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U. S. A R M Y
TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

TRECOM TECHNICAL REPORT 63-55 ✓

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INVESTIGATION OF THE FEASIBILITY
OF AN AIRCRAFT-OIL ANALYSIS SYSTEM
FOR OPERATIONAL USE IN THE FIELD,

PHASE II,

17

Task 1D141812D18423

(Formerly Task 9M89-02-015-23)

15

Contract DA 44-177-TC-789

November 1963

prepared by:

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KAMAN NUCLEAR
Colorado Springs, Colorado

JAN 30 1964

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HEADQUARTERS
U S ARMY TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

This report has been prepared by Kaman Nuclear, a division of Kaman Aircraft Corporation, under the terms of Contract DA 44-177-TC-789.

This contract called for feasibility and design studies that would lead to the development of the most desirable lubricating-oil analysis technique for use with Army aircraft in the field. The investigations conducted included a feasibility and design study of field equipment for the analysis of metal content in lubricating oil, a statistical study of the R1820-86 engine oil analysis data to prove the merits of the oil analysis program, and feasibility and design studies of an in-flight warning device for aircraft lubricating systems.

The conclusions and recommendations set forth in this report are concurred in by this Command.

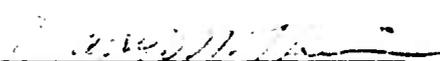
It is anticipated that controlled experiments will be conducted in-house during FY 1964 to accumulate comprehensive oil analysis data immediately preceding component failure, in an endeavor to establish accurate prediction of time of failure.


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Task 1D141812D 18423
(Formerly Task 9M89-02-015-23)
Contract DA 44-177-TC-789
TRECOT Technical Report 63-55
November, 1963

INVESTIGATION OF THE FEASIBILITY
OF AN AIRCRAFT-OIL ANALYSIS SYSTEM
FOR OPERATIONAL USE IN THE FIELD

PHASE II

Report Number KN-676-2 (FR)

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FOREWORD

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This report was written by Vernon Peckham, Phil Jessen and Richard Vogel, of Kaman Nuclear. The work reported was performed during the period starting July 31, 1962 and ending May 31, 1963. Previous reports on work performed on this contract include monthly progress letter reports.

This work was a sequel to that performed during the first five months of 1962 under Phase I of the contract. The previous effort was reported in TCREC Technical Report 62-91 of 1 May 1963 entitled, "Investigation of the Feasibility of an Aircraft-Oil Analysis System for Operational Use in the Field", Phase I.

Acknowledgement is made of the assistance of the personnel of the Overhaul and Repair Base, U. S. Navy, Pensacola, Florida, for providing oil analysis data and oil samples. Mr. Leonard Bartone and Lt. L. Remillard, both of USATRECOM, gave many helpful suggestions in regard to the work and also assisted in procuring oil samples.

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SUMMARY

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Atomic absorption spectrometry and neutron activation analysis were chosen from the many methods available as the best for possible development into field measurement equipment for the analysis of metal content in oil. The spectrometry method appears to be the more suitable of the two using present-day techniques.

Statistical studies of the R1820-86 engine oil analysis data were continued and showed that further work on evaluation of the data is needed in order to prove the merits of the oil analysis program.

An experimental in-flight detector was designed. Further work is needed to improve the temperature stability of the circuit. Actual running tests are needed to prove its application and usefulness as in in-flight warning device.
↗

CONCLUSIONS

Since the contract work was directed principally in the two areas of equipment and data analysis, the conclusions arising from completion of the work are likewise separated. In a manner of speaking, the work on statistical data was aimed at proving the need for equipment, but as is pointed out in the following paragraph, the need was not emphasized or diminished as a result of the statistical studies.

The statistical studies of the R1820-86 did not prove that oil analysis is a good or a bad method of detecting incipient failure in aircraft engines. The principal reason for the lack of assignment of worth to the method is what may be called the missing "controlled experiment" in obtaining data and relating the data to engine condition. In attempting to determine the reliability of an experiment, an examination of the experimental techniques used must show that no factors are entering in which will cause the results to be in error. Such an examination was not possible prior to the statistical studies performed under this contract, so the results must be regarded with skepticism but only because the initial data available are in doubt.

The work on evaluation of equipment for oil analysis work in the field showed that the atomic absorption spectrometer is the best available method using present-day techniques. This method has only the principal drawback of an inability to detect aluminum, which may be important for some types of lubricated mechanisms. Portability and facility of measurement are easily obtained with the equipment necessary for this method. By using automatic referencing circuits, a spectrometer can be made which requires less than 15 minutes for an analysis of five to six elements in one oil sample.

RECOMMENDATIONS

Since the benefits to be gained from a successful oil analysis program are great both in terms of economics and, in the extreme, of human lives, it is recommended that further effort be directed toward the study of existing oil analysis data and the accumulation of new data. The principal necessity for the studies is the establishment of a set of conditions with regard to metal content or trends which will allow a more reliable estimate of engine condition. In the accumulation of data in the future, it is recommended that controlled experiments be run with engines containing known defects so that definite relationships between metal content and faulty parts can be established.

The continuation of an oil analysis program at the first or second echelon of maintenance will require the use of a field measurement system as outlined in this report. It is recommended that the equipment be developed and tested in field use as the next step in the program.

The experimental in-flight detector should be tested in controlled experiments in the field. Further work should be considered on the in-flight circuit, with the end purpose of developing a temperature-stable prototype.

DISCUSSION

INTRODUCTION

The background of the need for an oil analysis program will be briefly stated here for the benefit of readers not previously familiar with the program.

The overhaul of aircraft engines and other components at specified time intervals is a long-standing practice. It has been recognized that the efficiency of this method is not high because of the large percentage of overhauls on components which display no discrepancies when disassembled. It is then evident that the overhaul procedure would become more efficient if a reliable system for detecting incipient failure could be devised. The effectiveness of the system would be apparent by the lengthened overhaul lifetime. The added bonus of removing components from service which have discrepancies before those discrepancies cause a disaster is an outcome which in itself makes the system worthwhile.

Of the several techniques envisioned as holding incipient failure detection possibilities, oil analysis was considered to be the most promising. Over a period of years, the use of filters in lubricating oil systems in engines had become standard. The filters served to remove from the oil, particles which would disrupt engine operation by causing excessive wear, if not direct stoppage. After some experience, it became evident that the amount of metal particles trapped by the filters could be directly correlated to engine wear or parts breakdown. It was also seen that the malfunction was in a highly progressive state before the particles appeared of sufficient size to be trapped by a filter. To investigate the relationship between metal particles in oil and engine condition for the advantage of detecting incipient failure, oil analysis programs were initiated. The U. S. Army established an oil analysis laboratory at Ft. Rucker, Alabama, and the U. S. Navy placed a similar facility in operation at Naval Air Station, Pensacola, Florida. Various civilian agencies, such as the Denver and Rio Grande Western Railroad Co., also established oil analysis laboratories.

After the oil analysis laboratories had been in operation for a time, it was decided that if field facilities were available, the usefulness of the program would be considerably improved because of the inability of one base facility to serve a continental and intercontinental service using thousands of aircraft. An outcome of this decision was the need for a feasibility study of chemical and physical analysis equipment for application to field use; the work on this contract served to that end.

The purpose of the work reported herein was two-fold in nature. Primary was the experimental investigation of oil analysis techniques which might be applied in the development of in-the-field equipment to be used in the Army aviation maintenance programs at the first and second echelons. A secondary objective was the design of an experimental in-flight system intended to give a continual indication of gross oil contamination.

The prelude to this program was a 5-month effort which was Phase I of the contract. During Phase I, data were accumulated from oil analysis laboratories for the purpose of performing statistical analyses on wear rate and on threshold values of metal contamination in oil from aircraft power mechanisms. The collected data were tabulated on IBM cards and analyzed with the help of an IBM-1620 data processing system. The outcome of the statistical portion of Phase I was a set of data related to the confidence with which one can view the results of oil analysis using set threshold values. Reasonable confidence was shown for copper, silver, aluminum, chromium and iron as engine condition indicators. Any metal, when treated as a unit, and sums of metals failed to give a good confidence number. In addition to the data analysis, a study was made of the various methods and apparatus which could be used to measure oil contamination. The purpose was that of determining those systems which might be feasible for aircraft maintenance at the first and second echelons. The techniques studied included vapor phase (chromatography, flame spectrophotometry (emission and absorption), radio frequency mass spectrometry, time-of-flight mass spectrometry, and neutron activation analysis. The outcome of this work was a recommendation that the techniques of absorption spectrometry and neutron

activation analysis be further investigated since they were deemed to hold the most promise for an analytical device which could be adapted to field use.

As further effort during Phase I, the groundwork was laid for the design of an experimental in-flight system. Calculations were made of the sensitivity of a pickup coil to metal particles in the coils inductive field.

Proceeding from the work of Phase I, Phase II commenced with experimental investigations of the two analysis methods as selected. Further statistical studies were completed and the experimental in-flight device was designed and constructed. The following sections are a report of the work and outcomes in these areas.

OIL ANALYSIS TECHNIQUES

As stated in the introduction, two systems — atomic absorption spectrometry and neutron activation analysis — were selected from the many considered during Phase I for further experimental investigation with the end purpose of determining their adaptability to field use. Both techniques were studied and used experimentally to the extent possible in evaluation of their possibilities. This section is devoted to a report of the work accomplished and experimental results along with estimates of field-use system complexity based on available technology.

1. Atomic Absorption Spectrometry

Atomic absorption spectrometry is based on the principle that atoms in the ground state absorb light at frequencies which are characteristically emitted by those same atoms when in an excited or ionized state. Research and development in this field has been under way for many years, and considerable information is available in literature on the basic principles and relative usefulness of the method in detecting various elements.¹ Very little, if any, of the previous reported work has been directed toward the use of atomic absorption as a tool for use in the field. Other types of spectrometry, however, have been used in

portable laboratories under severe field conditions, so the extension of available techniques in absorption to the Army maintenance problem seemed to offer no difficulties.

Basically, the equipment needed for a measurement setup consists of a light source, an optical lens arrangement, an atomizer-burner, and a monochromator with photomultiplier amplifier at the output. The light source is special in that it is a gas-filled discharge tube with a hollow cathode. The cathode is lined with the high-purity metal which is to be analyzed and emits strong spectral lines characteristic of that metal when voltage is applied and discharge initiated. For the use of ultraviolet lines, the lamp is constructed with a high-transmittance quartz window at the end. The light from the lamp is passed through the flame of the atomizer-burners and on to the input slit of the monochromator. The monochromator is adjusted to the correct wavelength, and amplitude of the spectral line is read out as a voltage from the photomultiplier tube. Figure 1 is a sketch of the basic setup just described and illustrates the light paths in better detail.

The purpose of the atomizer-burner is that of obtaining disassociated atoms of the element to be analyzed from the sample carrying the atoms. In the typical unit, the atomizer sprays the solution into the flame in very fine droplets. The flame raises the temperature high enough so that the solute is vaporized and the metallic atoms are disassociated from their chemically attached ions of the solution.

Since the path of the light from the hollow-cathode sources is in the flame, the number of atoms present which are absorbing the light is reflected in the output of the monochromator by a proportionately lower voltage. The output indicator can be calibrated in terms of percent absorption or, as might be more practical in this case, in parts per million (ppm) of contaminant in the sample.

The work completed in the evaluation of atomic absorption spectrometry consisted of experimental determination of sensitivities of five elements of

pertinent interest in water solutions, oil sample testing, effects of metal particles on results, and the initial design of a semiautomatic system for use in the field.

The atomic-absorption spectrometer purchased for evaluation was the Jarrell-Ash Company Model #82-010 Ebert Spectrometer. This instrument is equipped with 25 micron entrance and exit slits manual wavelength adjustment, multipass flame attachment, and a Beckman triple-burner flame unit. All components are mounted on a rigid bar to ensure proper alignment. Five hollow cathode lamps (iron, copper, nickel, chromium and magnesium) were obtained for the experiments as being representative of metals normally found in contaminated oil.

The results of analysis of water solutions of iron, copper, nickel and magnesium can be seen in Figures 2, 3, 4 and 5, respectively. The apparent sensitivity of the method to these elements is:

<u>Element</u>	<u>Sensitivity in PPM</u>
Iron	2
Copper	1
Nickel	1-2
Magnesium	1

Chromium is not listed in the sensitivity table because it apparently requires a more sensitive amplifier circuit in the output than was available for these tests. Previous reports indicate difficulty in the detection of chromium². It should also be noted that the same workers report sensitivities to the elements listed above one order of magnitude better. That is, in laboratories using especially calibrated and referenced measurements, it is not uncommon to measure as low as 0.1 ppm concentrations of iron, copper and nickel with 2 to 3 percent accuracy. Such sensitivities are not necessary in oil analysis work because the danger level or thresholds normally run from 8 to 35 ppm depending on the type of metal or engine. Reliable sensitivities of 1 to 5 ppm for most metals will provide sufficiently accurate oil analyses.

Following the testing of water solutions, oil samples obtained from Ft. Rucker, Alabama, and NAS, Pensacola, were tested. Twenty-four samples containing various amounts of contaminants were first diluted with xylene to decrease viscosity so that proper atomization would occur in the Beckman burner. The oil samples as received had been previously tested by the service Oil Analysis Laboratories so that calibration and cross-check information was available. The results of analyzing the oil samples are shown in Figures 6, 7, 8, and 9. The curves show the output voltage measured versus the metal content as observed by the service measurements. For the most part, good correlation is observed between voltage readings and contamination level. An exception to this is magnesium, as seen in Figure 9. The scattered observations here are believed to be due to the presence of aluminum which is found in some quantity in most samples. The influence of aluminum on the determination of magnesium has been used by some researchers as a method of detecting aluminum, which is not detectable in atomic absorption using normal methods. Since magnesium and aluminum are used in the construction of some engines, simplified measurements of oil from these engines are not readily obtained.

The application of atomic absorption spectrometry to oil analysis in the field places the following requirements on the equipment:

1. It must be portable and self contained, with immunity to environmental conditions.
2. Simplicity of operation and calibration must be such as to require only a basically trained operator.
3. The complete analysis of a sample for its metal content must take a minimum of time. Fifteen minutes or less is preferred.
4. Reliability of indication must be kept at a high level.

With the above-listed points in mind, a preliminary feasibility model of an atomic absorption spectrometer for field use was designed. Although the system has not been developed or proven as such, the intent of the design was principally to show that with existing techniques and components the device would be feasible. A functional layout of the field spectrometer is shown in Figure 10. Referring to the diagram, operations for a sample analysis would be as follows:

The sample is introduced into metering pump, P₁. The pump injects a given volume of sample into a magnetic stirring unit, M₁. Metering pump P₂ injects a controlled volume of solvent, the purpose of which is to adjust the viscosity of the sample prior to atomization in the burner. Mixing is carried on for a few seconds to assure a uniform solution. The mixture is then transferred to the metering pump, P₃, which transfers a controlled volume to the burner aspiration cup, C₁. Metering pump, P₄, injects a controlled volume of a known standard into C₁, mixing in the cup being forced by a magnetic mixer, M₂.

The spectrophotometer described herein (see Figure 10) utilizes six hollow cathode lamps (L1 through L6). Each of these lamps emanates a specific wavelength of light which is suitable for detection of one of the desired elements (copper, silver, nickel, chromium, iron and the known standard). The lamps are disposed radially with their light outputs being directed toward a common point. A quartz prism, Q1, is placed at this common point. The prism is rotated at a constant velocity, so that light is successively selected from each of the six lamps. The prism directs the light output from each lamp along a common path through the flame generated by burner B1. The burner is fired by an oxygen acetylene mixture. The burner aspirates the prepared sample from the aspiration cup, C1. The light from the lamps passes through the flame, and the light from each lamp is absorbed by an amount proportional to the concentration of the kind of atoms

having the characteristic wavelength equal to that of the lamp radiation.

A second rotating prism, Q2, is mechanically coupled to prism Q1. Q2 is used to direct the light that passes through the flame through a filter (or grating), G1 through G6, which passes only the light from the lamp at which prism Q1 is aimed. This filter prevents light from the flame from impinging on the light detector. A mirror system directs the light from any of the gratings to a single photomultiplier light detector.

The lamps are energized by a 480 cycle per second alternating current. This causes their light output to be modulated at this frequency. The electrical output of the photomultiplier is passed through a 480 cycle per second filter. Light interference from excited atoms, the flame light output, or any light leakage is thus eliminated, since all of these light sources are essentially constant (unmodulated) in nature.

The output from the filter is directed to a synchronous detector. The detector is synchronized with rotation of the prisms. The output for each lamp position is thus always directed to the same one of six output channels. Each of these six electrical outputs will represent relative concentration of one of the six elements. Since one of these is of known concentration, comparison of each of the other five outputs to the known output will yield concentration data for each of the five unknown elements.

The major variables that will effect system accuracy are: lamp output intensity, flame temperature and physical stability, and transfer function (gain) of the photomultiplier.

The lamps have been shown to be stable over relatively long periods.² Significant changes (due to lamp intensity change) in calibration would not be expected to occur more frequently than every 3 to 6 months in normal use.

The majority of flame variables are slow relative

to the rate at which the lamps are switched. Flame variability will affect the known in the same way it affects the unknowns (if the flame temperature is held above a known minimum). The method of comparison to a known sample thus effectively eliminates flame variability effects.

The same rationale as that for flame variability applied to photomultiplier variability. The variability in the photomultiplier is relatively slow. Since all of the light outputs are detected by the same photomultiplier, the known will be affected by the same ratio as would the unknowns, effectively eliminating photomultiplier variability.

The absorption spectrometer just described meets the requirements for portability because it would occupy a volume approximately 3 feet by 5 feet by 6 feet and would have a total weight near 400 pounds. These figures include the spectrometer with electronic power and gas supplies but do not include a primary source of power such as a motor-generator unit. A complete system would easily be transported by a small enclosed truck.

2. Neutron Activation Analysis

Neutron activation analysis was the second method chosen for detailed study of its potential application for performing oil analyses in the field. This method is based on the principle that neutron bombardment of various elements creates unstable isotopes which decay to a stable form, releasing particles or energy of various forms. By measuring the energy content of the decay particles, correlation can be made to a particular element; the number of particles released with a given energy is related to the number of atoms of the element which was radiated with neutrons.

Gamma radiation, in particular, is the most useful form of the decay products. For the problem of oil analysis, the elements of interest and the gamma energy associated with their activation are shown in Table 1. Also listed in Table 1 are relative figures of merit related to the sensitivity of the activation of the elements.

TABLE I
NEUTRON ACTIVATION ANALYSIS
REACTION PRODUCTS AND FIGURES OF MERIT FOR
OIL CONTAMINANTS

Element	Gamma Radiation Energy in Mev	Figure Of Merit*
Copper	0.51	540
Aluminum	0.84, 1.02	68
Silver	0.44, 0.62	510
Chromium	1.44	179
Iron	0.84, 1.81, 2.13	23
Tin	0.51	8
Nickel	0.025, 0.056	48

*The figure of merit is calculated from an approximate equation related to the radiation product half-life, percent abundance, sensitivity of the element to neutron reaction (σ), and parts per million threshold of the oil contaminant. This equation is

$$F \text{ of } M = \frac{(\text{PPM Threshold}) (\sigma) (\% \text{ Abundance})}{(\text{Product half-life})}$$

The equipment necessary for a neutron activation analysis system is shown in Figure 11. It includes a neutron generator with control unit and power supplies, a transfer system, and an output device. One of the principal advantages of this method is that no sample preparation would be necessary to run an analysis. The oil as removed from an engine would be placed in a polyethylene cup in a position close to the generator. After radiation, the transfer system moves the sample cup to the crystal detector, and the gamma rays emitted by the sample are counted and sorted with respect to energy and stored in a memory in the pulse height analyzer. The size and weight of the system are such that the system would easily fit on a small truck.

The operation of the neutron generator imposes a health hazard on nearby personnel; therefore, for any field system, consideration must be given to radiation

shielding. Several materials which will moderate high energy neutrons and lessen the hazard can be used; but for a transportable system, the bulk becomes appreciable. Distance is probably the best shield because the intensity reduces by a factor of the square of the distance from the source. As such, the system can be made so that the operator controls the measurements from a removable control panel at a distance from the truck. One hundred feet is a safe distance from an unshielded neutron generator with an output of 10^9 neutrons per second.

The evaluation of neutron activation analysis consisted of a series of experiments to determine first the activation spectra of the individual metal contaminants in small amounts and then the spectra of a combination of these metals in proportions likely to be found in a typical oil sample.

Data taken from the activation of copper, iron, chromium, and aluminum are shown in Figures 12, 13, 14 and 15, respectively. The data were taken using a generator with an output of approximately 8×10^8 neutrons per second, an irradiation time of 30 seconds, a transfer time of 30 seconds and a counting time from 4 to 10 minutes, depending on the half-life of the element radiated. Further experiments were run using samples containing known amounts of several contaminants. The results were not readily analyzed because the separation and identification of the contaminants from the data obtained were difficult. The interferences between the activations of several metals and carbon, silicon, and oxygen which occur naturally caused the output records to yield no significant data. There recently have been developed techniques for the reduction of the output data from activation which will separate the wanted from the interfering information. The use of the fact that most of the activated elements have different half-lives is one method which appears promising. Equipment is available which will permit oil analysis to be accomplished rapidly and accurately.

At the present time, a comparison of neutron activation analysis and absorption spectrometry shows that neutron activation analysis is a method which is more automatic and requires no sample preparation.

Atomic absorption cannot be used to detect aluminum, one of the more important condition indicators for some engines. Neutron activation analysis is more expensive, but the next few years will likely show a drop in costs because of new techniques now being developed.

STATISTICAL STUDY OF OIL ANALYSIS DATA

During Phase I, a study was made of oil analysis data taken at the Oil Analysis Laboratory, NAS, Pensacola, Florida. This study was continued during Phase II for the purpose of amplifying Phase I results and of examining the data in greater detail. The original data cards at Pensacola were photographed on microfilm for use at Colorado Springs and included oil analysis from many engine types. The R1820-86 engine used in the T-28 aircraft had been analyzed more thoroughly than the others, so it was selected for the study.

The engines were divided into three major groups and sequentially numbered within each group. The first group contained histories of engines which had records of no discrepancies, the second group contained histories of engines with discrepancies and the third group contained histories of engines which experienced catastrophic failures. Having been separated, the data were then punched on IBM cards in the following format:

<u>Card Columns</u>	<u>Information Contained</u>
1-2	Engine identification number.
5-7	Last three digits of the engine number.
11-16	Number of hours since last engine overhaul.
19-23	Decimal point in column 15. Number of hours since last oil change.
26-28	Decimal point in column 22. PPM of copper found in oil
31-33	Decimal point in column 28. PPM of silver found in oil.
36-38	Decimal point in column 32. PPM of nickel found in oil. Decimal point in column 38.

41-43	PPM of iron found in oil. Decimal point in column 43.
46-48	PPM of chromium found in oil. Decimal point in column 48.
51-53	PPM of silicon found in oil. Decimal point in column 53.
56-58	PPM of tin found in oil. Decimal point in column 58.
61-63	PPM of aluminum found in oil. Decimal point in column 63.
66-68	Identification number of oil analysis chart or sheet.
	Group 1 (no discrepancies) numbered 0-399
	Group 2 (discrepancies) numbered 600-999
	Group 3 (catastrophic failures) numbered 400-499
71-72	Sequential numbers of oil analysis within a card or sheet.

The analysis began with the evaluation of the current "U.S. Navy Threshold Values" of metal content in oil. We first asked: "Is the threshold value a good indicator in determining the condition of an aircraft engine, and how sensitive is this value?" Threshold values and the data were sorted by groups and by whether the ppm value was above or below the threshold values for each of the metals except silicon. Figures 16 through 22 contain these contingency tables. Examination of these tables indicated that the threshold values would not have detected the majority of the "bad" engines, groups 2 and 3, except in the case of nickel. However, even in this case, we would have had to overhaul the majority of the "good" engines, group 1, to detect the 58% of the faulty ones.

To digress for a moment, the economics of the oil analysis procedure must also be considered. For example, using the oil analysis Navy threshold value for copper, we would have detected 10.5% of the bad engines and needlessly overhauled 5.9% of the good engines. Whether or not the ability to detect as little as 10% of the bad engines is of value must be weighed against the objectives

of the program and the cost of needlessly examining the good engines. At any rate, these percentages are given in Figures 16 through 22 to aid in the evaluation of the Navy threshold concept. This preliminary examination raised the question of whether there even existed a threshold number based on oil analysis alone that could improve the detection of engine failure.

Frequency distributions in terms of percent of total count for each of the metals for groups based on ppm readings were constructed. See Figures 23 through 29. If high metal content in the oil is indicative of engine failure,* one would expect group 2 to have a large number of observations at high metal content and group 1 to have relatively few observations at high metal content. Examination of these frequency diagrams did not indicate a threshold number that would separate the groups; in fact, a statistical test ** indicated that no significant differences existed between the distribution of group 1 and the distribution of group 2 or group 3.

The possibility of the oil sample's containing two or more high metal readings as indicative of engine failure was investigated. A random selection of observations of aluminum versus iron was plotted (see Figure 30) and indicated no relationship to engine failure. Plots of the total sum of all the metal readings versus the three different groups also showed no relationship with engine failure.

At this point the variable time, hours since overhaul, was introduced. It was felt that possibly high amounts of metal were being deposited in the oil during the "break-in" period of the engine, and after this initial period high metal readings would be indicative

* Based primarily on the frequency of the oil analysis, one can only assume that a part failure would add metal to oil over a relatively long period of time.

** Chi Square Goodness of Fit Test.

of engine failure. The metal content for each of the groups was averaged over 25 hour intervals and graphed. Figures 31, 32, and 33 show graphs of iron, nickel and copper. The graphs of iron and copper show a general decrease of metal content with time after overhaul, which was anticipated; but, unfortunately, groups 2 and 3 did not appear to differ significantly from group 1. Hence, the introduction of the variable time did not help to separate the "good" engines from the "bad" ones.

The last investigation dealt with the calculation of wear rate and time to failure. It was suggested that the wear rate could be computed from the rate at which the metal was being deposited in the oil, and from this rate the time to threshold or failure could be calculated. Between each oil analysis, the rate of metal increase, only if it increased (increase in metal content between oil changes divided by the time between oil changes), and the time it would take to reach the Navy threshold number were computed. The time to failure is computed from the following equation:

$$H = \frac{(T - P_2) \Delta h}{P_2 - P_1}$$

where

H is the hours to failure
T is the threshold level
P₁ is ppm before P₂
P₂ is ppm reading
Δh is hours of engine operation between
P₁ and P₂

Cumulative frequency diagrams of time to failure by groups are plotted and appear in Figures 4 and 5. It was hoped that the "bad" engines, groups 2 and 3, would show large frequencies for short time to failure and that the "good" engines, group 1, would have longer times to failure, but this was not found to be true.

Before strong conclusions are made concerning the outcome of this study on oil analysis, the variabilities

of the original data must be investigated. With few exceptions, very little information was found on data cards regarding engine condition at the time of overhaul. Although an attempt was made to correlate the notes on the cards with the condition of the engines' oil-wetted parts, it cannot be said with certainty that even fair results were obtained when engines were labeled as either "good" or "bad". As a result, the outcome of the statistical work must be downgraded in its true worth insofar as establishing the merits of oil analysis as an incipient failure detection method is concerned.

EXPERIMENTAL IN-FLIGHT DETECTOR

The purpose of the development work on an experimental in-flight detector was that of establishing the feasibility of monitoring continuously the metal particle content of an engine as a supplement to ground-based maintenance procedures. An in-flight detector would be of value in giving an early warning of an incipient failure. In most aircraft lubrication systems in use today, magnetic chip detectors are installed to give an indication of the heavy build-up of metal (iron) particles in the oil. These detectors do not give a linear indication of the build-up, nor will they provide warning of a severe malfunction until just seconds before the engine stops operating. The experimental in-flight detector is intended to give a linear output related to metal content (principally iron) in the oil so that, in many cases, 15 to 30 minutes of time will be gained before engine wrap-up.

The circuit of the experimental in-flight detector is shown in Figure 36. It utilizes a grid-quenched superregenerative oscillator, the feedback of which is controlled by the detector coil inductance. The detector coil is tuned to a frequency slightly lower than the oscillator frequency. Particles of iron in the near vicinity of the coil cause the detector impedance to decrease; hence more feedback is available to the oscillator and the output voltage increases.

The superregeneration is achieved by applying a square wave to the grid of the oscillator tube, 6CW4, alternately raising and lowering the gain of the tube. When the grid voltage is high, the tube starts to oscillate, the output rising exponentially from the circuit noise level. After reaching a detectable nonsaturated level, the gain of the tube is reduced to zero and the output declines exponentially. The amplitude of the oscillator output is proportional to the oil contamination level. A free-running multivibrator supplies the grid quenching waveform.

The oscillator output is envelope-detected, amplified, filtered and stretched to give a direct current at the output terminals. A meter across the output will read approximately 5 volts for a contamination level of iron of 500 ppm. The nominal no-contamination level is approximately 0.5 volt.

Packaging of the circuit hinged on the use of printed circuit boards for the majority of interconnections. Two boards were made, one holding the power supply and the other the principal circuitry.

A slotted container was made to hold the printed circuit boards' external power supply connections, detector cable and output meter connections.

The development of this configuration was straightforward and offered no difficult design problems. Of particular interest is the excellent mechanical stability achieved with this packaging method. Although not required for this experimental model, the circuit lends itself to mechanical stability through the use of plotting in the internal spaces of the package. The temperature stability of the circuit is not good at this stage of development. It is expected that future development will improve this feature.

BIBLIOGRAPHY

1. Analytical Chemistry, Vol. 34 No. 5, American Chemical Society. April 1962.
2. Elwell, W. T. and Gidley, J. A. F., Atomic Absorption Spectrophotometry, The Macmillan Co., New York 1962.

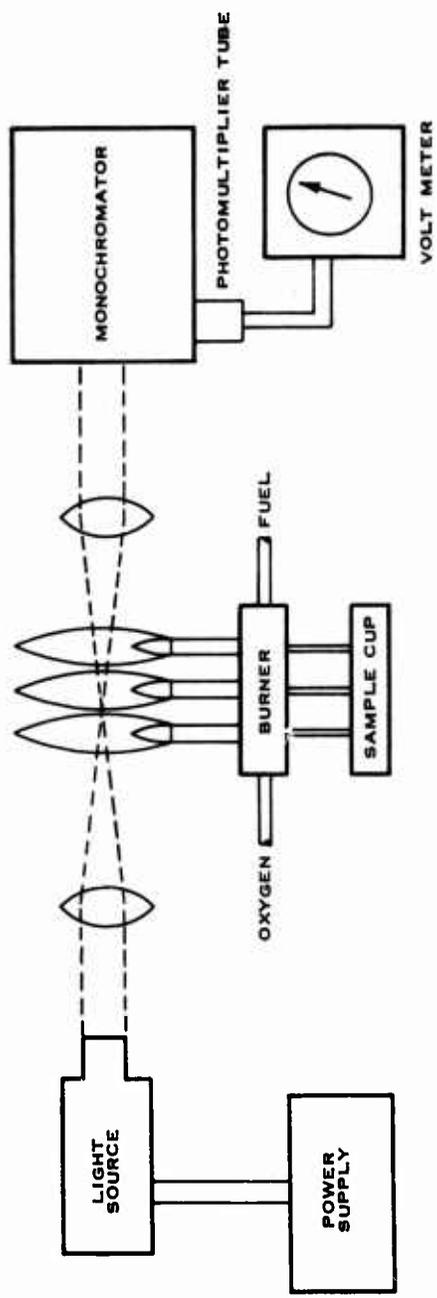


FIGURE 1
ATOMIC ABSORPTION SPECTROMETER
BASIC EQUIPMENT SETUP

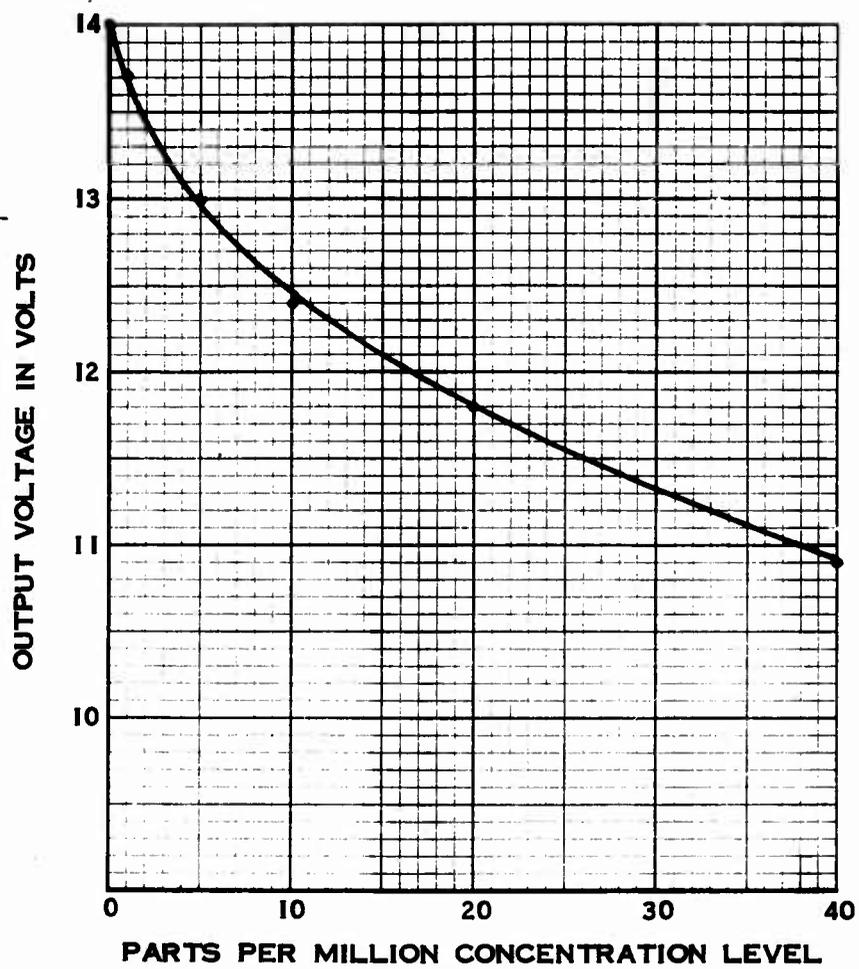


FIGURE 2
WORKING CURVE FOR IRON
ATOMIC ABSORPTION SPECTROMETER

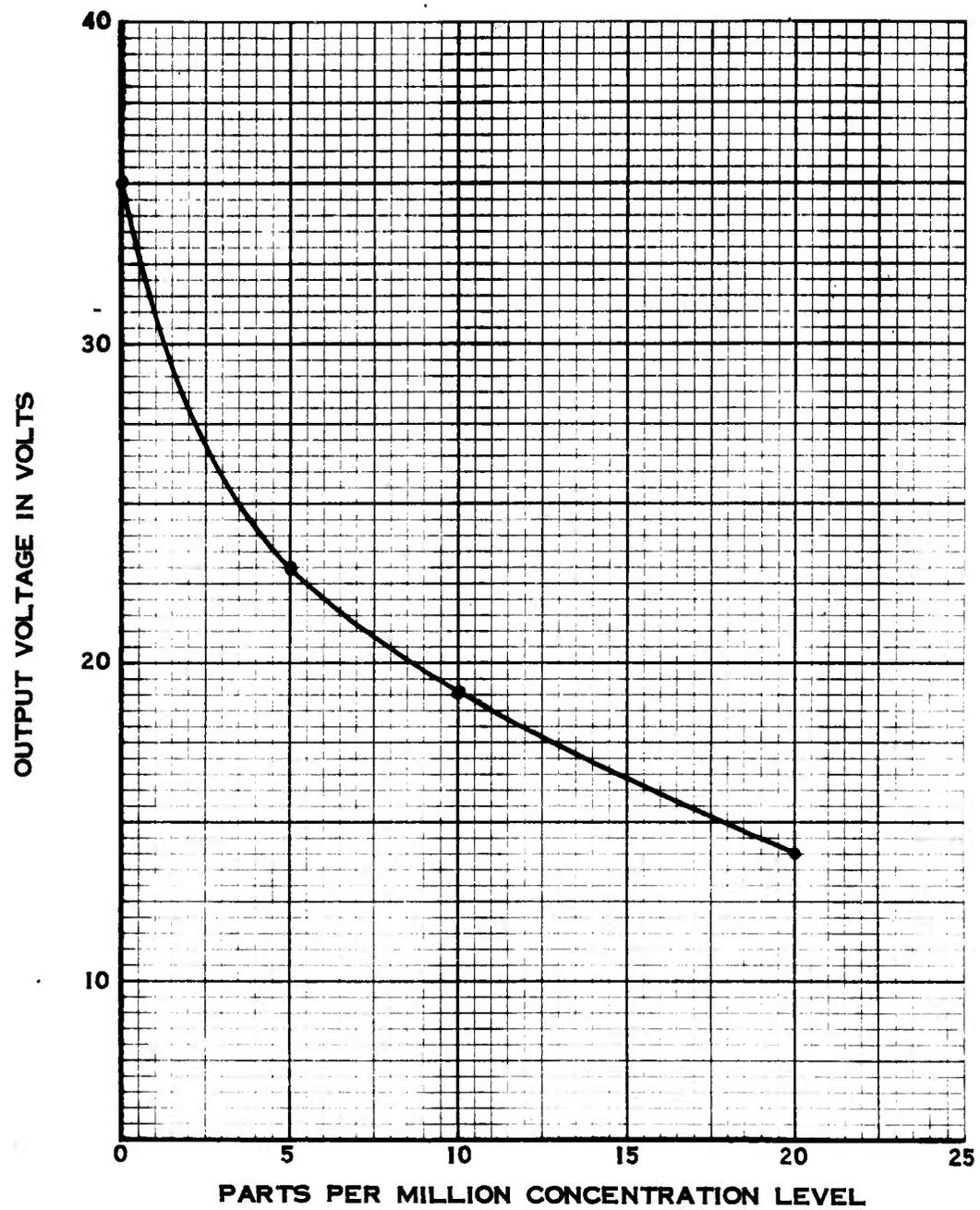


FIGURE 3
WORKING CURVE FOR COPPER
ATOMIC ABSORPTION SPECTROMETER

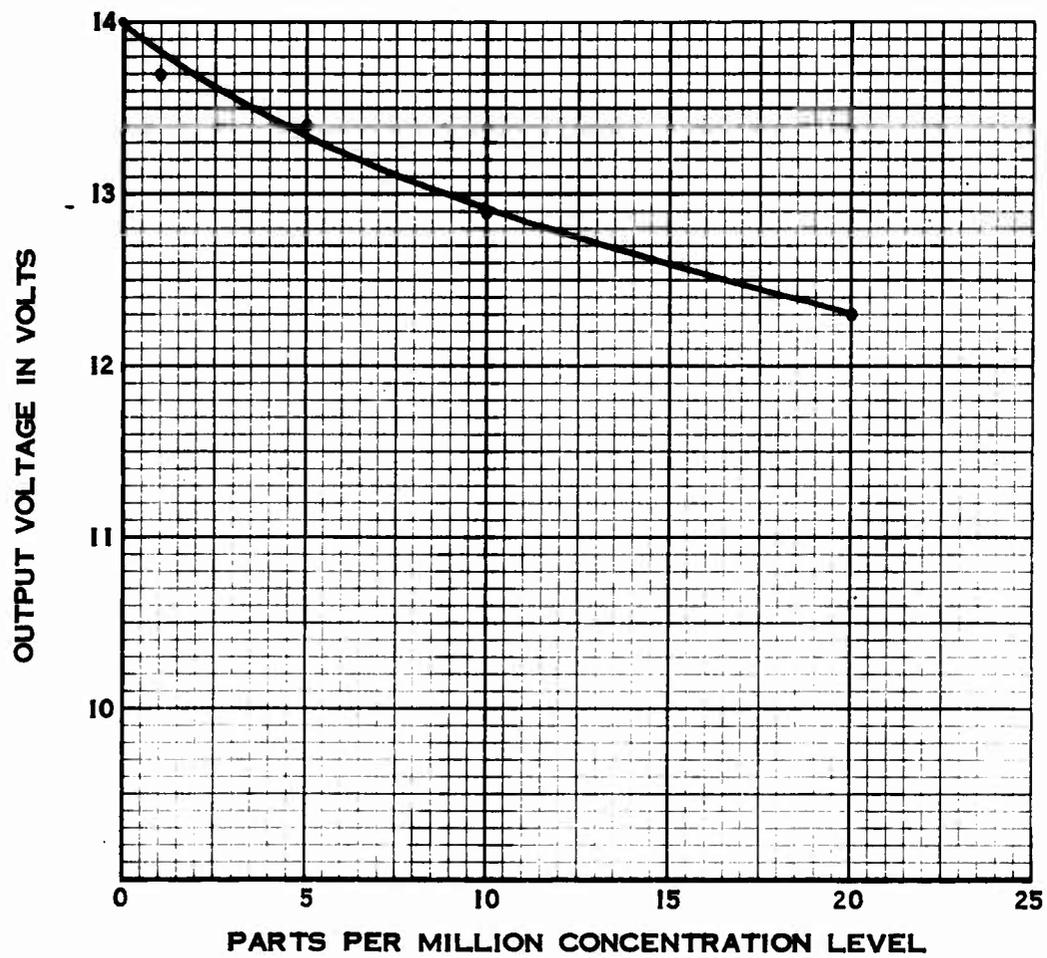


FIGURE 4

WORKING CURVE FOR NICKEL
ATOMIC ABSORPTION SPECTROMETER

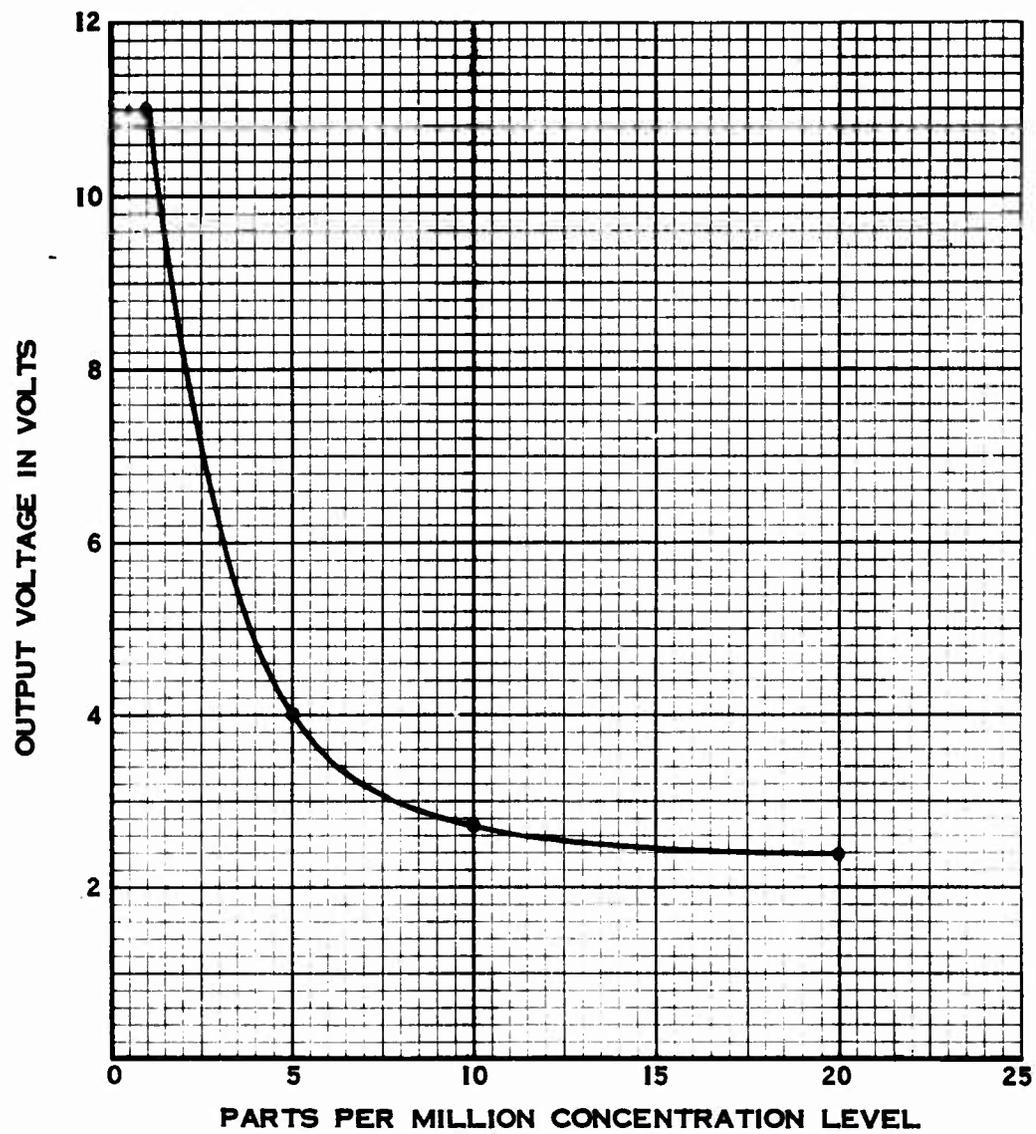


FIGURE 5

WORKING CURVE FOR MAGNESIUM
ATOMIC ABSORPTION SPECTROMETER

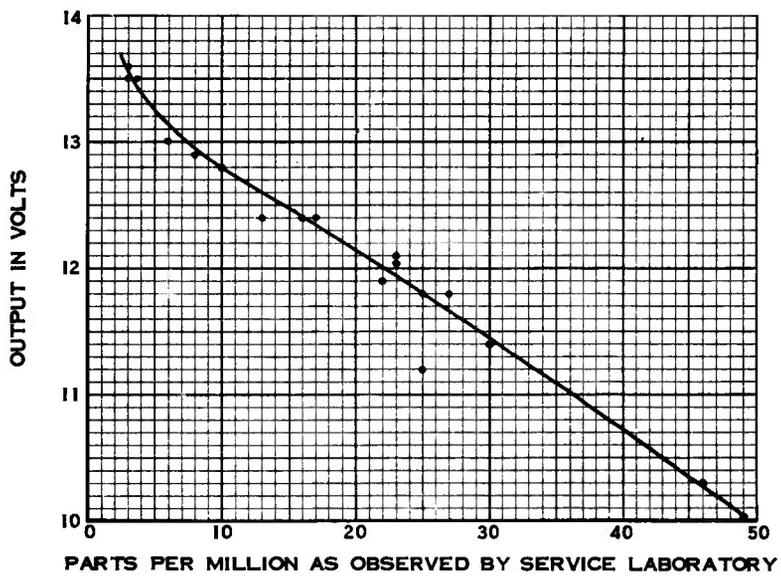
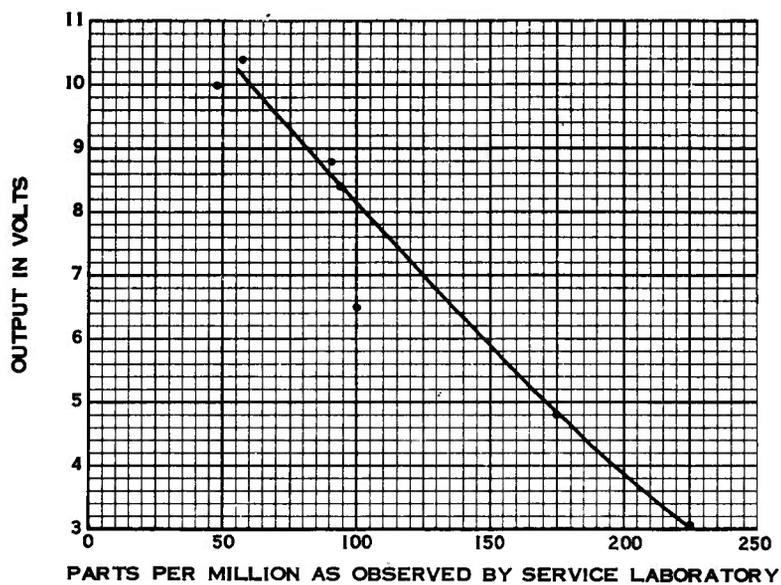


FIGURE 6
ANALYSIS OF OIL SAMPLES FOR IRON
ABSORPTION SPECTROMETER OUTPUT VERSUS
SERVICE LABORATORY READINGS

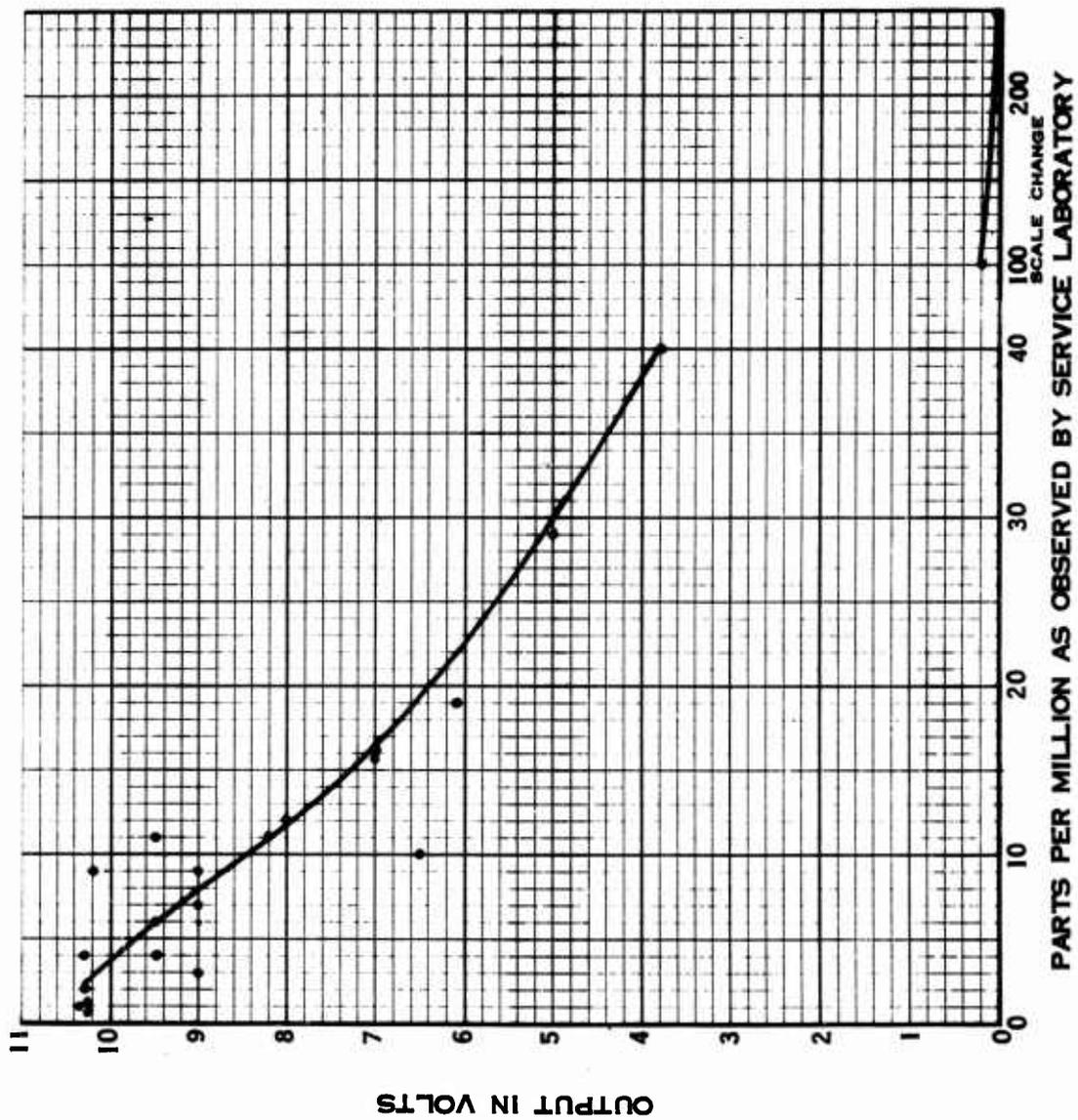


FIGURE 7
ANALYSIS OF OIL SAMPLES FOR COPPER

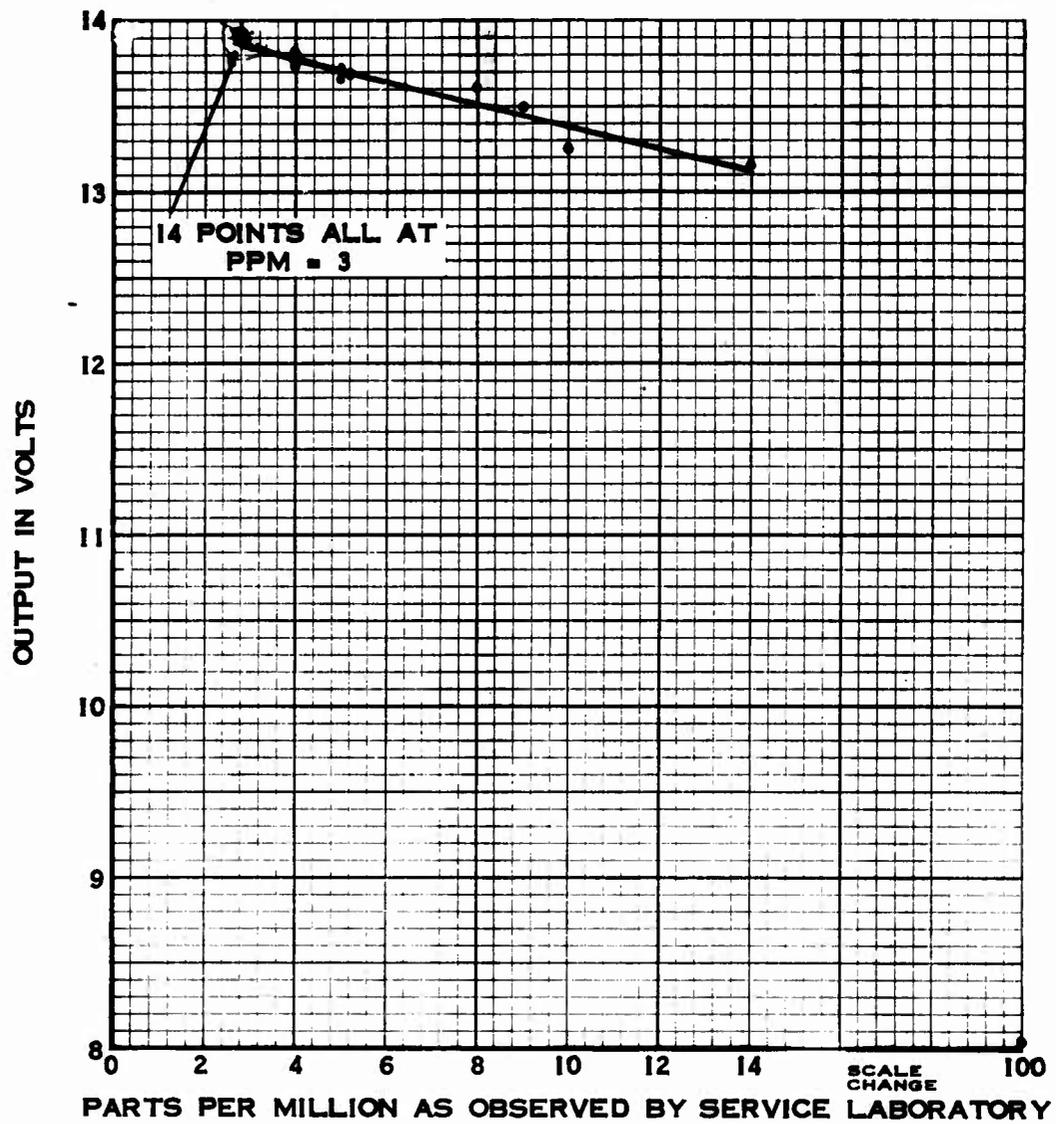


FIGURE 8
ANALYSIS OF OIL SAMPLES FOR NICKEL

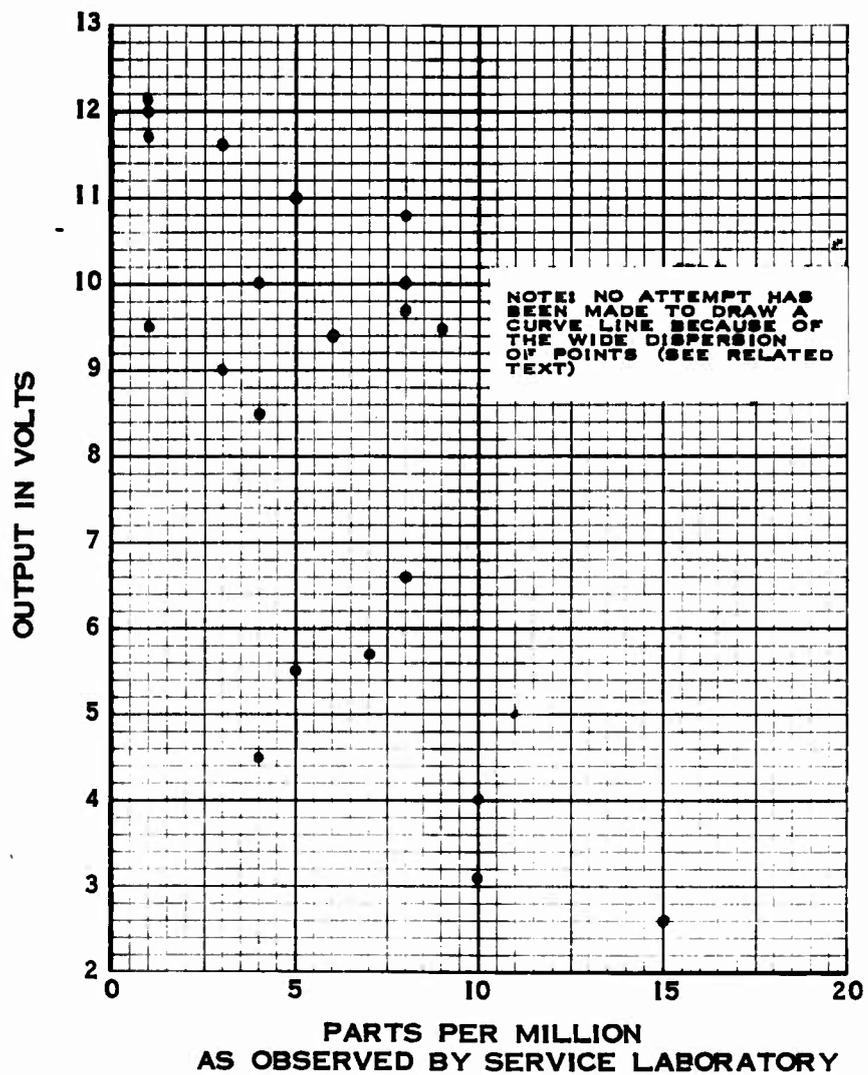


FIGURE 9
ANALYSIS OF OIL SAMPLES FOR MAGNESIUM

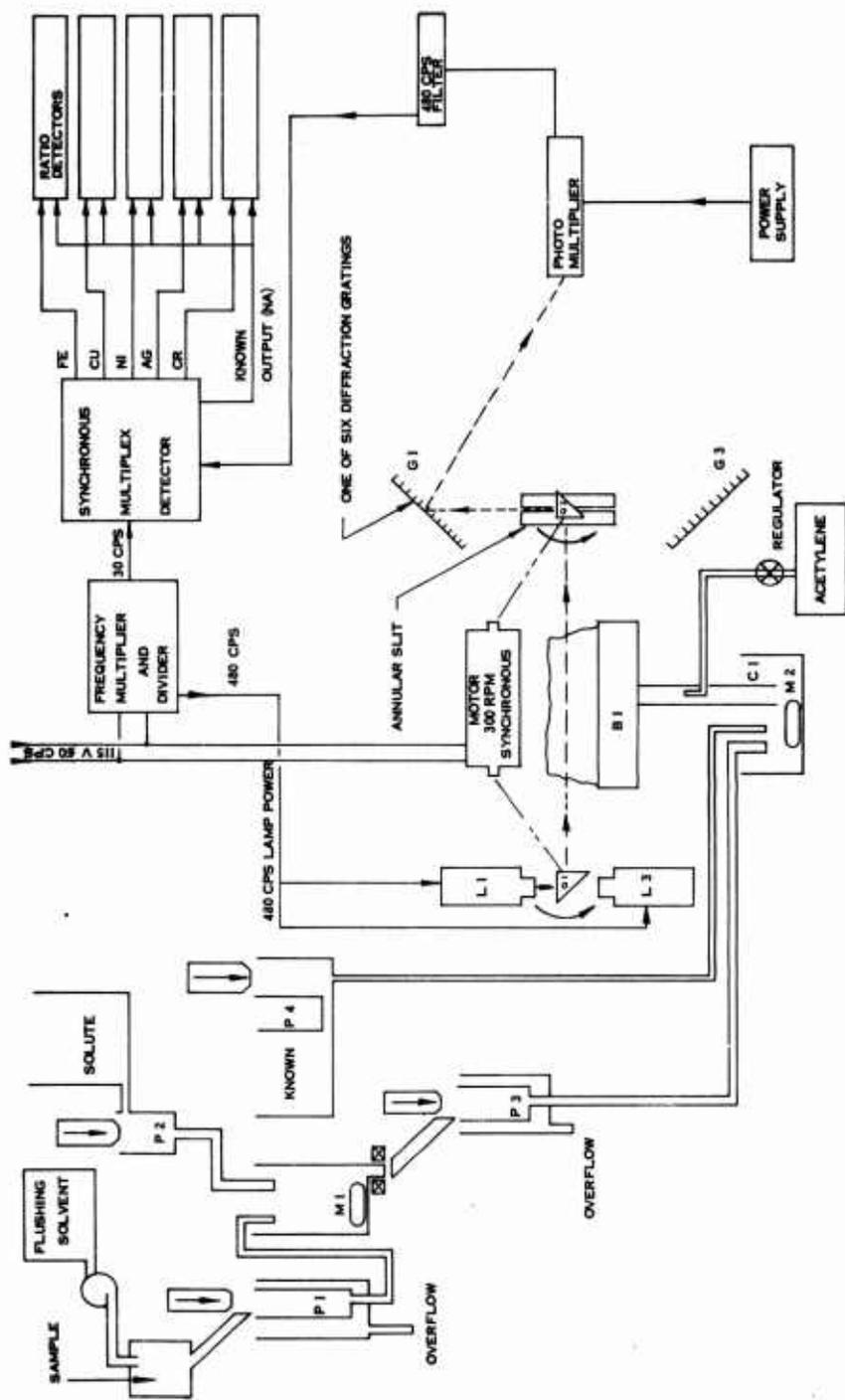


FIGURE 10
 AUTOMATIC ATOMIC ABSORPTION
 SPECTROMETER SYSTEM SCHEMATIC

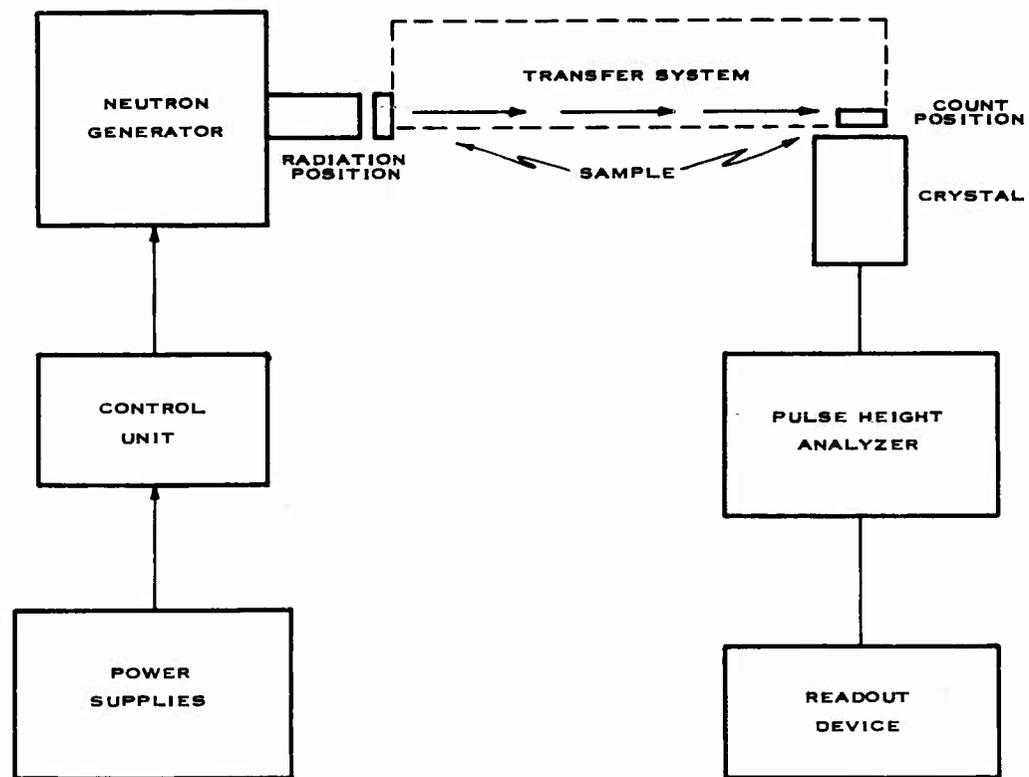


FIGURE II
NEUTRON ACTIVATION ANALYSIS
SYSTEM SCHEMATIC

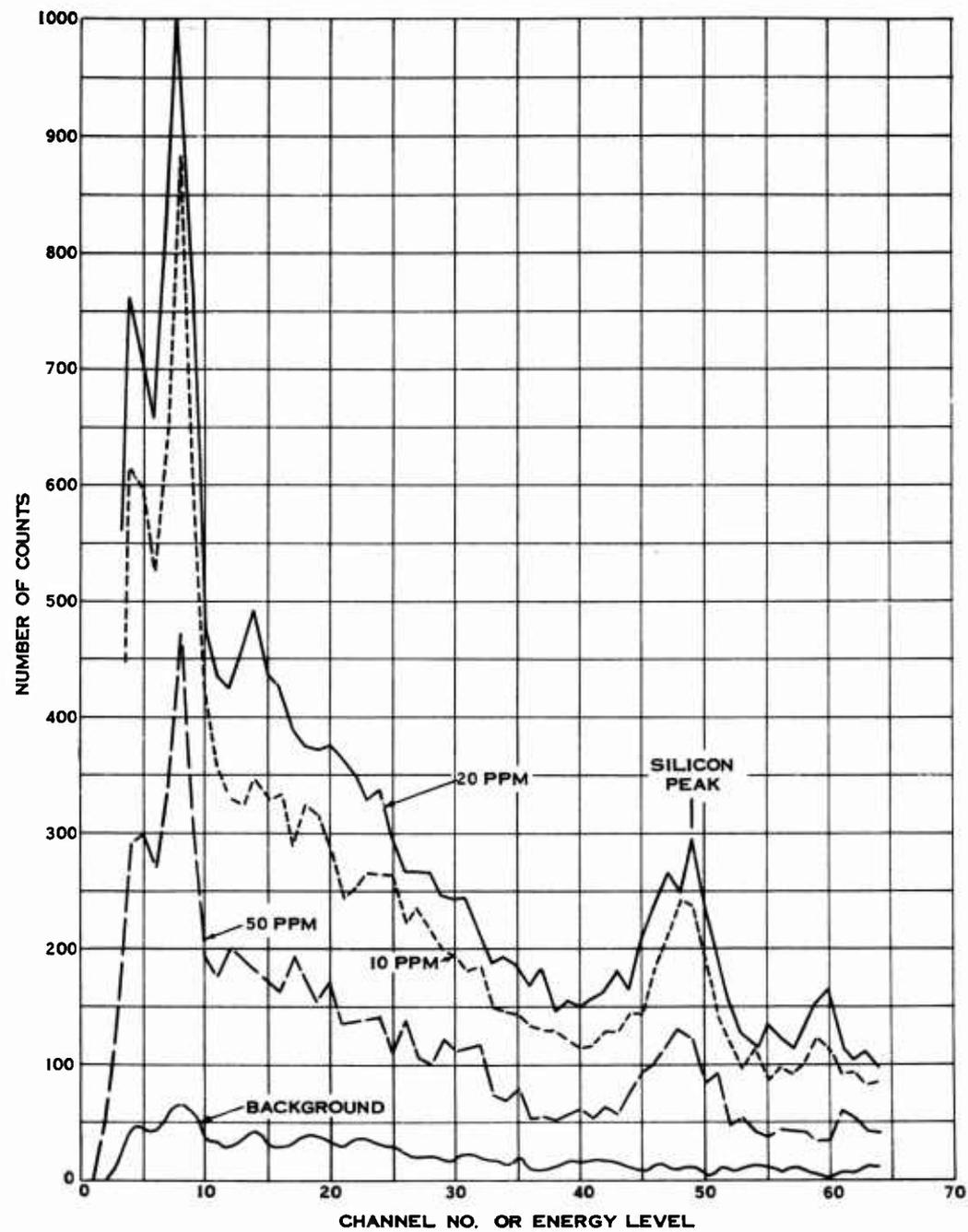


FIGURE 12
 NEUTRON ACTIVATION ANALYSIS, COPPER SOLUTION IN WATER,
 10^9 NEUTRONS/SECOND 30 SECONDS

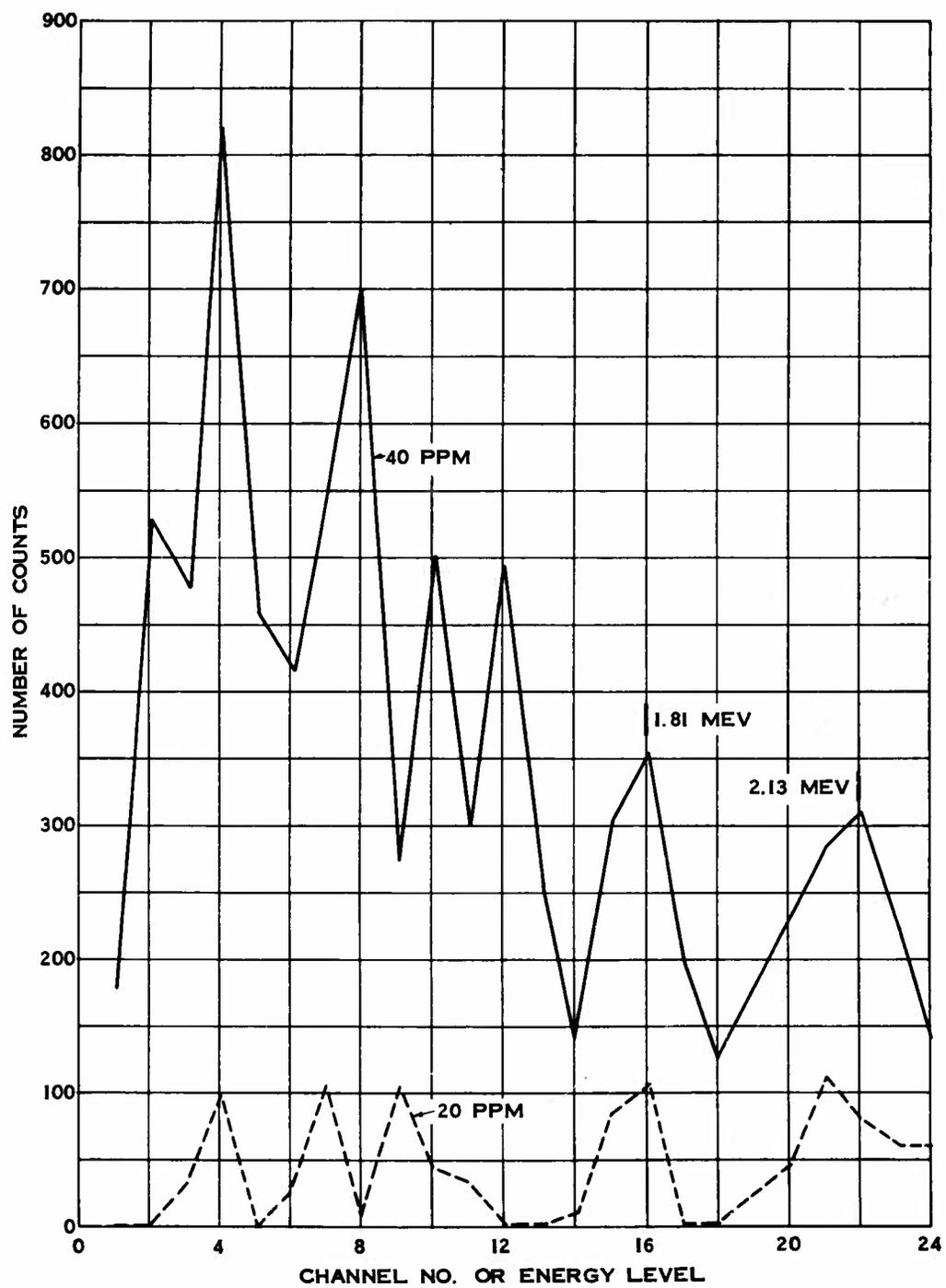


FIGURE 13
NEUTRON ACTIVATION ANALYSIS, IRON SOLUTIONS IN WATER
 10^9 NEUTRON/SECOND 30 SECONDS, BACKGROUND SUBTRACTED
 -34-

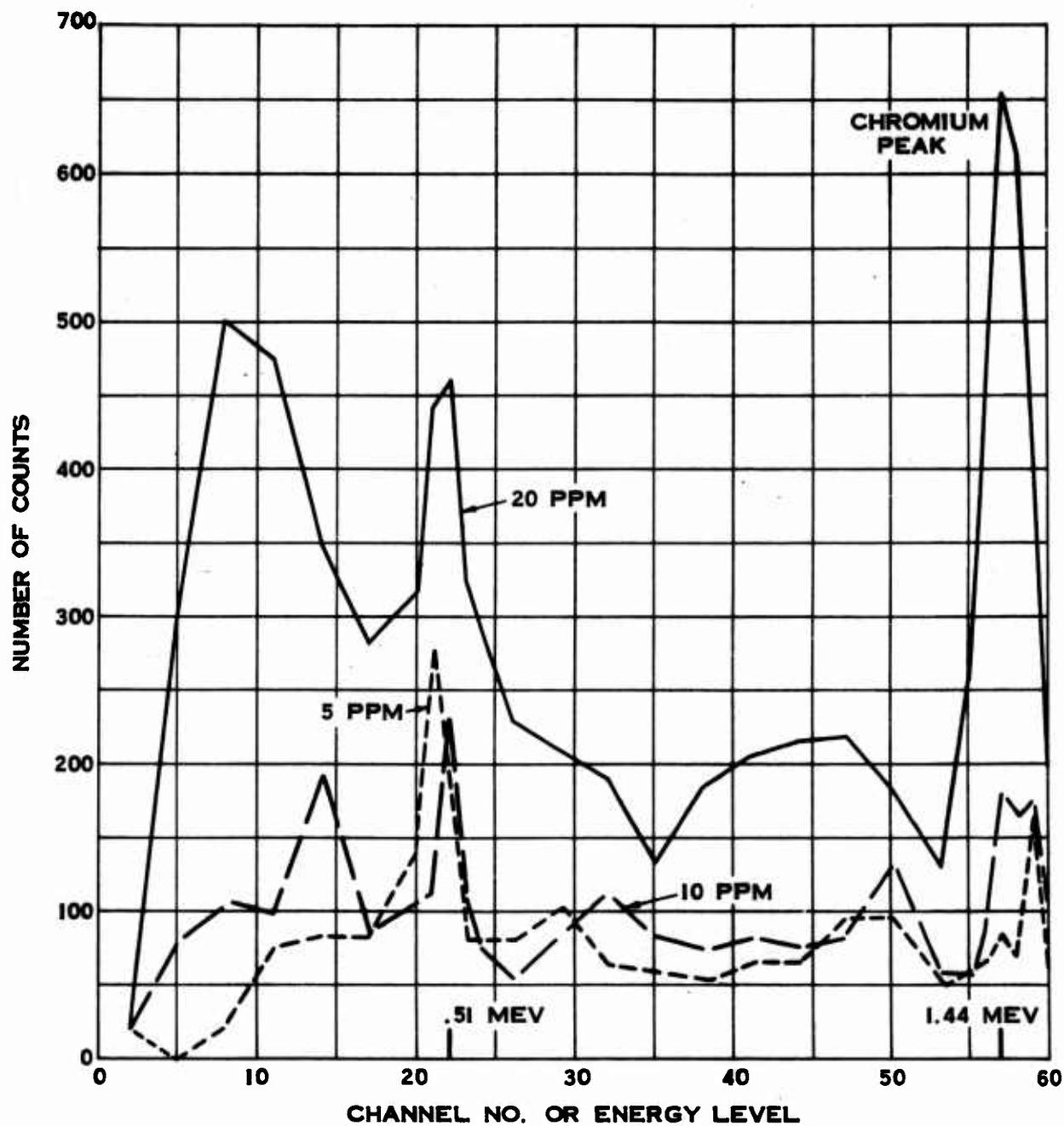


FIGURE 14
 NEUTRON ACTIVATION ANALYSIS, CHROMIUM SOLUTIONS IN WATER
 10^9 NEUTRON/SECOND 30 SECONDS, BACKGROUND SUBTRACTED

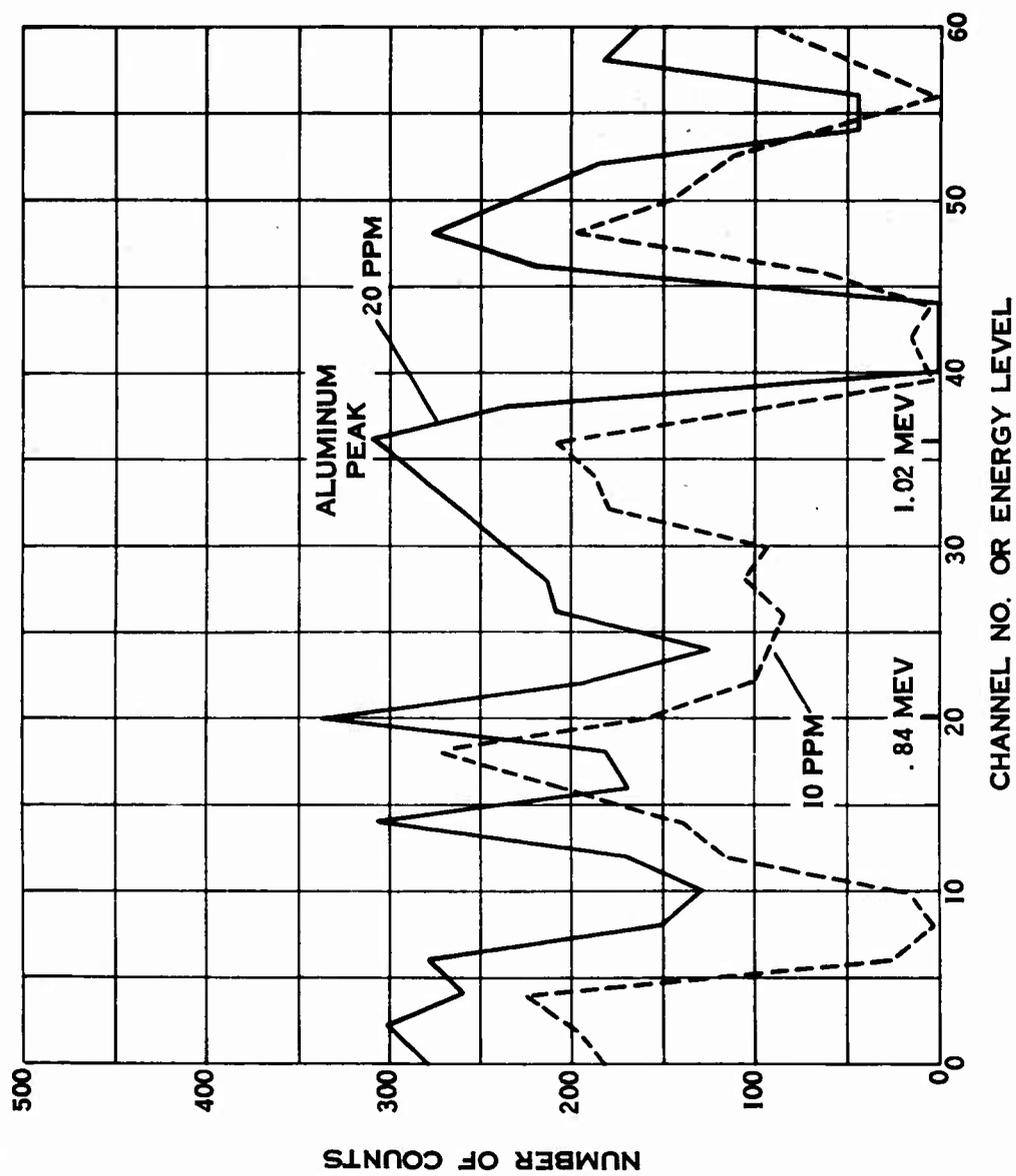


FIGURE 15

NEUTRON ACTIVATION ANALYSIS, ALUMINUM SOLUTIONS IN WATER,
 10^6 NEUTRON/SECOND 30 SECONDS, BACKGROUND SUBTRACTED

FIGURE 16

COPPER

U.S. Navy Threshold Value = 14 PPM

	Group 1		Groups 2 3	
	Observed	% of Total	Observed	% of Total
≥ 14 PPM	18	5.9	24	10.5
< 14 PPM	289	94.1	205	89.5
Total	307		229	

	Group 1		Groups 2 3	
	Observed	% of Total	Observed	% of Total
≥ 12 PPM	47	15.3	59	25.8
< 12 PPM	260	84.7	170	74.2
Total	307		229	

	Group 1		Groups 2 3	
	Observed	% of Total	Observed	% of Total
≥ 16 PPM	5	1.6	9	3.9
< 16 PPM	302	98.4	220	96.1
Total	307		229	

FIGURE 17

SILVER

U.S. Navy Threshold Value = 3 PPM

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 3 PPM	7	2.3	18	7.9
< 3 PPM	300	97.7	211	92.1
Total	307		229	

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 2.5 PPM	8	2.6	19	8.3
< 2.5 PPM	299	97.4	210	91.7
Total	307		229	

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 7 PPM	3	1	15	6.6
< 7 PPM	304	99	214	94.4
Total	307		229	

FIGURE 18

NICKEL

U.S. Navy Threshold Value = 8 PPM

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 8 PPM	187	60.9	133	58.1
< 8 PPM	120	39.1	96	41.9
Total	307		229	

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 7 PPM	273	88.9	198	86.5
< 7 PPM	34	11.1	31	13.5
Total	307		229	

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 9 PPM	87	28.3	65	28.4
< 9 PPM	220	71.7	164	71.6
Total	307		229	

FIGURE 19

CHROMIUM

U.S. Navy Threshold Value = 10 PPM

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 10 PPM	8	2.6	12	5.2
< 10 PPM	299	97.4	217	94.8
Total	307		229	

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 9 PPM	14	4.6	14	6.1
< 9 PPM	293	95.4	215	93.9
Total	307		229	

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 11 PPM	4	1.3	7	3.1
< 11 PPM	303	98.7	222	96.9
Total	307		229	

FIGURE 20

IRON

U.S. Navy Threshold Value = 35 PPM

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 35 PPM	53	17.3	54	23.6
< 35 PPM	254	82.7	175	76.4
Total	307		229	

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 31 PPM	94	30.6	98	42.8
< 31 PPM	213	69.4	131	57.2
Total	307		229	

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 39 PPM	20	6.5	30	13.1
< 39 PPM	287	93.5	199	86.9
Total	307		229	

FIGURE 21

TIN

U.S. Navy Threshold Value = 20 PPM

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 20 PPM	17	5.5	14	6.1
< 20 PPM	290	94.5	215	93.9
Total	307		229	

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 18 PPM	20	6.5	15	6.5
< 18 PPM	287	93.5	214	93.5
Total	307		229	

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 22 PPM	10	3.3	9	3.9
< 22 PPM	297	96.7	220	96.1
Total	307		229	

FIGURE 22.

ALUMINUM

U.S. Navy Threshold Value = 8 PPM

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 8 PPM	49	15.9	45	19.6
< 8 PPM	258	84.1	184	80.4
Total	307		229	

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 7 PPM	90	29.3	84	36.7
< 7 PPM	217	70.7	145	63.3
Total	307		229	

	Group 1		Groups 2 and 3	
	Observed	% of Total	Observed	% of Total
≥ 9 PPM	27	8.8	28	12.2
< 9 PPM	280	91.2	201	87.8
Total	307		229	

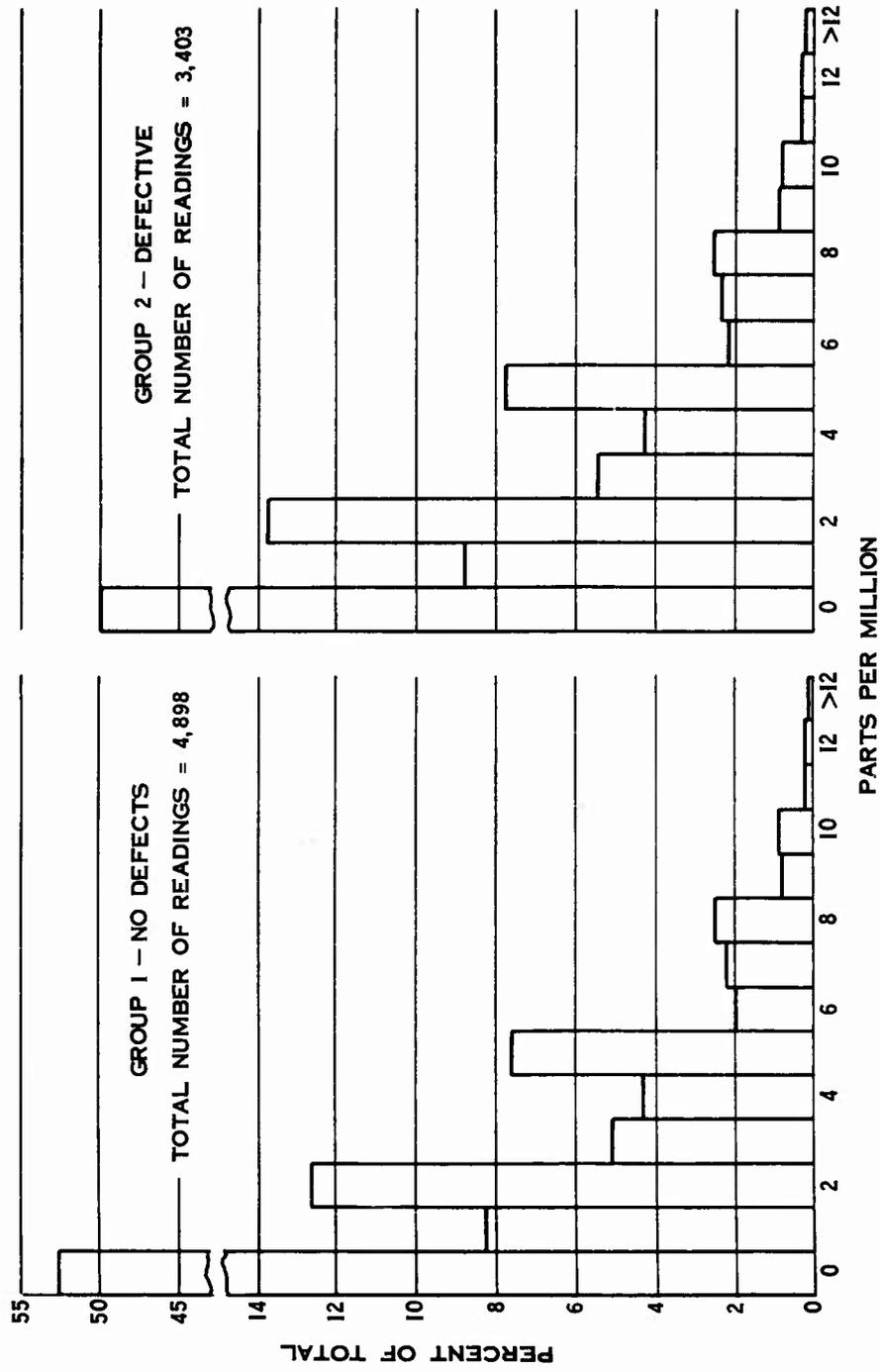


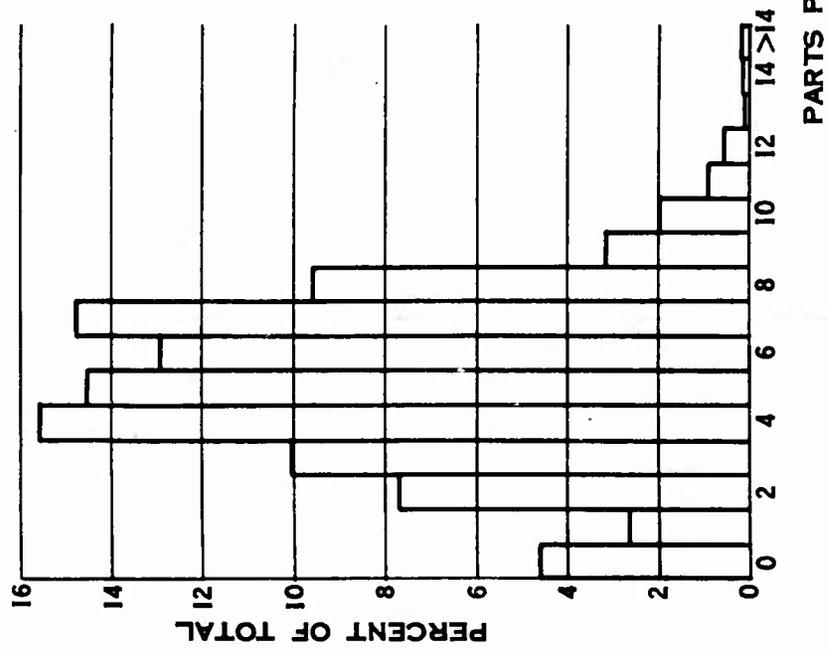
FIGURE 23

FREQUENCY DISTRIBUTION OF OIL ANALYSIS READINGS FOR NICKEL

RI820-86 ENGINE

GROUP 1 - NO DEFECTS

TOTAL NUMBER OF READINGS = 4,898



GROUP 2 - DEFECTIVE

TOTAL NUMBER OF READINGS = 3,403

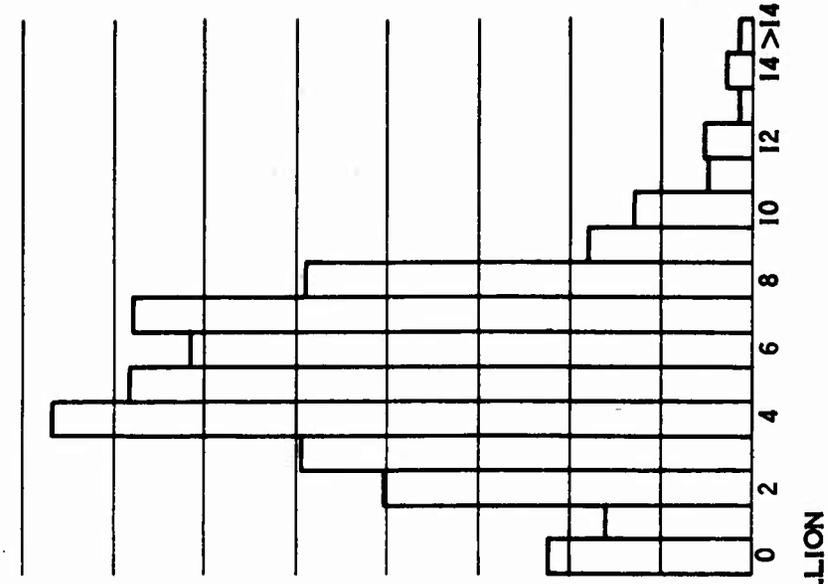


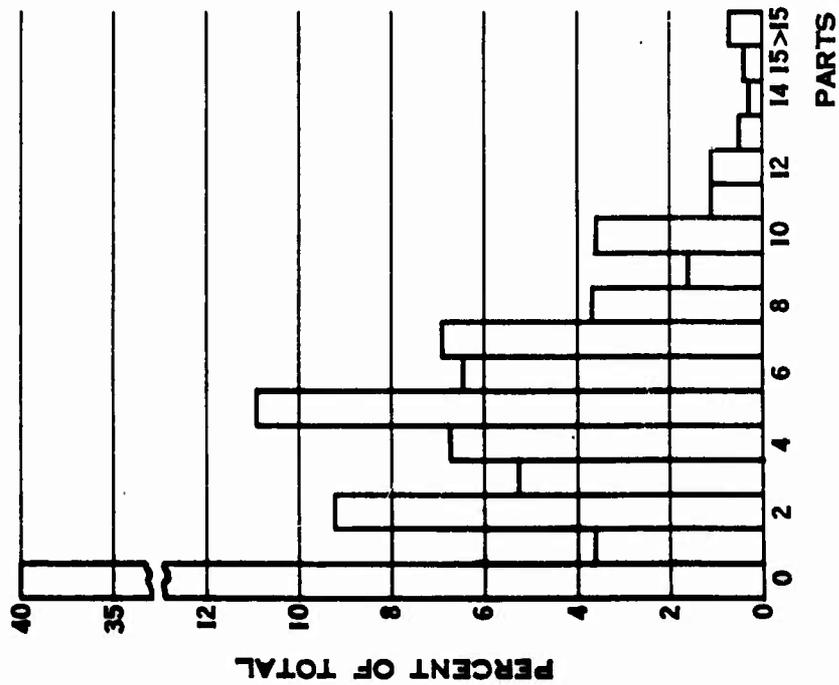
FIGURE 24

FREQUENCY DISTRIBUTION OF OIL ANALYSIS READINGS FOR COPPER

R1820-66 ENGINE

GROUP 1 -- NO DEFECTS

TOTAL NUMBER OF READINGS = 4,898



GROUP 2 -- DEFECTIVE

TOTAL NUMBER OF READINGS = 3,403



FIGURE 25

**FREQUENCY DISTRIBUTION OF OIL ANALYSIS READINGS FOR TIN
R1820-86 ENGINE**

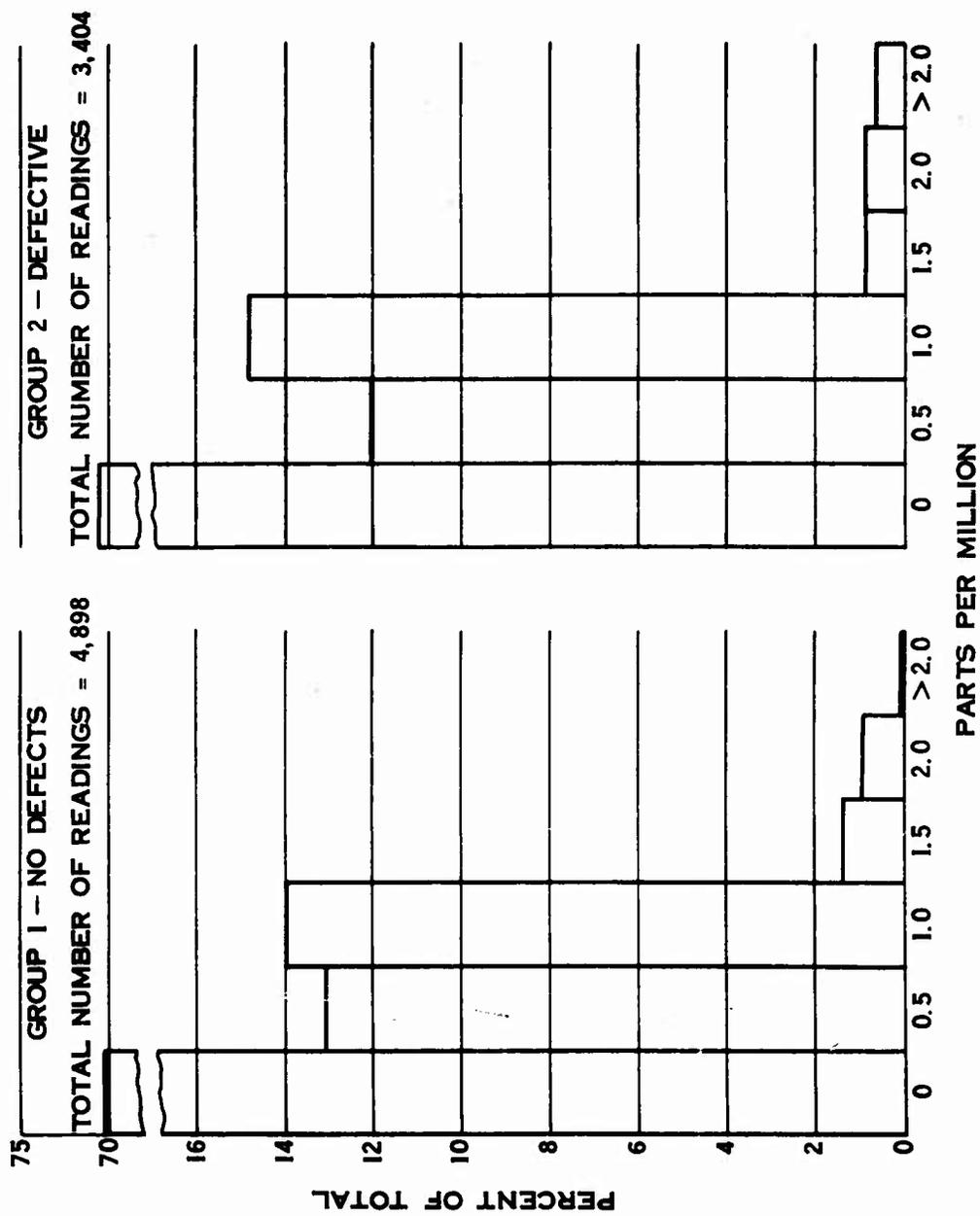


FIGURE 26
FREQUENCY DISTRIBUTION OF OIL ANALYSIS READINGS FOR SILVER
R1820-86 ENGINE

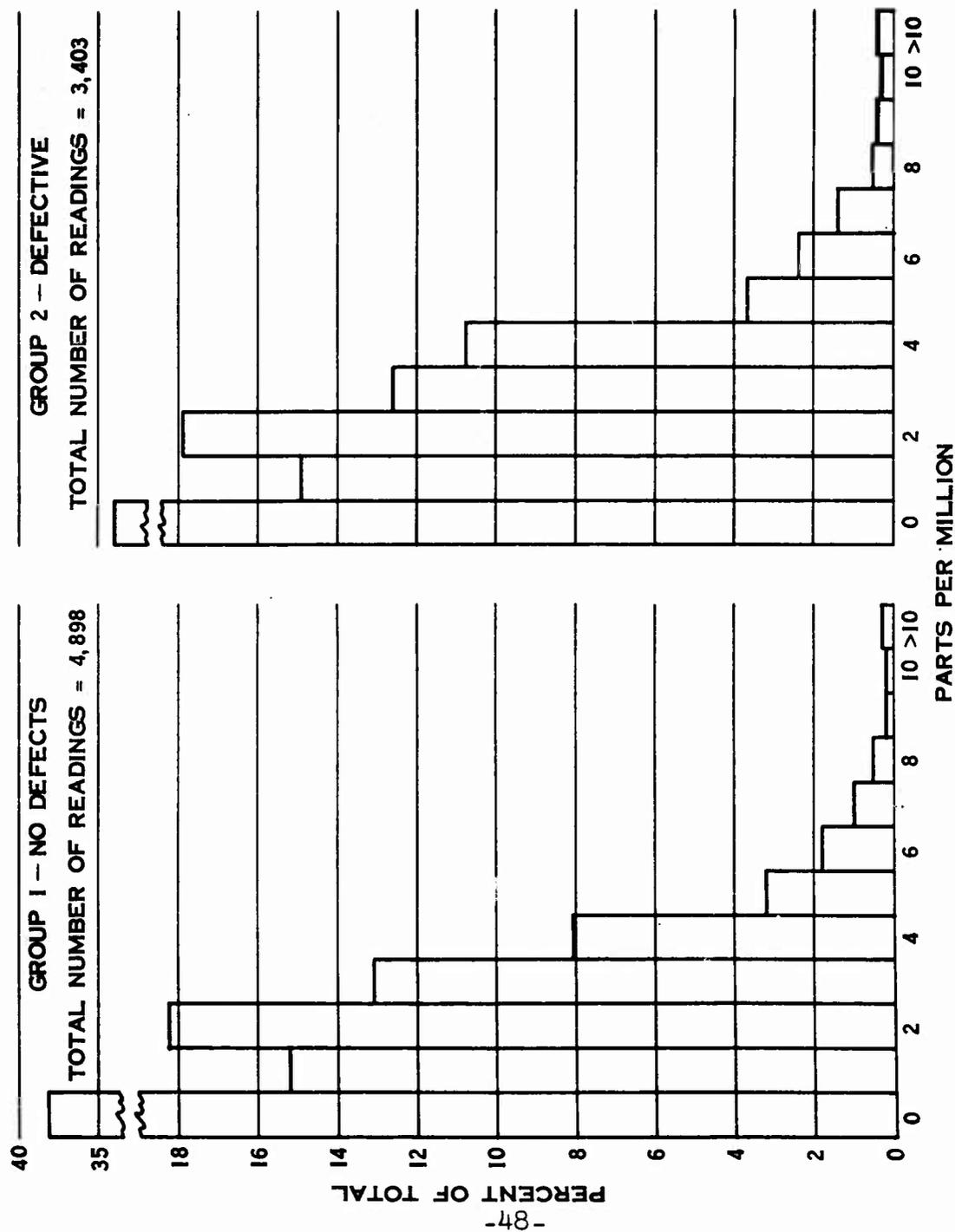
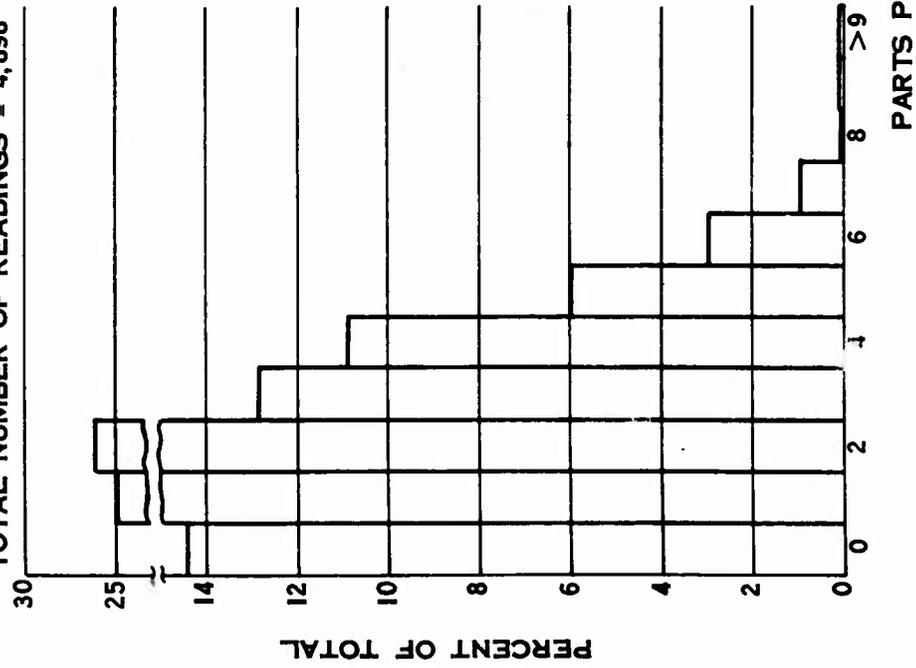


FIGURE 27

FREQUENCY DISTRIBUTION OF OIL ANALYSIS READINGS FOR ALUMINUM
R1320-86 ENGINE

GROUP 1 -- NO DEFECTS

TOTAL NUMBER OF READINGS = 4,898



GROUP 2 -- DEFECTIVE

TOTAL NUMBER OF READINGS = 3,403

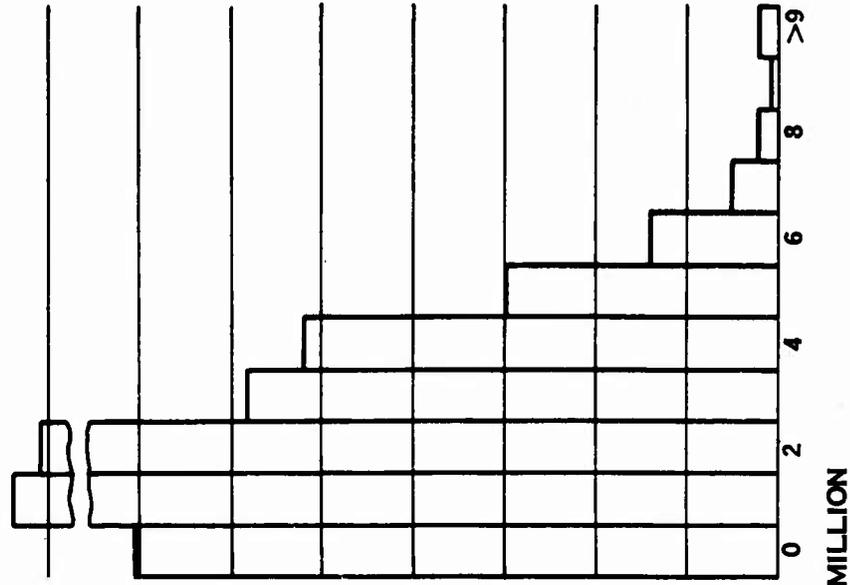
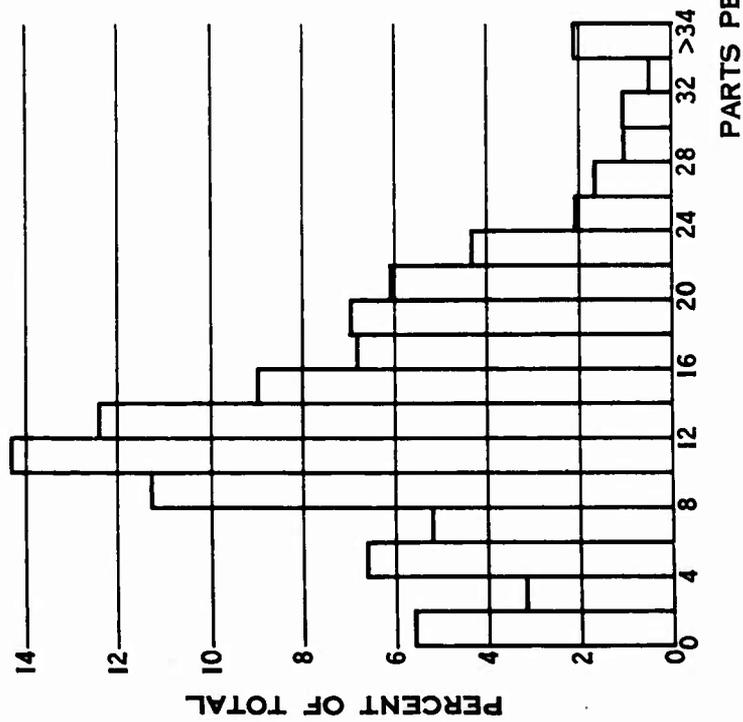


FIGURE 28
 FREQUENCY DISTRIBUTION OF OIL ANALYSIS READINGS FOR CHROMIUM
 R1820-86 ENGINE

GROUP 1 - NO DEFECTS

TOTAL NUMBER OF READINGS = 4,898



GROUP 2 - DEFECTIVE

TOTAL NUMBER OF READINGS = 3,403

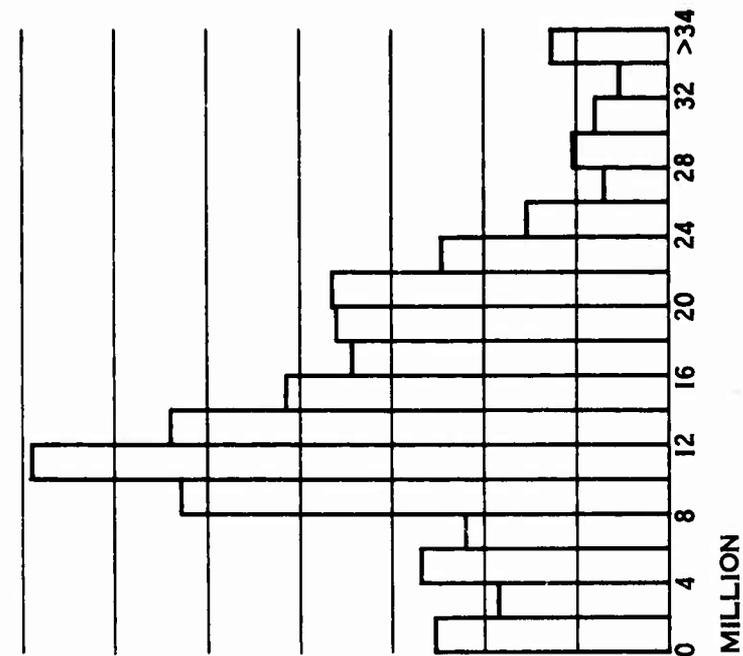


FIGURE 29

FREQUENCY DISTRIBUTION OF OIL ANALYSIS READINGS FOR IRON

R1820-86 ENGINE

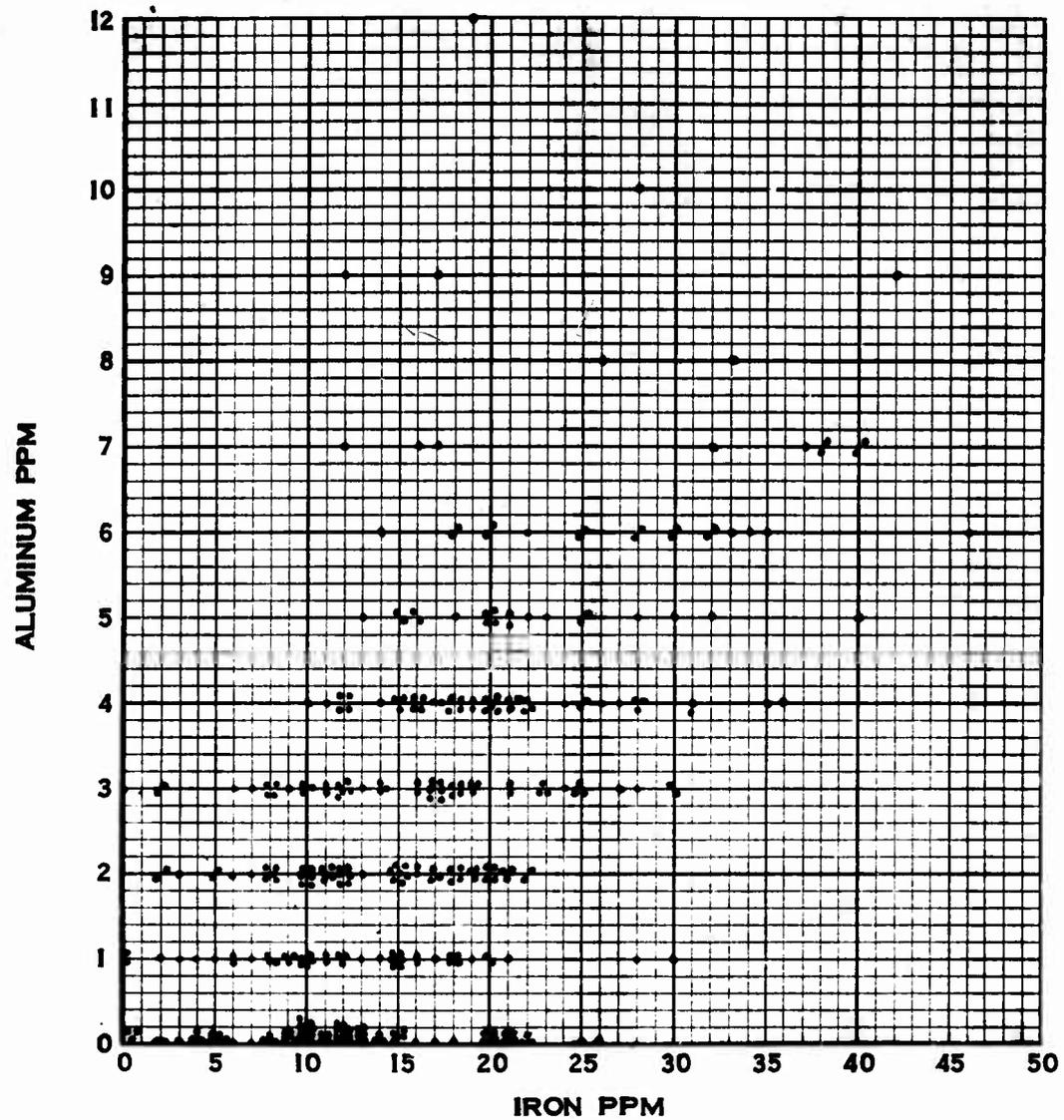


FIGURE 30

**OIL ANALYSIS IRON READINGS VERSUS ALUMINUM READINGS
RANDOM SELECTION FROM DATA**

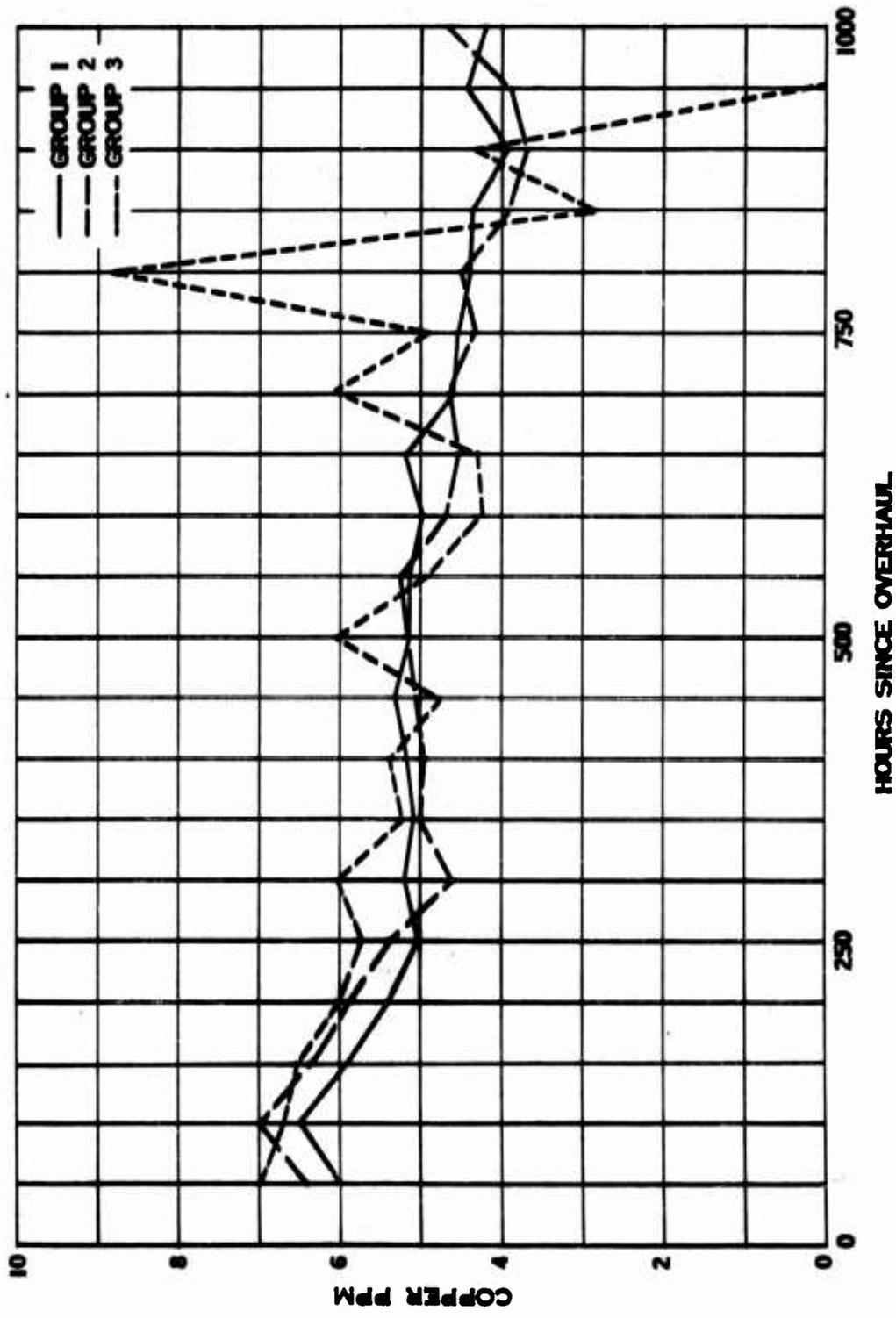


FIGURE 31

AVERAGE OIL ANALYSIS READINGS VERSUS HOURS SINCE OVERHAUL, COPPER
R1820-86 ENGINE

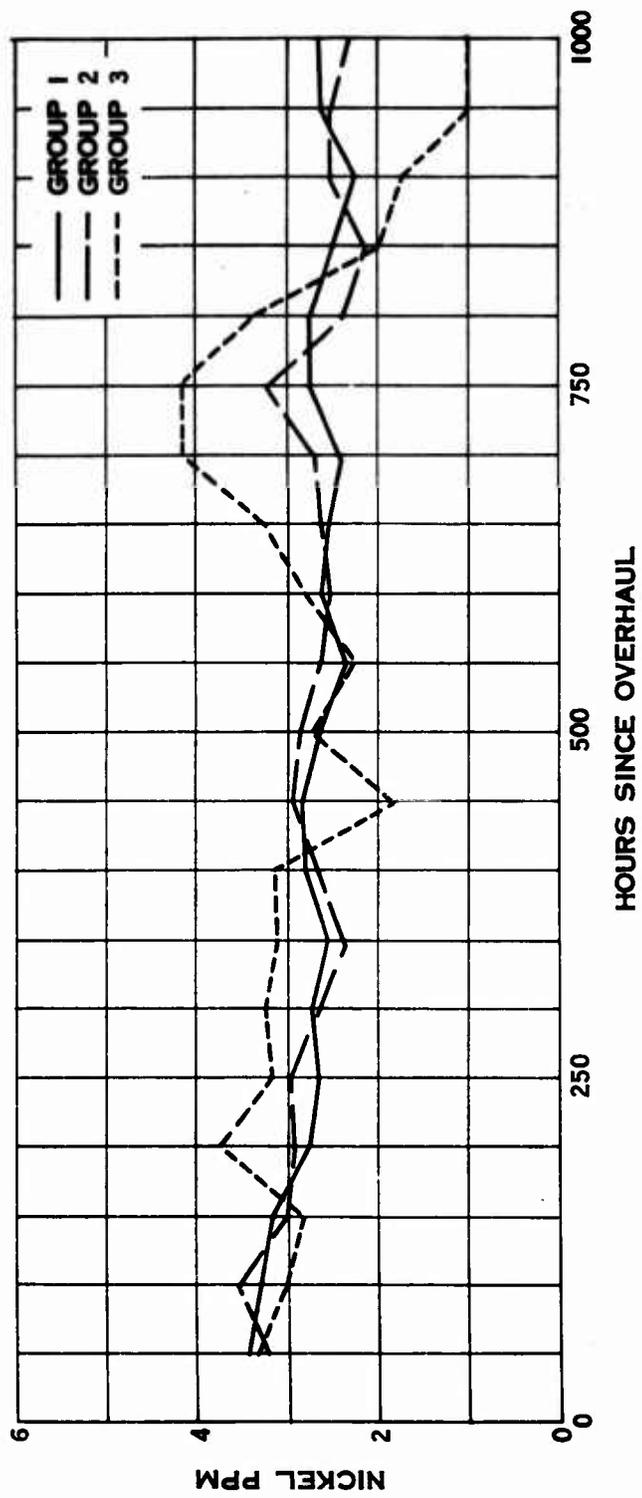


FIGURE 32

AVERAGE OIL ANALYSIS READINGS VERSUS HOURS SINCE OVERHAUL, NICKEL

R1820-86 ENGINE

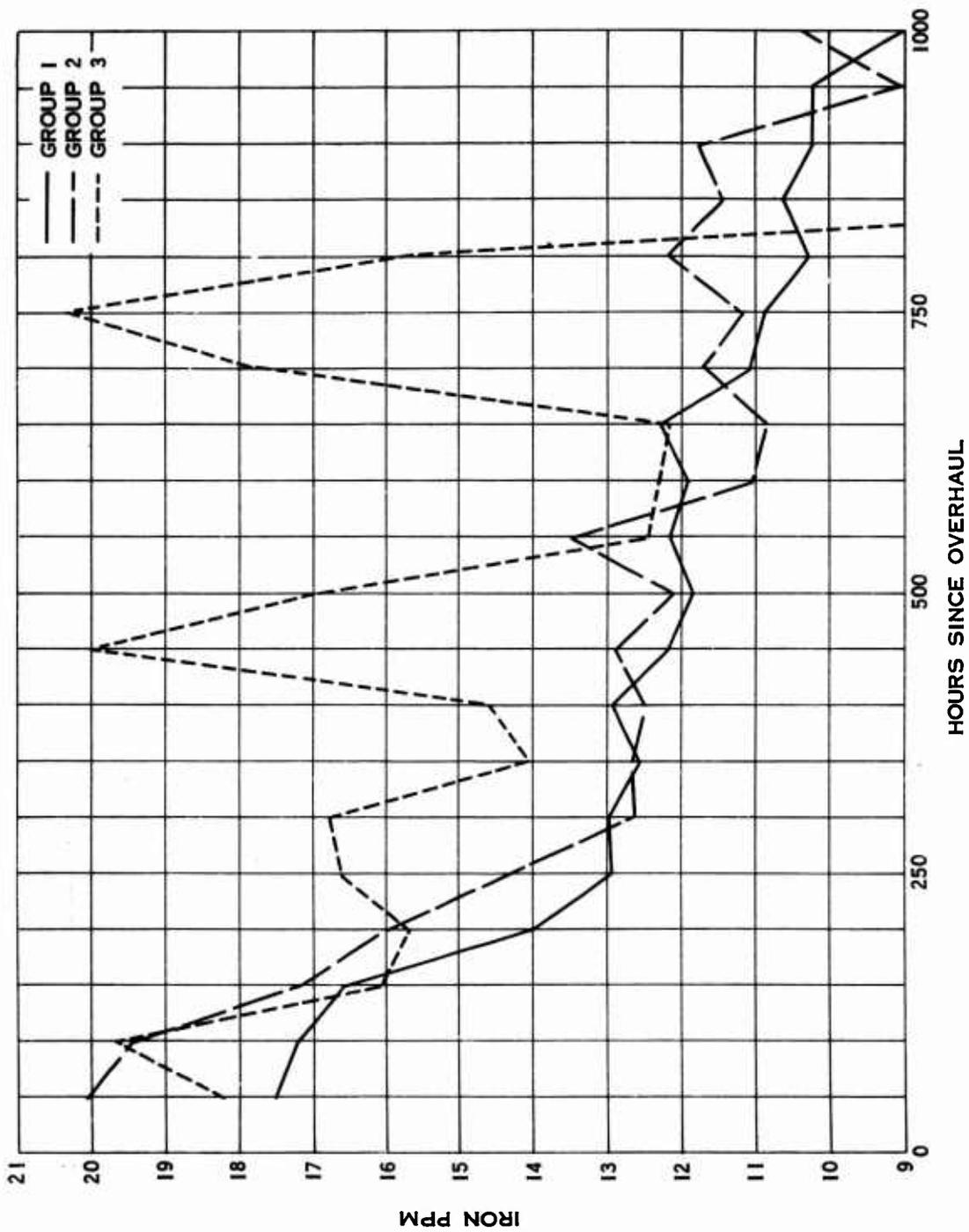


FIGURE 33
 AVERAGE OIL ANALYSIS READINGS VERSUS HOURS SINCE OVERHAUL, IRON
 R1820-86 ENGINE

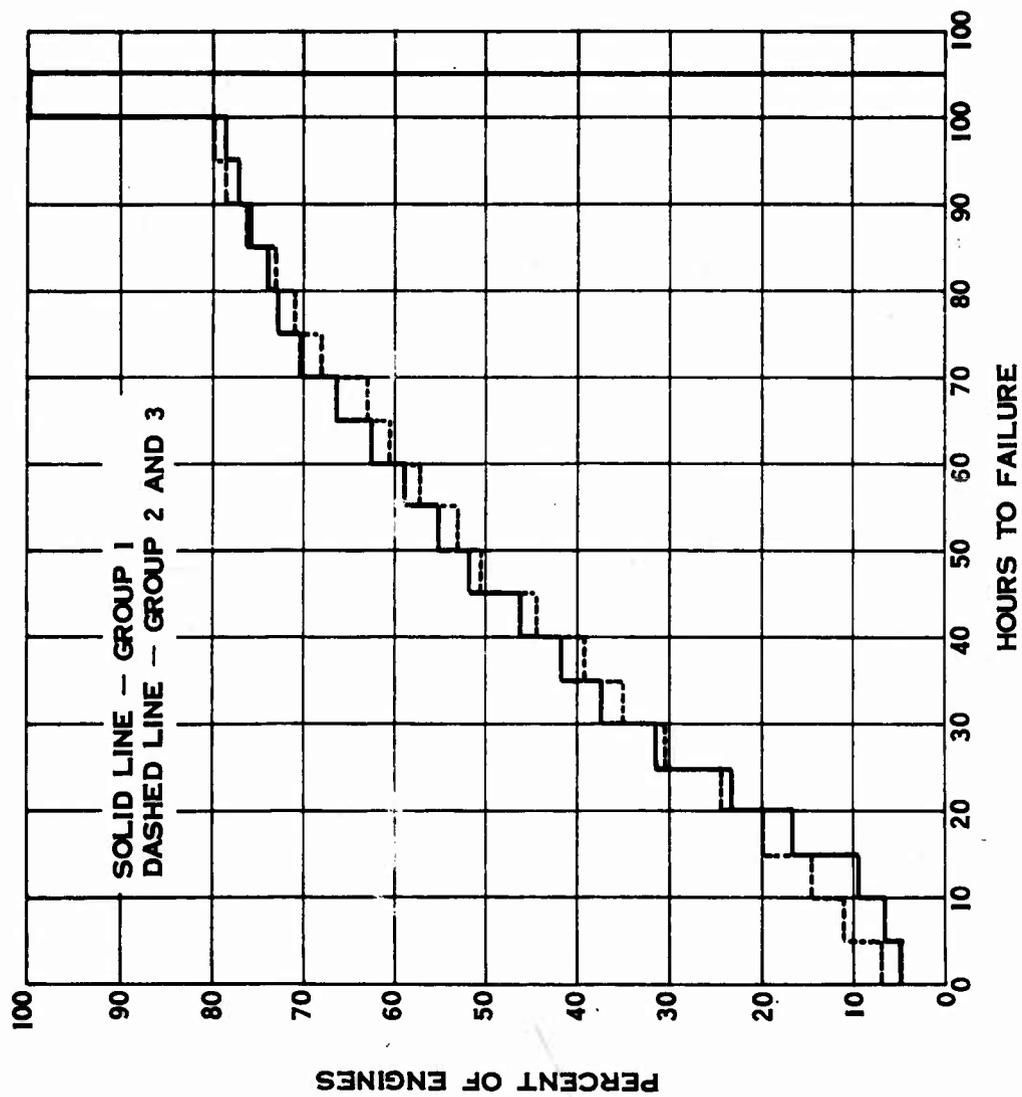


FIGURE 34
 CUMULATIVE FREQUENCY DIAGRAM OF TIME TO FAILURE, COPPER
 R1820-86 ENGINE

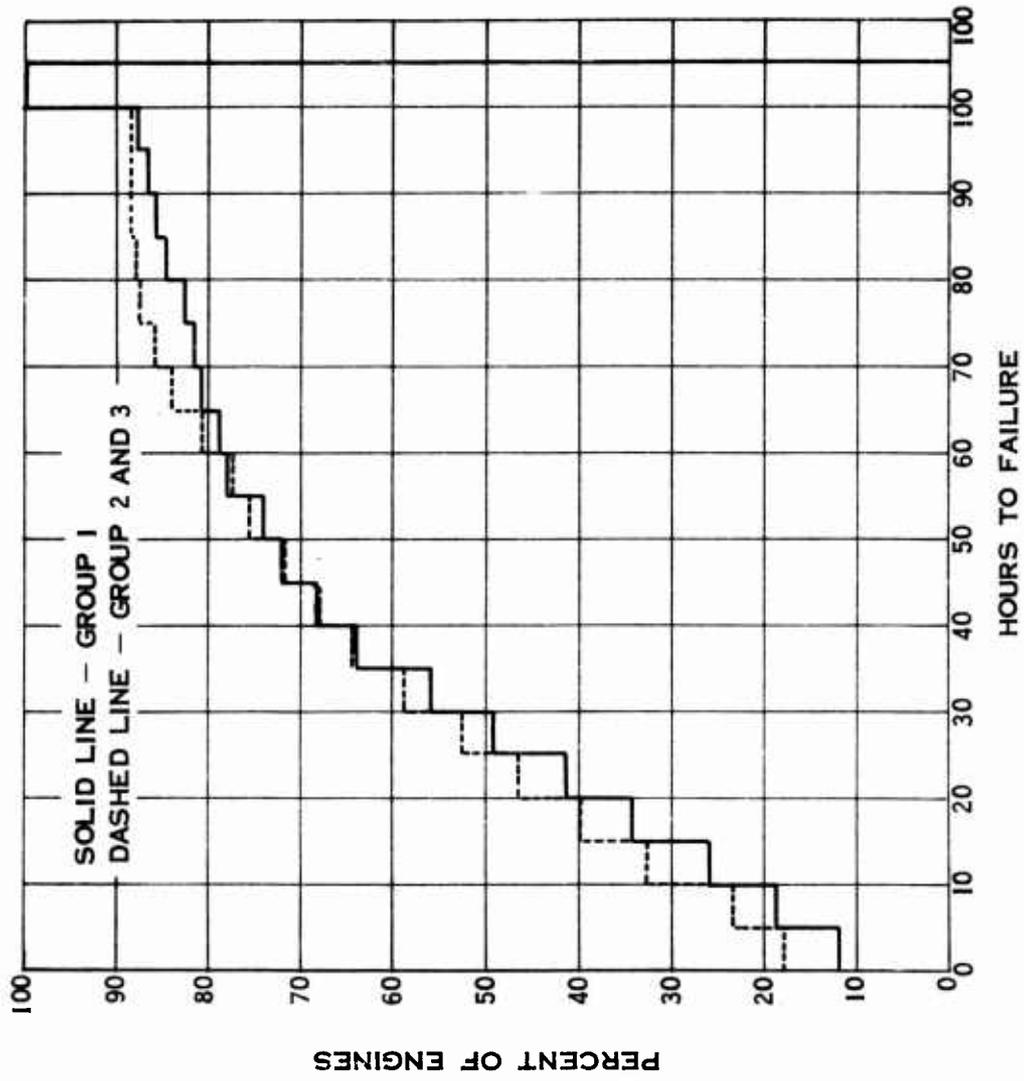


FIGURE 35
 CUMULATIVE FREQUENCY DIAGRAM OF TIME TO FAILURE, IRON
 R1820-86 ENGINE

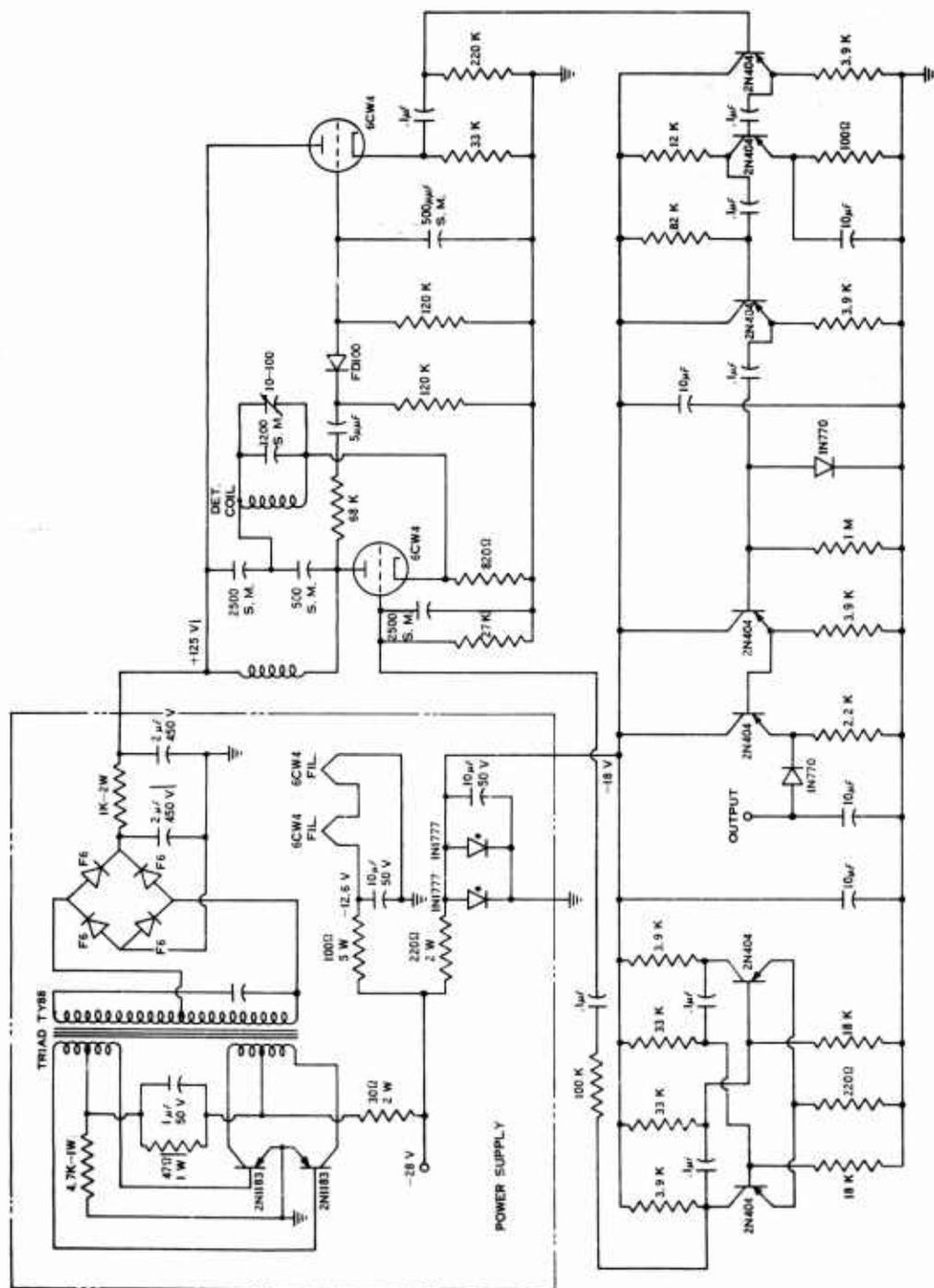


FIGURE 36
SUPERREGENERATIVE DETECTOR CIRCUIT DIAGRAM

DISTRIBUTION

U. S. Army Test and Evaluation Command	3
U. S. Army Infantry Center	2
U. S. Army Command and General Staff College	1
Army War College	1
U. S. Army Arctic Test Board	1
U. S. Army Armor Board	1
U. S. Army Aviation Test Board	1
Aviation Test Office, Edwards AFB	1
U. S. Army Polar Research and Development Center	1
Deputy Chief of Staff for Logistics, D/A	1
The Research Analysis Corporation	1
Army Research Office, Durham	2
Office of Chief of R&D, D/A	1
Naval Air Test Center	2
Army Research Office, D/A	1
U. S. Army Aviation School	1
Deputy Chief of Staff for Military Operations, D/A	1
U. S. Army Combat Developments Command	
Quartermaster Agency	1
U. S. Army Quartermaster School	1
U. S. Army Combat Developments Command	
Transportation Agency	1
U. S. Army Transportation Board	1
U. S. Army Aviation and Surface Materiel Command	20
U. S. Army Transportation Center and Fort Eustis	1
U. S. Army Transportation Research Command	26
U. S. Army Tri-Service Project Officer (MCLATS)	1
U. S. Army Transportation School	1
U. S. Army Airborne, Electronics and Special	
Warfare Board	1
Office of the United States Army Attache	1
U. S. Army Research and Development Group (Europe)	1
Air Proving Ground Center, Eglin AFB	1
Air University Library, Maxwell AFB	1
Air Force Systems Command, Wright-Patterson AFB	3
Chief of Naval Operations	1
Bureau of Naval Weapons	1
U. S. Naval Postgraduate School	1
U. S. Marine Corps	1
Marine Corps Schools	1

Marine Corps Liaison Officer,	
U. S. Army Transportation School	1
U. S. Coast Guard	1
National Aviation Facilities Experimental Center	1
NASA-LRC, Langley Station	1
Manned Spacecraft Center, NASA	1
Ames Research Center, NASA	1
Lewis Research Center, NASA	1
NASA Representative, Scientific and Technical Information Facility	2
U. S. Government Printing Office	1
Defense Documentation Center	10
Human Resources Research Office	2
U. S. Patent Office	1
U. S. Strike Command	1
U. S. Army Mobility Command	4
U. S. Army Materiel Command	8
U. S. Army Limited War Laboratory	1
U. S. Army Combat Developments Engineering Command	1
U. S. Army Combat Developments Command	1

AD Accession NO. Kaman Nuclear, Colo. Spgs., Colo.
INVESTIGATION OF THE FEASIBILITY
OF AN AIRCRAFT-OIL ANALYSIS SYSTEM
FOR OPERATIONAL USE IN THE FIELD
Phase II - V.D. Peckham, et al.
Task 9R89-02-015-23, TCREC 63-
55 (Contract DA 44-177-TC789)
1 Nov.1963, Unclassified Report

Atomic absorption spectrometry and neutron activation analysis were evaluated as the best methods for development into field measurement equipment for oil analysis. Statistical studies on R1820 engine oil analysis data showed the need for more precise data. An experimental inflight metal detector was designed and built.

UNCLASSIFIED
1. Oil Analysis System Contract No. AD 44-177-TC789
2.

AD Accession NO. Kaman Nuclear, Colo. Spgs., Colo.
INVESTIGATION OF THE FEASIBILITY
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