reactive hydrocarbons; and (3) sludges formed from the reaction of acid oxidation products with the metals of the system. Kishline(51) defines "varnish" as a synthetic resinous, oil-insoluble compound precipitated by little known chemical reactions, by oxidation, and by presence of foreign materials such as dirt or water. Davis(26) defines resins and lacquers as oxygen containing hydrocarbons and polymers insoluble in oil.

Catalysis of the Oxidation Process. Haslam and Frolich(44) report that the rate of oxidation of highly refined oils increased with elevation of temperature, and that the acceleration was five times as rapid with pure oxygen as it was with air. Pomeroy(70) states that the extent to which the oil is atomized, split up, or aerated, will affect the rate of oxidation by exposing a larger surface of the oil to the oxygen in the atmosphere.

Larsen, Thorpe, and Armfield⁽⁵⁵⁾ found that aromatic compounds whose unstability was supposedly responsible for rapid oxidation of the oil are not unstable; but some, particularly the polynuclear ones are very stable. They concluded that the presence of small amounts of natural inhibitors determined the oxidation rate of the oil rather than the hydrocarbon components of the oil. Dornte and Ferguson⁽³⁰⁾ and Dornte, Ferguson, and Haskins⁽³¹⁾ made extensive studies on various types of oils and found that some oils when oxidized yield products that retard the oxidation reaction, other types yield products that do not affect the reaction, and a third type yields products which appear to accelerate the reaction. Many investigators⁽¹⁷⁾⁽⁵⁴⁾⁽⁵⁷⁾⁽⁷⁰⁾ found that the primary catalysts of lubricating oil oxidation in engine service are finely divided bits of metals such as iron, lead, copper, bronze, and cadmium and their compounds. Larsen and Armfield⁽⁵³⁾ state that the amount of iron present in a lubricant system is materially greater than any other metal. They found that the total catalytic effect of the iron was greater than the other metals, with copper second in activity. Burk and co-workers⁽¹⁷⁾ report that the metal catalysts are present initially in the massive condition; and it is not known with certainty whether catalytic

action occurs on the surface, or due to the formation of oil-soluble soaps from the metals, or both. The latter are strong catalysts(49). The soaps are formed in the engine by reaction of metals, or metal oxides, with acidic constituents formed by the oxidation of the oil. Larsen and Armfield(53) and Burk and co-workers(17) determined that lead bromide contained in leaded gasolines enters the lubricating oil from the combustion zone. The metals react with the lead bromide forming metal halides which are effective catalytic materials. Hauson and Egerton(43) found that oxides of nitrogen which entered the oil from the combustion zone were pro-oxidant. Burk and co-workers(17) in laboratory tests ascertained the amount of oxides of nitrogen entering the oil to be less than 0.0%. This quantity, however, failed to affect their results obtained in the oil oxidation.

Extrinsic Factors Affecting Lubricant Deterioration.

Davis(26) attributes a major source of oil deterioration in service as the action on the oil by the extrinsic contaminants which are dependent upon the mechanical condition of the engine being lubricated. The extrinsic contaminants can be listed as follows: fuel, water, dust, dirt, soot, carbon particles, blow-by materials, and metal particles(6)(26)(70).

Dilution of lubricating oils by unburned fuels of internal combustion engines entering the oil from the combustion space is reported by Davis⁽²⁶⁾. The dilution often decreases the viscosity of the oil below the safe lower limit causing failure⁽⁶⁾. Pomeroy⁽⁷⁰⁾ states that the presence of water, dust, and dirt, in the crankcase of the lubricating system will cause the formation of harmful emulsions in the oil. Water enters the crankcase either through condensation of the hydrogen component of the fuel on the cylinder walls or by leaks in the cooling system. Dust and dirt are common external contaminants of lubricants, their entry occurring either through the crankcase breather pipe or through combustion chamber air intake.

One of the functions of a lubricant in an internal combustion engine is to provide a seal around the piston rings⁽¹⁹⁾. Often this seal does not exist permitting the passage of lubricant from the crankcase to the combustion space, and also permitting the entry of gaseous blow-by and solid materials from the combustion zone to the crankcase. The lubricant that enters the combustion chamber usually burns incompletely, resulting in some carbon particles working their way down into the crankcase. Solid

materials, such as soot, lead compounds, and carbon particles, formed from incomplete combustion of the fuel and fuel additives, will enter the crankcase⁽⁶⁾. Gaseous blow-by material consists of the oxides of nitrogen, carbon monoxide, carbon dioxide, and sulfur compounds; all of which have a deteriorating effect on the lubricant⁽⁶⁾⁽⁷⁰⁾. Pomeroy⁽⁷⁰⁾ states that metallic particles and oxides result from wear and rusting of parts of the lubrication system. Rescorla, Carnahan, and Fenske⁽⁷⁶⁾ conclude that some metal particles result from abrasion of metallic surfaces by dust and from the chemical attack of acids in the oils.

Effect of Oil Deterioration on Engines. Burk and co-workers⁽¹⁷⁾ state that oxidation of lubricating oil occurs mainly at the engine crankcase temperature, but small amounts of oil are exposed to higher temperatures in the cylinder and bearing zones. Keyser and Miller⁽⁵⁰⁾ found that no petroleum oil can stand the high temperature of the cylinder zone; and thermal decomposition, partial or complete, results. This, coupled with the oxidation and other chemical reaction of the oil, yields the products that shorten the life of the oil; and that

cause ring-sticking, hard carbonaceous deposits on pistons, cylinders, and in the crankcase; engine wear; bearing corrosion; decrease in oil viscosity; and, eventually complete stoppage of the engine(6)(70).

TESTING OF ENGINE LUBRICANTS

Carpenter(20) in 1909 remarked that, "There is no known testing in the world which can give as erroneous opinions or give as much erroneous results as what we get in testing motor oils." Mougey(63) (1945) concludes that considerable progress has been made in the ensuing years, but that the subject is still difficult. Testing of engine lubricants resolves itself into three phases, namely; (1) laboratory chemical, physical, and mechanical tests, (2) laboratory engine tests, and (3) engine service or field tests.

Laboratory Chemical, Physical, and Mechanical Tests.

In 1913, Tipper(85) pointed out the conventional laboratory tests on lubricating oils are of value in checking uniformity of shipments and controlling refinery processes, but they do not show the value of the oil under service conditions. In 1928, Wilson and Barnard(89) showed that general laboratory tests do not demonstrate the value of

the oil in service. Bouman⁽¹⁵⁾ in 1939 states that only a few of the service characteristics of motor oils can be determined by physical and chemical analysis, and that the tests are conducted to show whether the oil shows promise as a good lubricant before subjecting it to the more expensive and time-consuming engine tests. Chemical tests include oxidation, acidity, carbon and sulfur content, corrosion, and saponification and precipitation numbers. The more important tests are as follows:

1. Oxidation. Mougey⁽⁶³⁾, Bouman⁽¹⁵⁾, and Kalichevsky and Stagner⁽⁴⁹⁾ conclude that oxidation tests do not represent the various processes of deterioration that take place in engine service. Mougey⁽⁶³⁾ states that over 200 laboratory oxidation tests have been developed, and the three most generally used tests being the Sligh Oxidation Method⁽³⁴⁾, the Underwood Oxidation Test⁽³⁴⁾, and the Indiana Oxidation Test⁽¹¹⁾.

2. Neutralization Number. A test for acidity in the oil is conducted according to A.S.T.M. specifications⁽¹¹⁾. Pomeroy⁽⁷⁰⁾ states it is not accurate as a measure of oxidation because all oxidation products are not acid in character. Davis and co-workers⁽²⁷⁾ state that as yet there has been no clear definition of what the neutralization number signifies. They further

conclude that there is no relation between metallic corrosion and the "acids" as determined by the neutralization number. Davis⁽²⁶⁾ finds that the neutralization number is not a measure of the total acids present. It may or may not measure the rate of oxidation. Mougey and Moller⁽¹⁷⁾ conclude that the neutralization number is a composite measure of many different things, including the amounts of certain inhibitors present. They further state that an oil possessing a high neutralization number may not contain any free acid; and a neutralization number of an oil, even if it is due to free acid, is not of necessity any indication as to whether or not the oil is corrosive to bearings. Davis and co-workers⁽²⁷⁾ conclude that although the change in neutralization number of an oil in use does not serve as a suitable basis for the prediction of the behavior of an oil in an engine, it is a valuable tool for the determination of the general trend of oxidation because it is easily and quickly determined and usually shows the same order of increase as do other oxidation products.

3. Carbon Residue. (A.S.T.M. Specifications⁽¹¹⁾). Bouman⁽¹⁵⁾ reports that the test is of some value with regard to carbon formation in the combustion space; not, however, with regard to carbon formation in piston-ring grooves.

4. Corrosion. (Federal Specifications⁽³⁴⁾). Loane and Gaynor⁽⁵⁷⁾ state that the numerous laboratory bearing corrosion test methods are of value only in so far as they predict service performance or help explain the nature or mechanism of the corrosion phenomenon.

The physical laboratory tests include cloud and pour-point tests, color tests, flash and fire point tests, dilution, emulsification, evaporation, viscosity, viscosity-index, specific gravity, and water and sediment tests⁽²³⁾. The more important tests are as follows:

1. Pour Point. The A.S.T.M.⁽¹¹⁾ pour point of an oil is the temperature at which it will just flow under prescribed conditions.

2. Flash and Fire Points. The A.S.T.M.⁽¹¹⁾ flash point of an oil is the lowest temperature, in degrees Fahrenheit, at which sufficient vapors are given off to form an inflammable mixture with air that will burn momentarily when a small flame is applied.

3. Dilution. The A.S.T.M.⁽¹¹⁾ laboratory test determines the percentage of unvaporized fuel that has worked past the piston into the crankcase oil.

4. Viscosity. (A.S.T.M. Specifications⁽¹¹⁾). The viscosity or body of an oil is the measure of its resistance to flow. Paterson⁽⁶⁹⁾ states that the viscosity test is the most important of all the physical tests.

There are numerous mechanical tests for oil stability, oiliness, film strength, and functional characteristics⁽²³⁾. Several oil-testing machines generally used are as follows:

1. The Almen Extreme Pressure Lubrication Testing Machine. This machine is used to compare and evaluate the film strength of fluid lubricants⁽²⁴⁾.
2. Herschel's Machine. This machine was developed primarily for studying the oiliness of the lubricant and the variation in frictional resistance produced by different combinations of bearing metals⁽²⁵⁾.
3. Navy-Work Factor Machine. This is a laboratory machine for evaluating lubricating oils from the standpoint of their stability⁽³⁴⁾.

Laboratory Engine Test. Mougey⁽⁶³⁾ and Georgi⁽⁴⁰⁾ state that laboratory engine tests have been under development for a number of years because of the failure of chemical and physical laboratory tests to give results indicative of actual service. Georgi⁽⁴⁰⁾ conducted a series of oil tests on the Lauson one-cylinder test engine, and the results, as compared with chemical and physical test results on the same oils, were not correlative. Sibley and Baldwin⁽³¹⁾ conclude that actual service tests are accurate but are time-consuming and costly. Bench engine

tests are used to subject the oil under test to accelerated conditions of extreme severity on the premise that if it "stands up" under such conditions, it will stand up in service; and because they are time-saving and inexpensive⁽²⁾. Sands, Livingstone, and Gruse⁽⁷⁹⁾ conclude that a laboratory engine test capable of producing fifty hours of average service in five hours of accelerated testing is the ideal procedure. Average service is defined by them as the extreme conditions or demands made on heavy-duty equipment. Mougey⁽⁶²⁾ and Mougey and Moller⁽⁶⁴⁾ found that the Caterpillar series⁽²⁾ of laboratory Diesel engine tests (480 Hour Endurance Test, Accelerated Run-In and High Load Test, 120 Hour Oil Stability and Bearing Corrosion Test) quite adequately define the detergent properties of the oil. They further concluded that the General Motors Diesel 500-Hour Test defines and describes the combination of the detergent properties and the oxidation characteristics of the oil. Other tests were required, however, to measure resistance to ring sticking, resistance to valve sticking and tendency to form carbon. The U.S. Army Specification 2-104-B⁽¹³⁾ in 1942 specified that all lubricating oils sold to the Army must undergo the Coordinating Research Council engine tests which were essentially the same as

those used by Mougey and Moller (above). U.S. Navy Department Specification 14-0-13a⁽⁶⁵⁾ specifies that all lubricating oils accepted by the Navy must undergo tests for periods of not less than 300 hours in three or more types of one-cylinder Diesel test engines, and for periods of not less than 500 hours in two or more types of full-size Diesel engines.

Sands and co-workers⁽⁷⁹⁾ found that a multiplicity of test engines exists, none of which give comparable test results. They suggested a standardized prototype be developed capable of making all tests. Mougey and Moller⁽²⁰⁾ pose four fundamental questions to be used as the basis for establishing a standardized laboratory test engine. The questions are as follows:

1. Is the test procedure sufficiently reproducible so that different laboratories can obtain comparable results?

2. Do the test conditions make it possible to show differences between different types of oils?

3. Are the differences that are shown related to performance in service? That is, are the conditions of the test procedure such that the test data may be used to predict performance in service, at least in respect to certain properties of the oil?

4. What other additional test procedures are necessary before general predictions can be made with regard to the performance of the oils under such widely different operating conditions as city driving with gasoline engines, heavy-duty service with gasoline engines, and heavy-duty service with Diesel engines of different types?

Foster⁽³⁸⁾ describes a new oil test engine designed by the Gulf Oil Company that has great flexibility of test conditions.

At the conclusion of all laboratory engine tests, the engine parts are inspected for lacquer and sludge deposits, corrosion, scuffing, and the engine is rated in comparison with results obtained on tests of different type oils⁽²⁾. Sludge deposits are usually analyzed to determine the causes of oil deterioration. A.S.T.M. Specifications⁽¹¹⁾ and the Federal Standard Stock Catalogue⁽³⁴⁾ give similar tentative methods for analyzing sludge content. These tentative tests analyzed the oil sludge for "petroleum naphtha insolubles" and for "chloroform insolubles". Davis and co-workers⁽²⁷⁾ define petroleum naphtha insolubles as a measure of the so-called sludge content of a used oil. The naphtha precipitates the extrinsic contaminants and asphaltenes. Chloroform

insolubles measure only the insoluble contaminating material whose source is considered extraneous to the lubricating oil system. These insolubles include dust, metal particles, lead halides, and carbon from the combustion zone.

The asphaltenes mentioned as insoluble in petroleum naphtha are by definition⁽²⁶⁾ the difference between the naphtha insolubles and the chloroform insolubles. The asphaltenes or asphaltic resins are a measure of those oxidation products that are approaching oil insolubility, that is, those products which if oxidized to any further extent will be precipitated as sludge or may "bake out" on hot surfaces and appear as lacquer or varnish.

Davis and co-workers⁽²⁷⁾ state that the above two tests are purely arbitrary classifications of insolubles, although their extensive use and correlation with engine conditions make them of real value. As yet, no standard procedure has been adopted; and widely different results may be obtained, depending upon the fineness of the filter medium used.

Ludeman⁽⁵⁸⁾, Ebrey⁽³³⁾, Levin and Toune⁽⁵⁶⁾, and Hall, Levin, and McMillan⁽⁴²⁾ propose procedures for sludge analysis that vary in types of solvents used and mechanics followed.

Engine Field Tests. Kalichevsky and Savage⁽⁴⁸⁾

observe that accelerated laboratory engine tests are not accurate because accelerated conditions are not typical of service runs. They conclude that field testing is the only answer to the oil-evaluating problem. Bouman⁽¹⁵⁾ found that laboratory engine test results were not applicable to actual engines in practice. Clower⁽²²⁾ states that the importance of the properties of oils as measured by laboratory tests has been over-emphasized, because oils in service only retain their original properties for a comparatively short period of time. Therefore, service tests are required. Sands, Livingstone, and Gruse⁽⁷⁹⁾ conclude that in the present state of knowledge concerning lubricants and lubrication that accelerated engine laboratory tests should be reserved for information-seeking purposes only and that acceptance tests should be made under field conditions. Conditions of abnormal or subnormal service arise in field service which make heavy demands on the oil and which are not duplicable in the laboratory. It is primarily these operating conditions that create the demand for field tests⁽²⁾.

Field tests of engine lubricating oils are usually conducted in gasoline and Diesel engines operating in widely varying services including bus, truck, tractor, marine, stationary, and railroad.

III EXPERIMENTAL

Purpose of Study

The investigation was undertaken with a three-fold purpose:

1. The installation of accessory equipment required for the control of the engine test conditions, and the assembly of the one cylinder, two-stroke test engine.
2. The determination of the breakdown characteristics of a solvent refined, asphalt base oil at varying conditions of temperature and load in the test engine.
3. The correlation of the breakdown characteristics of the oil with the performance of the test engine so as to rate the engine as a possible test unit for evaluation of lubricating oils.

Plan of Investigation

The plan of investigation was as follows:

Preliminary Construction. The installation of control accessories required for control of test conditions in the Delco test engine. The control accessories are as follows:

1. Crankcase immersion heater with thermostat control.

2. 600 watt lamp bank to secure maximum engine-generator load.

3. Auxiliary gasoline tank.

4. Thermometers.

Plan of Test Runs.

1. Tests to be conducted on the one-cylinder, two stroke Delco Light Plant, Model 850.

2. Tests to be run on a solvent refined asphalt base, commercial brand of oil.

3. Tests to be run under varying conditions of time, engine load, and crankcase temperatures as tabulated in Table I.

4. Oil samples to be drawn from the crankcase at the completion of each run. Each sample will be analyzed for the following:

a. Neutralization Number

b. Viscosity, Saybolt Universal

c. Sludge Content

(1) Petroleum Naphtha Insolubles

(2) Chloroform Insolubles

(3) Asphaltic Resins

5. The connecting rod bearings to be weighed before and after each test to determine the loss in weight by wear and corrosion.

TABLE NO. I

PLANNED OPERATIONAL TESTS ON DELCO LIGHT UNIT MODEL 850

Run Number	Length of Run--Hrs.	Generator Load--Watts	Crankcase Temp. °F.
1	8	0	120
2	16	0	120
3	24	0	120
4	8	600	120
5	16	600	120
6	24	600	120
7	8	600	170±4.5
8	16	600	170±4.5
9	24	600	170±4.5
10	8	600	210±4.5
11	16	600	210±4.5
12	24	600	210±4.5
13	8	600	240±4.5
14	16	600	240±4.5
15	24	600	240±4.5
16	8	600	270±6.5
17	16	600	270±6.5
18	24	600	270±6.5
19	8	600	300±6.5
20	16	600	300±6.5
21	24	600	300±6.5
22	32	600	270±6.5

6. The piston, piston rings, cylinder, bearings, and the engine in general to be rated at the end of each run on cleanliness, sludge, varnish, and lacquer deposits.

7. Data to be recorded on the CO₂ content of the exhaust gas, gasoline consumption, r.p.m., and generator load of the test unit.

Correlation of Results. Efforts will be made to rate the engine as a possible test unit for lubricating oils from the breakdown characteristics of the test oils.

Materials

The following experimental materials were used in the investigation:

Gasoline, Esso Extra. (165 gals.) Octane rating of 76.5. Used as motor fuel in test engine. Obtained from the Standard Oil Company of New Jersey, Christiansburg, Virginia.

Kerosene, (25 gals.) Used as a cleaning solvent for motor parts and crankcase. Obtained from the Standard Oil Company of New Jersey, Christiansburg, Virginia.

Acid, Benzoic, Standard Sample 39F. (30 grams) Used as a standardizing agent in the Neutralization Number tests. Obtained from the National Bureau of Standards, U. S. Department of Commerce, Washington, D. C.

Oil, Motor, Esso No. 3. (14 gals.)

S.A.E. No. 30	
Refining Method	Solvent
Degree of Refining	Heavy
Flash Point °F.	440
Fire Point °F.	495
Viscosity, SSU at 130°F.	267
Viscosity, SSU at 210°F.	72.4
Pour Point °F.	-10
Gravity, °API	29.8
Viscosity Index	120.8
Conradson Carbon Residue	0.11
Ash, Weight %	0.01
Sulfur (Bomb), Weight %	0.54
Additives	(1) Oxidation Inhibitor
	(2) Pour Depressant

Used as a test oil. Obtained from the Standard Oil Company of New Jersey, Christiansburg, Virginia.

Alcohol, Ethyl, 95%, Scientific Grade. (2 gals.)

Used in the Neutralization Number determinations. Manufactured by the U. S. Industrial Chemicals, Inc., Baltimore, Maryland.

Alcohol, Methyl, c. p. ($\frac{1}{2}$ gal.) Used in the Neutralization Number determinations on test oil. Manufactured by the U. S. Industrial Chemicals, Inc., Baltimore, Maryland.

Asbestos, Medium fiber, Washed in acid. (1 pound) Lot No. 6846. Used as a filter medium in sludge analysis of used test oil. Manufactured by the J. T. Baker Chemical Co., Phillipsburg, New Jersey.

Chloroform, U.S.P. (5 gals.) Lot. No. 71946.

Used as solvent in sludge analysis of used test oil. Manufactured by the J. T. Baker Chemical Co., Phillipsburg, New Jersey.

Potassium Hydroxide, c.p. (1 pound) Lot

No. 102245. Used in Neutralization Number determinations on test oil. Manufactured by the J. T. Baker Chemical Co., Phillipsburg, New Jersey.

Phenolphthalein, U.S.P., powder. (1 ounce) Lot

No. 72845. Used in Neutralization Number determinations on test oil. Manufactured by the J. T. Baker Chemical Co., Phillipsburg, New Jersey.

Ether, Petroleum, c. p. (Benzine B. P. 65°-80°C.)

(27 pounds)

Initial Boiling Point	38.5%
Dry Flask end point	55.1%
Dist. under 55°C. (min.)	95.0%
Dist. under 40°C. (max.)	50.0%
Sp. Gr. at 15°C.	0.83%
Acids	0.00

Lot. No. 72646. Used as a solvent in the sludge analysis of the used test oil. Manufactured by the J. T. Baker Chemical Co., Phillipsburg, New Jersey.

Celite, Hypo Super-cel (Filter aid). (1 pound)

Used as a filter medium in sludge analysis of used oil. Manufactured by the Johns-Manville Corporation, New York, New York.

Barium, Hydroxide, c. p. (5 grams) Lot

No. 1415. Used to precipitate potassium carbonate from KOH solution in the Neutralization Number determinations on test oil. Manufactured by the J. T. Baker Chemical Co., Phillipsburg, New Jersey.

Air (20 psig) Used for cooling engine cylinder head and carburetor during high temperature test runs. Obtained from the Nash Hytor Compressor in the Chemical Engineering Department Laboratory, Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Apparatus

The following apparatus and equipment was used in the investigation:

Unit, Light, Delco, Model 850. (One) Used as test engine. Manufactured by the Delco Appliance Division, General Motors Corporation, Rochester, New York.

Pistons, Delco. (Three) Part No. 82003. Used as replacement test pistons. Manufactured by the Delco Appliance Division, General Motors Corporation, Rochester, New York. Obtained from the J. B. Mitchell Co., Baltimore, Maryland.

Bearings, Connecting Rod, Babbitt, Delco. (24) Used as replacement test bearings. Part No. 82526. Manufactured by the Delco Appliance Division, General Motors Corporation, Rochester, New York. Obtained from the J. B. Mitchell Co., Baltimore, Maryland.

Rings, Piston, Delco. (24 sets of two compression and one oil ring per set). Used as replacement test rings. Part No. 5070370. Manufactured by the Delco Appliance Division, General Motors Corporation, Rochester, New York. Obtained from the J. B. Mitchell Co., Baltimore, Maryland.

Arm, Breaker, Ignition, Delco. (Two) Part No. 12411. Used for replacement. Manufactured by the

Delco Appliance Division, General Motors Corporation, Rochester, New York. Obtained from the J. B. Mitchell Co., Baltimore, Maryland.

Gaskets, Delco. (Five) Part No. 27677. Used as replacements for front cover plate gaskets of test engine. Manufactured by the Delco Appliance Division, General Motors Corporation, Rochester, New York. Obtained from the J. B. Mitchell Co., Baltimore, Maryland.

Gaskets, Delco. (Ten) Part No. 28323. Used as replacements for cylinder-to-crankcase gaskets of test engine. Manufactured by the Delco Appliance Division, General Motors Corporation, Rochester, New York. Obtained from the J. B. Mitchell Co., Baltimore, Maryland.

Heater, Immersion, Calrod, G. E. (One) 230 volts, 2 KW. Length of bulb, 1-1/8". Diameter of heater, 1-5/8". Catalog No. 15x831. Used to heat oil in crankcase during tests. Manufactured by the General Electric Company, Schenectady, New York. Obtained from the General Electric Supply Corporation, Richmond, Virginia.

Thermostat, Automatic with Temperature-Setting Indicator. (One) Range 170°-240°±4.5°F. Diameter of bulb, 1/2". Length of bulb, 7-1/8". No. 4980281G116. Used to regulate oil pan temperature. Manufactured by General

Electric Company, Schenectady, New York. Obtained from the General Electric Supply Corporation, Richmond, Virginia.

Thermostat, Automatic with Temperature-Setting Indicator. (One) Range 270° - $370^{\circ} \pm 6.5^{\circ}$ F. Diameter of bulb, $\frac{1}{2}$ ". Length of bulb 7- $\frac{1}{8}$ ". No. 4980281G124. Used to regulate oil pan temperature. Manufactured by the General Electric Company, Schenectady, New York. Obtained from the General Electric Supply Corporation, Richmond, Virginia.

Wrench, Torque. (One) 150 foot-pound capacity. One-half inch drive. Used to tighten connecting rod bolts on test engine. Obtained from Sears, Roebuck and Company, Roanoke, Virginia.

Socket, (One) 9/16"x $\frac{1}{2}$ " drive. Used in conjunction with torque wrench to tighten connecting rod bolts. Obtained from Sears, Roebuck and Company, Roanoke, Virginia.

Lampbank, 600 Watts. (One) Used to load motor-generator test unit. Constructed with four 150 watt light bulbs in parallel. Materials obtained from the Chemical Engineering stockroom, Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Ammeter, D. C. (One) Range: 0-50 amperes. Used to determine generator output through the lampbank.

Manufactured by the Jewell Electrical Instrument Company, Chicago, Illinois. Obtained from the Electrical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Bottles, glass. (24) 250 ml. capacity, Bakelite, screw top, small mouth. Used to store oil samples of test runs. Obtained from the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Flasks, Erlenmeyer, Pyrex. (Eight) Ground-glass stoppered, 250 ml. capacity. Used in sludge analyses of test oils. Obtained from the Chemistry Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Burette. (One) 50 ml. capacity, 0.1 ml. graduation. Used to make Neutralization Number titrations. Obtained from the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Hot Plate. (One) 115 volts, 5 amperes. Used to heat solutions in Neutralization Number determinations. Manufactured by the Fisher Scientific Company, Pittsburgh, Pennsylvania. Obtained from the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Oven, Drying, Electric, Sargent. (One) 110 volts, 660 watts. Used for drying samples in sludge content determinations. Manufactured by E. H. Sargent and Company, Chicago, Illinois. Obtained from the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Balance, Analytical, Chainomatic. (One) 200 gms. capacity. Graduation 0.0001 grams. Used for weighing test connecting-rod bearings and analytical samples. Manufactured by the Will Corporation, Rochester, New York. Obtained from the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Balance, Laboratory, Ohaus. (One) 5kg. capacity. Graduation 0.1 grams. Used to weigh crankcase oil for test runs. Manufactured by the Fisher Scientific Company, Pittsburgh, Pennsylvania. Obtained from the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Counter, Speed. (One) Hand operated. Range 10000 rpm. Used to measure the revolutions per minute of the engine test unit. Manufactured by the Veeder-Root, Incorporated, Hartford, 2, Connecticut. Obtained from the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Viscosimeter, Saybolt, Universal, A.S.T.M. (One)
Accessories complete. No. 13349. Used to determine vis-
cosity of test oils. Manufactured by the Will Corporation,
Rochester, New York. Obtained from the Chemical Engi-
neering Department, Virginia Polytechnic Institute, Blacks-
burg, Virginia.

Crucibles, Gooch. (Eight) 25 ml. capacity.
Used in sludge analysis of used test oil. Obtained from
the Chemical Engineering Department, Virginia Polytechnic
Institute, Blacksburg, Virginia.

Funnel, Buchner. (Two) 750 ml. capacity. Used
in sludge analysis of used test oil. Obtained from the
Chemistry Department, Virginia Polytechnic Institute,
Blacksburg, Virginia.

Glassware, Assorted. Used to make up analytical
solutions for test oils. Obtained from the Chemical En-
gineering Department, Virginia Polytechnic Institute,
Blacksburg, Virginia.

Flasks, (Six) 1000 ml. capacity.

Flasks, Erlenmeyer. (Three) 250 ml.
capacity.

Cylinder, Measuring, Graduated. (One)
100 ml. capacity.

Batteries, Storage. (Three) 6 volts, 15 plates. No. A115. Used as ignition source for Delco test engine. Manufactured by the Goodyear Tire and Rubber Co., Inc., Akron, Ohio. Obtained from the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Apparatus, Gas, Fisher-Orsat, Type B. (One) 100 ml. burette, 0.10 ml. graduation. Used to determine CO₂ content of exhaust gases from engine test unit. Manufactured by the Fisher Scientific Company, Pittsburgh, Pennsylvania. Obtained from the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Thermometer, Weston. (One) Range: 0°-300°F. Two degree increments. Used to indicate engine crankcase temperature. Manufactured by the Weston Electrical Instrument Corporation, Newark, New Jersey. Obtained from the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Tank, Gasoline, (One) 15 gallon capacity. Used as auxiliary gasoline supply tank for test unit. Obtained from the Speedway Esso Station, Blacksburg, Virginia.

Timer, Precision, "Time-it". (One) 110 volts, 60 cycles. Manufactured by the Precision Scientific

Company, Chicago, Illinois. Obtained from the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Light, Titrating. (One) 60 watt lamp. Used in Neutralization Number determinations. Obtained from the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Methods of Procedure

Preliminary Construction. Control accessories for the Delco Light Unit Model 850 used as a test engine were installed as follows:

(Note: Unless otherwise stated all references to equipment will refer to Drawing No. 1)

A 15 gallon oil can was erected on a stand support (F and G) near the engine unit to serve as an auxiliary fuel tank. A 1/8" pipe line (H) was installed between the 15 gallon tank and the conventional one-gallon gasoline tank (I) from which the motor obtained its supply of fuel by suction. This one-gallon tank was suspended from a 1/2" compressed air line (J) used to supply cooling air for the carburetor during high temperature tests. This assembly of two fuel tanks in series allowed sufficient fuel to permit successful overnight test runs.

The combined engine and generator set was completely dismantled and cleaned with kerosene.

A 1-5/8" hole was drilled in the bottom of the crankcase 2-5/8" from the right side wall, through which was inserted a General Electric calrod immersion flat type heater (A).

A 3/8" hole was drilled and tapped in the left side of the crankcase, through which was inserted the bulb of the temperature controlling thermostat (D).

Two holes, 2 1/4" apart, were drilled and tapped for 3/8" pipe in the right wall of the crankcase flush with the crankcase floor. A copper thermometer well was inserted into one of the openings. A six-inch length of 3/8" pipe was secured into the second tapped hole, with a globe valve on the outlet end. This was used as the crankcase oil drain (B and C).

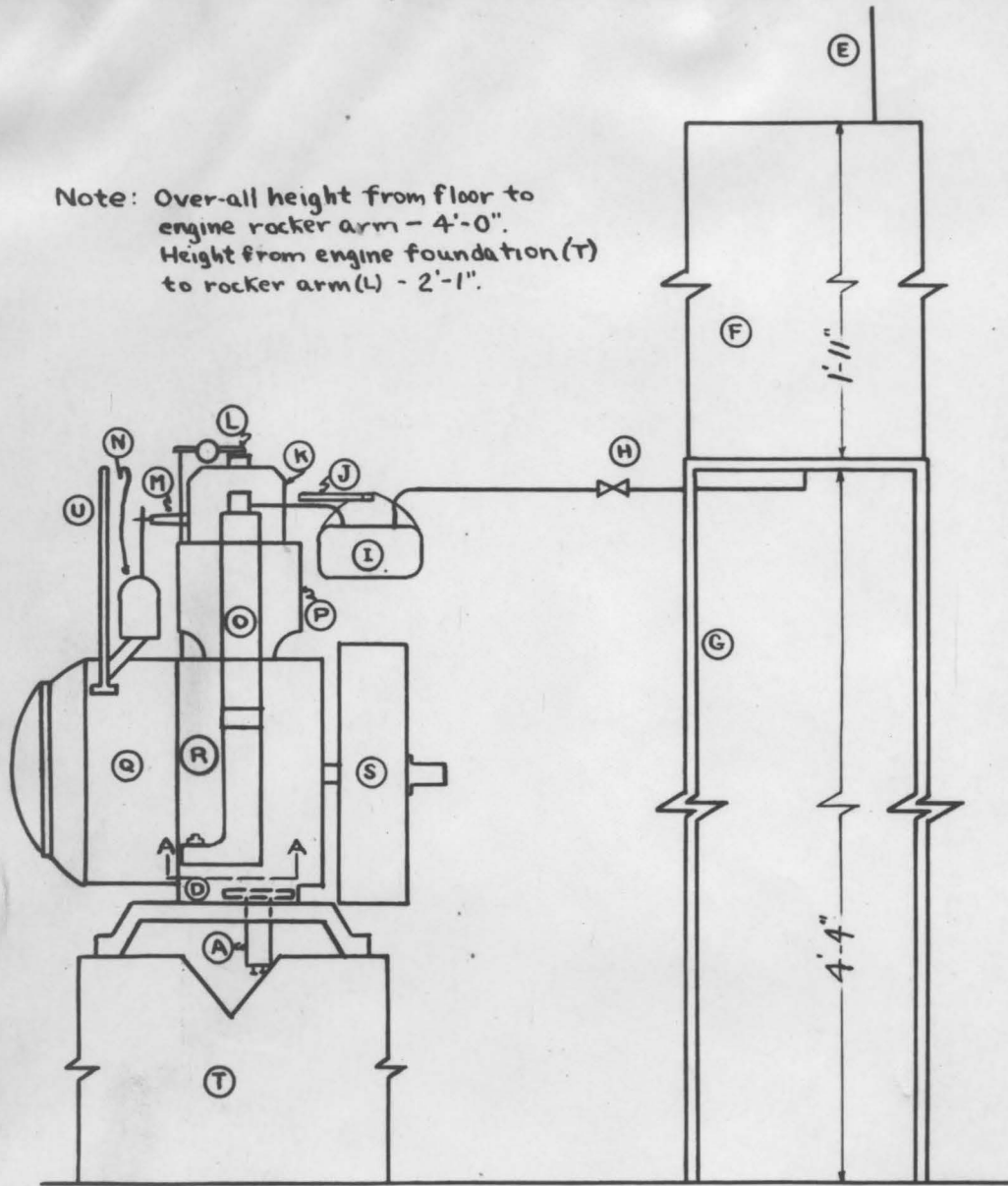
The motor-generator set was assembled on the concrete stand block (T).

The 600 watt lampbank previously constructed by Bryan⁽¹⁹⁾ with four 150 watt lamps in parallel, was used to load the motor-generator set (Drawing No. 2). This loaded the set to only 70.5 per cent of its rated capacity. Any additional load, however, would stop the motor.

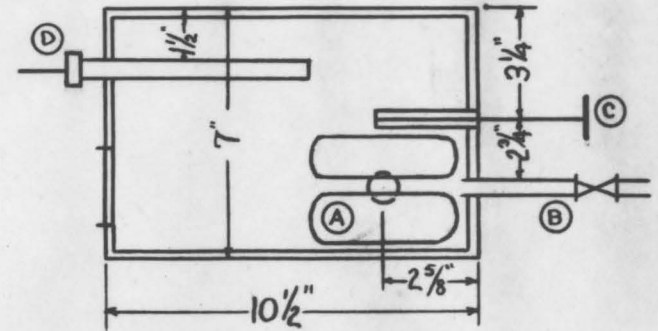
LEGEND

- A- Immersion Heater
- B- Drain Pipe
- C- Thermometer
- D- Thermostat
- E- Gasoline Gage
- F- Auxiliary Gas Tank
- G- Gas Tank Support
- H- Gas Control Valve
- I- Gasoline Tank
- J- Air Jet
- K- Cylinder Head
- L- Rocker Arm
- M- Spark Plug
- N- Spark Coil
- O- Breather Pipe
- P- Cylinder Block
- Q- Generator
- R- Distributor
- S- Flywheel
- T- Engine Foundation
- U- Electrical Control Panel

Note: Over-all height from floor to engine rocker arm - 4'-0".
 Height from engine foundation (T) to rocker arm (L) - 2'-1".



Scale: $\frac{3}{32}'' = 1''$



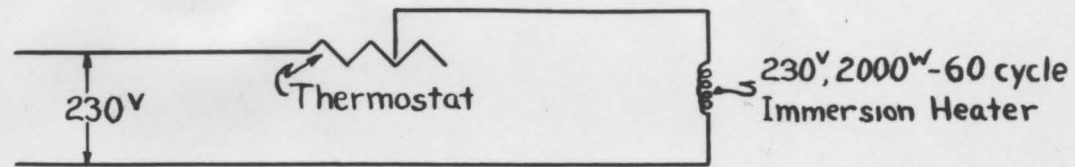
Section A-A
 Top View of Oil Pan
 Scale: $\frac{3}{16}'' = 1''$

DEPARTMENT OF CHEMICAL ENGINEERING
 VIRGINIA POLYTECHNIC INSTITUTE
 Blacksburg, Virginia

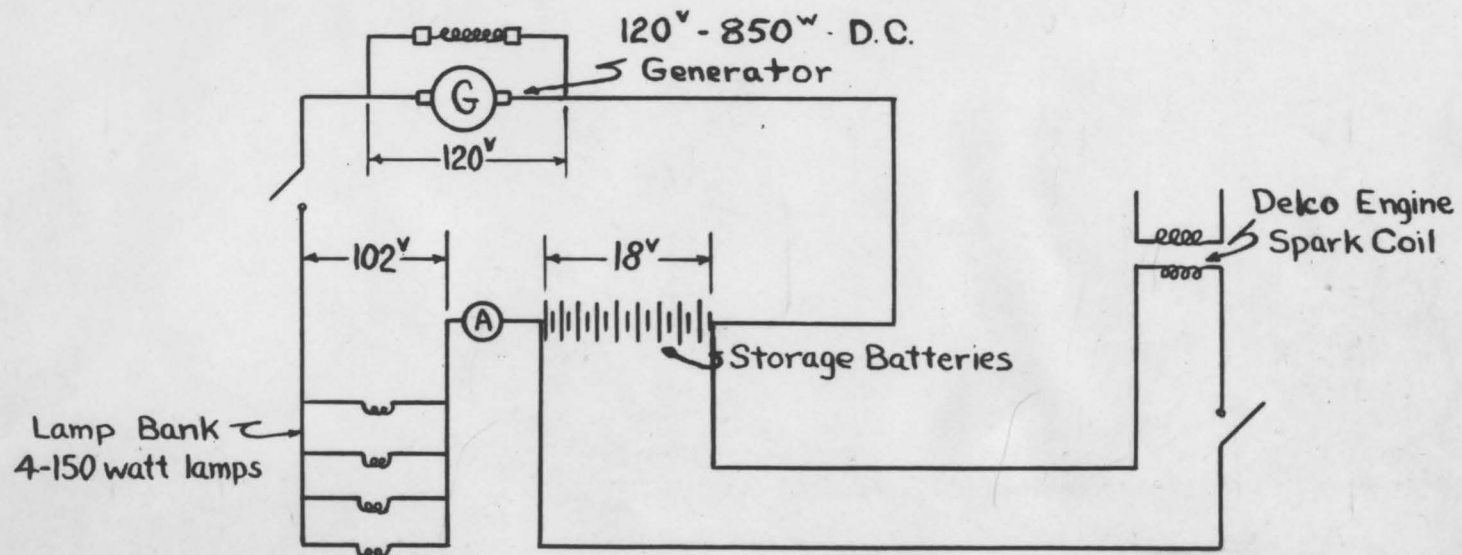
Deko-Light Unit WORKING LAYOUT

Drawn by C.C.G Date: 2/28/47
 Checked by Date:
 Approved by FwB Date: 3/3/47

Drawing No 1



A-C Immersion Heater Circuit



DEPARTMENT OF CHEMICAL ENGINEERING
VIRGINIA POLYTECHNIC INSTITUTE
Blacksburg, Virginia

Delco-Light Unit

WIRING DIAGRAM

Drawn by C.C.G. Date 2/27/47
Checked by R.R.W. Date 2/27/47
Approved by fwb Date 3/3/47

Drawing No 2

The generator, lampbank, and immersion heater were wired as shown in Drawing Two.

The finest possible adjustment on the control thermostat was $\pm 4.5^{\circ}\text{F}$. of the desired temperature.

Test Procedure. The cylinder, cylinder head, flywheel, crankcase cover, and the connecting rod assembly were removed from the test engine.

A new bearing (weighed to ± 0.0001 gm.) was wiped free of lint and grease, and then placed in the connecting rod assembly. Connecting rod bearing shims were inserted between the opposing edges of the two halves of the bearing. Attempts were made to secure uniform tightness on each of the two connecting rod bearing bolts by the use of a torque wrench which indicated the exerted pressure in foot-pounds. The bolts were tightened until the lubricated crankshaft could not be turned by hand--the nuts were then backed off one-sixth of a turn. This procedure was followed in all test runs. Efforts were made to use the same number of shims and the same torque pressure for each of the test bearings, although with some test bearings this could not be accomplished.

A new or clean piston with a set of new piston rings (set contained two compression rings and one oil ring) was secured to the connecting rod by the wristpin.

The engine was completely reassembled, and approximately two and a half quarts of Esso No. 3 motor oil were poured into the crankcase. The oil was previously weighed on a laboratory balance to ± 1 gram. This was done in order to obtain more accurate comparative oil consumption data for the various tests.

The valve rocker arms were released and the engine was cranked by hand for several minutes to ensure primary lubrication of the crankshaft prior to starting.

The current to the crankcase immersion heater was turned on and the thermostat control set to the desired test temperature. As soon as the oil in the crankcase reached the desired temperature, the engine was started.

On all of the test runs, for crankcase oil temperatures of 170°F. to 300°F., cooling air on the carburetor was required. This was supplied by the Nash Hytor Compressor (20 psig.), the air being supplied through a $\frac{1}{8}$ " jet.

When the engine was started, the cooling action of the flywheel decreased the crankcase temperature by approximately 20°F. to 30°F. Several minutes were required to bring the crankcase oil back to the desired temperature. When the temperature of the oil again reached the desired temperature, the test run was officially begun.

During the test run, hourly readings of engine r.p.m., exhaust gas CO₂ content, gasoline consumption, generator amperage, and crankcase oil temperature were recorded.

At the completion of the test run, the immersion heater, the Hytor, and the Delco engine were turned off.

Oil was drained from the engine into screw cap sample bottles and labeled for analytical determinations. Oil not used for analytical determination was drained, weighed, and discarded.

The engine was disassembled and the bearing removed from the connecting rod assembly. The bearing was washed with kerosene, dried, wiped with a clean cloth and reweighed on an analytical balance.

The piston, piston rings, crankcase floor and walls, cylinder, valves, and the immersion heater were examined for carbon deposits and for lacquer and varnish stains.

The oil pan was flushed with kerosene and the immersion heater was scraped clean of all carbon deposits, resulting mainly from oil decomposition at the higher test temperatures. The foregoing test procedure was followed for setting up and conducting a test run. The schedule of runs enumerated in Table I was followed.

Difficulty was experienced in obtaining a crankcase oil temperature of 300°F. for test runs number 19, 20, and 21. To obtain the temperature, one-half of the cooling action of the flywheel was eliminated by brazing a 1½" strip of sheet metal around one-half of the outside periphery of the flywheel.

Analytical Procedure

Neutralization Number. This was determined according to the A.S.T.M. Specification D118-41T, and the Federal Specifications for Lubricants and Liquid Fuels as given in the Federal Standard Stock Catalog⁽³⁴⁾.

One hundred milliliters of a KOH neutralized C₂H₅OH solution were added to twenty grams of test oil. Two layers, one alcohol-water, the other oil, formed and were heated to boiling. After vigorous shaking, the mixture was titrated with a 0.09 Normal KOH solution with phenolphthalein as the indicator. The end point was reached when the first pink color appeared in the alcohol-water layer. The neutralization number of the oil was calculated as the number of milligrams of KOH required per gram of oil.

The titration had to be carried out in the presence of bright sunlight or a 60-watt titrating lamp to enable the end point to be determined accurately.

Sludge Analysis. This consisted of two phases; namely, the determination of petroleum naphtha insolubles and the determination of chloroform insolubles.

Petroleum Naphtha Insolubles. The Federal Specifications for Lubricants and Liquid Fuels as pertaining to Petroleum Naphtha Insolubles given in the Federal Standard Stock Catalog were followed.

A ten gram sample of oil was added to 90 ml. of petroleum naphtha and allowed to stand, after vigorous shaking, in a glass-stoppered Erlenmeyer flask for an hour in a room temperature of $25^{\circ}\text{C.} \pm 2^{\circ}$.

The oil-naphtha solution was then carefully filtered under a reduced pressure of three to four inches of mercury through a 25 ml. Gooch crucible (previously weighed) containing a prepared filter bed of asbestos and super-cel filter aid.

The crucible was dried for two hours at $221^{\circ}\text{F.} \pm 2^{\circ}$ and then weighed.

The naphtha insolubles were the weight of the insoluble material, expressed as a percentage of the weight of test oil used.

Chloroform Insolubles. The identical procedure as given for petroleum naphtha insolubles was followed for the chloroform insoluble determinations with the substitution of chloroform for naphtha in the analysis.

Asphaltic Resins. The petroleum naphtha selectively extracted only the oil from the oxidized test oil, leaving the extrinsic materials and the oxidized oil products on the filter medium. The chloroform extracted the oil and the oxidized products, leaving the extrinsic materials such as dust, dirt, gasoline, lead halides, metals, carbon, etc., on the filter medium. The asphaltic resins or oxidized material were determined by subtracting the per cent chloroform insolubles from the per cent petroleum naphtha insolubles.

Saybolt Viscosity. This test was conducted according to A.S.T.M. Specification D88-44 as set forth in the Federal Standard Stock Catalog⁽³⁴⁾. All tests were made at a temperature of 210°F. on the Saybolt Viscosimeter.

Data and Results. The data and results are presented in Tables II through X and in Figures I through VIII.

Tables II through VIII tabulate the data recorded for each of the 22 test runs. All runs conducted at the same temperature but at different lengths of time are recorded on the same table. The column, Time (Clock Hours) is the actual time of the run according to the time of day the test was performed. Hourly readings are missing for overnight test runs and time taken at meal times.

Table IX sums up the test data and gives for each test the results of the analysis of the used test oil; namely, neutralization number, viscosity, naphtha insolubles, chloroform insolubles, and asphaltic resins.

Table X evaluates the condition of the test engine's piston, piston rings, crankcase, and bearings at the completion of each test run. The rating of the engine parts was performed according to a numerical scale. The lowest number in the scale represents the cleanest part--the highest number represents the heaviest carbon covered part.

Figures I and II depict graphically the rate of oil oxidation as determined by the neutralization number of the test oil. Figure I shows the plot of neutralization number vs. time in hours for the different test runs. Figure II shows a plot of the neutralization number vs. the temperature in °F.

Figure III depicts the change in viscosity of the test oil due to oxidation. Viscosity in Saybolt seconds is plotted against time in hours.

Figures IV and V depict the rate of oil deterioration of the test oils. Figure IV shows the plot of per cent naphtha insolubles vs. time in hours. Figure V shows the plot of per cent naphtha insolubles vs. temperature in °F.

Figures VI and VII also depict the rate of oil deterioration of the test oils. Figure VI shows the plot of per cent chloroform insolubles vs. time in hours. Figure VII shows the plot of per cent chloroform insolubles vs. temperature in °F.

Figure VIII depicts the rate of formation of oil oxidation products as determined by the sludge analysis of the test oils. Per cent asphaltic resins is plotted vs. temperature in °F.

TABLE II

OPERATING TEST CONDITIONS FOR MODEL 850 DELCO LIGHTUNIT USING ESSO NO. 3 MOTOR
OIL AT A CRANKCASE OIL TEMPERATURE OF 120°F. AND A GENERATOR LOAD OF 0.0 WATTS

8 Hrs. Duration			:	16 Hrs. Duration			:	24 Hrs.- Duration		
Time- Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)	:	Time- Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)	:	Time Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)
9 a.m.	9.5	8.2	:	5 p.m.	11.0	9.0	:	11 a.m.	9.75	8.4
10	9.25	7.7	:	6	10.8	9.2	:	12	9.6	7.9
11	9.0	8.1	:	7	10.55	8.8	:	1 p.m.	9.4	8.2
12	8.75	8.1	:	8	10.3	9.9	:	2	9.25	8.2
1	8.55	8.2	:	9	10.05	9.4	:	3	9.0	7.9
2	8.3	8.1	:	10	9.80	9.5	:	4	8.76	7.6
3	8.05	8.2	:	11	9.65	9.1	:	5	8.5	7.2
4	7.8	8.5	:	12	9.40	8.8	:	6.	8.3	7.2
5	7.5	8.3	:	8 a.m.	7.15	8.8	:	7	8.1	7.0
			:	9	6.9	8.9	:	8	7.8	6.2
			:				:	9	7.55	6.8
			:				:	10	7.25	6.6
			:				:	11	7.0	6.1
			:				:	12	6.75	5.2
			:				:	8 a.m.	4.25	5.6
			:				:	9	4.0	5.8
			:				:	10	3.76	6.0
			:				:	11	3.55	5.8

R.P.M.--1120±10
Gen. Amp.--0

Oil Wt. (Init.) 2084 gms.
Oil Wt. (Final) 1860 gms.
Oil Wt. (Loss) 224 gms.

Bearing Wt. (Init.) 169.7158 gms.
Bearing Wt. (Final) 169.6123 gms.
Bearing Wt. (Loss) 0.1035 gms.

R.P.M.--1120±10
Gen. Amp.--0

Oil Wt. (Init.) 2054 gms.
Oil Wt. (Final) 1810 gms.
Oil Wt. (Loss) 244 gms.

Bearing Wt. (Init.) 171.6485 gms.
Bearing Wt. (Final) 171.5415 gms.
Bearing Wt. (Loss) 0.1070 gms.

R.P.M.--1120±10
Gen. Amp.--0

Oil Wt. (Init.) 2084 gms.
Oil Wt. (Final) 1580 gms.
Oil Wt. (Loss) 504 gms.

Bearing Wt. (Init.) 171.7262 gms.
Bearing Wt. (Final) 171.6049 gms.
Bearing Wt. (Loss) 0.1213 gms.

TABLE III

OPERATING TEST CONDITIONS FOR MODEL 850 DELCO LIGHT UNIT USING ESSO NO. 3 MOTOR
OIL AT A CRANKCASE OIL TEMPERATURE OF 120°F. AND A GENERATOR LOAD OF 600 WATTS

8 Hrs.-Duration			:	16 Hrs.-Duration			:	24 Hrs.-Duration		
Time- Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)	:	Time- Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)	:	Time- Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)
4 p.m.	8.9	7.8	:	10 p.m.	9.0	7.9	:	3 p.m.	10.5	8.1
5	8.55	8.2	:	11	8.75	7.6	:	4	10.24	7.6
6	8.30	8.3	:	12	8.5	7.6	:	5	9.98	8.0
7	8.05	8.3	:	8 a.m.	6.4	7.8	:	7	9.73	8.1
8	7.85	7.5	:	9	6.15	8.0	:	8	9.48	8.0
9	7.60	7.9	:	10	5.9	7.9	:	9	9.23	7.0
10	7.35	8.0	:	11	5.65	7.7	:	10	9.00	8.1
11	7.1	7.6	:	12	5.40	7.6	:	11	8.74	8.1
12	6.8	8.8	:	1 p.m.	5.15	7.6	:	12	8.4	8.5
			:	2	4.9	7.9	:	8 a.m.	5.93	8.1
			:				:	9	5.67	8.0
			:				:	10	5.42	7.8
			:				:	11	5.17	7.9
			:				:	1 p.m.	4.52	8.1
			:				:	2	4.27	7.8
			:				:	3	4.0	7.8

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2054 gms.
Oil Wt. (Final) 1780 gms.
Oil Wt. (Loss) 274 gms.

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2084 gms.
Oil Wt. (Final) 1780 gms.
Oil Wt. (Loss) 304 gms.

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2114 gms.
Oil Wt. (Final) 1580 gms.
Oil Wt. (Loss) 534 gms.

Bearing Wt. (Init.) 172.4469 gms. Bearing Wt. (Init.) 172.2366 gms.
Bearing Wt. (Final) 172.3702 gms. Bearing Wt. (Final) 172.1425 gms.
Bearing Wt. (Loss) 0.0767 gms. Bearing Wt. (Loss) 0.0941 gms.

Bearing Wt. (Init.) 171.8718 gms.
Bearing Wt. (Final) 171.7973 gms.
Bearing Wt. (Loss) 0.0745 gms.

TABLE IV

OPERATING TEST CONDITIONS FOR MODEL 850 DELCO LIGHT UNIT USING ESSO NO. 3 MOTOR
OIL AT A CRANKCASE OIL TEMPERATURE OF 170°F. AND A GENERATOR LOAD OF 600 WATTS

8 Hrs.-Duration			:	16 Hrs.-Duration			:	24 Hrs.-Duration		
Time-Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)	:	Time-Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)	:	Time-Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)
11 a.m.	9.75	8.3	:	4 p.m.	9.7	9.0	:	1 p.m.	9.75	9.0
12	9.5	8.6	:	5	9.43	8.8	:	2	9.5	8.3
1 p.m.	9.2	9.4	:	6	9.16	8.5	:	3	9.2	8.0
2	8.95	8.2	:	8	8.91	8.6	:	4	8.95	8.6
3	8.65	8.3	:	9	8.65	8.0	:	5	8.7	8.1
4	8.40	8.3	:	10	8.40	8.4	:	7	8.42	8.1
5	8.15	8.6	:	11	8.13	8.8	:	8	8.17	8.6
6	7.90	8.8	:	12	7.88	8.6	:	9	7.92	8.0
7	7.65	8.3	:	8 a.m.	5.85	8.0	:	10	7.67	8.3
			:	9	5.6	8.2	:	11	7.40	8.8
			:				:	8 a.m.	4.5	8.7
			:				:	9	4.26	8.7
			:				:	10	4.0	7.9
			:				:	11	3.7	8.2
			:				:	12	3.45	8.8
			:				:	1 p.m.	3.15	8.6

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2054 gms.
Oil Wt. (Final) 1645 gms.
Oil Wt. (Loss) 409 gms.

Bearing Wt. (Init.) 171.5947 gms.
Bearing Wt. (Final) 171.4386 gms.
Bearing Wt. (Loss) 0.1561 gms.

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2054 gms.
Oil Wt. (Final) 1499 gms.
Oil Wt. (Loss) 555 gms.

Bearing Wt. (Init.) 171.8914 gms.
Bearing Wt. (Final) 171.7685 gms.
Bearing Wt. (Loss) 0.1229 gms.

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2074 gms.
Oil Wt. (Final) 1470 gms.
Oil Wt. (Loss) 604 gms.

Bearing Wt. (Init.) 171.5026 gms.
Bearing Wt. (Final) 171.4141 gms.
Bearing Wt. (Loss) 0.0885 gms.

TABLE V

OPERATING TEST CONDITIONS FOR MODEL 850 DELCO LIGHT UNIT USING ESSO NO. 3 MOTOR OIL AT A CRANKCASE OIL TEMPERATURE OF 210°F. AND A GENERATOR LOAD OF 600 WATTS

8 Hrs.-Duration			:	16 Hrs.-Duration			:	24 Hrs.-Duration		
Time-Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)	:	Time-Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)	:	Time-Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)
11 a.m.	7.2	7.9	:	4 p.m.	11.05	8.0	:	1 p.m.	10.25	8.2
12	7.9	8.2	:	5	10.75	7.5	:	2	10.0	8.2
1 p.m.	6.65	8.5	:	6	10.5	8.2	:	3	9.73	8.6
2	6.4	8.1	:	7	10.24	7.0	:	4	9.45	8.9
3	6.12	8.0	:	8	9.95	7.1	:	5	9.2	8.7
4	5.82	8.4	:	9	9.7	7.2	:	7	8.6	8.0
5	5.55	8.4	:	10	9.45	8.0	:	8	8.35	8.8
6	5.30	8.3	:	11	9.2	7.6	:	9	8.1	8.5
7	5.05	7.8	:	12	8.95	7.6	:	10	7.85	8.4
			:	8 a.m.	6.90	7.2	:	11	7.60	9.6
			:				:	12	7.35	8.8
			:				:	8 a.m.	4.88	9.6
			:				:	9	4.6	8.7
			:				:	10	4.35	8.6
			:				:	11	4.1	8.4
			:				:	12	3.8	8.6
			:				:	1 p.m.	3.55	8.2

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2114 gms.
Oil Wt. (Final) 1520 gms.
Oil Wt. (Loss) 594 gms.

Bearing Wt. (Init.) 171.9486 gms.
Bearing Wt. (Final) 171.8098 gms.
Bearing Wt. (Loss) 0.1388 gms.

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2031 gms.
Oil Wt. (Final) 1350 gms.
Oil Wt. (Loss) 681 gms.

Bearing Wt. (Init.) 172.6846 gms.
Bearing Wt. (Final) 172.4915 gms.
Bearing Wt. (Loss) 0.1931 gms.

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2054 gms.
Oil Wt. (Final) 1250 gms.
Oil Wt. (Loss) 804 gms.

Bearing Wt. (Init.) 170.2896 gms.
Bearing Wt. (Final) 170.2034 gms.
Bearing Wt. (Loss) 0.0862 gms.

TABLE VI

OPERATING TEST CONDITIONS FOR MODEL 850 DELCO LIGHT UNIT USING ESSO NO. 3 MOTOR
OIL AT A CRANKCASE OIL TEMPERATURE OF 240°F. AND A GENERATOR LOAD OF 600 WATTS

8 Hrs.-Duration			:	16 Hrs.-Duration			:	24 Hrs.-Duration		
Time- Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)	:	Time- Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)	:	Time- Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)
1 p.m.	8.30	8.0	:	6 p.m.	8.9	7.1	:	2 p.m.	11.5	7.2
2	8.10	8.1	:	7	8.65	7.6	:	3	11.25	7.8
3	7.85	9.0	:	8	8.4	7.6	:	4	11.0	8.2
4	7.55	8.8	:	9	8.15	7.2	:	5	10.75	8.3
5	7.3	8.7	:	10	7.85	7.0	:	7	10.45	8.8
7	6.7	8.3	:	11	7.6	7.1	:	8	10.18	8.6
8	6.40	8.7	:	12	7.45	7.0	:	9	9.90	8.8
9	6.10	8.1	:	8 a.m.	5.30	7.8	:	10	9.60	8.6
			:	9	5.05	7.2	:	11	9.32	8.4
			:	10	4.8	6.8	:	12	9.05	8.6
			:				:	8 a.m.	6.50	8.5
			:				:	9	6.25	7.5
			:				:	10	6.0	8.0
			:				:	11	5.73	8.2
			:				:	12	5.48	8.5
			:				:	2 p.m.	4.9	8.2

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2094 gms.
Oil Wt. (Final) 1455 gms.
Oil Wt. (Loss) 639 gms.

Bearing Wt. (Init.) 172.1349 gms.
Bearing Wt. (Final) 172.0591 gms.
Bearing Wt. (Loss) 0.0758 gms.

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2076 gms.
Oil Wt. (Final) 1370 gms.
Oil Wt. (Loss) 706 gms.

Bearing Wt. (Init.) 171.7892 gms.
Bearing Wt. (Final) 171.7049 gms.
Bearing Wt. (Loss) 0.0843 gms.

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2057 gms.
Oil Wt. (Final) 1233 gms.
Oil Wt. (Loss) 824 gms.

Bearing Wt. (Init.) 171.9182 gms.
Bearing Wt. (Final) 171.8576 gms.
Bearing Wt. (Loss) 0.0606 gms.

TABLE VII

OPERATING TEST CONDITIONS FOR MODEL 850 DELCO LIGHT UNIT USING ESSO NO. 3 MOTOR
OIL AT A CRANKCASE OIL TEMPERATURE OF 270°F. AND A GENERATOR LOAD OF 600 WATTS

8 Hrs.-Duration			16 Hrs.-Duration			24 Hrs.-Duration			32 Hrs.-Duration		
Time Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)	Time Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)	Time Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)	Time Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)
2 p.m.	8.2	7.9	5 p.m.	9.5	6.1	8 p.m.	11.23	7.0	12 a.m.	12.0	7.0
3	7.95	8.4	6	9.25	5.5	9	10.95	5.2	1 p.m.	11.75	5.2
4	7.7	8.2	7	9.0	6.0	10	10.70	7.2	2	11.5	7.6
5	7.45	7.9	8	8.78	6.5	11	10.52	7.8	3	11.22	7.4
7	6.85	7.5	9	8.5	6.0	12	10.25	7.6	4	10.95	7.2
8	6.6	8.0	10	8.25	7.0	8 a.m.	7.65	8.0	5	10.65	7.8
9	6.35	7.7	11	8.0	7.2	9	7.40	8.1	7	10.05	7.6
10	6.1	7.8	12	7.75	7.0	10	7.12	8.0	8	9.75	7.9
			8 a.m.	5.54	8.2	11	6.87	8.2	10	9.20	8.6
			9	5.3	7.6	1 p.m.	6.35	7.6	11	8.95	8.0
						2	6.08	7.6	12	8.68	8.2
						3	5.83	7.8	8 a.m.	6.65	8.1
						4	5.65	8.0	9	6.40	8.0
						5	5.40	8.5	10	6.15	8.0
						6	5.15	8.1	11	5.90	7.8
						8	4.60	8.4	1 p.m.	5.32	7.6
									2	5.05	7.5
									3	4.80	7.6
									4	4.53	7.8
									5	4.28	7.4
									7	3.25	7.5
									8	3.0	8.0

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2021 gms.
Oil Wt. (Final) 1372 gms.
Oil Wt. (Loss) 649 gms.

Bearing Wt. (Init.) 172.0076 gms.
Bearing Wt. (Final) 171.9233 gms.
Bearing Wt. (Loss) 0.0843 gms.

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2041 gms.
Oil Wt. (Final) 1310 gms.
Oil Wt. (Loss) 731 gms.

Bearing Wt. (Init.) 170.4840 gms.
Bearing Wt. (Final) 170.2660 gms.
Bearing Wt. (Loss) 0.2180 gms.

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2139 gms.
Oil Wt. (Final) 1330 gms.
Oil Wt. (Loss) 859 gms.

Bearing Wt. (Init.) 171.7085 gms.
Bearing Wt. (Final) 171.5063 gms.
Bearing Wt. (Loss) 0.2022 gms.

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2077 gms.
Oil Wt. (Final) 1080 gms.
Oil Wt. (Loss) 997 gms.

Bearing Wt. (Init.) 170.6504 gms.
Bearing Wt. (Final) 170.5281 gms.
Bearing Wt. (Loss) 0.1223 gms.

TABLE VIII

OPERATING TEST CONDITIONS FOR MODEL 850 DELCO LIGHT UNIT USING ESSO NO. 3 MOTOR
OIL AT A CRANKCASE OIL TEMPERATURE OF 300°F. AND A GENERATOR LOAD OF 600 WATTS

8 Hrs.-Duration			:	16 Hrs.-Duration			:	24 Hrs.-Duration		
Time- Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)	:	Time- Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)	:	Time- Clock Hours	Gas Level (Gals.)	CO ₂ (Vol.%)
4 p.m.	8.3	8.2	:	2 p.m.	10.	7.0	:	8 p.m.	12.1	7.6
5	8.12	6.0	:	3	9.75	7.6	:	9	11.85	7.8
7	7.57	6.8	:	4	9.48	7.2	:	10	11.58	7.9
8	7.23	7.8	:	5	9.20	8.2	:	11	11.3	7.8
9	6.98	8.0	:	7	8.95	7.6	:	12	11.0	8.2
10	6.71	7.2	:	8	8.7	8.1	:	8 a.m.	8.5	8.0
11	6.45	7.9	:	9	8.45	8.0	:	9	8.25	7.7
12	6.2	8.2	:	10	8.2	8.3	:	10	8.0	7.9
			:	11	7.92	7.8	:	11	7.75	7.6
			:	12	7.67	7.9	:	1 p.m.	7.25	7.8
			:	6 a.m.	5.9	8.2	:	2	7.0	7.2
			:				:	3	6.75	6.8
			:				:	4	6.50	6.9
			:				:	5	6.25	7.2
			:				:	7	5.66	7.0
			:				:	8	5.4	8.0

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2112 gms.
Oil Wt. (Final) 1420 gms.
Oil Wt. (Loss) 692 gms.

Bearing Wt. (Init.) 172.4600 gms.
Bearing Wt. (Final) 172.3962 gms.
Bearing Wt. (Loss) 0.0638 gms.

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2067 gms.
Oil Wt. (Final) 1260 gms.
Oil Wt. (Loss) 807 gms.

Bearing Wt. (Init.) 172.2125 gms.
Bearing Wt. (Final) 171.9809 gms.
Bearing Wt. (Loss) 0.2316 gms.

R.P.M.--980±10
Gen. Amp.--5

Oil Wt. (Init.) 2086 gms.
Oil Wt. (Final) 1150 gms.
Oil Wt. (Loss) 936 gms.

Bearing Wt. (Init.) 172.3903 gms.
Bearing Wt. (Final) 172.2121 gms.
Bearing Wt. (Loss) 0.1782 gms.

TABLE IX

CALCULATED RESULTS OF BREAKDOWN TESTS OF ESSO MOTOR OIL NO. 3
IN MODEL 850 DELCO LIGHT UNIT UNDER VARYING TEST CONDITIONS

Test No.	Conditions			Oil Consumption (%)	Gas Consumption (Gals.)	Bearing Weight Loss (Gms.)	Neut. No.	Viscosity Sec.	Naphtha Insol. (%)	CHCl ₃ Insol. (%)	Asphaltic Resins (%)
	Time (Hrs.)	Temp. (°F.)	Load Watts								
1	8	120	0	10.7	2.0	0.1035	--	--	--	--	--
2	16	120	0	11.9	4.1	0.1070	--	--	--	--	--
3	24	120	0	24.2	6.2	0.1215	--	--	--	--	--
4	8	120	600	13.3	2.1	0.0767	0.05	76.0	0.0801	0.0328	0.0472
5	16	120	600	14.5	4.1	0.0941	0.05	76.0	0.104	0.0478	0.0562
6	24	120	600	25.2	6.5	0.0745	0.052	76.1	0.112	0.052	0.060
7	8	170	600	20.0	2.1	0.1561	0.05	76.3	0.100	0.0566	0.0434
8	16	170	600	27.0	4.1	0.1229	0.062	77.8	0.120	0.0607	0.059
9	24	170	600	29.2	6.6	0.0665	0.114	78.75	0.140	0.065	0.075
10	8	210	600	28.1	2.15	0.1388	0.075	76.75	0.126	0.0612	0.0648
11	16	210	600	33.5	4.15	0.1931	0.087	77.5	0.151	0.0745	0.076
12	24	210	600	39.2	6.7	0.0868	0.165	80.3	0.157	0.0801	0.077
13	8	240	600	30.5	2.2	0.0753	0.075	77.1	0.130	0.068	0.062
14	16	240	600	34.1	4.1	0.0841	0.125	78.2	0.097	0.0618	0.038
15	24	240	600	40.2	6.6	0.0603	0.200	80.5	0.190	0.11	0.088
16	8	270	600	31.8	2.1	0.0846	0.080	78.4	0.136	0.0827	0.053
17	16	270	600	35.8	4.2	0.2181	0.132	80.8	0.160	0.102	0.058
18	24	270	600	41.2	6.6	0.2021	0.237	81.5	0.220	0.140	0.080
19	8	300	600	32.6	2.1	0.0631	0.100	79.0	0.140	0.101	0.040
20	16	300	600	38.9	4.1	0.2311	0.199	81.0	0.167	0.112	0.055
21	24	300	600	45.	6.7	0.1781	0.375	58.8	0.271	0.126	0.145
22	32	270	600	48.3	9.0	0.1221	0.267	84.6	0.362	0.175	0.187
Original Oil Sample							0.045	76.0	0.068	0.039	0.029

TABLE X

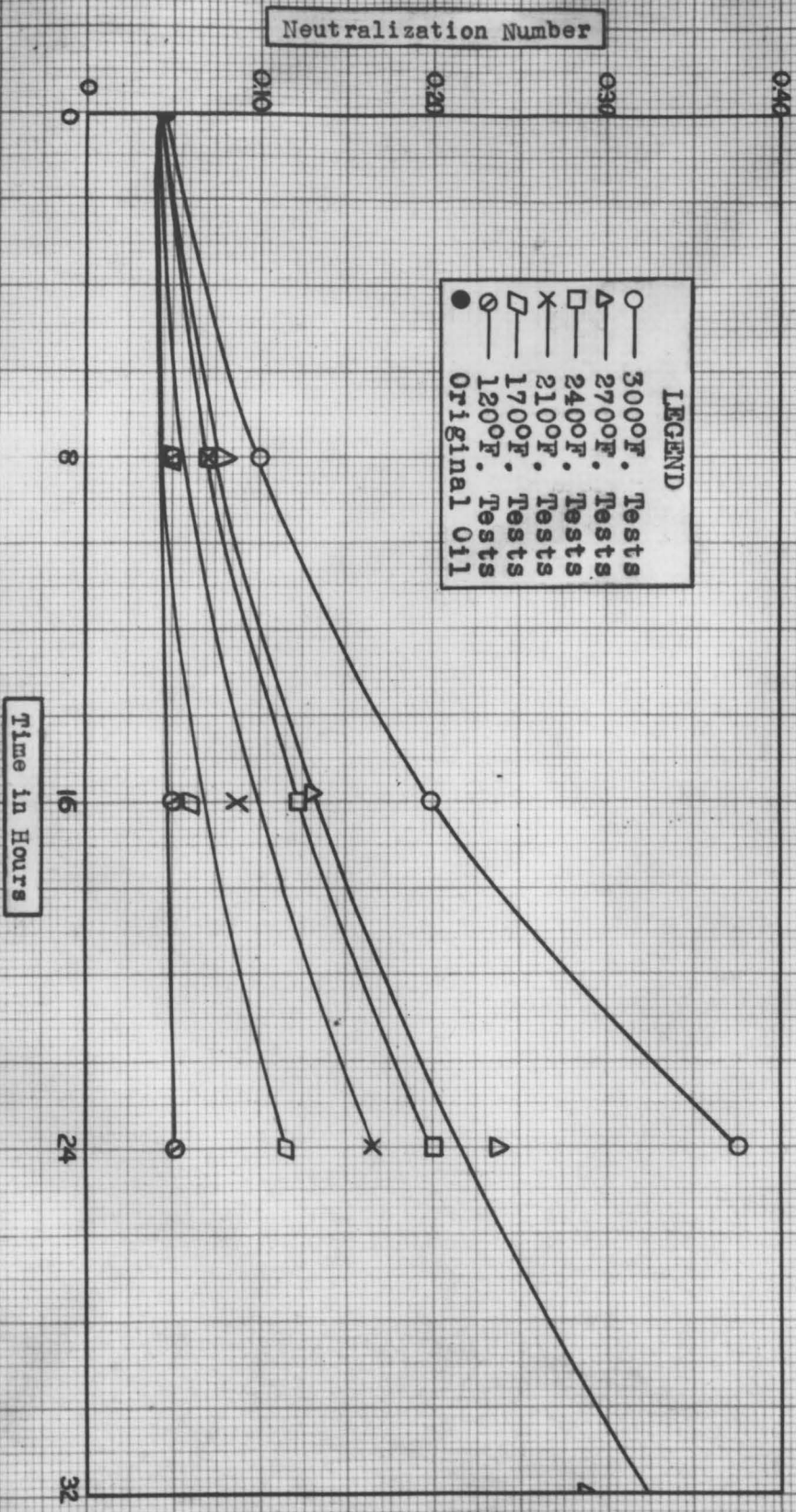
OBSERVED RESULTS OF BREAKDOWN TESTS OF ESSO MOTOR OIL NO. 3
IN MODEL 850 DELCO LIGHT UNIT UNDER VARYING TEST CONDITIONS

Test No.	Conditions			Piston		Carbon in Ring Grooves	Rings		Crankcase		Bearings			Immersion Heater-- Carbon Coated
	Time (Hrs.)	Temp. (°F.)	Load Watts	Carbon on Top	Varnish on Side		Free and Clean	Stuck	Clean	Varnish Deposits	Wiping	Well Lubri- cated	Dis- colo- ration	
1	8	120	0	2	2	3	1	No	Yes	No	1	Yes	3	--
2	16	120	0	3	2	3	1	No	Yes	No	1	Yes	3	--
3	24	120	0	4	2	3	1	No	Yes	No	1	Yes	3	--
4	8	120	600	1	1	1	1	No	Yes	No	1	Yes	1	--
5	16	120	600	3	2	2	1	No	Yes	No	1	Yes	2	--
6	24	120	600	3	3	4	1	No	Yes	No	1	Yes	4	--
7	8	170	600	2	1	2	1	No	Yes	No	1	Yes	2	3
8	16	170	600	2	3	3	1	No	Yes	No	2	Yes	3	3
9	24	170	600	3	3	2	1	No	Yes	No	2	Yes	3	3
10	8	210	600	1	1	1	1	No	Yes	No	1	Yes	3	2
11	16	210	600	2	2	3	1	No	Yes	No	1	Yes	2	1
12	24	210	600	4	4	4	1	No	Yes	No	2	Yes	5	1
13	8	240	600	2	3	3	1	No	Yes	No	2	Yes	3	1
14	16	240	600	2	2	4	1	No	Yes	No	2	Yes	4	1
15	24	240	600	4	4	4	2	No	Yes	No	2	Yes	4	1
16	8	270	600	3	4	4	1	No	Yes	No	2	Yes	4	2
17	16	270	600	4	3	4	1	No	Yes	No	3	Yes	4	3
18	24	270	600	5	5	4	2	No	Yes	No	4	Yes	5	5
19	8	300	600	3	4	4	1	No	Yes	No	4	Yes	4	4
20	16	300	600	4	5	4	2	No	Yes	No	4	Yes	4	4
21	24	300	600	4	6	5	3	Oil Ring Comp. Rings	Yes	No	4	No	5	5
22	32	270	600	6	6	6	3		Yes	No	4	No	6	6

Numerical Scale

Smallest Number: Least Carbon or Varnish Covered
Highest Number: Heaviest Carbon or Varnish Covered

FIGURE I
RATE OF OIL OXIDATION
(Neutralization Number vs. Time in Hours)



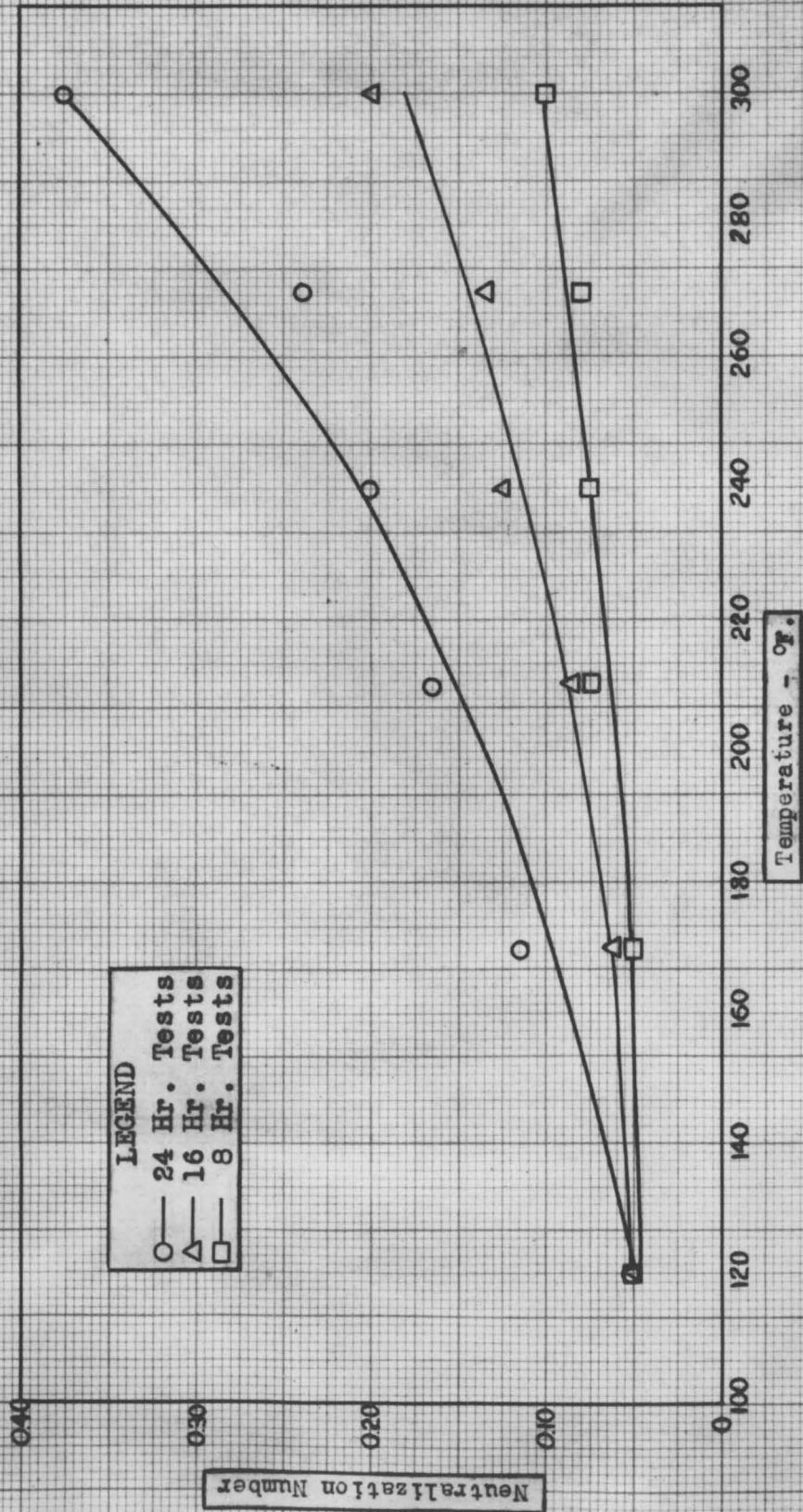
LEGEND

- 300°F. Tests
- △ 270°F. Tests
- 240°F. Tests
- × 210°F. Tests
- ◇ 170°F. Tests
- Original Oil

Neutralization Number

Time in Hours

FIGURE II
RATE OF OIL OXIDATION
(Neutralization Number vs. Temp. °F)



LEGEND
○ — 24 Hr. Tests
△ — 16 Hr. Tests
□ — 8 Hr. Tests

FIGURE III
VISCOSITY
(Saybolt Seconds vs. Time in Hours)

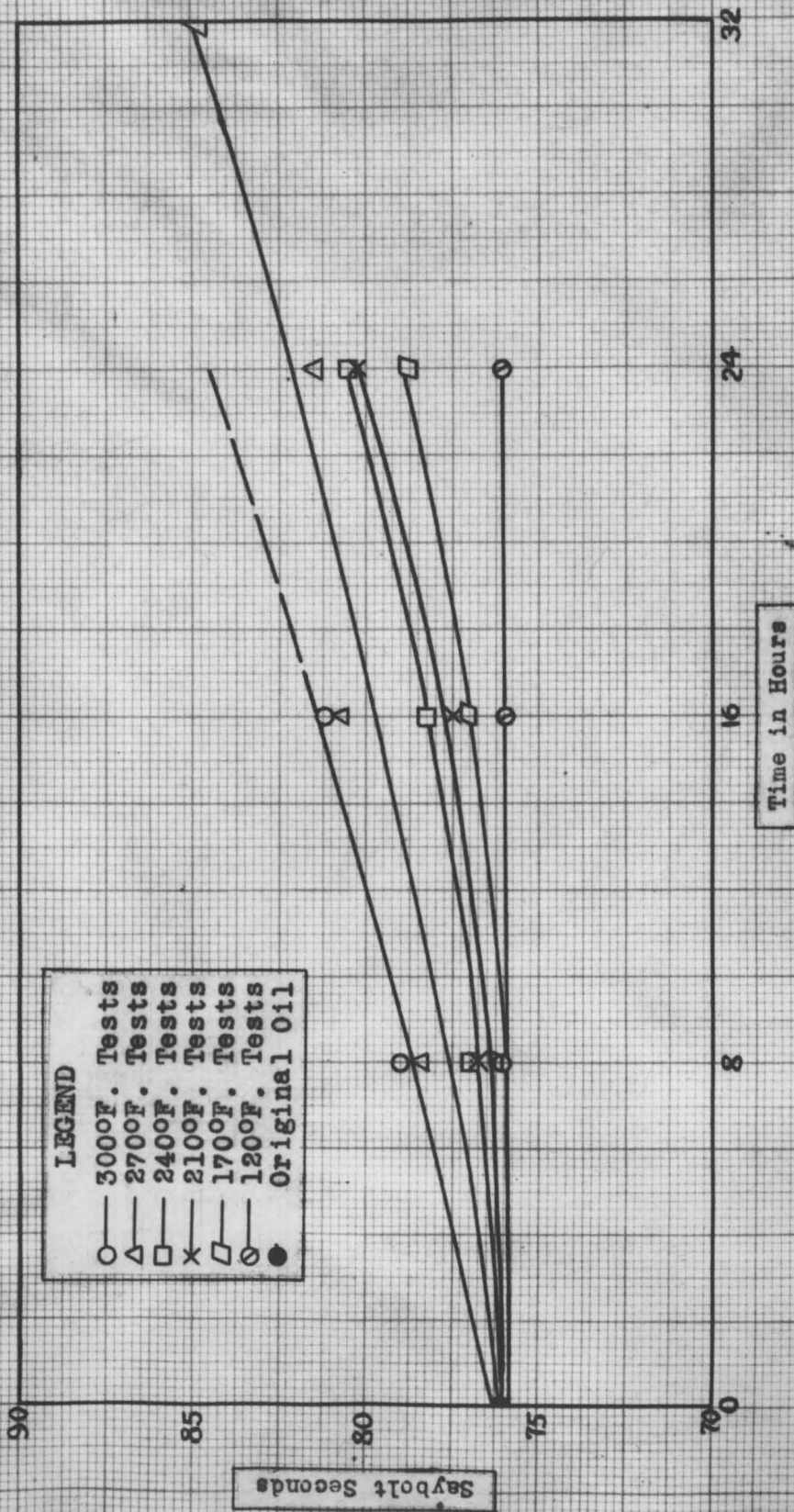


FIGURE IV
RATE OF OIL DETERIORATION
 (Per Cent Naphtha Insolubles vs. Time in Hours)

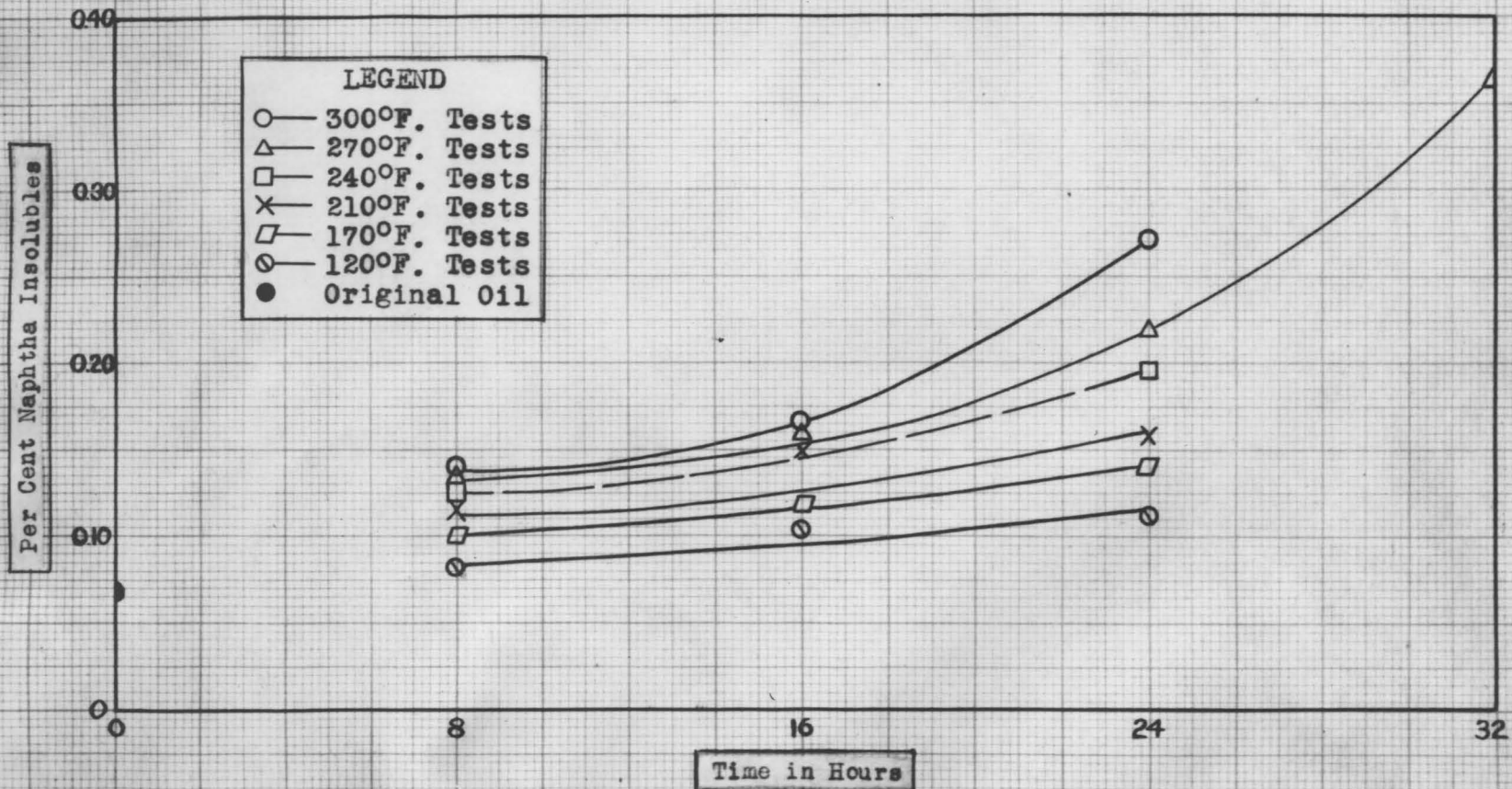


FIGURE V
RATE OF OIL DETERIORATION
(Per Cent Naphtha Insolubles vs. Temp. °F)

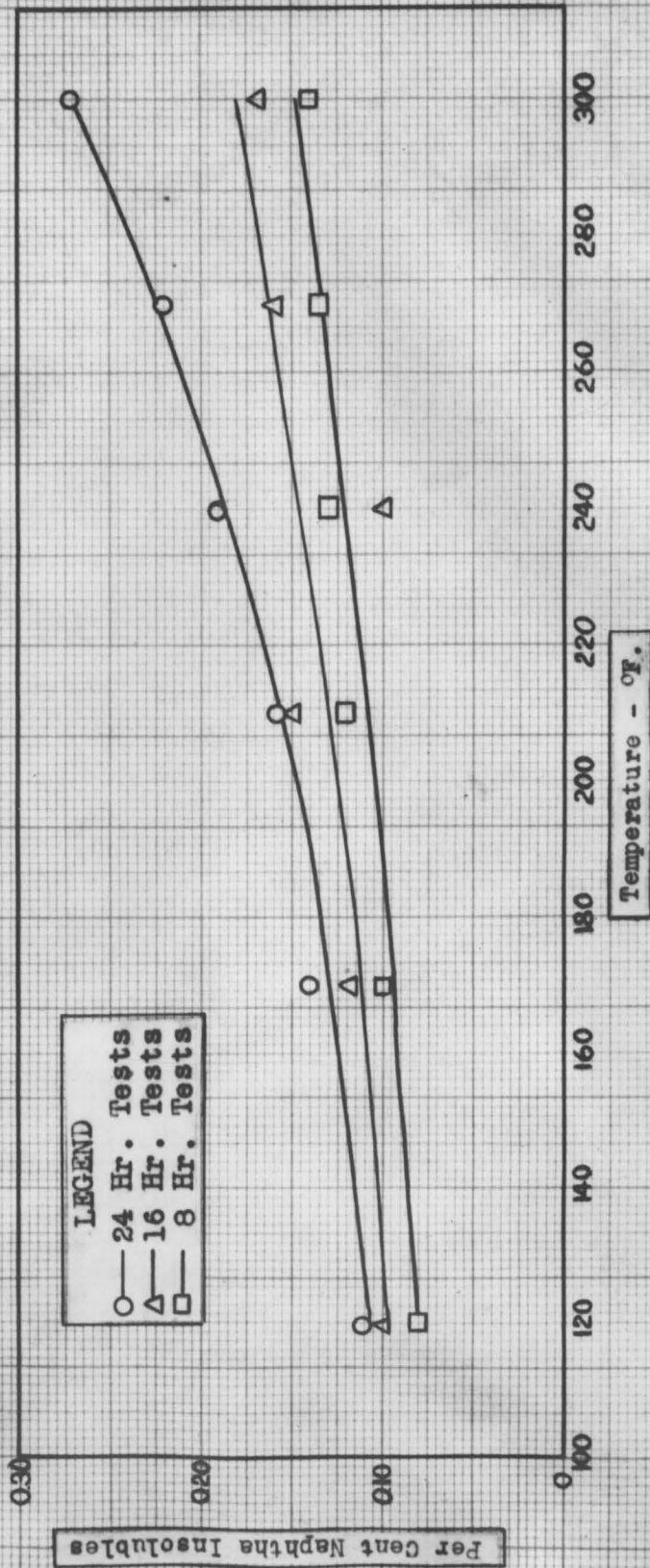


FIGURE VII
RATE OF OIL DETERIORATION
(Per Cent Chloroform Insolubles vs. Temp. °F)

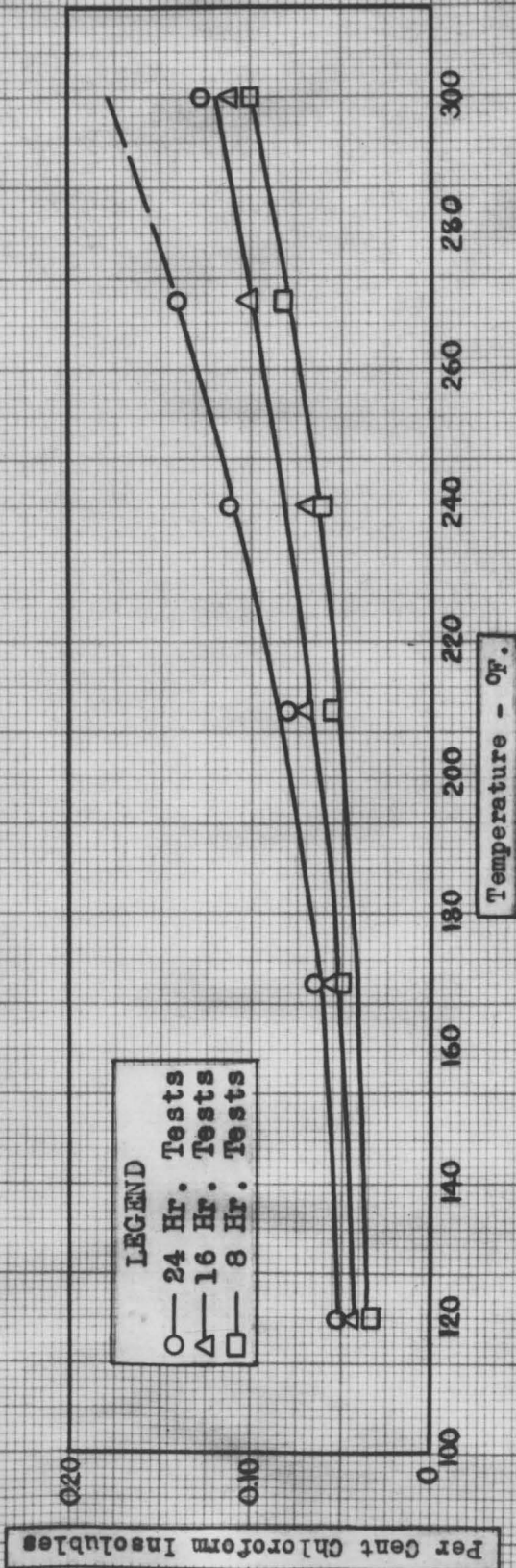
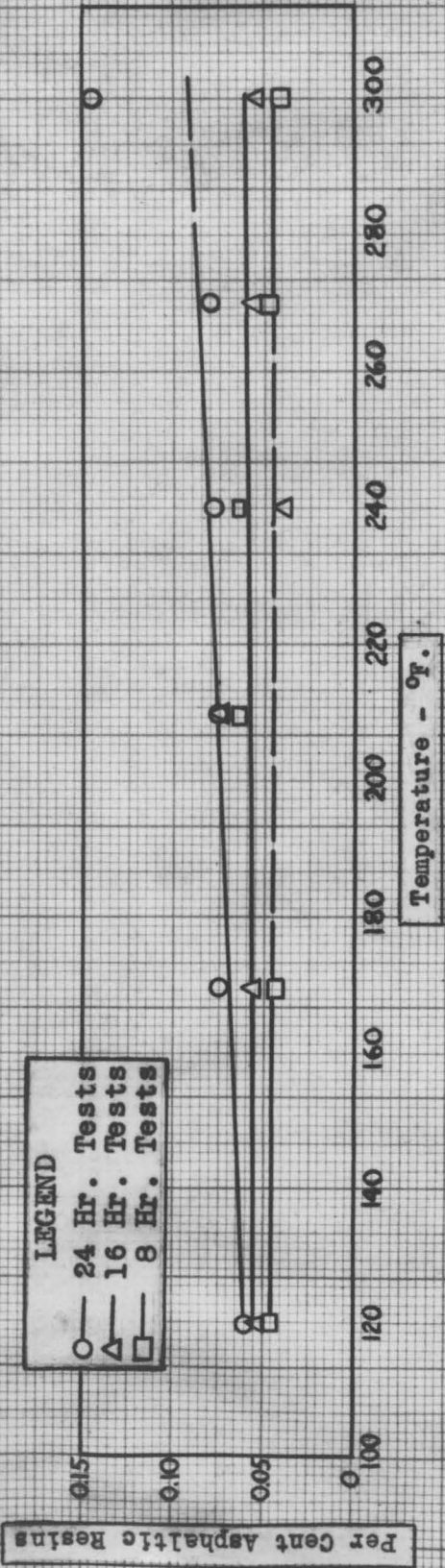


FIGURE VIII
RATE OF OIL OXIDATION
(Per Cent Asphaltic Resins vs. Temp. of)



IV. DISCUSSION

Engine Test Conditions. Gasoline consumption, CO₂ content of the exhaust gas, r.p.m. of motor, and generator amperage were recorded in an attempt to determine if constant conditions of engine performance could be maintained for all test runs.

The CO₂ content of the exhaust gases varied within the limits of 7.5±1% indicating a fairly constant rate of fuel combustion. For all test conditions at full engine load, the r.p.m. of the motor was 980±10; while for all test conditions at no engine load the r.p.m. was 1120±10; indicating constant speed of performance. The constant reading of 5 amperes on the generator ammeter indicated a constant generator output.

Total gasoline consumption in gallons is enumerated in Table IX. The 24-hour duration test runs at a full generator load required an average of 6.6 gallons per test. The 24-hour test conducted at no load required only 6.2 gallons. This decrease would be expected as less work is required of the engine when operating under no load.

The gasoline consumption for the 8 and 16-hour test runs resulted in an average of 2.1 and 4.1 gallons per

test respectively. No variation in consumption was noted due to changes in load. Also, an increase in crankcase oil temperature did not effect gasoline consumption.

Oil Consumption. An analysis of the comparative amounts of oil consumed (weight per cent) in the various test runs (Table IX) indicates that the per cent oil consumption increased as time, temperature, and load increased. Tests conducted at 120°F. and no load for 8, 16, and 24 hours resulted in a per cent consumption of 10.7, 11.9, and 24.2 respectively. Tests conducted at 120°F. with a 600-watt load, for 8, 16, and 24 hours resulted in a per cent consumption of 13.3, 14.5, and 25.2 respectively. This clearly indicates the effect of load upon oil consumption. Tests conducted at 300°F. and a 600-watt load for 8, 16, and 24 hours resulted in a per cent consumption of 32.6, 38.9, and 45. respectively--thus illustrating the effect of increased temperature upon oil consumption. The intermediate test runs also resulted in increasing oil consumption with increasing time, temperature, and load.

Duration of Tests. The Delco engine used as a test unit has a splash type of lubrication. Clower⁽²³⁾ states that adequate lubrication is assured with this system as long as the oil level is correctly maintained. The oil consumption in the longest test run, 32 hours at 270°F.

approached 50%. It was felt that additional time of testing would not give accurate results of oil oxidation due to insufficient oil present for adequate lubrication. Efforts were made to conduct a test at 300°F. and 32 hours. However, the 300°F. temperature could not be obtained due to partial failure of the crankcase immersion heater.

Bearing Weight Loss. The loss in weight in grams of the babbitt bearings in the test runs was recorded in an attempt to evaluate the stability of the test oil. Raymond⁽⁷⁴⁾ states that bearing corrosion occurs mainly from the action of oil oxidation products, such as organic acids, on the metal bearing. Raymond⁽⁷⁴⁾ further states that a rise in oil temperature of 30°F. was much more destructive in its corrosive effects on a bearing than a five-fold increase in operating time. From these statements it would be expected that the bearing weight loss of the test runs would fall in a definite pattern. Actually, however, the results were at a complete variance. Bearing weight losses for the 300°F. tests were 0.1782 gms. for a 24-hour test, 0.2316 gms. for a 16-hour test, and 0.0638 gms. for the 8-hour test. Tests conducted at 270°F. resulted in bearing weight losses of 0.1223 gms. for a 32-hour run, 0.2022 gms. for a 24-hour test, 0.2180 gms. for the 16-hour test, and 0.0843 gms. for the 8-hour test. The results for the other test runs were also erratic. The

only series of test that gave bearing weight loss increase with increase in time in the right order was in the 120°F., no load series. The losses were for 8 hours, 0.1035 gms.; for 16 hours, 0.1070 gms.; and for 24 hours, 0.1213 gms.

Pomeroy⁽⁷⁰⁾ relates that the acids formed by the oil oxidation are very weak and normally do not attack metals. However, at elevated temperatures (230-300°F.) corrosion of certain metals did occur; namely, lead, zinc, copper, and cadmium. Barnard and co-workers⁽¹²⁾ determined copper-lead bearing weight losses averaging 0.542 gms. on a S.A.E. 30 oil with a Viscosity Index corresponding to Esso No. 3 motor oil in tests conducted on a Chevrolet test engine at 230°F. for 36 hours. Babbitt bearings, Pomeroy⁽⁷⁰⁾ found, were not affected by the elevated temperatures. Raymond⁽⁷⁴⁾ states that babbitt bearings are highly resistant to corrosion. That some corrosion did take place in the tests is evidenced, however, by the high bearing weight losses at some of the higher temperatures over the low losses at the lower temperatures.

Discoloration to varying degrees was evidenced in all of the test bearings at the completion of the test runs, indicating that perhaps the oil film had broken down and that oxidation products had been ground into the metal or that oxidation products had reacted with the metallic oxide.

All of the test bearings except the ones for the 300°F. 24-hour test and the 270°F. 32-hour test appeared to be well lubricated at the completion of the test. The above two mentioned exceptions resulted in bearing surfaces that did not appear to be well lubricated. The bearing faces were not completely covered with an oil film, and the small amount of oil present on the bearing faces was extremely black and fluid in appearance.

The variance in loss in weight of the bearings may have been due mainly to the mechanism of inserting the bearings in the connecting rod assembly. Inside calibration failed to disclose any deviation in the various test bearings prior to use. Calibration of the crankshaft failed to show any deviation in roundness. Yet, in inserting the different test bearings, a different number of bearing shims would be required. Also the same torque wrench pressure could not be applied to all bearings. Failure to have all bearings tightened alike would result in different thicknesses of lubricating oil films. This would cause a greater or lesser bearing wiping action which would result in varying bearing weight losses.

Neutralization Number. This test was conducted in an effort to ascertain the acid-forming tendencies

resulting from the oxidation of the test oils at the various temperatures and times. Graphical plots (Figures I and II) of the resulting neutralization numbers portray smooth curves of ascending order. The neutralization number increased from 0.045 for a new oil prior to testing to 0.375 for the 300°F. 24-hour test.

Mougey and Moller⁽⁶⁴⁾ in tests conducted on a S.A.E. 30 oil with inhibitor, in a Chevrolet engine at 280°F. for 36 hours, obtained a maximum neutralization number of 3.0. Davis and co-workers⁽²⁷⁾ in tests conducted on a S.A.E. 30 oil, with inhibitor, in a Chevrolet engine at 280°F. for 36 hours, obtained a neutralization number of 3.5. Their graphical plots show the same ascending order as the curves shown in Figures I and II.

No information was given as to the type of oxidation inhibitor contained in the preceding test oils. Different inhibitors have varying effects on oils. It is clear, however, using the neutralization number as a basis, that excessive oxidation did not occur under the test conditions set up for this investigation. The oxidation inhibitor in Esso No. 3 motor oil may have been very effective in preventing oil oxidation.

Also, there is no correlation evident in this investigation between "acids" as determined by the neutralization

number and bearing corrosion as determined by bearing weight loss.

Petroleum Naphtha Insolubles. This test was conducted on the used test oil in conjunction with the chloroform insolubles analysis in an effort to obtain the sludge content resulting from the oxidation of the test oil.

The petroleum naphtha extracts only the oil content of the oil-sludge mixture, leaving on the filter medium the oxidized oil products and the extrinsic materials such as metal particles, carbon, blow-by materials, and dust⁽²⁶⁾⁽²⁷⁾. Results were reproducible by the investigator within 0.2%. Davis and co-workers⁽²⁷⁾ state that it is a purely arbitrary classification of insolubles, but is correlative with engine conditions.

The results of each test are plotted in Figures IV and V. Smooth curves largely result, all in ascending order of magnitude beginning at the low temperatures and low hours of testing. Values of per cent naphtha insolubles increase from 0.068% for the test oil prior to testing to a maximum of 0.362% for the 32-hour, 270°F. test run.

Georgi⁽⁴⁰⁾ in tests conducted on a S.A.E. 30 oil, with inhibitor, and a Viscosity Index of 110, in a

test engine, for 36 hours at 280°F. obtained an average value from fourteen laboratories of 0.5% for naphtha insolubles.

Barnard⁽¹²⁾ in a 50-hour test, at 240°F., on a Chevrolet test engine, on an inhibited S.A.E. 30 oil of 100 Viscosity Index, obtained maximum naphtha insolubles of 1.59%.

Davis and co-workers⁽²⁷⁾ in a 36-hour test, at 280°F., on the Chevrolet test engine, on an inhibited S.A.E. 30 oil of 101 Viscosity Index, obtained no increase in the per cent petroleum naphtha insolubles over the naphtha insoluble content prior to testing. Using a S.A.E. 30 oil, Viscosity Index of 98, and containing no inhibitor, under the same conditions, Davis obtained no increase in naphtha insolubles until 36 hours of testing had been accomplished. Then the rate of oxidation accelerated rapidly. Davis further concluded that oil oxidation in crankcases has three periods: (1) an initial period of slow oxidation; (2) a period of rapid oxidation, and (3) a period where oxidation continues at a relatively high rate.

The graphical plots shown by the above mentioned investigators follow the same trend as Figures IV and V.

From the low maximum value of naphtha insolubles obtained in this investigation, it is evident that excessive oil oxidation was not realized. It is possible that only the first period mentioned by Davis--that of slow oxidation--was realized in the tests. The inhibitor in the test oil may be extremely effective in decreasing oxidation.

The test oil is a heavy solvent-refined oil, the effect of which would be the removal of many of the sludge forming characteristics of the oil. The refining process would also remove some of the natural oxidation inhibitors of the oil. The addition of an oxidation inhibitor, however, would increase the oxidation resistance of the oil, either by decreasing the rate of oxidation or by lengthening the time before oxidation started.

Chloroform Insolubles. The chloroform selectively removes the oil and the oxygenated compounds termed asphaltenes or chloroform solubles formed during the oxidation of the oil (26)(27). The sludge remaining in the filter medium after treatment with chloroform is composed of the extrinsic materials--lead halides, metal particles, dirt, dust, and carbon from the combustion zone.

The graphical plots of the per cent chloroform insolubles are presented in Figures VI and VII. These plots follow closely the plots for petroleum naphtha insolubles.

Values of per cent chloroform insolubles increase from 0.039% for the test oil prior to testing to 0.175% for the 32 hour, 270°F. test run. Davis⁽²⁶⁾ found that heavily oxidized S.A.E. 30 oils gave chloroform insolubles averaging 2.27%. He further found that oils giving a low value for chloroform insolubles--0.07%--have no peptizing value. That is, the insoluble materials are precipitated in the engine as fast as they are formed, thus giving a relatively dirty engine. In this investigation, however, a low chloroform insoluble value was realized, but the engine crankcase floor and walls were not dirty. Therefore, it could be concluded that excessive oil oxidation was not realized in this investigation. The reasons as expounded for the lack of oil oxidation as given previously for petroleum naphtha insolubles would apply here also.

Asphaltic Resins. By subtracting the per cent chloroform insolubles (measure of extrinsic materials) from the per cent naphtha insolubles (measure of extrinsic materials, plus oxidized products) the oxygenated resins or products of the oil oxidation are obtained⁽²⁶⁾⁽²⁷⁾. The values obtained from the tests are plotted in Figure VIII. The 8-hour plot shows no increase in oxidized products formed from 120°F. to 300°F. The 16-hour plot

shows an increase from 0.056% for 120°F. to 0.058% for 270°F., a negligible increase. The 24-hour plot shows a very gradual increase from 0.06% to 0.088% for 270°F. The 300°F. run at 24 hours gave an asphaltene value of 0.145%. The 270°F. run at 32-hours duration resulted in an asphaltene value of 0.187%.

Barnard and co-workers⁽¹²⁾ in testing an inhibited S.A.E. 30 oil in a Chevrolet test engine at 280°F. for 36 hours obtained a maximum asphaltene value of 0.81%. Georgi⁽⁴⁰⁾ in testing an inhibited S.A.E. 30 oil, Viscosity Index of 100, in a Chevrolet test engine for 36 hours at 280°F. obtained an average asphaltene value of 0.1%.

Comparing the values obtained in this investigation with the above figures, it would appear evident that very little oxidation occurred in the test runs up to and including the 24-hour, 270°F. runs. However, the greater values for the 24-hour, 300°F. test run, and the 32-hour, 270°F. test run, would indicate that some oxidation of the test oil was beginning to take place in those two test runs.

However, in the plotting of Figure VIII it will be noted that the high value for the 300°F., 24-hour run, has been shown, but the curve was drawn as a straight line

function. This was done because with only one value, it was difficult to ascertain whether or not there was a sharp increase in the direction of the curve due to an increased resinous content from the oil oxidation or due to experimental error.

Viscosity. The oxidation of lubricating oil effects changes in the characteristics of the oil because of the presence of oxidation products⁽¹²⁾⁽²⁷⁾⁽⁷⁰⁾. One of the important changes is in viscosity, which according to Pomeroy⁽⁷⁰⁾ and Davis⁽²⁷⁾ is the most important of the physical tests. Davis further states that it is an excellent measure of the extent of oil oxidation. This is an accurate statement when viewed from the results of this investigation. The viscosity in Saybolt seconds is plotted in Figure III. The plots fall in the same general pattern of increase as do the curves for naphtha insolubles and for chloroform insolubles. The viscosity increased from 76.0 seconds for a new test oil to a maximum of 84.6 seconds for the 270°F., 32-hour run. The viscosity value for the 300°F., 24-hour test was only 58.8 seconds. This is obviously incorrect, but can be explained as follows: during the test run (one of three runs in which gravity fuel feed was used) excess gasoline

ran into the carburetor during one of the short stoppage periods which occurred due to mechanical difficulties. Fuel dilution of the oil decreased the viscosity.

Davis and co-workers⁽²⁷⁾ in testing an inhibited S.A.E. 30 oil, Viscosity Index of 101, in a Chevrolet test engine for 36 hours at 230°F. obtained a viscosity increase of 63 seconds to 200 seconds. Further testing on another inhibited S.A.E. 30 oil, Viscosity Index of 92, resulted in a negligible viscosity increase until after 36 hours of testing. A third test oil gave an increase of 60 seconds to 90 seconds in the Chevrolet test engine at 36 hours and 230°F. Additional time of testing resulted in a sharp increase of viscosity. The graphical plots for the above tests for 36 hours resemble the plots in Figure III.

From consideration of the above values it would appear that excessive oil oxidation did not occur in the investigation, but if additional time of testing had been allowed, sharp increases in viscosity would have been noted.

Engine Condition at End of Run. The results of observed engine condition at the end of each test run are given in Table X. The rating was made in an attempt

to correlate the engine condition at the completion of the test with the results determined by analysis of the used oil. At low test temperatures where oxidation is negligible, it would be expected to find a clean engine. As test temperatures increased, oxidation would increase, resulting in greater oil sludge formation with corresponding dirtier engines. The results in Table X are not correlative to an exact degree, that is they are not of a regular increasing order of magnitude with respect to increasing temperature and time of runs.

The engine crankcase appearance was the same at the end of all of the tests as at the beginning with respect to varnish or sludge deposits. Either the oil was not being heavily oxidized, or it had an excellent peptizing ability--the ability to keep sludge material in suspension.

The condition of the piston, with respect to carbon and varnish formation, showed some changes with respect to temperature and time. The formation of hard carbon particles on top of the piston generally increased in amount as the temperatures of the tests were increased. The test at 120°F. and 24 hours was given a rating of 3 in the numerical scale. The 270°F., 24-hour test was given a rating of 5, showing an increase in carbon formation.

This carbon formation resulted mainly from the pyrolysis of the oil which worked up from the crankcase past the piston rings. Some formation of the carbon would also occur from incomplete combustion of the gasoline in the combustion chamber. However, CO_2 content of the exhaust gases for all test runs varied within the limits of $7.5 \pm 1\%$. From this it would be expected that carbon formation from the gasoline would remain fairly constant. Any increase in carbon formation during test runs would come from the pyrolysis or decomposition of the test oil at the high piston temperatures.

Carbon formation in the ring grooves and varnish stain on the piston skirts followed in general the same trend as the carbon formation on top of the piston. At the higher test temperatures the carbon and varnish formations were heavier than at the lower temperatures. The carbon formation was heaviest in all tests in the top ring groove. Keyser and Miller⁽⁵⁰⁾ state that the temperature of the top piston ring will average 100°F . higher than that of the bottom ring. A higher temperature would result in an increase of oil decomposition.

In all tests except the 300°F ., 24-hour test, and the 270°F ., 32-hour test, the rings were clean and movable,

even though carbon was deposited in the piston ring grooves. In the 300°F., 24-hour test, the oil ring was stuck, and the two compression rings were clean and movable. In the 270°F., 32-hour test, the two compression rings were stuck and the oil ring was clean and movable. Sticking of these rings was caused by excessive hard carbon deposits in the piston ring grooves, resulting from deterioration or decomposition of the oil and incomplete combustion of the fuel.

In general, there was not enough deviation between each set of runs as regarding time and temperature to properly evaluate the oxidation properties of the oil. However, it was possible to see some distinct differences between a high temperature test and a low temperature test.

Immersion Heater. The immersion heater was constructed of copper. Larsen and Armfield⁽⁵³⁾ state that copper ranks next to iron as a catalyst in the oxidation of the test oil. In this investigation, results of oil oxidation (neutralization number, viscosity, and insolubles) increased gradually as time and temperature of testing increased. It would be gained from this that the catalytic effect of the copper or iron was constant or negligible. However, in the test runs on crankcase oil at the temperatures above 120°F., the heater, at the com-

pletion of each test, was highly coated with a hard bottom layer of carbon and a soft top layer of carbon. This indicated that oil decomposition had taken place in the area surrounding the heater. No apparent effects of this decomposition were noted in the analysis of the test oils, since no abrupt changes of values were obtained in any property of the oil. If longer tests had been conducted, these decomposition products may have had a serious effect on the amount of carbon contained in the sludge.

Recommendations

In view of the failure of this investigation to obtain a high rate of oil oxidation under the accelerated test conditions used, it is suggested that tests be conducted on the test unit at more elevated temperatures than used in the investigation (within 20°F. of the test oil flash point). A modification of the oil system should be made to permit tests for 36-hour duration to correspond to the time of the standard Chevrolet engine test for oil oxidation.

Copper-lead bearings are more susceptible to corrosion from oil oxidation products than babbitt bearings⁽³⁶⁾. Many internal-combustion engines operating under heavy loads employ high-strength alloy bearings such as copper-lead⁽⁴⁾. Better correlation of bearing weight losses may result when the high loss due to wiping, as evidenced by the use of the softer babbitt bearings, is eliminated.

Luderman⁽⁵⁸⁾ states that in the determination of sludge in an used oil, the solvents, isopentane, n-pentane, and n-heptane, all precipitate greater amounts of sludge than does petroleum naphtha. He also found that benzene extracted more of the resinous materials from the oil-

sludge mixture than did chloroform. Investigation should be made as to the possible use of the above mentioned solvents for sludge analysis, since standard procedure (A.S.T.M. Standards⁽¹¹⁾) are available for the petroleum naphtha and chloroform only.

Generally accepted tests in the Caterpillar series of tests on detergency and ring-sticking properties of oil involve oil temperatures of 230°F., engine jacket temperatures of 200°F., and test times ranging from 120 to 500 hours. An accelerated detergency and ring-sticking test may be developed on the Delco test unit by increasing the engine jacket temperature materially over the normal jacket temperature.

Limitations

Three major limitations were evident in this investigation. The length of test runs was limited to 32 hours--oil consumption approached 50% preventing further testing because of inadequate lubrication. Test temperatures of 300°F. was the maximum temperature achieved with the use of the 2 Kw. crankcase immersion heater. Highest possible load on the engine-generator set was only 70.5% of its rated capacity.

V. CONCLUSIONS

From the tests made on the Model 850, Delco Light Unit, operating at 980 ± 10 r.p.m., with a generator load of no load, and loaded to 70.5% of rated capacity; using Esso Motor Oil No. 3 as a test oil under test conditions of 120° , 170° , 210° , 240° , 270° , and 300°F. for 8, 16, and 24 hours duration; the following may be concluded:

1. The neutralization number increased from a minimum of 0.045 for a new test oil to a maximum of 0.375 for the 300°F. , 24-hour test.

2. The viscosity in Saybolt seconds increased from a minimum of 76 seconds for a new test oil to a maximum of 84.6 seconds for the 270°F. , 32-hour test.

3. The per cent naphtha insolubles increased from a minimum of 0.068% for the new test oil to a maximum of 0.362% for the 270°F. , 32-hour test.

4. The per cent chloroform insolubles increased from a minimum of 0.039% for the new test oil to a maximum of 0.175 for the 270°F. , 32-hour test.

5. The per cent asphaltic resins increased from a minimum of 0.029% for the new test oil to a maximum of 0.187% for the 270°F. , 32-hour test.

6. The used test oil values for neutralization number, viscosity, per cent naphtha insolubles, per cent

chloroform insolubles, and per cent asphaltic resins were indicative of the progress of oxidation of the oil in the test unit.

7. No correlation could be found between bearing weight loss and operating conditions of time, temperature, and load as evidenced by the erratic results in the following sample runs: In the tests at 120°F., full load, the bearing weight losses were 0.0767 gms. for the 8-hour test; 0.0941 gms. for the 16-hour test; and 0.0745 gms. for the 24-hour test. Bearing weight losses in the 270°F., full load tests were 0.0843 gms. for 8 hours; 0.2180 gms. for 16 hours; 0.2022 gms. for 24 hours; and 0.1223 gms. for 32 hours.

8. Using the numerical rating scale (lowest figure indicating least carbon and varnish formation) to evaluate the general appearance of the test engine at the end of the test runs, the least severe conditions (120°F., 8 hours, 600 watts) resulted in an average value of one, while the most severe conditions (270°F., 32 hours, 600 watts) resulted in an average value of six.

VI. SUMMARY

THE EVALUATION OF A ONE-CYLINDER DELCO GASOLINE
ENGINE AS AN ACCELERATED LUBRICATING OIL TEST UNIT

Many laboratory engine oil test units varying from single cylinder to multicylinder engines exist. Tests conducted on these units employ a wide range of oil temperatures and duration of tests, and give a wide range of results. The purpose of this investigation was to develop a one-cylinder gasoline engine capable of manipulation so that it can accurately test a lubricating oil for tendency to oxidation and bearing corrosion under accelerated test conditions.

The test engine used was a Model 850, Delco Light Unit, using Delco replacement test bearings, pistons, and piston rings. A G. E. 2 Kw. crankcase immersion heater with thermostatic control supplied the heat for the elevated temperature runs. Twenty-two tests were conducted on Esso Motor Oil No. 3; with the test engine operating at 980 ± 10 r.p.m., under a generator load of no load and loaded to 70.5% of rated capacity; and at test conditions of 120° , 170° , 210° , 240° , 270° , and 300°F . for 8, 16, and 24 hours duration.

The changes in the lubricating properties of the oil were determined by a study of the results of the oil oxidation. Values were obtained for the neutralization number, Saybolt viscosity, sludge content (petroleum naphtha insolubles, chloroform insolubles, per cent asphaltic resins), and bearing weight loss of each test oil. The neutralization number increased from a minimum value of 0.045 for the new test oil to a maximum of 0.375 for high temperature tests. An increase to 84.6 seconds from 76.0 seconds was noted in viscosity tests. The petroleum naphtha insolubles increased from a minimum of 0.068% to a maximum of 0.362%. Chloroform insolubles increased from 0.039% to 0.175%, and asphaltic resins increased from 0.029% to 0.187%. Bearing weight losses were highly erratic for all tests and no correlation could be found between it and operating conditions of time, temperature, and load.

Rating of engine condition at the completion of test runs resulted in a general rating of one (least carbon deposits) for the low temperature tests and a rating of six for high temperature tests.

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