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SEG-TR-65-37

SPECTROMETRIC OIL ANALYSIS FOR THE DETECTION OF INCIPIENT TURBOJET ENGINE FAILURES

SQUADRON LEADER ALLAN BOND, RAF

DON C. KITTINGER

TECHNICAL REPORT SEG-TR-65-37

JULY 1965

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SYSTEMS ENGINEERING GROUP
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICES

100 - October 1965 - 773-9-198

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FOREWORD

This report was prepared by the Propulsion and Power Branch of the Systems Support Division of the Directorate of Crew & AGE Subsystems Engineering. The work was initiated under Project 3147, "Turbojet Engine Analyzer System," and Task 314705, "Military Turbojet Engine Spectrometric Oil Analysis." Don C. Kittinger was the task engineer. The report constitutes an evaluation of the effectiveness of the spectrometric oil analysis technique in indicating incipient engine failure of turbojet engines. The period covered by the report is from July 1963 through October 1964 when oil samples from turbojet engines of aircraft of the Tactical Air Command were analyzed by the Naval Air Station (NAS) laboratory at Pensacola, Florida.

This report was submitted by the authors 11 June 1965.

This technical report has been reviewed and is approved.

JOSEPH C. SCOTT
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Engineering

ABSTRACT

A turbojet engine may represent 20 to 35% of total aircraft cost, and a large proportion of overall maintenance spending goes toward assuring its serviceability. In the area of flight safety, particularly with single-engined aircraft, the engine more than any other airborne equipment has an influence upon accident, incident, and mission completion. Consequently early warning of an engine failure trend is of immense importance and the monitoring of oil system contamination is a potentially rewarding technique in this area.

The objective of Task 314705 was to investigate (with particular reference to military turbojet engines) the technical validity of the spectrometric oil analysis approach to the identification of abnormal engine wear and impending engine failure. Program procedure called for the routine extraction of engine oil samples from aircraft at various bases and the mailing of these samples to the NAS laboratory at Pensacola, Florida for analysis. Evaluation has been concentrated on a sixteen month period from July 1963 through October 1964 when the laboratory analyzed over 7000 oil samples and prescribed engine maintenance as thought necessary from analysis results.

To assess validity of the spectrometric technique, findings of maintenance actions directed by the laboratory were monitored by SEG. Over the first twelve months of the period under review, analysis results showed a high enough metal contamination level for the laboratory to direct maintenance action on 27 engines. Unfortunately, engine examination data relative to seven of these engines was lost but, of the remaining twenty engines, 55% were found to be defective. There was no mechanical evidence to prove analysis findings in 45% of the cases. Over the last four months of the period correct predictions rose to 70% of the engines examined, and it is reasonable to suppose that this figure will be improved upon as threshold limits become more firmly established and operating techniques are improved.

The task has shown that a sound technical foundation exists for the spectrometric technique. This does not mean that in every case analysis indication will be substantiated by maintenance findings and, at the present state of the art, it may be that of every ten engines pulled or examined some three or four will be found to be apparently serviceable. This test has not proved that the program is cost-effective if considered solely as a means of indicating defects before progression to more costly repair or replacement. However, from the flight safety aspect, and because of the large financial saving which occasionally will accrue from crash prevention, the technique must be held to be cost-effective with respect to single-engined aircraft. This may not be so for multiengined aircraft.

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SECTION I

INTRODUCTION

1. BACKGROUND

Any machine will suffer some degree of wear as its various parts move against each other and, in an oilswept system, the wearing away of bearing surfaces will result in oil contamination by the metallic particles produced. An abnormal amount of wear metal production is a symptom of failure which, if recognized, will serve to direct remedial action. For some time, filters and detector plugs have been used to collect and disclose the larger metal flakes or particles carried around by the lubricant. However, a method to reveal the submicroscopic particles generated in the first stages of engine wear is advantageous and, if the nature and degree of this metallic contamination can be discovered, the wearing surfaces can be identified and the severity of wear assessed. Spectrometric analysis of oil samples taken from the system being monitored has this capability. With the spectrometric technique the contaminating metallic atoms in the sample are energized to a state where they absorb or emit characteristic light spectra the wavelength and intensity of which will, respectively, identify and show the quantity of the metal present. Usually, for spectrological purposes, a specimen is vaporized by heat energy and the light output separated into its component parts (by wavelength) at a defraction grating. The spectral light then passes through exit slots so positioned in the focal curve as to receive the wavelengths of the various metals in the sample. The device may require photomultiplier tubes positioned behind the wear metal exit slots to transform the spectral light into electric current for amplification and calibration into parts per million at a measuring device.

2. PREVIOUS DEVELOPMENT

The technique of determining the health of engine oil-wetted parts from the degree of wear metal contamination in the lubricant is not new. The main requirement is the establishment of a normal wear metal concentration and the application of this standard to subsequent testing. These normal limits have been arrived at for many reciprocating engines, gearboxes, and transmissions. Their establishment for gas turbine engines is relatively new. One of the earliest applications of the technique is ascribed to a railroad company in the 1940's and the Navy and Army have been active in the field (principally with piston-engined aircraft) since 1955 and 1960 respectively.

3. ORIGIN OF TASK

In March 1961, Project 3147 (which covered the development of a jet engine analyzer system) was amended to include Task 314704, an investigation of the spectrometric oil analysis technique. Initially oil and exhaust carbon samples were taken from Strategic Air Command (SAC), and later from Aeronautical Systems Division (ASD), aircraft operating out of Wright-Patterson AFB using analysis facilities of the Cleveland Technical Center, Inc. However, no work of any importance was accomplished in this way and at the end of 1962 the program was greatly enlarged and reconstituted under Task 314705. This task had the objective of evaluating the oil analysis technique as a maintenance tool for military turbojet engines, and plans were made to monitor engines of three different models at various Tactical Air Command (TAC) bases and to utilize the spectrometric analysis capability of the Naval Air Station laboratory at Pensacola, Florida.

SECTION II

ORGANIZATION OF THE PROGRAM

1. EARLY OBJECTIVES

Accomplishments of Task 314705 called for two early objectives:

The establishment of threshold limits for the different turbojet engines; and

The utilization of threshold limits as corrective maintenance criteria.

Simply, a threshold limit may be defined as the level at which metal particulate contamination of the oil is indicative of a degree of engine wear that justifies some kind of maintenance action. Whether this action is merely an increased rate of sampling, minor rectification, or engine teardown depends upon an educated assessment of data. The first aim of the task, therefore, was the establishment of the differences between normal and abnormal wear metal concentrations so that these standards could be applied later in the program. To this end, initial oil samples from each of the engines in the program were taken and analyzed and analysis results compared and studied. Teardown examinations were then ordered on those engines where metal contamination appeared abnormally high or grossly different from the norm of all the engines. From correlation of the teardown reports with their related analysis findings, NAS Pensacola was able to set provisional threshold limits which, in some cases, were refined as the program progressed and experience was gained. These threshold limits, established in parts per million (indicated), for the analysis of 7808 oil on equipment calibrated to 1100 oil are shown in Table I.

2. INDOCTRINATION

Accomplishment of the objectives of the program called for an accurate and easy flow of information between the TAC bases concerned, SEG at Wright-Patterson AFB, and NAS at Pensacola. Project officers were established at each base and made responsible for the overall conduct of base participation including sampling procedure, personnel training, and data transmission. Base participation was preceded by a personnel indoctrination program which emphasized the various requirements for successful sampling. Additionally, a Navy training film was shown before the start of the program at each base and periodically during the program.

TABLE I

THRESHOLD LIMITS
PPM (INDICATED)

ELEMENTS		TYPE ENGINES		
		A	B	C
Aluminum	(Al)	5	9	9
Iron	(Fe)	29	29	29
Chromium	(Cr)	5	7	9
Silver	(Ag)	3	3	3
Copper	(Cu)	5	9	21
Tin	(Sn)	15	18	21
Magnesium	(Mg)	18	18	12
Nickel	(Ni)	7	29	9
Silicon (Si) and lead (Pb) were monitored initially but since they proved not to be significant no threshold limits were set.				

SECTION III

MECHANICS OF THE PROGRAM

1. ACTION AT BASES

Under TAC test 63-26, routinely at every ten flying hours and on other occasions when specially called for, oil samples were drawn off by the operating activities by a technique designed to ensure that the sample was truly representative of the oil circulating in the system. Instructions were issued which covered:

The taking of samples before the addition of new oil.

The taking of samples while the oil was agitated after engine run.

The use of expendable polythene sampling tubes (special to the engine installation) which go deep enough into, but do not touch the bottom of, the oil tank.

Strict regard for cleanliness and contamination prevention.

After extraction the oil was drained from the tubes into a small glass bottle, packed with an oil analysis request form, and dispatched to the NAS laboratory at Pensacola, Florida. A duplicate copy of the request form was sent to SEG at Wright-Patterson AFB. For later use in evaluation and correlation, the analysis request form contained the following data:

Operating unit, sample number, and date of sample.

Engine model and serial number.

Aircraft model and serial number.

Engine operating hours since overhaul or new.

Engine operating hours since oil change.

Number of previous engine overhauls, the last overhauling activity, and the engine hours at which the overhaul was made.

The type of oil.

The reason for sample submission.

2. ACTION AT THE NAS LABORATORY

The samples for Task 314705 were analyzed spectrometrically for (parts per million by weight) content in respect to the ten elements aluminum, iron, chromium, silver, copper, tin, magnesium, nickel, lead, and silicon. The analytical instrument used in the later stages of the program was a Baird Atomic, 3 meter, emission spectrometer of special manufacture which delivers analytical results automatically in parts per million to an IBM 870 document writing system consisting of an IBM 836 card punch and an IBM 866 slave typewriter. The completed IBM punch card identifies the sample by date, base, and engine serial number, shows the reason for the taking of the sample, indicates the hours since overhaul and oil change, and lists the concentrations of the ten elements. Having a full understanding of the nature of the task and associated problems and from knowledge of threshold limits, Pensacola was then able to recommend to the operating activity any special action required. If the sample showed no deviation from the norm then no action was called for; alternatively the decision to increase rate of sampling or specify particular maintenance action was decided from the degree and/or rate of increase of the contaminant.

3. ACTION AT SEG (SEMSJ)

The routine part of program management by SEG (SEMSJ) was in coordinating the efforts of bases, laboratory, and overhaul depots. Engine and operating data was extracted from the oil analysis requests submitted by the bases and married to the related analysis results and maintenance recommendations shown on the record cards from the NAS laboratory. Engine teardown reports were processed, and overhaul findings and the results of base maintenance actions studied for correlation with the laboratory recommendations which called for the actions. Finally the data was assembled for computer runs and the resulting reports reviewed for trend analysis.

SECTION IV

SYNOPSIS OF PROGRAM

1. EVALUATION PERIODS

The theory of the spectrometric oil analysis technique is that, if an engine lubricant is ''abnormally'' contaminated by wear metal particles, an abnormal and possibly dangerous amount of wear is taking place somewhere in the engine. The first laboratory requirement, therefore, was to establish a demarcation line between normal and abnormal contamination levels. To achieve this an initial analysis was made of oil samples from all the engines in the program, and those engines with an analysis result showing a high deviation from the norm were considered to be discrepant engines. Because of this the laboratory could make no recommendations for maintenance nor could the program be said to be started until many samples had been collected, analyzed, and compared. Further, proof of the validity of the theory was lacking until the maintenance findings of the earlier recommended actions were made known. For these reasons, although sampling started in May 1963, the start of the evaluation period has been fixed at July 1963 after recommendations for maintenance began to be made. Further, the time under evaluation has been considered in two separate periods, the first twelve months of evaluation and the final four months after threshold limits had been substantiated or revised as a result of early maintenance findings. These two separate evaluation periods are:

July 1963 through June 1964, and

July 1964 through October 1964.

2. PERIOD JULY 1963 THROUGH JUNE 1964

a. Over the period July 1963 through June 1964 there were 27 occasions on which the laboratory considered oil samples to be sufficiently metal-contaminated to justify recommendation for maintenance action. In 11 of these cases some deterioration of the engine or its associated components was found and rectified. In 9 cases there was no evidence of defect to explain the high readings, and all engines which remained in the program after the fruitless investigation continued to operate satisfactorily with normal contamination levels. In 7 cases evidence of the maintenance work called for by the laboratory was lost in channels and the results could not, therefore, be categorized. Table II identifies the 11 engines of the three different models on which maintenance findings positively correlated with the laboratory recommendation, and details the contaminating metal and parts found defective.

TABLE II

FIRST YEAR - POSITIVE CORRELATIONS

ENGINE NR	CONTAMINANT	DEFECTIVE PARTS IDENTIFIED
A1	Copper	Worn nr 4 bearing
A2	Iron	Worn nr 4 bearing
B1	Iron and magnesium	Scored oil pump
B2	Iron	Worn gearbox and oil pump
B3	Iron	Worn gearbox
C1	Iron	Worn lube pump
C2	Copper	Filings in nozzle pump
C3	Iron	Worn accessory gearbox
C4	Iron and copper	Worn auxiliaries
C5	Copper	Worn nozzle pump
C6	Copper	Worn lube pump

The 9 cases in which no evidence of engine failure was found consisted of one model A (A3), four models B (B4 to B7), and four models C (C7 to C10). The 7 cases which were uncategorized because of lack of backup information consisted of two models A (A4 to A5), three models B (B8 to B10), and two models C (C11 to C12).

b. During this phase of the program there were two very significant occurrences concerning engines not included in the foregoing categories. In the first case (engine A7) considerable delay occurred in the transmission of an oil sample from base to laboratory, and a recommendation from the laboratory (on the basis of high metal contamination) for precautionary flights only and an increased rate of sampling was too late to prevent engine failure in flight. It is reasonable to suppose that the same laboratory recommendation following prompt sample delivery would have alerted the base in time to prevent the in-flight failure. In the second case (engine B19) the sample was again delayed in transit and, although the metal contamination was high enough to justify the laboratory telephoning the base with a recommendation to ground the aircraft, it was too late to prevent in-flight engine failure and aircraft crash. The great imponderable of the program is an assessment of what might have happened to any aircraft had not its installed engine been rectified at the time that oil analysis indicated a defect. The fault might have revealed itself on the ground during engine checks or in the air with little inconvenience to the pilot. Possibly it might never have caused trouble. The significance of the last two occurrences is great therefore, since in both cases oil analysis indicated discrepancies which did, in fact, terminate disastrously.

3. PERIOD JULY 1964 THROUGH OCTOBER 1964

Over the period July 1964 through October 1964 categorized maintenance findings were found to correlate positively with analysis indication on 70% of laboratory recommendations. This was an increase of 15% from the results over the first twelve months. In fact, of a total of eleven recommendations engine defects were found in seven cases, engines were examined without defects being found three times, and there was only one case of data loss. Table III identifies the seven engines of different models on which maintenance findings correlated positively with the laboratory recommendations, and details the contaminating metal and parts found defective. The three cases in which no evidence of engine failure was found consisted of two model B (B17 to B18) and one Model C (C14). The one case not categorized because of lack of backup information was engine model A6.

TABLE III

LAST FOUR MONTHS - POSITIVE CORRELATIONS

ENGINE NR	CONTAMINANT	DEFECTIVE PARTS IDENTIFIED
B11	Iron	Worn nr 4 bearing
B12	Iron	Worn nr 4 bearing
B13	Iron	Worn nr 4 bearing
B14	Iron	Worn nr 4 bearing
B15	Iron	Worn nr 4 bearing and damaged nr 4 pump
B16	Iron	Numbers 2 & 4 bearings worn
C13	Copper	Worn emergency nozzle pump

SECTION V

COST EFFECTIVENESS

1. BASIS OF COST EFFECTIVENESS

The full cost effectiveness of a spectrometric oil analysis program cannot be measured since no precise figures can be put upon lives which might be lost or the deterioration in morale due to engine failures which result in aircraft crashes. Similarly nebulous with respect to cost is the reduction in mission effectiveness or the scheduled service disruption occasioned by in-flight shutdowns. With these limiting factors some assessment of dollar effectiveness can be made by comparing the cost of spectrometric monitoring and its associated maintenance actions with the possible or probable dollar savings in forestalling engine defect progression or preventing in-flight engine failure which could result in aircraft loss. In running the program, costs are generated by management, sample collection man-hours, the oil analysis procedure per se, and, by far the greatest, the recommended maintenance actions. Additionally, some computer time may be required for program control and trend analysis. With respect to maintenance actions it is reasonable to charge only the ''failures'' against the program (i.e., when engines are pulled or examined apparently needlessly) since, without oil analysis, the best that could happen to the engines which had proved defective would be that they were revealed as faulty by other means, in which case similar maintenance costs would arise.

2. ASSESSED COSTS

Table IV shows the various average replacement costs of the aircraft and engines in the program, the cost of engine Teardown Deficiency Report (TDR) or overhaul at depot, the assessed average cost of Jet Engine Field Maintenance (JEFM) at base, and an assessed figure per oil sample. In assessing this last figure notice has been taken that various commercial organizations have quoted from $3 to $6.50 per sample while in-house analysis probably costs about $1.50 per sample. In this evaluation a figure of $5.00 per sample has been used, this figure to cover management, monitoring, sample collection, indoctrination, and over-head.

TABLE IV

ASSESSED APPLICABLE COSTS

Average replacement cost of aircraft in program	$1,031,000
Average replacement cost of engines in program	$ 200,000
Cost of depot TDR	$ 24,550
Cost of depot overhaul	$ 17,950
Average JEFM (base) cost	$ 5,000
Sample analysis including management, monitoring, collection, and other overhead	$5 per sample

3. COST ANALYSIS FOR THE PERIOD JULY THROUGH OCTOBER 1964

a. By the last four months of the evaluation period threshold limits had been set and in some cases revised, and the program could be said to be reasonably soundly established. During this period 2722 samples were analyzed and, on seven of the ten engines categorized, laboratory recommendations were substantiated by maintenance action. In only three cases were engines found to be apparently serviceable when examined. The level of maintenance carried out and the findings are shown in Table V. From the assessed item costs in Table IV and the negative actions detailed in Table V, the total cost of running the oil analysis program for the four-month period, July through October 1964, can be computed and projected to an annual rate. This is shown in Table VI. From Tables V and VI it will be seen that, to run a program of the size that would over a year positively identify 21 engines as defective, the annual dollar outlay to make such identification possible would be $144,480. This outlay would be made up of the basic program costs and the amount spent on the erroneous removal and/or examination of apparently good engines. It is now necessary to consider whether it is worthwhile to spend $144,480 to identify the 21 defective engines at a time when they could be rectified with a minimum of effort and expense. If oil analysis had not identified them at this time, any of the following conditions might have been brought about:

(1) The engine wear revealed by oil analysis would have proved to be transitory and without deleterious effects to any of the engines. In this case the program would have been a total loss.

(2) The defects revealed by oil analysis would have been discovered by normal maintenance procedures. If this occurred concurrently with or shortly after the oil analysis indication, no progressive engine damage would have occurred and again the program would be worthless. Conversely, if normal maintenance did not indicate the defects until some time after oil analysis was capable of doing so, further engine deterioration might have taken place and repair and replacement costs would consequently be higher. However, for the program to be considered worthwhile under these latter conditions, it must be assumed that this difference in maintenance costs would cover the $144,480 outlay. That is to say that, on the average, each of the engines proved defective would have suffered further progressive deterioration to an average amount of $7000 per engine between the time when they would have been recognized by oil analysis and the time they were found by normal maintenance.

(3) The defects indicated by oil analysis would not have revealed themselves to other maintenance procedures and would have further deteriorated to the point where damage rendered the engine worthless. In fact, if oil analysis prevented just one of the 21 engines in the program from deteriorating to this stage, the dollar saving would more than pay for the entire program. (Based upon engine replacement value less the cost of the maintenance action to identify the discrepancy.)

(4) The defects indicated by oil analysis would not have revealed themselves to other maintenance procedures and further engine deterioration would have occurred so that inflight engine failure caused the aircraft to crash. If oil analysis prevented this happening with just one of the 21 defective engines, the dollar saving would be equivalent to seven times the program costs. (Based upon aircraft replacement value less the cost of the maintenance action to identify the discrepancy.)

b. As previously stated it is impossible to say categorically what would have happened to any one of the 21 defective engines had it not been rectified at the time that oil analysis indicated a defect. However, the two occurrences when oil analysis indicated defects which slow reaction time allowed to deteriorate further (to cause a crash and terminal engine failure respectively) suggest a strong probability that without oil analysis some of these 21 engines would have become progressively more defective and possibly dangerously so.

TABLE V

LAST FOUR MONTHS
CORRELATION BETWEEN ANALYSIS AND MAINTENANCE

ENGINE NR.	LEVEL OF MAINTENANCE		ANALYSIS INDICATION SUBSTANTIATED	
B12 & B17	Depot TDR		Yes	
B13	Depot TDR		No	
B11, 14, 15, & 16	JEFM (base)		Yes	
C13	JEFM (base)		Yes	
B18	JEFM (base		No	
C14	JEFM (base)		No	
TOTALS	TDR positive	2	TDR negative	1
	JEFM positive	5	JEFM negative	2
PROJECTED ANNUAL RATE	TDR positive	6	TDR negative	3
	JEFM positive	15	JEFM negative	6

TABLE VI

FOUR-MONTHLY AND PROJECTED ANNUAL COSTS

MAINTENANCE ACTIONS		FOUR-MONTHLY RATE	PROJECTED ANNUAL RATE
1 completed TDR	1 X $24,550	$24,550	$ 73,650
2 completed JEFM's	2 X $ 5,000	$10,000	$ 30,000
Sample analysis	2722 X $5	$13,610	$ 40,830
	TOTALS	$48,160	$144,480

SECTION VI

PROJECTED RELEVANT RATES AND COSTS

During the period July through October 1964 the average number of engines in the program at any one time was 343 and from these engines 2722 samples were sent to Pensacola for analysis. Because of analysis findings the laboratory recommended ten maintenance actions, seven of which confirmed analysis indication and three of which involved apparently needless examinations. Table VII shows the various relevant rates and costs projected to an annual rate.

TABLE VII

PROJECTED ANNUAL RATES

1. Annual program cost (Table VI)	$144,480
2. Average number of engines in program at one time	343
3. Samples analyzed per year (2,722 X 3)	8,166
4. Aircraft/engine flying hours per year (24,368 X 3)	73,104
5. Number of maintenance actions recommended (10 X 3)	30
6. Number of cases of correlation of maintenance with analysis	21
7. Number of times engines needlessly examined (3 X 3)	9
8. % of average number of engines in program confirmed defective per year	6%
9. Flying hours per confirmed defect	3,480
10. Cost per flying hour for oil analysis	$ 2.00
11. Cost per confirmed defect	$ 7,000
12. Overall cost per sample	$ 17.70
13. Cost per year per engine monitored	$ 420

SECTION VII

COMPUTER PROGRAM

As an aid in evaluating the large volume of data collected under this task a computer program (Problem Number 63-255-00) was established with the digital computer section (SESCD) at Wright-Patterson AFB. The various reports produced under this Problem Number were as follows:

Report 1. — The first report covered general data. The results of each of the analyses were recorded against the oil sample number, the model and serial numbers of the aircraft and engines concerned, and the base from which the sample originated. Also, the date of dispatch of the sample, the number of days the sample was in transit to the laboratory, and the average hours between samples were recorded.

Report 2. — The second report, which was in three parts, was used in assessing threshold limits for each of the three models of engine. To achieve this it was necessary to segrate the sample results into stepped increments of particulate contamination and to plot the number of times that each increment had occurred. Figure 1 shows the type of graph producible from this information and illustrates how an interim threshold limit can be determined from apparent engine discrepancies.

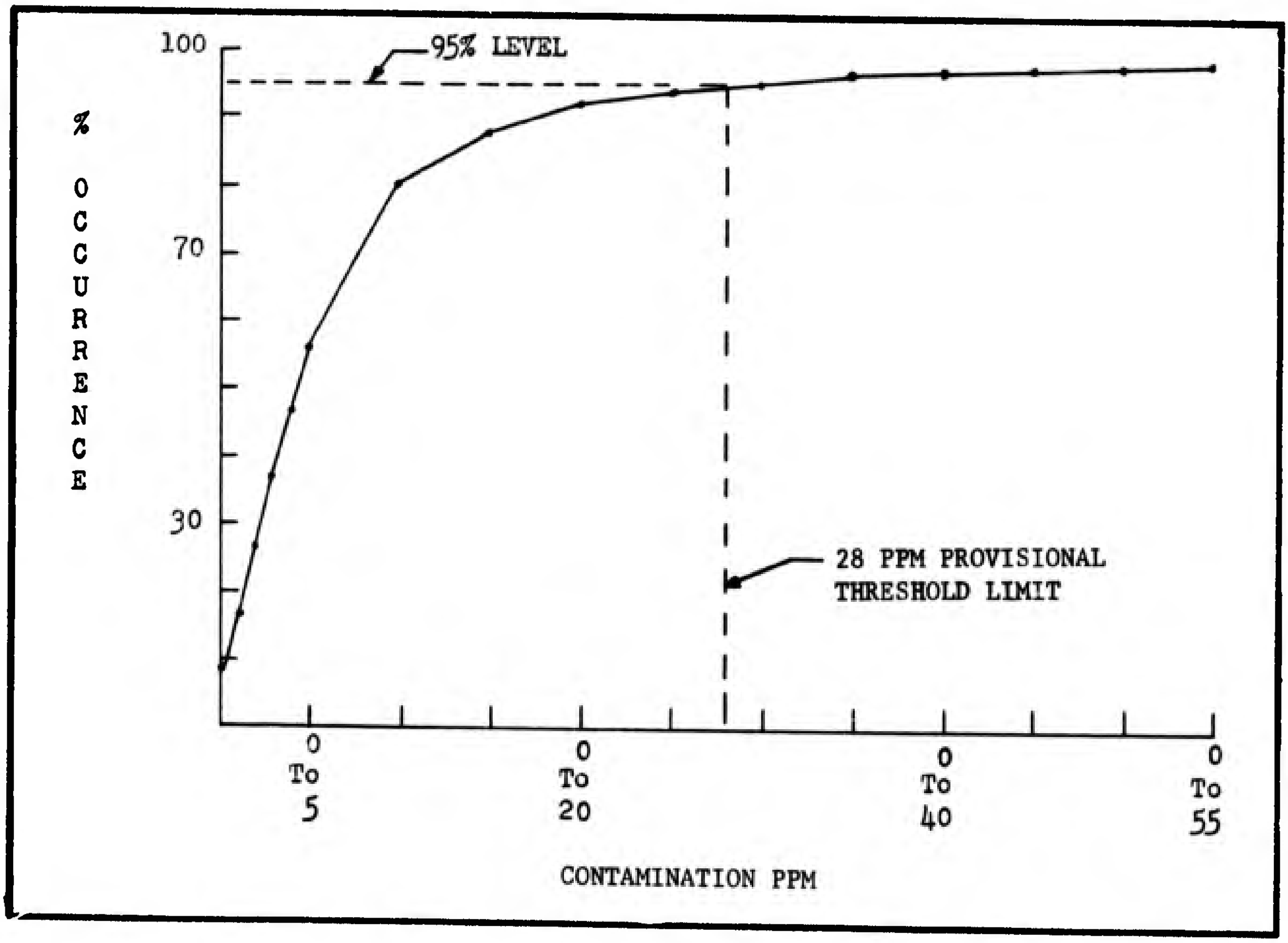


Figure 1. Cumulative Frequency Distribution, Engine Type B, Iron Contamination

Report 3. — If the spectrometric technique is to be credible, any analysis indication of an increase in contamination level must be meaningful. Consequently, the equipments used must have acceptable repeatability capabilities and analysis of consecutive samples from any good engine should be sensibly constant. That is to say that, where heavy or increasing contamination is indicated, there must be more than a reasonable probability that the engine concerned is defective. To show that erratic or irrational contamination readings were not randomly produced, the contamination differences between all consecutive samples were calculated and graphed. The report showed that in 99% of the cases the differences were slight.

Reports 4, 5, 6, 8, and 9. — All these reports were concerned with efforts to relate metal contamination to engine running hours since new, overhaul, or oil change. Figure 2 shows the average contamination levels for the metals iron, copper, and nickel for all samples taken during 50 hour increments of life of engines type B. It will be seen that the average readings for nickel and copper are random and show no trend that can relate average contamination level with engine life. Although, the results for iron are more nearly what would be expected, i.e., an initial contamination reduction after the engine is "run in" and an increase of wear towards the end of engine life, the average wear is still less than 50% of threshold limit at maximum engine life. The same data relative to engines type A and C were similar in result. It is interesting to note that the rate (in relation to engine life) at which actual defects were indicated by oil analysis follows the same pattern, that is, almost all the proved actions occurred in either the first or last third of engine life. However, the rate of these actions towards the end of engine life is not significant enough to suggest a reduction of time between overhauls.

Report 7. — This report counted and averaged the engines sampled during the program to establish some of the data used in this Technical Report.

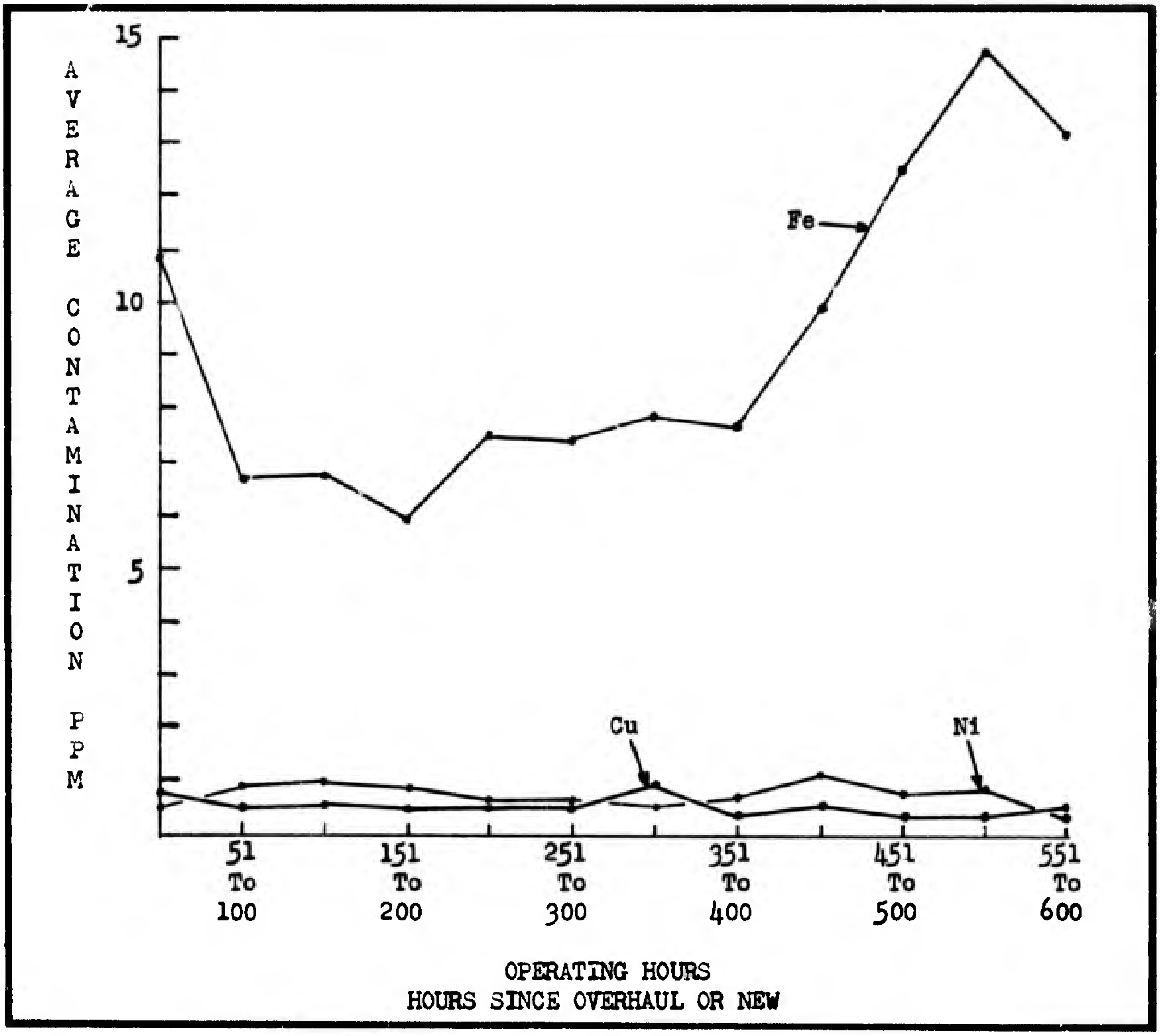


Figure 2. Average Contamination of Iron, Copper, and Nickel Versus Operating Hours, Engine Type B

SECTION VIII

CONCLUSIONS

1. QUESTIONS TO BE ANSWERED

The study was undertaken to evaluate the effectiveness of the spectrometric oil analysis technique in giving early warning of incipient engine failure of military turbojet engines. This evaluation called for answers to the following questions:

a. Are presently available equipments for, and techniques in, spectrometric oil analysis capable of speedily and accurately measuring contaminating metals in lubricating oils at concentrations between 1 and 500 parts per million by weight?

b. Is it possible to set up threshold limits or demarcation lines so that metal contaminations above or in excess of these limits can be taken to be indicative that engines are defective?

c. Can it be shown by engine examination that the defects indicated by oil analysis are significant enough to be likely to progress to a state involving more costly repair or danger to the aircraft?

d. Can the expense of the program and its associated maintenance actions be justified by the dollar saving represented by the difference between:

(1) The cost of repairs to engines found by oil analysis to be defective in the incipient stage of failure, and

(2) The repair or replacement cost of the same defects allowed to progress to the stage at which they are discovered by other means or revealed themselves catastrophically?

2. EQUIPMENT AND TECHNIQUES

Commercial instruments are available from several manufacturers which, in a laboratory environment, will measure elemental metal contamination indicative of engine wear to the standards of accuracy required. However, reliance upon central laboratory facilities with consequent sample mailing delays may not be the optimum way to discharge the program, and an AFSC (Systems Engineering Group) development of simplified analyzers for base level use will produce two prototype instruments in late 1965. Techniques of sample collection and analysis used during the task were adequate for the purpose of study. However, although the analytical data of the several Air Force laboratories now engaged in this task may be homogeneous, interchangeability of results with other Services or commercial facilities is not presently possible. Further studies and agreements are required on the use of common, identical calibration standards and the supply of uniform standard reference specimens of certified accuracy.

3. THRESHOLD LIMITS

By resolution of the results of oil analysis from a representative number of engines of one type or model, it is possible to set a demarcation line above which the samples can be said to be abnormally contaminated and the associated engine discrepant. This does not mean that the engine can yet be considered to be defective but only different. Action after the analysis of the first discrepant sample might call for merely an increased rate of sampling or a special check sample. Recommendations for minor rectification or engine teardown would be made only after an educated assessment of data.

4. THE SIGNIFICANCE OF DISCREPANCIES REVEALED

a. In Section IV, Synopsis of Program, reference is made to two significant occasions when, because of delay in sample transmission, the maintenance actions indicated as necessary by oil analysis were not taken. In neither case was the discrepancy revealed by other maintenance methods, one of the aircraft involved crashed, and the second made a difficult forced landing after complete engine failure. It cannot be said with any certainty that normal maintenance action would have been similarly blind in respect to all or even any of the other engine defects revealed by oil analysis and confirmed by engine inspection. Indeed, the program illustrated an opposite example (Engine C15, Table IX) when a defective transfer gearbox was revealed by ground checks for engine vibration before a laboratory request for a check sample (to confirm a high contamination reading) was received at the base.

b. No categorical answer can be given as a result of this program to a question as to whether or not the other defects revealed by oil analysis would have progressed to a state of involving more costly repair or endangering the aircraft. There are only very strong probabilities in this respect. For instance, when engine examination reveals badly scored roller bearings, although this confirms the oil analysis, finding it does not necessarily mean that the engine is in imminent danger of failure.

c. If a more definite answer is needed on program effectiveness, a base, operating multiengined aircraft (with something in excess of 100 engines), should be monitored as a separate task. Without the same danger of aircraft loss as exists with single-engined aircraft, it would be reasonable to run the same routine sampling procedure as was used in this program but merely to record the analysis answers and the maintenance actions indicated. Eventually, the effectiveness of what might have been done as the result of oil analysis could be compared with conditions brought about by progress of the engines to normal overhaul life, to defects detected by routine maintenance, or to eventual failure.

5. JUSTIFICATION OF COST

a. The basic costs of an oil analysis program arise from management, sample collection, and oil analysis per se. The amount spent in this way will be established by the number of engines monitored, the rate of sampling, and the purchase and operating costs of the spectrometers used. This expenditure, unvarying with success or failure of the program, amounts to only a minor part of the overall costs. The purpose of the program is to assess potential engine failures and to direct their timely correction with minimum maintenance costs. It is this direction of maintenance action that, when erroneous, accounts for the major part of the program expenditure since misdirected maintenance can cost up to $25,000 for each engine overhaul and report. Conversely, when correlated, direction of maintenance constitutes the whole potential of the program and, considering the average replacement cost of the aircraft monitored in this task, might save over a million dollars for each or any action. (This amount represents the difference between the replacement cost of the aircraft and the cost of a maintenance action which forestalled engine defect progression to in-flight failure and aircraft crash.)

b. It has been shown that savings can be made by the early indication of engine defects which would otherwise progress to in-flight failure (Section IV, Synopsis of Program). Although the rate at which such savings would arise cannot be proved, there is much more than a strong probability that it would be such as to make the program outstandingly cost-effective for single-engined aircraft.

c. The logical inference is that:

(1) Spectrometric oil analysis is valid procedure for the assessment of failure probability of turbojet-engine oil-wetted parts.

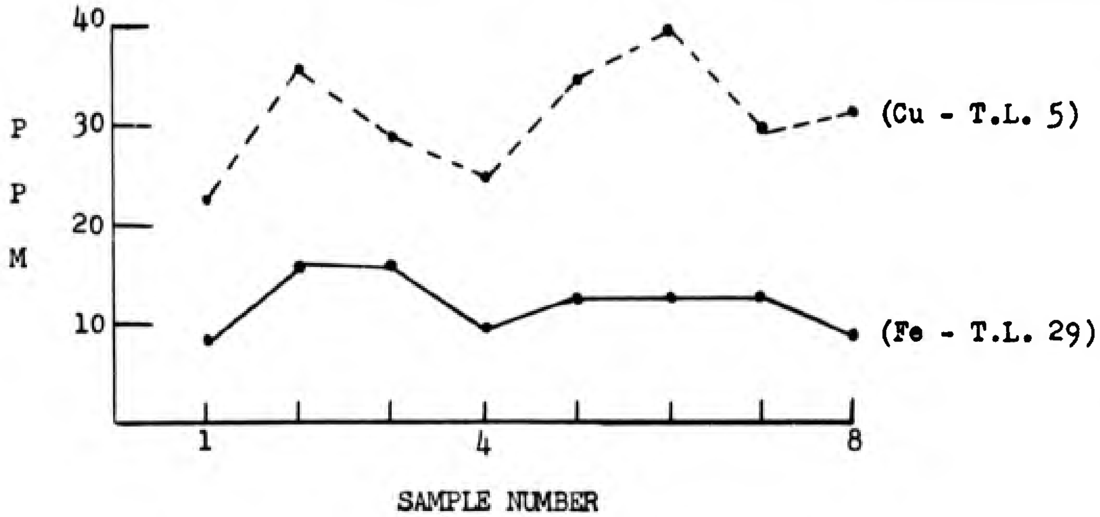
(2) With the present state of the art some erroneous indications of engine defects are to be expected.

(3) Unless the probabilities of crash prevention are accepted, basic program costs together with the cost of unnecessarily removing and/or examining good engines may not be recovered by the savings arising from timely repair before defect progression.

(4) From the flight safety aspect and because of the large financial savings which occasionally will accrue from crash prevention, the technique must be held to be cost-effective with respect to single-engined aircraft. This may not be so for multiengined aircraft.

APPENDIX

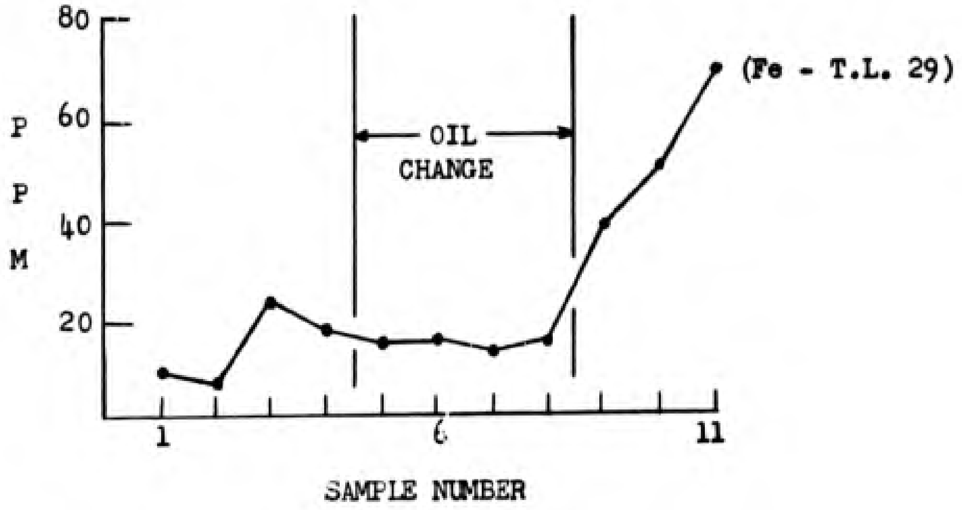
DATA ON INDIVIDUAL ENGINES INCLUDING GRAPHICAL REPRESENTATION OF THE INCREASING WEAR METAL CONTAMINATION THAT GAVE RISE TO MAINTENANCE INVESTIGATION AND THE RESULTS OF SUCH INVESTIGATION



SMP. NR.	Hours Since		Analysis	
	O.H.	O.C.	Fe	Cu
1	7	7	9	23
2	17	17	16	36
3	21	21	16	29
4	26	26	10	25
5	28	28	13	35
6	28	28	13	40
7	32	32	13	30
8	36	36	9	32

On 25 March 1964 NAS Pensacola reported that copper contamination of an oil sample was high and requested that the sampling rate be increased to every five hours. By 1 April the copper content had further increased and "after every flight" sampling was recommended. By 17 April the copper reading was so high that NAS recommended the grounding of the aircraft until the discrepancy was discovered. The discrepancy was not discovered and the engine was sent for TDR. The TDR revealed wear on the Nr 4 bearing.

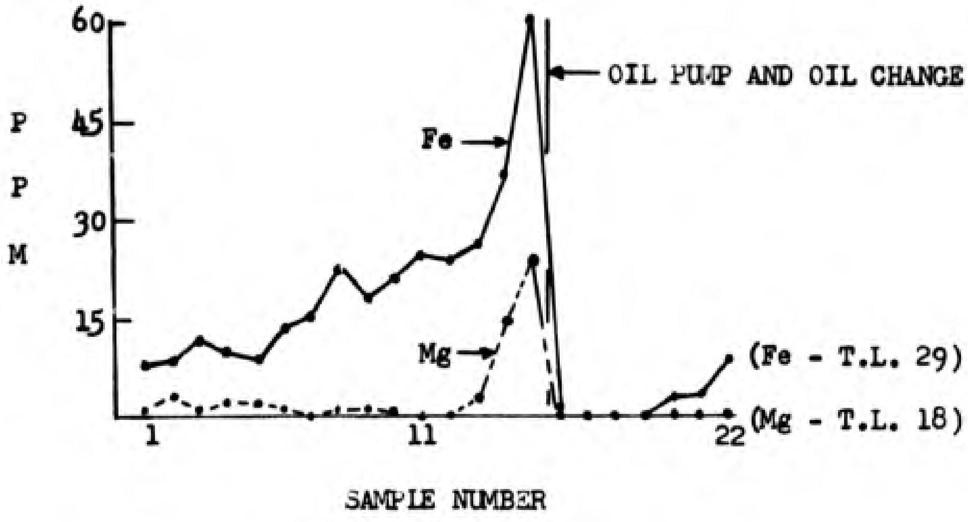
Figure 3. A1 Engine Data - Positive Correlation



SMP.	Hours Since		Analysis
NR.	O.H.	O.C.	Fe
1	214	34	9
2	224	44	7
3	247	67	24
4	271	91	18
5	272	1	14
6	294	23	15
7	313	42	13
8	335	64	15
9	364	23	39
10	284	43	50
11	389	48	69

On 13 December 1963 NAS Pensacola reported that a sample was iron-contaminated and recommended close supervision for two sampling intervals. The next two samples showed increasing iron (Fe) even though the oil was changed. Therefore, Pensacola recommended that the engine be sent for TDR, if the contamination source was not found. The engine was sent for TDR which revealed wear on the Nr 4 bearing, the bearing journal, and bearing spacer.

Figure 4. A2 Engine Data - Positive Correlation

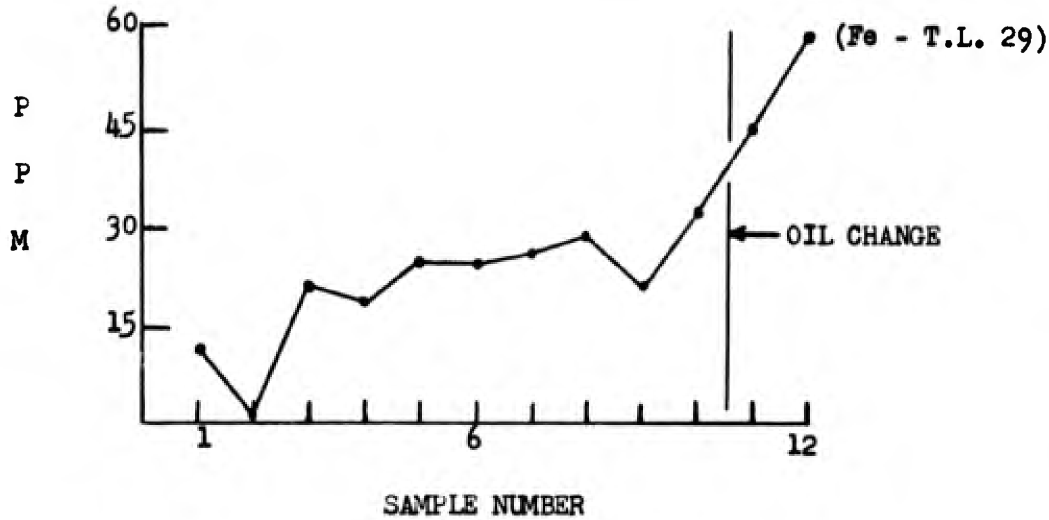


SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Mg
1	35	35	8	1
2	44	44	9	4
3	54	54	12	1
4	64	64	10	2
5	80	80	9	2
6	90	90	14	1
7	101	101	16	0
8	112	112	23	1
9	112	112	19	1
10	118	118	22	1
11	128	128	25	0

SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Mg
12	152	152	24	0
13	165	165	26	3
14	178	178	37	15
15	181	181	61	25
16	181	0	1	0
17	181	0	0	0
18	181	0	0	0
19	181	0	0	0
20	181	0	3	0
21	181	0	3	0
22	181	0	8	0

On 4 May 1964 NAS recommended that oil pump be inspected for damage indicated by high iron and magnesium. The base reported excessive scoring in boost and scavenge sections of oil pump.

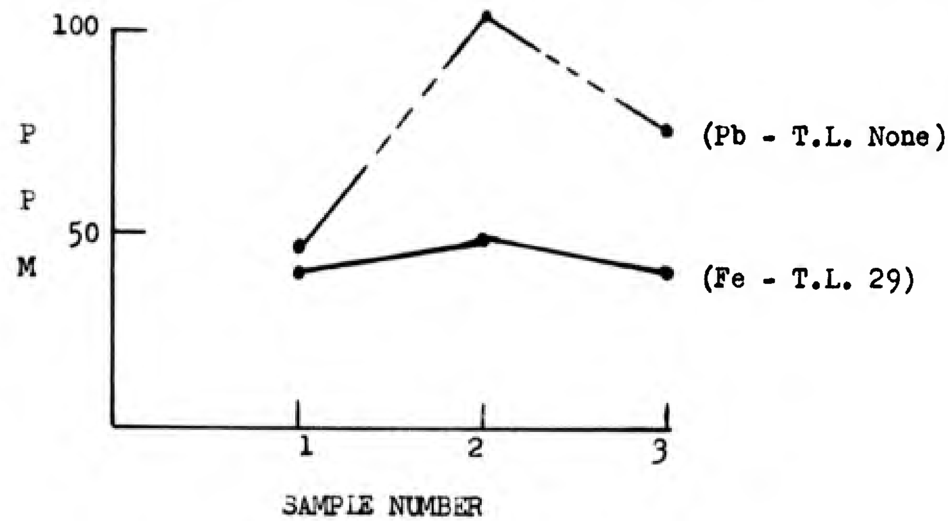
Figure 5. B1 Engine Data - Positive Correlation



SMP.	Hours Since		Analysis
NR.	O.H.	O.C.	Fe
1	286	86	12
2	300	100	2
3	309	109	22
4	322	122	19
5	333	133	25
6	344	144	24
7	355	155	26
8	367	167	29
9	379	179	21
10	392	192	32
11	401	1	45
12	408	8	59

On 1 November 1963 NAS Pensacola reported an increase in iron contamination from 32 to 45 ppm and recommended removal of the engine. A further sample received by Pensacola after this recommendation showed that iron content had risen to 59 ppm. Engine was removed and sent for TDR, which revealed wear in the accessory drive and also the inner walls of the pump bodies were scored, gouged, and eroded.

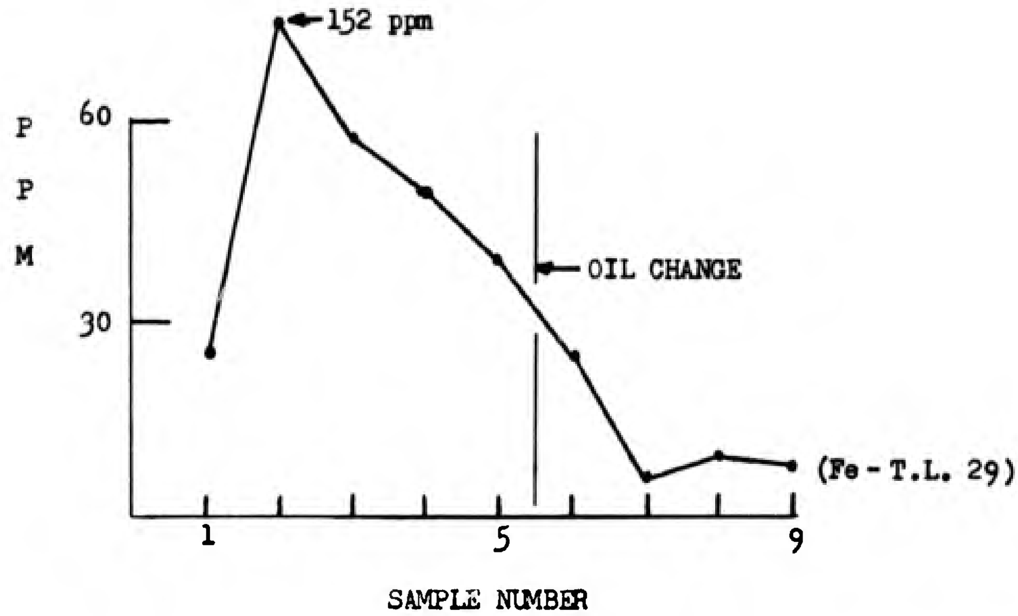
Figure 6. B2 Engine Data - Positive Correlation



SMP.	Hours Since		Analysis	
NR.	O.H.	O.C.	Fe	Pb
1	490	90	40	45
2	492	92	47	103
3	507	107	40	75

On 29 May 1963 NAS Pensacola reported sample contamination of above average iron and lead. The second sample showed a continuing increase in the contamination levels of the elements. NAS recommended the removal of the engine for a TDR. The TDR results revealed that the iron wear was coming from the accessory drive and the lead from the plating on the Nr 4 bearing. It was determined from this TDR and consultations with the engine manufacturers that the loss of lead from the engine parts has no significant effect on engine integrity. For this reason a threshold limit for lead was not established for the type of jet engines being monitored under this task.

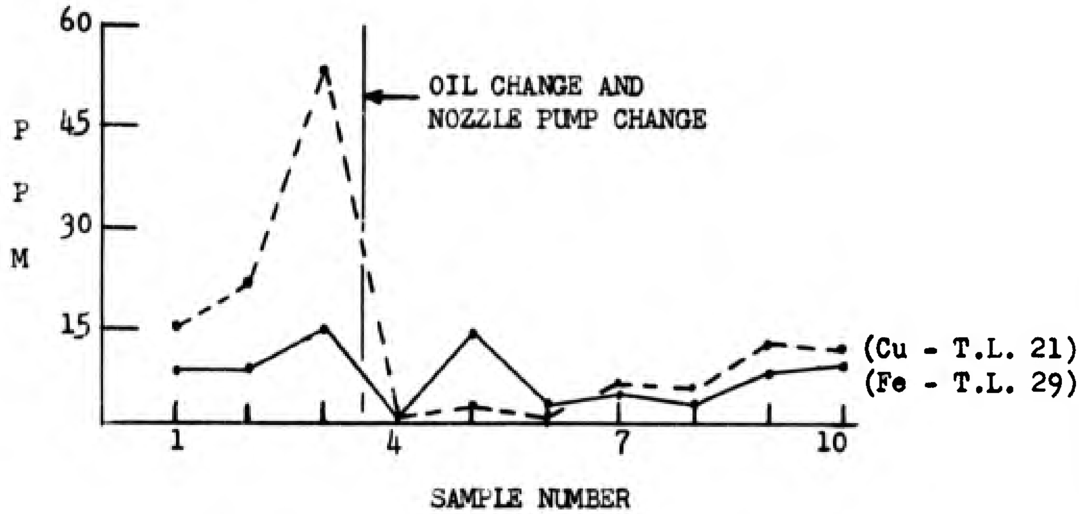
Figure 7. B3 Engine Data - Positive Correlation



SMP.	Hours Since		Analysis
NR.	O.H.	O.C.	Fe
1	113	113	25
2	126	126	152
3	138	138	58
4	146	146	50
5	146	146	40
6	146	0	25
7	146	0	6
8	146	0	10
9	146	0	8

On 19 May 1964 NAS Pensacola reported high iron in a routine sample and recommended grounding the aircraft pending a check sample. Further check samples of 26 May and 1 June confirmed the high iron reading and Pensacola recommended an inspection for the contamination source, suggesting auxiliary pumps and drives and gearbox. The base reported visual confirmation of wear in main lube pump and a change of this equipment. Subsequent check samples were analyzed as normal.

Figure 8. C1 Engine Data - Positive Correlation

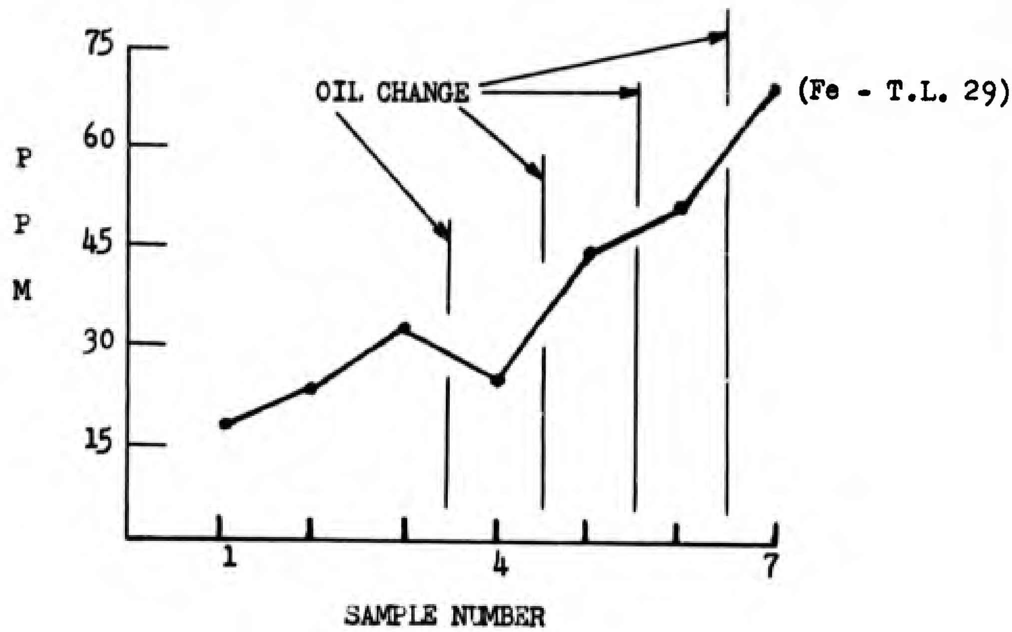


SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Cu
1	50	50	8	15
2	57	57	8	22
3	82	82	15	54
4	91	0	1	1
5	91	0	14	3

SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Cu
6	92	1	2	1
7	112	21	5	6
8	124	23	3	5
9	148	47	8	13
10	182	81	9	11

Between 27 March and 7 April 1964 analysis showed either high or marginal copper. By 13 May sample analysis showed copper to be high enough for NAS Pensacola to recommend grounding the aircraft and submission of check samples after ground running. At this time the unit changed the emergency nozzle pump and after flushing the system subsequent samples proved to be normal. Motivation for removal of the nozzle pump was the discovery of metal particles in the emergency nozzle system filters during inspection to determine the origin of the oil/metal contamination. Although, there was no visual confirmation of wear of the nozzle pump the metal particulate filter contamination is considered to correlate the oil analysis finding.

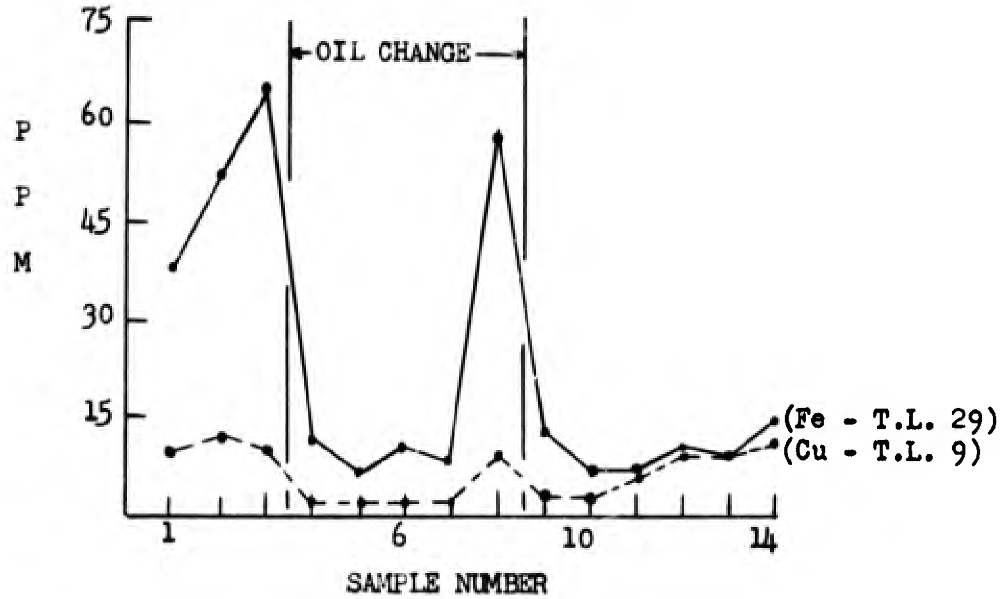
Figure 9. C2 Engine Data - Positive Correlation



SMP.	Hours Since		Analysis
NR.	O.H.	O.C.	Fe
1	589	3	18
2	599	13	23
3	611	25	33
4	620	6	25
5	647	13	44
6	684	22	50
7	693	9	69

As with engine C15, a sample showed high iron immediately prior to the engine being shipped for scheduled modification. The depot was requested to complete a TDR concurrently with modification, to determine the source of iron. The TDR revealed wear in the transfer gearbox.

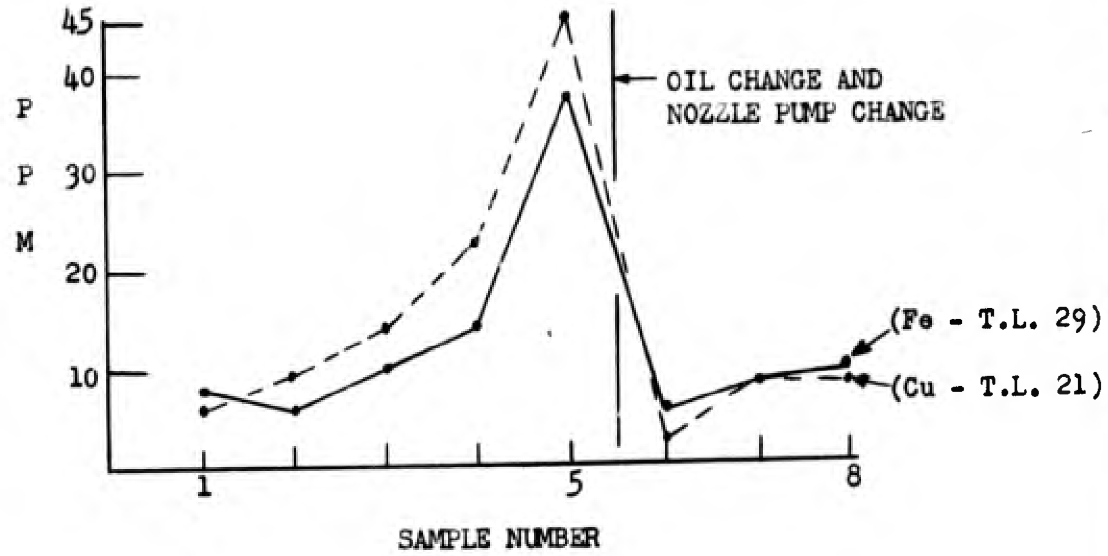
Figure 10. C3 Engine Data - Positive Correlation



SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Cu
1	21	21	38	10
2	30	30	52	12
3	37	37	65	10
4	37	0	12	2
5	37	0	7	2
6	37	0	11	2
7	37	0	8	2
8	37	0	58	10
9	37	0	13	3
10	37	0	7	3
11	61	24	7	6
12	71	34	11	10
13	91	54	10	10
14	108	71	14	11

On 28 March 1964 NAS Pensacola reported both high iron and copper in oil samples and called for sampling after every flight. On 7 April 1963 after continuing high iron and copper, NAS recommended removal of the engine for examination of nozzle pump, auxiliary pumps, and gearbox. Base removed the designated auxiliary components and sent for TDR. The TDR revealed wear in the oil scavenge pump, the hydraulic emergency pump, and the main lube pump.

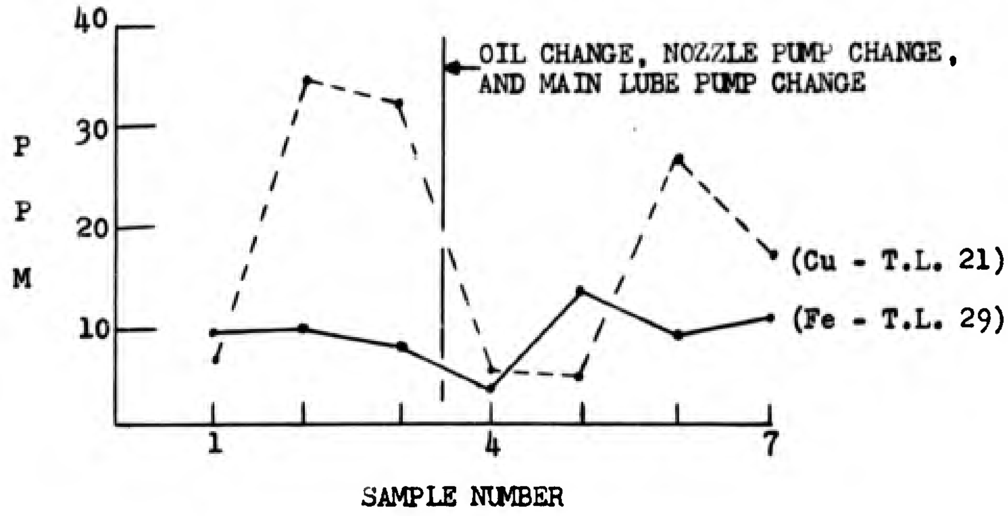
Figure 11. C4 Engine Data - Positive Correlation



SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Cu
1	52	52	8	6
2	62	62	6	9
3	77	77	10	14
4	86	86	14	22
5	88	88	37	45
6	92	3	5	2
7	183	83	8	8
8	187	0	9	8

Between 17 April and 4 May 1964 samples showed an increase from first marginal to finally high copper. Samples taken on 12 May following a change of nozzle pump were found to be normal. Base examination of the nozzle pump revealed signs of excessive wear.

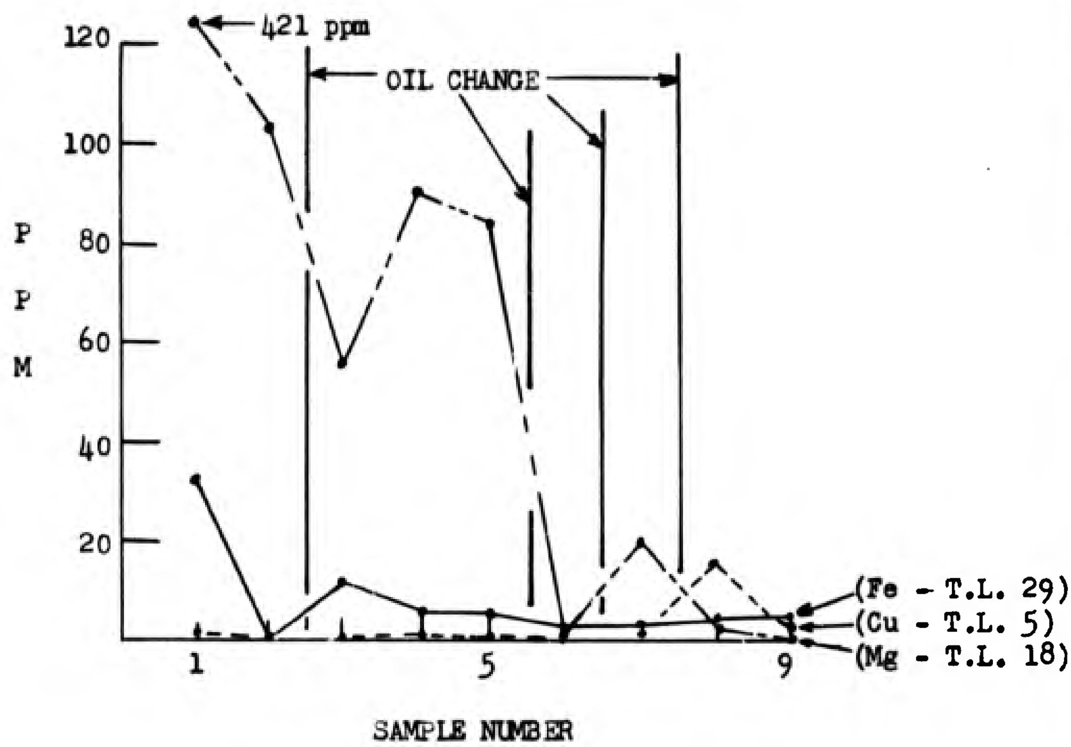
Figure 12. C5 Engine Data - Positive Correlation



SMP.	Hours Since		Analysis	
NR.	O.H.	O.C.	Fe	Cu
1	84	84	9	6
2	96	96	10	35
3	96	96	8	32
4	97	1	3	5
5	108	12	14	5
6	136	40	9	27
7	188	92	11	17

After a routine oil sample showed high copper on 8 April 1964, NAS Pensacola recommended that the aircraft be grounded pending analysis of a further check sample. A sample submitted on 1 May proved satisfactory and NAS Pensacola requested details of any precautionary maintenance. Base reported that emergency nozzle pump and main lube pump had been changed because of evidence of excessive wear. Such evidence was visual.

Figure 13. C6 Engine Data - Positive Correlation

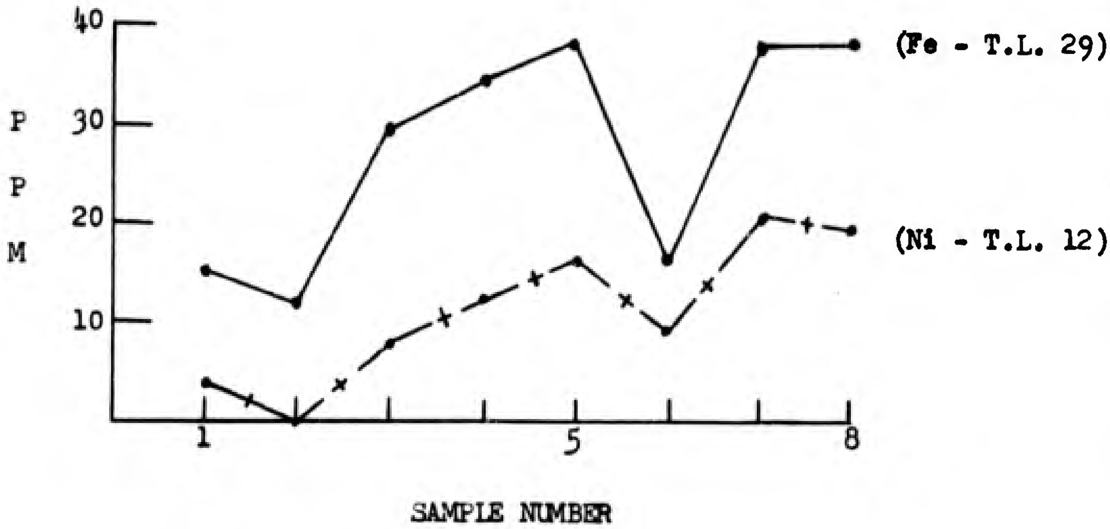


SMP NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Cu	Analysis Mg
1	81	76	32	1	421
2	91	86	0	0	103
3	145	30	11	0	55
4	159	44	5	1	90
5	169	54	5	1	84

SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Cu	Analysis Mg
6	179	9	3	0	1
7	189	1	3	1	20
8	212	8	4	17	2
9	215	11	5	3	0

On 15 August 1963 sample analysis showed high magnesium and lead and marginal iron. Since lead has not proven useful on the jet engines being monitored under this task, lead is not shown on this graph. On 19 August 1963 sample analysis only magnesium was shown high. At this time Pensacola requested further check sample to confirm conflicting data. There was then no further action until 17 January 1964 when Pensacola reported copper and recommended determination of a suspected bearing failure. After engine strip and rebuild, oil samples were satisfactory. However, the engine disassembly revealed no discrepancy and all bearings were said to be satisfactory.

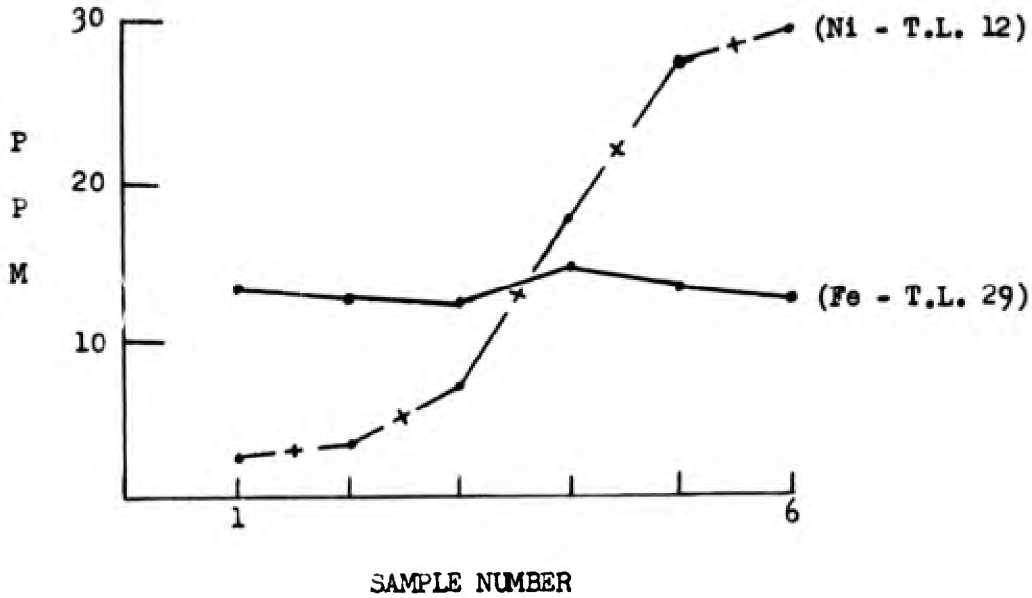
Figure 14. A3 Engine Data - Negative Correlation



SMP.	Hours Since		Analysis	
NR.	O.H.	O.C.	Fe	Ni
1	424	24	15	4
2	435	35	12	0
3	452	52	30	8
4	466	66	34	12
5	478	78	38	16
6	487	87	16	9
7	539	139	38	21
8	539	139	38	19

On 21 November 1963 NAS Pensacola reported a sample analysis as indicating marginal iron and marginal nickel. By 14 February 1964 the contamination had increased to high nickel with marginal iron and TAC Hq ordered removal of engine. On 19 February 1964 NAS Pensacola supported the decision to remove the engine for investigation of the cause of metal contamination. The TDR revealed no wear, and was one of several that dictated the change of the nickel threshold limit from 12 ppm to 29 ppm.

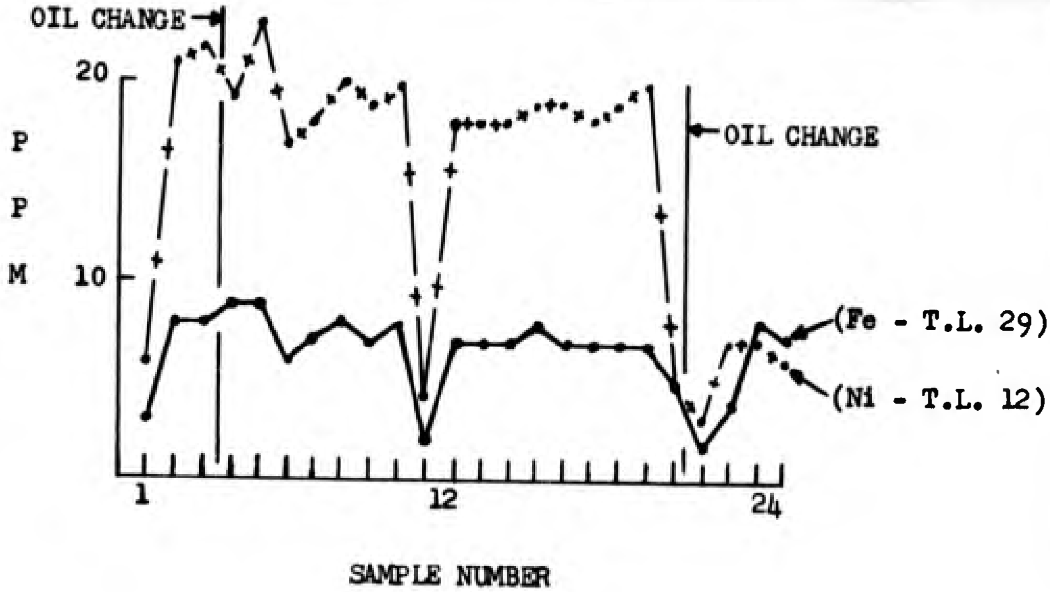
Figure 15. B4 Engine Data - Negative Correlation



SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Ni
1	8	8	13	2
2	12	12	12	3
3	23	23	12	7
4	32	32	14	17
5	37	37	13	27
6	37	37	12	29

On 28 February 1964 NAS Pensacola reported high nickel contamination of oil sample and later (on 10 March 1964) a very high nickel reading. At the time of the last reading NAS recommended the removal of the engine. The TDR revealed no wear, and this TDR was one of several that dictated the change of the nickel threshold limit from 12 ppm to 29 ppm.

Figure 16. B5 Engine Data - Negative Correlation

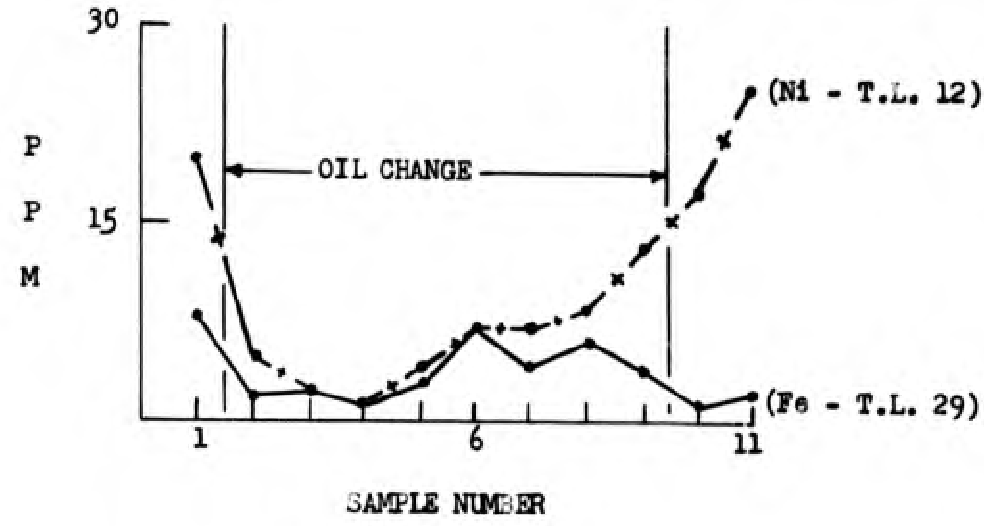


SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Ni
1	304	104	6	3
2	362	162	8	21
3	372	172	8	22
4	405	5	9	19
5	415	15	9	23
6	419	19	6	17
7	420	20	7	18
8	422	22	8	20
9	424	25	7	19
10	425	25	8	20
11	435	35	2	4
12	437	37	7	18

SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Ni
13	438	38	7	18
14	439	39	7	18
15	441	41	8	19
16	442	42	7	19
17	444	44	7	18
18	446	46	7	19
19	447	47	7	20
20	447	0	5	5
21	447	0	2	3
22	447	0	4	7
23	447	0	8	7
24	448	1	7	6

Over the period 13 February 1964 to 11 March 1964, NAS Pensacola made several analyses which indicated either marginal or high nickel contamination of the engine oil. On 6 March 1964 NAS recommended the removal of the engine and change of the auxiliary gearbox. The TDR revealed no discrepancies or excessive wear in the auxiliary gearbox or any other oil-wetted engine parts. This TDR was one of several that dictated the change of the nickel threshold limit from 12 ppm tc 29 ppm.

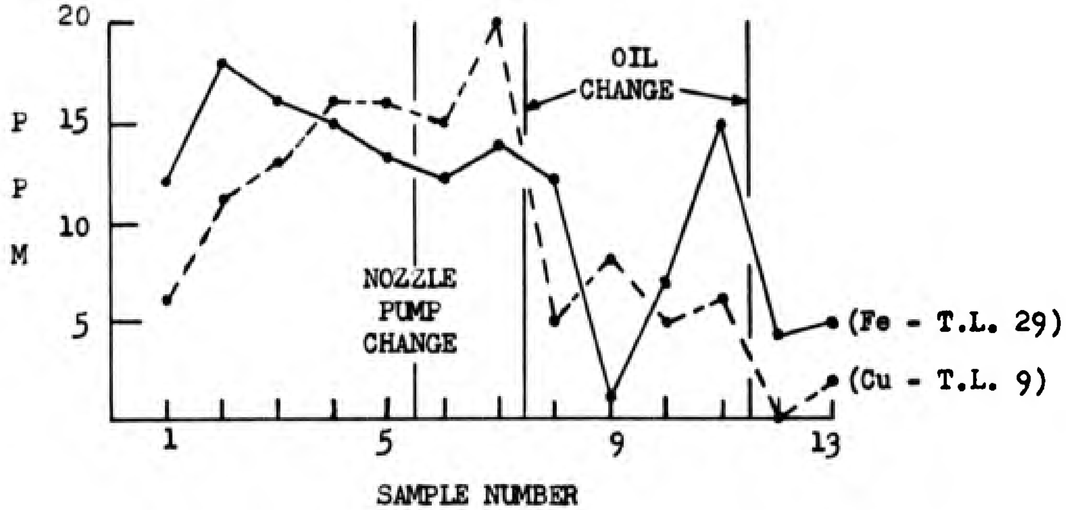
Figure 17. B6 Engine Data - Negative Correlation



SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Ni
1	87	87	8	20
2	87	0	2	5
3	87	0	2	2
4	87	0	1	1
5	88	1	3	4
6	91	4	7	7
7	93	6	4	7
8	94	7	6	8
9	95	8	4	5
10	149	25	1	18
11	160	36	2	25

On 13 February 1964 NAS Pensacola analysis showed high nickel and the base was advised to change the engine. In a letter dated 19 August 1964, the base advised that no specific maintenance was carried out as a result of NAS report, the gearbox was not changed, and no part was found discrepant. Subject engine flew 73 hours without reported defect between NAS recommendation and the last sample taken from this engine on 29 June 1964. This engine action was one of several that dictated the change of the nickel threshold limit from 12 ppm to 29 ppm.

Figure 18. B7 Engine Data - Negative Correlation

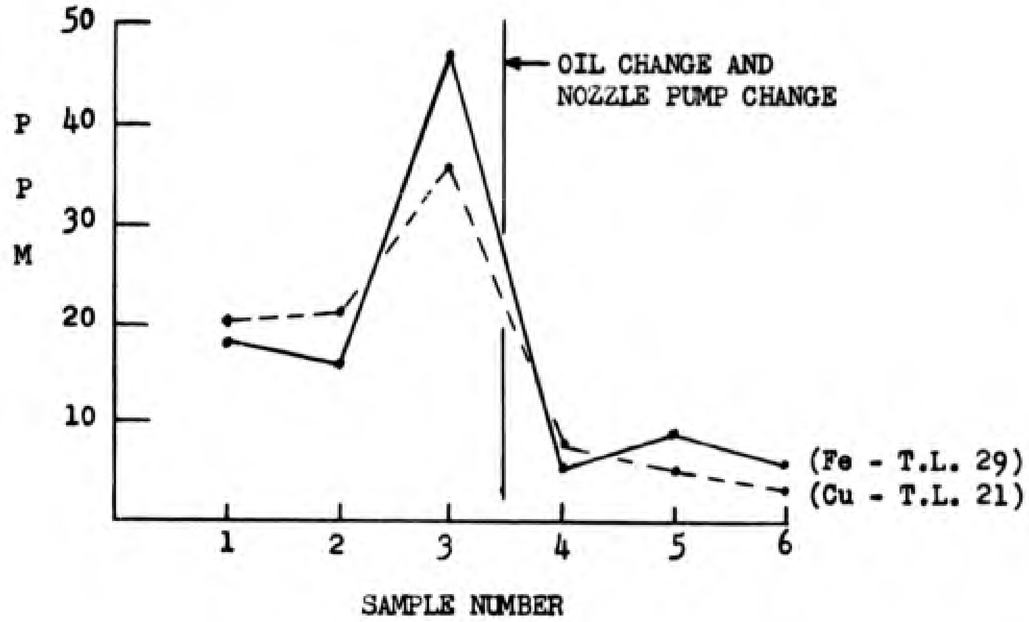


SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Cu
1	10	10	12	6
2	21	21	18	11
3	50	50	16	13
4	59	59	15	16
5	69	69	13	16
6	69	69	12	15
7	101	101	14	20

SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Cu
8	102	1	12	5
9	137	36	1	8
10	173	72	7	5
11	196	95	15	6
12	197	0	4	0
13	197	0	5	2

Copper content of samples rose from 10 ppm to 16 ppm between 19 November 1963 and 9 January 1964; at the later date the laboratory recommended close observation. On 15 January 1964 a further sample confirmed the 16 ppm reading. On this date, too, the base reported a nozzle pump change. After the reported N.P. change the copper level remained high (15 ppm) until oil change after which the samples were normal. When checking on state of the removed nozzle pump, it was discovered that it had not been changed but only removed, bench checked, and replaced. There was, therefore, no maintenance finding to explain the high copper and no explanation of why the copper level failed to build up again after oil change. At the time of this action the threshold limit for copper was 9 ppm. Because of this action and other actions it was raised to 21 ppm.

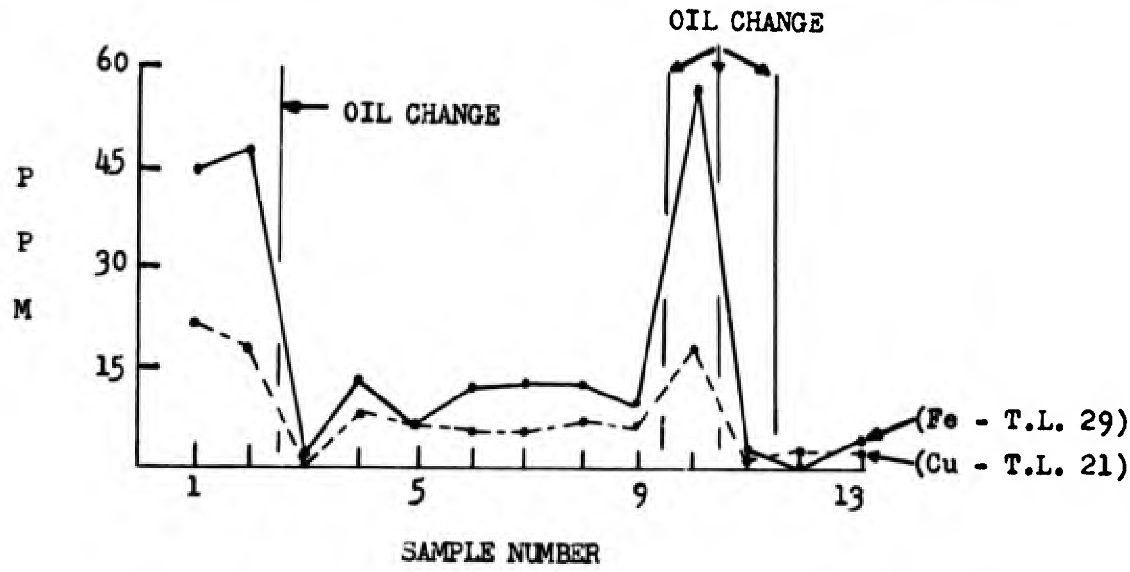
Figure 19. C7 Engine Data - Negative Correlation



SMP.	Hours Since		Analysis	
NR.	O.H.	O.C.	Fe	Cu
1	41	41	18	20
2	51	51	16	21
3	62	62	47	36
4	62	0	5	7
5	62	0	9	5
6	70	8	6	3

On 8 February 1964 Pensacola reported 21 ppm copper and recommended grounding aircraft and checking source. On 18 March 1964 Pensacola reported one sample with high iron and copper with following samples satisfactory after nozzle pump change and six hour test cell run. Subsequent samples were satisfactory. The (defective) pump was shipped for TDR. The TDR stated that disassembly revealed no discrepancies and pump was serviceable on basis of disassembly findings.

Figure 20. C8 Engine Data - Negative Correlation

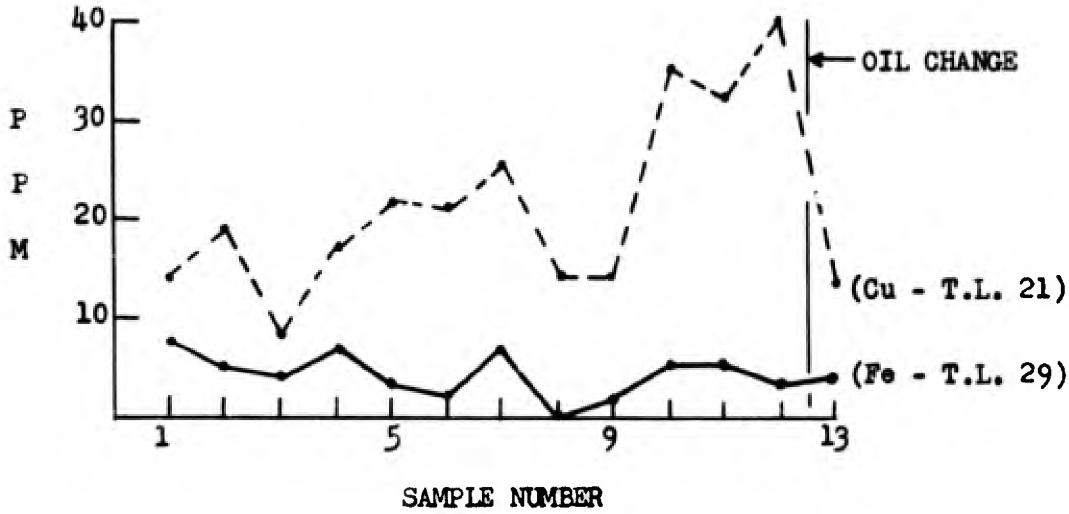


SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Cu
1	9	9	44	22
2	18	18	48	18
3	18	0	1	0
4	18	0	13	8
5	19	1	6	6
6	46	28	12	5
7	58	40	13	5

SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Cu
8	70	52	13	7
9	90	72	9	6
10	103	3	58	19
11	103	0	2	1
12	117	2	0	2
13	117	2	4	2

On 6 November 1963 Pensacola reported high iron and copper in an oil sample and recommended that the aircraft be grounded and check samples forwarded after ground run. This check sample again showed high iron and copper, and Pensacola recommended changing the oil before submission of a further check sample. This latter sample proved to be normal and engine was released for flight. On 31 March 1964 a sample showed very high iron and copper, and Pensacola recommended that the aircraft be grounded for inspection for probable failure of bearings or emergency nozzle pump. The unit reported examination of all oil-wetted components with negative results. No parts were found defective, or changed. After flushing oil system subsequent samples proved normal.

Figure 21. C9 Engine Data - Negative Correlation



SMP.	Hours Since		Analysis	
NR.	O.H.	O.C.	Fe	Cu
1	66	66	8	14
2	98	98	5	19
3	115	115	4	8
4	118	118	7	17
5	120	120	3	22
6	131	131	2	21
7	140	140	7	26

SMP.	Hours Since		Analysis	
NR.	O.H.	O.C.	Fe	Cu
8	143	143	0	14
9	148	148	2	14
10	157	157	5	35
11	163	163	5	32
12	173	173	3	40
13	196	0	4	13

Between 14 March 1964 and 13 June 1964 oil samples twice showed marginal copper with subsequent samples showing normal copper. On 7 July 1964 after two samples showing high copper Pensacola recommended inspection of emergency nozzle pump and associated filters for contamination source. Base inspection failed to reveal any reason for contamination and subsequent samples showed normal copper.

Figure 22. C10 Engine Data - Negative Correlation

TABLE VIII

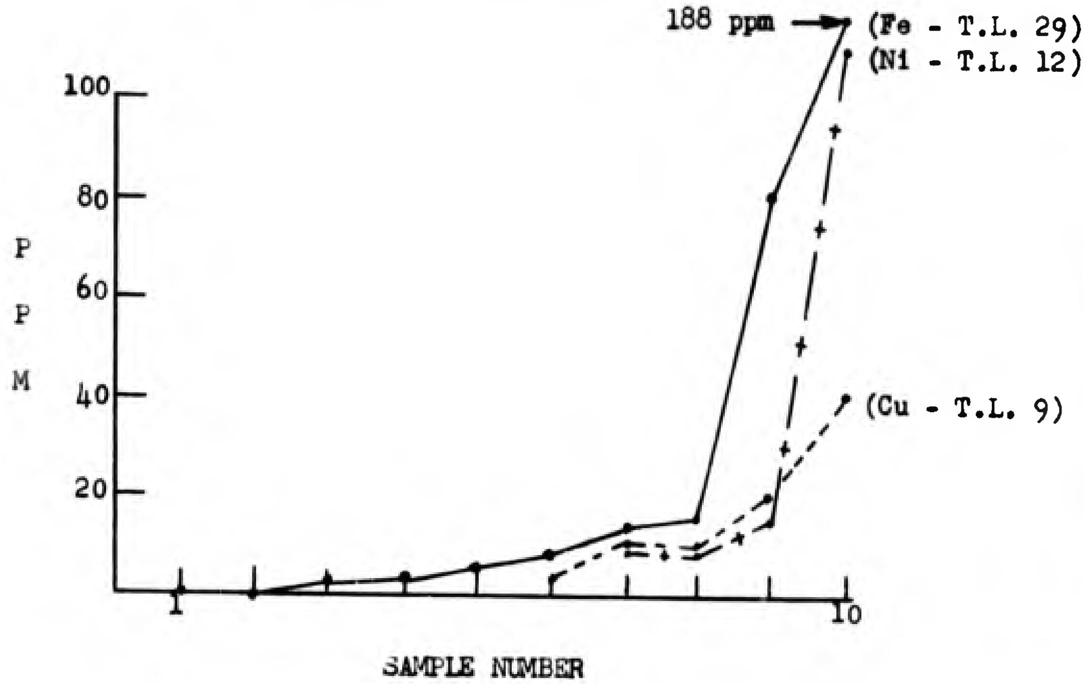
LOST DATA - FIRST TWELVE MONTHS

ENGINE SERIAL NUMBER	NUMBER SAMPLES ANALYZED	ELEMENT(S) AND HIGH READING	DISCUSSION
A4	3	Fe - 57ppm Cu - 57ppm	Between 19 and 30 March 1964 samples showed first marginal copper and finally high copper and very high iron. At the time of the latter reading Pensacola recommended removal of engine, inspection, and repair. The engine was erroneously sent through normal overhaul channels without TDR request.
A5	10	Fe - 28ppm Cu - 32ppm	Samples between 17 and 31 January 1964 showed copper increasing to a high contamination level and NAS Pensacola recommended removal of the engine if the discrepancy was not found. The engine was removed and sent for overhaul without TDR.
B8	32	Fe - 52ppm	Between November and December 1963 oil sample analysis showed an increasing iron content and Pensacola recommended replacement of the gearbox and TDR action on the replaced component. After replacement of the gearbox the iron again increased through marginal to high but later returned to normal without maintenance actions. No information could be obtained as to the condition of the changed gearbox.
B9	5	Fe - 66ppm	On 11 May 1964 NAS Pensacola reported high iron contamination of a routine oil sample and recommended grounding the aircraft pending analysis of a check oil sample. By 14 May 1964 the check sample was found to confirm the high iron contamination and Pensacola recommended that the aircraft remain grounded until the trouble was located and corrected. Because of an overload of engine maintenance at the Base, the engine was canned and sent to depot with a request for TDR. The request was lost in channels and no TDR was performed.
B10	13	Fe - 69ppm	Between 21 November and 4 December 1963 several samples showed a high iron content and NAS Pensacola recommended a TDR. Details of the TDR request were lost in channels and no TDR was performed.

TABLE VIII (Cont'd)

LOST DATA - FIRST TWELVE MONTHS

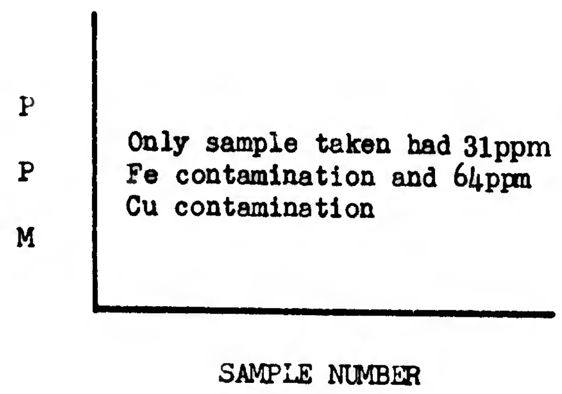
ENGINE SERIAL NUMBER	NUMBER SAMPLES ANALYZED	ELEMENT(S) AND HIGH READING	DISCUSSION
C11	8	Fe - 74ppm	Between 17 and 23 March 1964 samples showed an increase in iron contamination from high to very high and NAS Pensacola recommended removal of the engine for strip examination or TDR. At this stage a change of oil pump was reported with subsequent normal samples. No further information could be obtained as to the condition of the removed pump.
C12	1	Fe - 9ppm Cu - 18ppm	On 10 March 1964 an oil sample showed a high copper content and, since the aircraft was due to be deployed overseas, NAS concurred in special inspection to determine the source. During the maintenance action the nozzle pump was changed but the suspect pump was erroneously returned through normal repair channels without request for TDR. The only other sample taken after pump change on this engine (20 Oct 64) showed normal analysis for all ten elements.



SMP.	Hours Since		Analysis		
NR.	O.H.	O.C.	Fe	Cu	Ni
1	335	8	0	0	2
2	346	19	0	0	0
3	356	29	2	2	1
4	377	50	3	1	1
5	389	62	5	4	6
6	400	73	8	4	5
7	416	89	13	10	9
8	424	97	15	9	8
9	438	111	81	19	14
10	440	113	188	40	108

A sample taken on 30 January was a week in transit and not received by NAS until 6 February. At analysis the iron (particularly) and copper and nickel were so high that Pensacola called the base to advise grounding the aircraft for engine inspection. Unfortunately, the aircraft had crashed on the 3rd of February. Samples taken after the crash showed that the iron had risen still further (from 81 to 188 ppm). With prompt delivery of the sample and the same reaction for the laboratory the aircraft would have been grounded and the engine investigated before the flight which ended in the crash. The accident was caused by an engine failure which was caused by a material failure of the Nr 4 1/2 bearing.

Figure 23. B19 Engine Data - Engine Failure



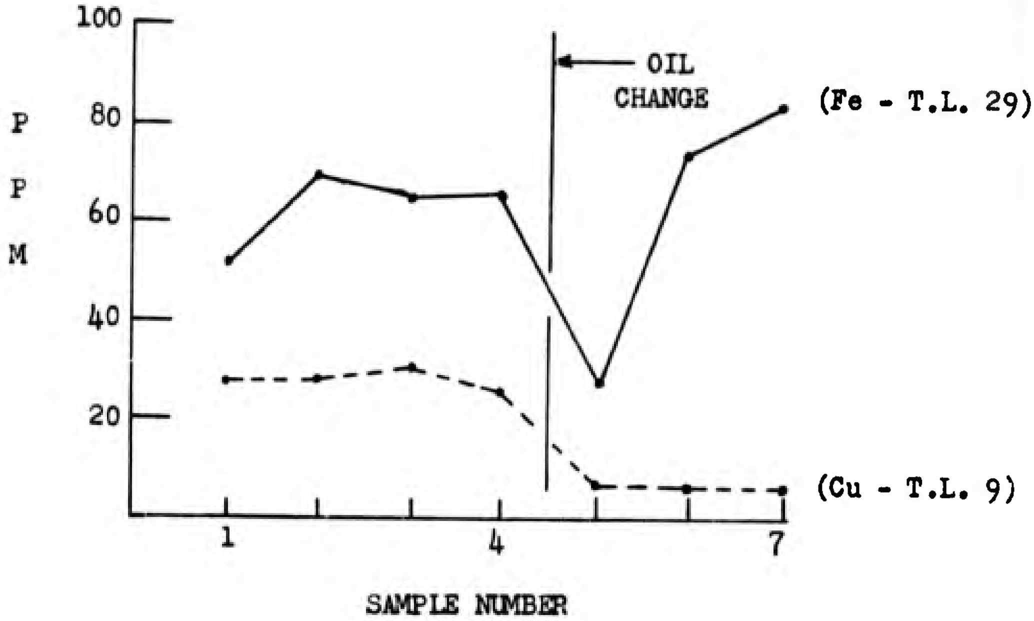
Engine failed internally on 11 December 1963. On 13 December 1963 Pensacola reported high iron and very high copper on only sample received. This sample, taken at the base on 12 October 1963, was so delayed in transmission from base to laboratory that it was not analyzed by Pensacola until 13 December 1963. The result of this analysis was such (high iron and very high copper) that Pensacola sent a message to the base recommending only precautionary flights for the next sampling period. Only at this time was Pensacola made aware that the engine had failed in flight two days earlier. Between the time this last sample was taken and engine failure the aircraft flew 76 hours; therefore, it is reasonable to suppose that prompt sample delivery and the taking of subsequent samples at the correct intervals would have revealed the metal buildup and warranted engine investigation. After failure, ground checks revealed that Nr 4 bearing failed and 3, 5, and 6 bearings were scored. Worn bearings allowed compressor to rub on shroud and vane and caused compressor stall. The potential success of the system was negated by poor reaction time. At the same time the prediction ability of oil analysis was indicated.

Figure 24. A7 Engine Data - Engine Failure

TABLE IX

OTHER ACTIONS DATA - FIRST TWELVE MONTHS

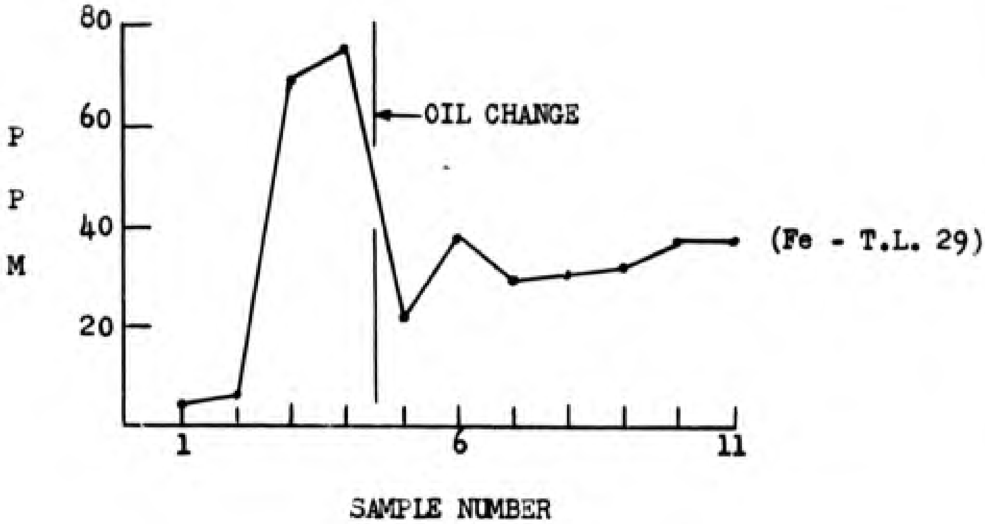
ENGINE SERIAL NUMBER	NUMBER SAMPLES ANALYZED	ELEMENT(S) AND HIGH READING	DISCUSSION
B20	6	Al - 48ppm	In December 1963 NAS Pensacola analyzed high aluminum contamination in engine oil and recommended inspection of auxiliary pumps for source and removal of engine if the source was not found. The base had knowledge of airframe maintenance performed in area of oil tank. Subsequent oil change gave clear samples indicating that airframe maintenance caused contamination. Oil analysis indicated a contamination which was real although not indicative of engine deterioration.
B21	17	Ni - 14ppm	NAS Pensacola had analyzed only marginal nickel contamination on the first sample and had made no recommendation for engine inspection or teardown. The samples after the first marginal nickel readings were satisfactory and NAS recommended routine sample rate. The engine was removed because of foreign object damage and sent to the overhaul depot. A TDR was requested concurrent with the overhaul to determine any information about the marginal nickel contamination analysis. Although there was no evidence of impending failure, there was sufficient wear found on the Nr 5 and Nr 6 bearings to support the finding of marginal nickel.
C15	1	Fe - 46ppm	After the first sample (which was extracted at 819 operating hours and 16 hours since oil change) taken from this engine contained iron contamination, Pensacola requested a check sample to confirm the first reading. Before the request for the check sample was received by the base this engine was removed because of vibration. The engine was sent for overhaul and a TDR requested. The TDR revealed wear in the transfer gearbox. Although the TDR proved the validity of the oil analysis contamination reading, engine failure diagnosis must be attributed to maintenance action in picking up the vibration.



SMP.	Hours Since		Analysis	
NR.	O.H.	O.C.	Fe	Cu
1	9	1	52	27
2	9	1	69	28
3	9	1	64	30
4	9	1	65	26
5	10	1	26	6
6	15	6	74	6
7	17	8	83	6

Sample analysis ranged through high iron and marginal copper, marginal iron and normal copper to very high iron on 20 August, 3 September,and 9 September respectively. On the last mentioned date, Pensacola recommended grounding the aircraft pending discovery of source of iron. On 5 October 1964 the engine was removed from service for disassembly. Inspection of the engine revealed wear on the Nr 4 bearing.

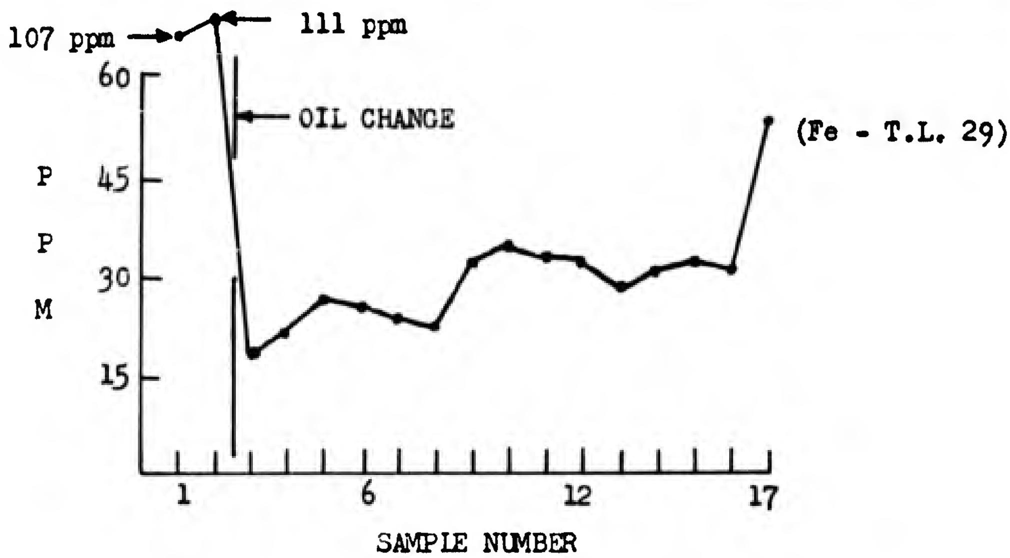
Figure 25. B11 Engine Data - Positive Correlation



SMP.	Hours Since		Analysis
NR.	O.H.	O.C.	Fe
1	10	10	5
2	19	19	6
3	28	28	69
4	31	31	76
5	31	0	22
6	31	0	38
7	31	0	30
8	31	0	31
9	31	0	32
10	31	0	38
11	31	0	38

In late September 1964 after a routine sample showed high iron contamination, NAS Pensacola recommended grounding the aircraft pending the results of a check sample. The check sample confirmed the previous high iron reading and Pensacola recommended inspection of the oil pump for wear. Further check samples in October, submitted without change of oil pump and taken after periods of ground running, showed a continuing increase in iron contamination. At this stage, NAS Pensacola recommended engine removal for TDR if the contamination source could not definitely be identified as from one of the engine accessories. The engine was sent for TDR which revealed wear on the Nr 4 bearing.

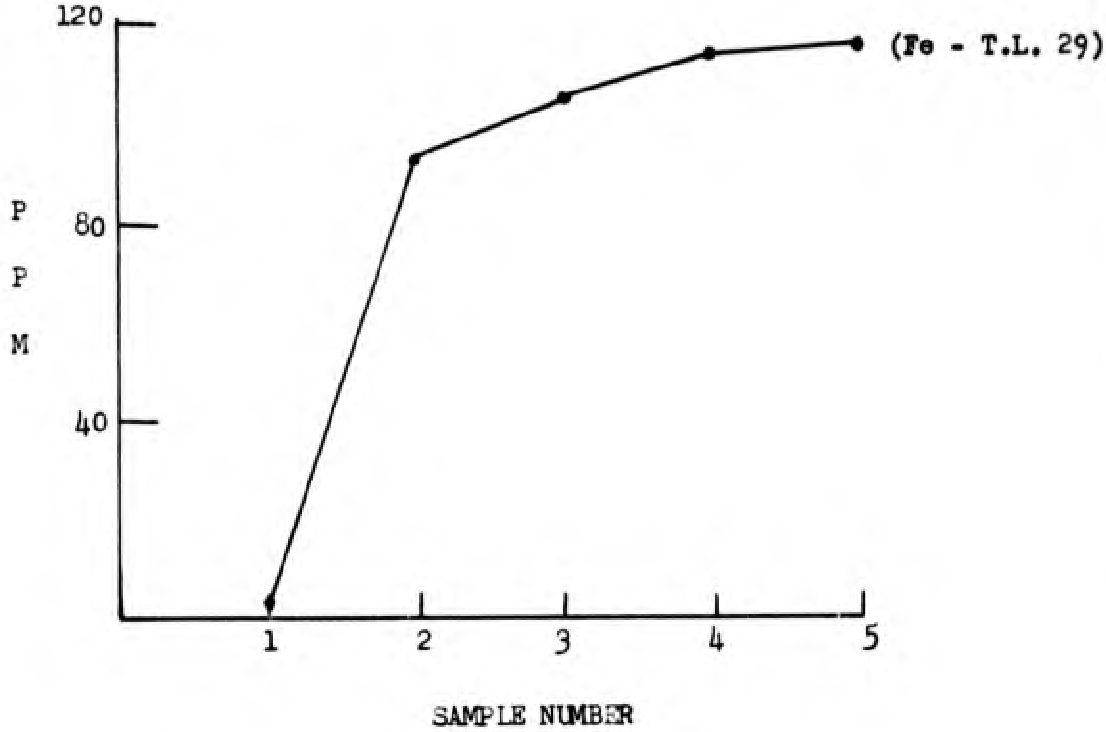
Figure 26. B12 Engine Data - Positive Correlation



SMP.	Hours Since		Analysis	SMP.	Hours Since		Analysis
NR.	O.H.	O.C.	Fe	NR.	O.H.	O.C.	Fe
1	11	11	107	10	11	0	35
2	11	11	111	11	11	0	33
3	11	0	18	12	11	0	32
4	11	0	21	13	11	0	28
5	11	0	27	14	11	0	31
6	11	0	26	15	11	0	32
7	11	0	24	16	11	0	31
8	11	0	23	17	11	0	54
9	11	0	32				

On 22 October 1964 NAS Pensacola reported very high iron in an initial oil sample and requested check samples after engine run without oil change. The second sample taken without oil change and subsequent samples taken after oil change confirmed the high iron analysis and the engine was sent for TDR on NAS recommendation. The TDR revealed wear on the Nr 4 bearing.

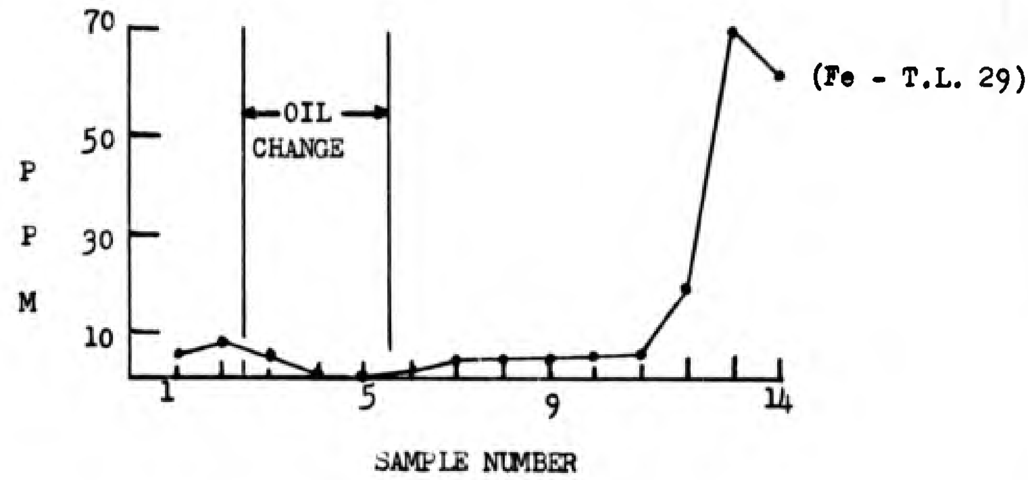
Figure 27. B13 Engine Data - Positive Correlation



SMP.	Hours Since		Analysis
NR.	O.H.	O.C.	Fe
1	212	15	2
2	225	28	93
3	231	34	105
4	231	34	112
5	231	34	116

On 8 September 1964 NAS Pensacola reported very high iron in oil sample and recommended grounding the aircraft pending analysis of a further check sample. On 9 September 1964 the laboratory reported a further increase in iron and recommended grounding the aircraft until the source was discovered. The engine was removed from the aircraft and disassembled at base in October 1964. Disassembly and inspection revealed wear on the Nr 4 bearing.

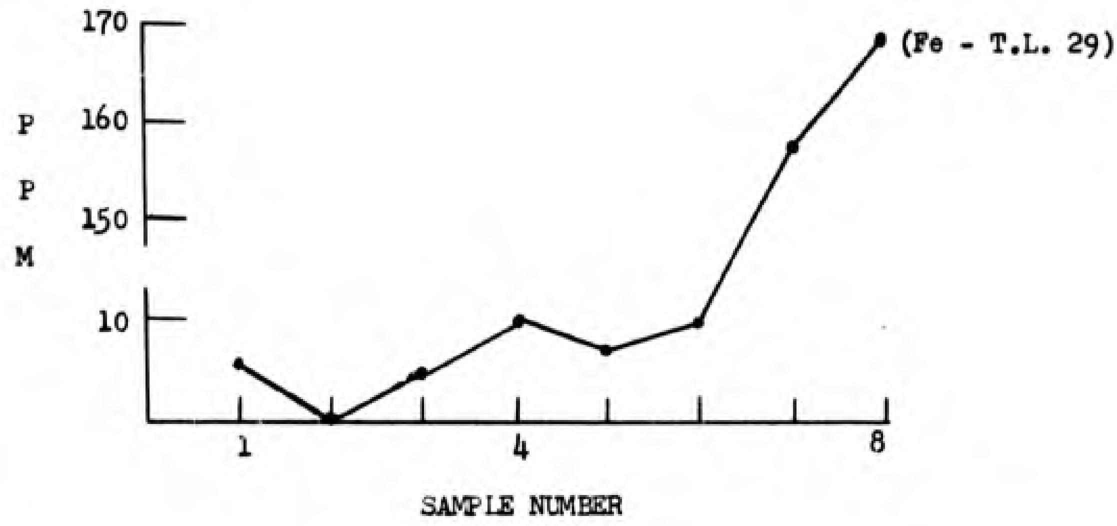
Figure 28. B14 Engine Data - Positive Correlation



SMP.	Hours Since		Analysis
NR.	O.H.	O.C.	Fe
1	14	14	5
2	24	24	7
3	26	2	5
4	35	11	1
5	45	21	0
6	51	2	1
7	61	12	4
8	65	16	4
9	76	27	4
10	86	37	5
11	94	45	6
12	106	57	18
13	114	65	70
14	119	70	62

On 4 August 1964 NAS Pensacola reported that a routine oil sample showed high iron and requested a check sample as soon as possible without oil change. By 10 August 1964 the check sample was found to confirm the first high iron reading and NAS recommended grounding the aircraft until the source of the oil contamination was determined. Subsequent base inspection revealed a piece of metal, possibly a manufacturing machining, approximately one half by one thirty-second of an inch, in the Nr 4 pump screen. Another piece found in the Nr 4 pump element and gears had grooved the pump body. Further, the Nr 4 bearing balls appeared to be skipping.

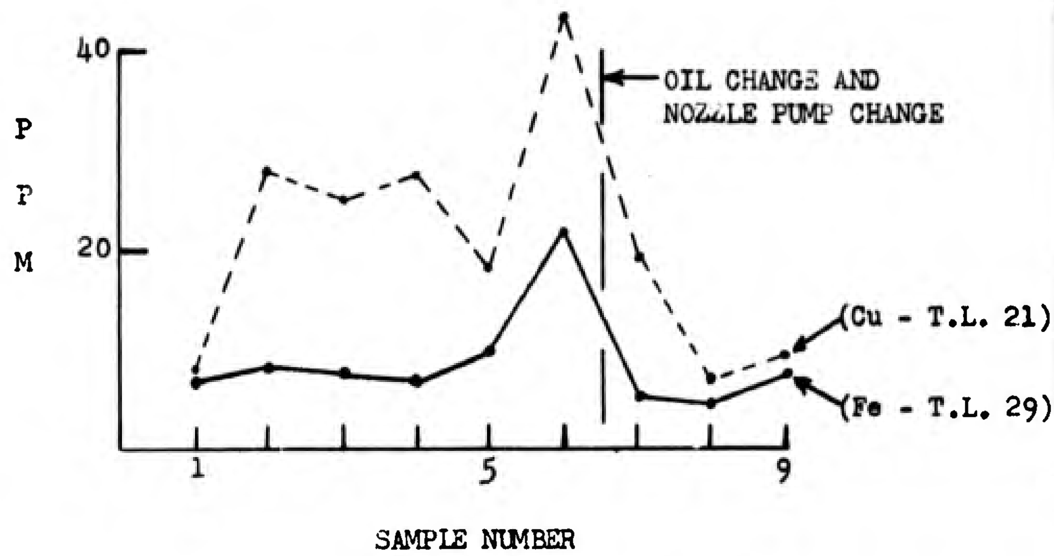
Figure 29. B15 Engine Data - Positive Correlation



SMP.	Hours Since		Analysis
NR.	O.H.	O.C.	Fe
1	22	2	6
2	30	10	0
3	39	19	5
4	48	28	10
5	57	37	7
6	66	46	10
7	75	55	158
8	75	55	169

On 18 September 1964 NAS Pensacola reported that a routine oil sample showed very high iron and recommended grounding the aircraft pending results of a check sample. By 21 September 1964 the check sample confirmed the first very high iron reading at which time Pensacola recommended determination of iron contamination source before engine was used for flight. Subsequent base examination revealed wear on the Nr 2, Nr 4, and Nr 5 bearings.

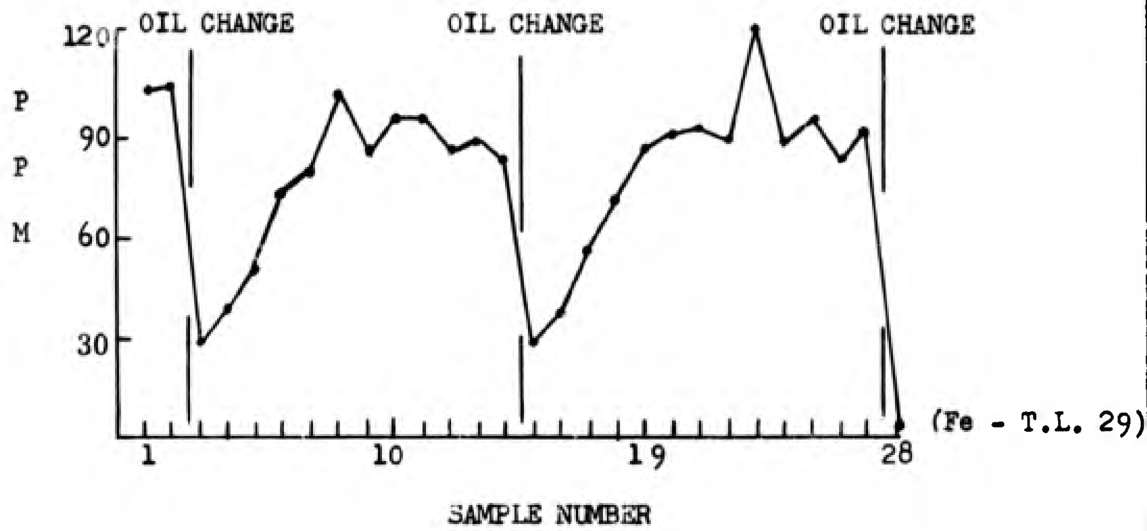
Figure 30. B16 Engine Data - Positive Correlation



SMP.	Hours Since		Analysis	
NR.	O.H.	O.C.	Fe	Cu
1	49	49	7	8
2	64	64	8	28
3	64	64	8	25
4	109	109	7	28
5	119	119	10	18
6	129	129	22	44
7	139	0	5	19
8	139	0	5	7
9	157	18	8	9

On 15 and 25 April 1964 oil samples showed high copper and Pensacola recommended a 5 hour sampling rate. Later, copper contamination reduced to marginal (28 July 64) and normal (8 August 1964). By 24 August copper contamination again increased to the very high level and Pensacola recommended grounding the aircraft for investigation. During investigation the nozzle system filter was pulled and showed evidence of impending pump failure. Examination of the nozzle pump showed excessive wear. The nozzle pump was changed and samples taken afterwards were analyzed as normal.

Figure 31. C13 Engine Data - Positive Correlation

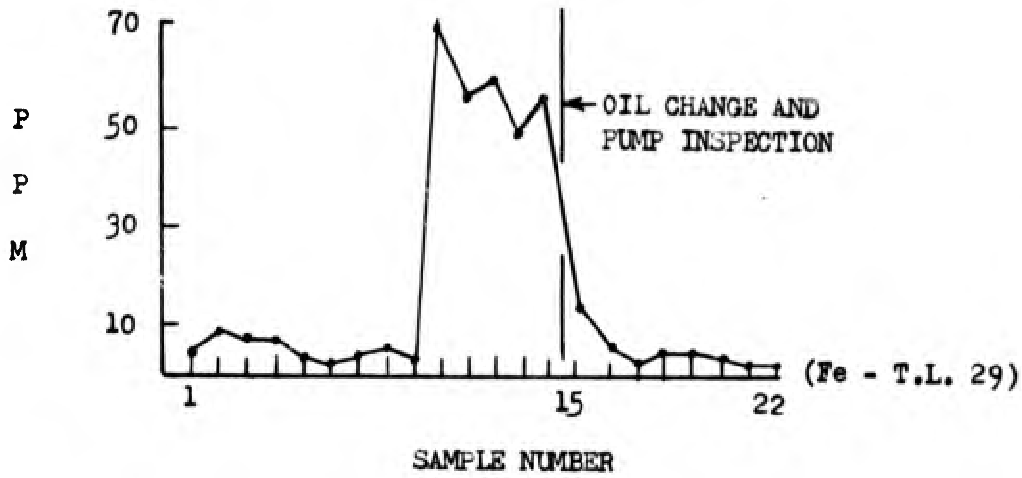


SMP.	Hours Since		Analysis
NR.	O.H.	O.C.	Fe
1	46	35	104
2	46	35	116
3	46	0	29
4	46	0	38
5	46	0	51
6	46	0	74
7	46	0	80
8	46	0	104
9	46	0	88
10	46	0	97
11	46	0	97
12	46	0	86
13	46	0	90
14	46	0	84

SMP.	Hours Since		Analysis
NR.	O.H.	O.C.	Fe
15	46	0	29
16	46	0	37
17	46	0	57
18	46	0	74
19	46	0	89
20	46	0	92
21	46	0	94
22	46	0	89
23	46	0	123
24	46	0	90
25	46	0	96
26	46	0	84
27	46	0	94
28	46	0	2

The first routine sample submitted by the base was analyzed by NAS as having a very high iron contamination content and a check sample was requested. The second sample confirmed the high iron readings and subsequent samples after oil change also were analyzed as high iron. The engine was removed for TDR, with the results revealing no evidence of wear to support the high iron readings.

Figure 32. B17 Engine Data - Negative Correlation



SMP.	Hours Since		Analysis
NR.	O.H.	O.C.	Fe
1	15	15	4
2	26	26	9
3	36	36	7
4	46	46	7
5	58	58	3
6	70	70	2
7	80	80	4
8	90	90	6
9	100	100	3
10	111	111	70
11	112	112	54

SMP.	Hours Since		Analysis
NR.	O.H.	O.C.	Fe
12	112	112	60
13	112	112	49
14	112	112	56
15	112	0	13
16	112	0	6
17	112	0	3
18	112	0	5
19	112	0	5
20	112	0	4
21	115	3	3
22	120	8	3

On 9 September 1964 NAS Pensacola reported high iron in a routine sample and requested a check sample after fifteen minutes ground run without oil change. By 24 September 1964 the check sample was found to confirm the first high iron reading and a recommendation was made to inspect oil pump and other areas for contamination source. The pump was inspected and found serviceable.

Figure 33. B18 Engine Data - Negative Correlation

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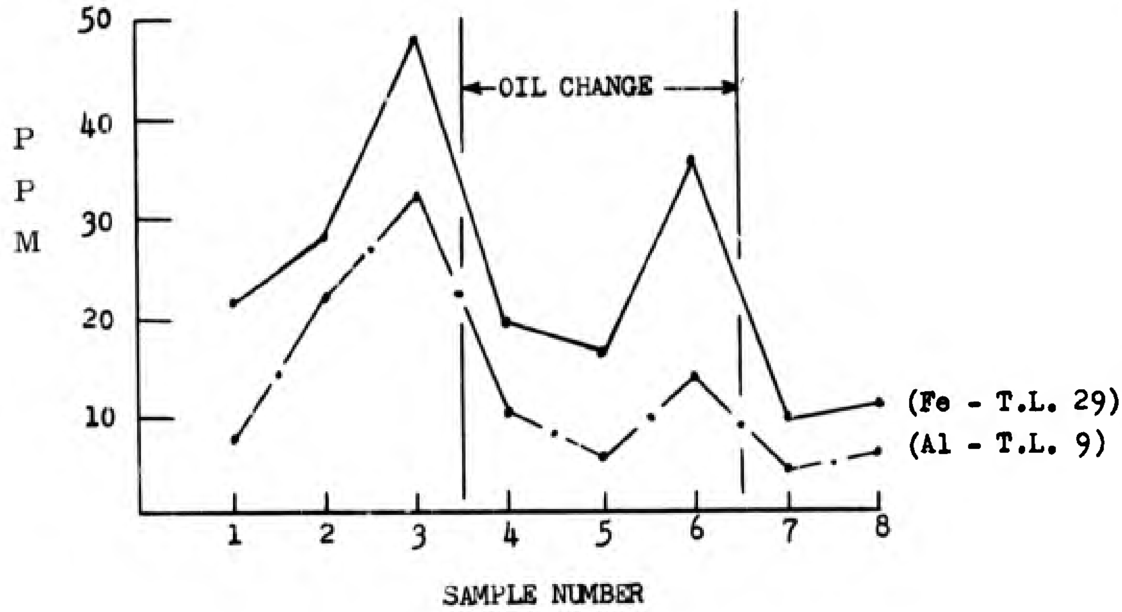

SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Al
1	21	21	21	7
2	31	31	28	22
3	47	47	48	32
4	50	0	19	10

SMP. NR.	Hours Since O.H.	Hours Since O.C.	Analysis Fe	Analysis Al
5	50	0	16	5
6	50	0	36	14
7	51	1	9	4
8	52	2	11	6

On 28 July 1964 NAS Pensacola reported readings of marginal iron and aluminum in a routine sample and requested a further sample after five hours running without oil change. On 10 August high aluminum and iron were reported and Pensacola recommended grounding the aircraft pending maintenance checks and further oil samples. On 20 August Pensacola recommended 5 hours test cell running and further check samples. By 18 September 1964 oil sample readings had returned to normal. Base reported a negative check of oil wetted components and confirmed that no maintenance, other than oil change, had been carried out.

Figure 34. C14 Engine Data - Negative Correlation

TABLE X

LOST DATA - LAST FOUR MONTHS

ENGINE SERIAL NUMBER	NUMBER SAMPLES ANALYZED	ELEMENT(S) AND HIGH READING	DISCUSSION
A6	8	Al - 21ppm	On 6 August 1964 NAS Pensacola reported high aluminum in a routine oil sample and requested a check sample after a fifteen minute ground run. By 11 August NAS reported that the check sample confirmed the high aluminum reading and advised a check of oil pump, screens, and filters. The base reported that while the aircraft was deployed overseas the oil pump had been changed and that the engine operated satisfactorily thereafter. The pump was returned to depot but no TDR was requested.

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3. REPORT TITLE Spectrometric Oil Analysis for the Detection of Incipient Turbojet Engine Failures	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report - Task Nr 314705	
5. AUTHOR(S) (Last name, first name, initial) Bond, Allan Sqn Ldr (RAF) Kittinger, Don C.	

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
July 1965	58	

8a. CONTRACT OR GRANT NO. b. PROJECT NO. 3147 c. Task No 314705 d.	9a. ORIGINATOR'S REPORT NUMBER(S) SEG-TR-65-37 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
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13. ABSTRACT

The objective of Task 314705 was to investigate (with particular reference to military turbojet engines) the technical validity of the spectrometric oil analysis approach to the identification of abnormal engine wear and impending engine failure. Program procedure called for the routine extraction of engine oil samples from aircraft at various bases and the mailing of these samples to the NAS laboratory at Pensacola, Florida for analysis. Evaluation has been concentrated on a sixteen month period from July 1963 through October 1964 when the laboratory analyzed over 7000 oil samples and prescribed engine maintenance as thought necessary from analysis results. To assess validity of the spectrometric technique, findings of maintenance actions directed by the laboratory were monitored by SEG.

The task has shown that a sound technical foundation exists for the spectrometric technique. This does not mean that in every case analysis indication will be substantiated by maintenance findings and, at the present state of the art, it may be that of every ten engines pulled or examined some three or four will be found to be apparently serviceable. This test has not proved that the program is cost-effective if considered solely as a means of indicating defects before progression to more costly repair or replacement. However, from the flight safety aspect, and because of the large financial saving which occasionally will accrue from crash prevention, the technique must be held to the cost-effective with respect to single-engined aircraft. This may not be so for multiengined aircraft.

DD FORM 1 JAN 64 1473

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Spectrometric Oil Analysis						
Engine Failure Detection						
Incipient Turbojet Engine Failures						
Flight Safety						
Monitoring Oil System Contamination						
Crash Prevention						
Single-Engined Aircraft						
Requirement for Base-Level Oil Analysis						

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