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IMPROVED CAPABILITIES TO DETECT INCIPIENT BEARING FAILURES.(U)
JUN 79 J A ALCORTA, L L PACKER F33615-78-C-2008

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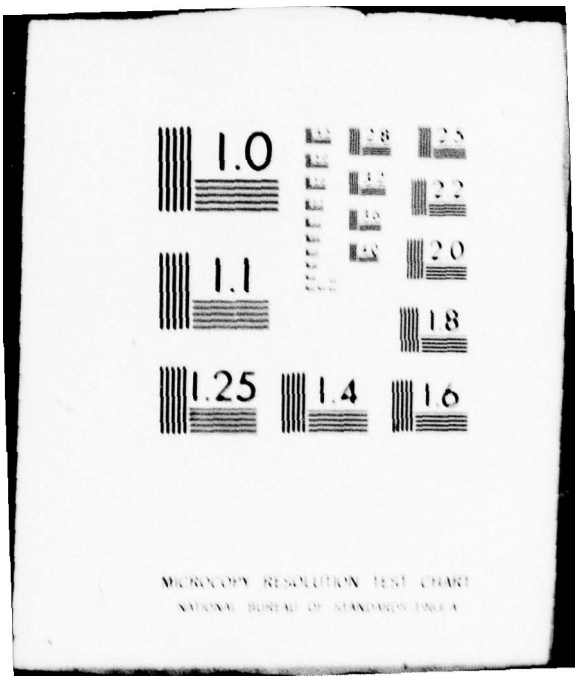
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IMPROVED CAPABILITIES TO DETECT INCIPIENT BEARING FAILURE

J. A. Alcorta
L. L. Packer

Pratt & Whitney Aircraft Group
Government Products Division
West Palm Beach, Florida 33402

2 June 1979

Interim Technical Report 1 May 1978 - 28 February 1979

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FOR THE COMMANDER

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A methodology using a low level radiation technique for the detection of wear in gas turbine engine mainshaft bearings has been developed. In conjunction with SOAP analyses, the radioactive tag will detect low levels of wear and will simultaneously indicate whether the tagged bearing is the source of the wear. Iron-55 is employed as the active tag owing to its low radiation levels, long half-life, and homogeneity of the isotope in the bearing rollers. The low levels of radiation existent in the tagged wear particles requires —

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the separation of wear debris from the oil. Membrane filtration of the oil for debris removal is undertaken due to its high recovery efficiency, simplicity of use, and adaptability for direct incorporation into the nuclear counting system. A gas flow proportional counter with cosmic guard detector and background shielding constitutes the most suitable low-level radioactivity measuring device for the iron-55 x-ray counting. The radioactive bearing tagging technique complements engine modularization by defining a diagnostic system that will identify specific engine bearings experiencing wear. By assessing the location of the distressed bearing, the tagging technique permits the confinement of engine teardown to the module in which the bearing is located.

PREFACE

This interim report describes the work performed by the Pratt & Whitney Aircraft Group Government Products Division (P&WA/Florida) of United Technologies Corporation, West Palm Beach, Florida, under US Air Force Contract F33615-78-C-2008. The report material was prepared by P&WA/Florida and covers the period from 1 May 1978 to 28 February 1979.

This program to study "Improved Capabilities to Detect Incipient Bearing Failures" in the aircraft turbine engine environment is sponsored by the Air Force Aero Propulsion Laboratory (AFAPL), Air Force Systems Command, Wright-Patterson Air Force Base, Ohio under the cognizance of P. W. Centers, Government Technical Manager, AFAPL. The P&WA/Florida Program Manager is J. A. Alcorta. Evaluation of the radioactive methods was conducted at United Technologies Research Center (UTRC) under the direction of L. L. Packer, Chief of the Radioisotope Laboratory.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION I
INTRODUCTION AND SUMMARY

Current Air Force operational procedures employ analyses of engine oil to detect abnormal wear of gas turbine oil wetted parts including mainshaft bearings. The technique employed to conduct these analyses is the Spectrometric Oil Analyses Program (SOAP). However, since SOAP does not determine the location at which wear occurs in the turbine engine, supplemental techniques such as radioactive tagging of mainshaft bearings and associated scanning of the wear metal debris are suggested to pinpoint the location of the distressed bearing. Additionally, the technique can detect low levels of wear in critical bearings that SOAP analysis would not disclose.

The objectives of this program, (Improved Capabilities to Detect Incipient Bearing Failures) are to develop and evaluate techniques for the detection of initial wear of turbine engine mainshaft bearings, to provide information as to the location of such distress, and to demonstrate the methods in a simulated turbine engine environment.

The program consists of five tasks. Task I comprises an evaluation of radioactive methods to tag mainshaft bearings and identify and count wear debris. In Task II, the bearing system to be used in the demonstration will be determined, and the bearings will be procured. Task III provides for the inspection of the selected bearing before and after tagging to assay the effects of the tagging on the metallurgical properties of the bearing alloys. The procedures to be used in the selected method will be developed and demonstrated under Task IV, in which the selected bearing system will be tagged and tested at simulated turbine engine operating conditions. The safety and handling considerations of the selected methods will be evaluated and the cost/benefit ratios for applying the selected method will be assessed in Task V.

The principal work undertaken during the first half of the program consisted of evaluating radioactive methods of tagging mainshaft bearings and the subsequent identification and counting of the wear metal debris. Specifically, the initial work determined the radioactive tag, the tagging method, the nuclear counting methods and the wear metal debris recovery technique. Safety and handling considerations resulting from the

radioactive nature of this program have been addressed as part of the decision process. The bearing system in which the techniques will be tested has been defined. The conclusions reached after the first half of the program are:

1) Radioactive Tagging Method

Iron-55 was chosen as the active tag due to the low radiation levels, long half life, and the homogeneity of the isotope in the bearing rollers. The neutron activated bearing material has revealed a linearity between nuclear counting and the parts per million concentration of iron debris in the oil. This provides both a means of recognizing distress in the tagged bearing and of identifying the amount of material loss from the same bearing. Alternate tagging methods examined included impregnation by krypton-85. Gaseous diffusion of krypton-85 was not considered acceptable, as the penetration into the bearing surface of this isotope was not deep enough to permit the detection of high speed roller bearing wear. However, krypton-85 impregnation might be acceptable for large, shallow wear measurements or in materials more porous than bearing steels.

2) Wear Metal Debris Recovery

Due to the low level of radiation in the bearing tagging technique, separation of wear metal debris from the lubricating fluid is required. The low level radioactive debris is filtered from the oil using a polycarbonate Nuclepore membrane filtration in the 0.5 to 1 micron range. Membrane filtration is used due to its high recovery efficiency and its simplicity of use. In addition, membrane filters deposit the wear metal debris on the filter surface, thereby permitting the direct incorporation of such debris into a nuclear

counting system. To obtain the required wear metal debris for radioactive measurements, approximately 130 ml of oil will have to be filtered.

3) Nuclear Counting Methods

Literature and instrument surveys showed that a gas flow proportional system for beta emissions and x-ray counting constitutes the most suitable low-level radioactivity measuring technique for both neutron-irradiation and krypton-impregnated bearing material. Highly sophisticated systems with cosmic guard detectors and background shielding to reduce environmental radiation are commercially available. Repeatable measurements in the picocurie range are attainable.

4) Government Regulations

The amount of radioactivity present on the test rollers will be limited to a level that does not impose any direct contact handling restriction during roller inspection, assembly, and installation. A "CAUTION: Radioactive Material" tag and inventory control will be the only Nuclear Regulatory Commission NRC regulation applicable during the test program. Disposition of used rollers by a licensed disposal company will be required. No restrictions on the used oil are expected. A study of the impact of technique in the Air Force maintenance environment will be made in the second year of this program.

5) Bearing System Selection

The F100-PW-100 No. 4 roller bearing was selected for radioactive tagging and rig test evaluation as a typical state-of-the-art high speed roller bearing.

Engine modularization has become an integral part of aircraft engine design to help achieve the goals of reduction in maintenance costs and engine down time. The radioactive bearing tagging technique herein described complements this modularization by defining an engine diagnostic system that will identify specific engine bearings experiencing above normal wear rates, thereby confining the amount of teardown to the particular bearing compartment in which the problem is located if different tags are used. Further, the detection capability of the system has been enhanced to permit identification of roller bearing wear distress in order to avoid unscheduled engine shutdowns.

SECTION II

RADIOACTIVE TAGGING METHODS

1. TAGGING FOR AIRCRAFT ENGINE MAINTENANCE

Presently, engine lubricants are routinely analyzed by the Air Force to detect incipient breakdowns in the oil-wetted sections of turbine engines. Evidence from the analyses of the liberated metal wear debris in the oil permits scheduled removal of the engine before a potential engine malfunction occurs. The engine condition monitoring method employed to conduct these analyses, Spectrometric Oil Analysis Program (SOAP), has provided a valuable means of measuring wear metal concentrations in the engine's lubricating oil. However, SOAP analyses is not totally effective in that it does not identify the wear location or detect small quantities of wear in the engine. Thus, extensive engine inspection of nearly all oil-wetted engine parts is required for identification of the damaged component. A wear metal identification system that will eliminate or diminish the extent of teardown and determine low wear levels could result in reduced maintenance costs and out of service time.

A diagnostic method utilizing radioactive tagging of key engine mainshaft bearings in conjunction with SOAP analyses could not only detect high metal wear rates, but could pinpoint the location of problem bearings. The proposed method consists of radioactive tagging of gas turbine engine mainshaft bearings.

Radioactive techniques have been previously used to measure wear on bearings. Engine wear metal debris measurements utilizing radioisotope excitation for x-ray fluorescence has been demonstrated by Pratt & Whitney Aircraft (P&WA) Group, Reference 1, to measure iron concentrations in oil systems. The system correlated well with SOAP techniques and achieved a standard deviation accuracy of ±3 parts per million (ppm). However, the system involves the use of an inflight electronic package which requires further refinement before it will be practical for normal maintenance procedures. Bearing wear tests were conducted (References 2 and 3) using reactor irradiation of rolling elements with radioactive iron as the active material. Although high measurement accuracies were attained (SKF Industries attained repeatable wear measurements of 3×10^{-10} g/1000

revolutions, Reference 2), the radioactivity levels were high, 100 to 200 millicuries (mCi), Reference 3. Radiation levels of this magnitude are unacceptable for engine maintenance procedures. To be practicable, the use of radioactive iron isotopes must be conducted at approximately a thousand times lower radioactivity levels in order to minimize safety and handling risks. The use of radioactive silver isotopes to measure cage wear is discussed in the "Investigation of Factors Controlling Engine Scheduled Overhaul" (Reference 4).

The use of kryptoalloys, solids into which radioactive isotopes of krypton have been incorporated, for temperature measurement studies has been extensively pursued by the United Technologies Research Center (UTRC) over the last decade. The temperature measuring technique has also been employed by P&WA and UTRC to investigate metal temperature in various engine turbine vanes and blades, such as TF30 turbine blades after 150-hr engine endurance testing, as well as the metal surfaces of the JT9D No. 3 ball bearing elements, and ATEGG blades.

While developmental work has been attained with the previously discussed radioactive techniques, the long term field use for specific bearing component oil debris identification has not been investigated. This program will use a very low level radioactive technique to detect bearing wear in a simulated gas turbine engine oil system.

The practical constraints of incorporating radioactive tagging of engine mainshaft bearings within the Air Force operational environment requires consideration of safety, handling, and maintenance procedures, as well as consideration of engine oil sample processing logistics. These constraints established the following criteria used in determining the optimum radioactive levels of the proposed methods.

a. Radioactive Half-Life

To provide off-the-shelf capabilities, the radioactive half-life of the isotope selected for the tagging program should be in excess of 2 years and should be activated to provide failure detection and location information for a period of no less than 5 years after tag incorporation. These periods are approximately the mean time between overhauls of operational aircraft. At each overhaul interval, the bearings could then be replaced with reactivated tags for another 5-year period.

b. Radioactive Emissions/Amount of Radioactivity

The amount of radioactivity present must be minimized to simplify handling procedures using the proposed method for turbine engines operated in the Air Force environment. Due to the low levels of radioactivity under consideration, the techniques will require only minimal restrictions on the direct material contact handling when assembling, installing, or inspecting the bearings. In order for such a situation to exist, the levels of radioactivity realized in the technique must not be considered environmentally significant under the Nuclear Regulatory Commission Rules and Regulations (Reference 5) exemption provisions.

c. Bearing Metallurgical Properties

Standard bearing handling, cleaning, and surface protection procedures will be strictly adhered to during the bearing material tagging process. The tagging procedure must not affect the metallurgical characteristics of the bearing steel.

d. Tagged Surface Area

The method used to tag the bearing material must be capable of incorporating the radioactive tag over the roller surface to a depth commensurate with that necessary to provide failure detection and location information.

Analytical and experimental results obtained in the initial task of the program are discussed in the following sections as shown below:

1) Bearing tags - neutron irradiation (iron-55) and gaseous diffusion (krypton-85)
2) Wear metal debris recovery
3) Low level radioactive detection measurements
4) Government Regulations
5) Bearing selection for rig testing.

2. NEUTRON IRRADIATION

a. General

Radioactive iron tagging for measuring the wear rates of oil-wetted components has been used on automotive engines (Reference 6) and on rolling element bearings (References 2 and 3). Reactor neutron irradiation of the predominantly iron-containing engine components produces both iron-59 (45-day half-life) and iron-55 (2.6-year half-life). The iron-59 had been selected as the primary radiotracer in previous investigations because its gamma ray emissions of 1.1 and 1.29 MeV are easy to detect, both during engine operation and in oil samples recovered from the engine. Iron-55 decays by electron capture and emits low energy 5.9-keV x-rays. The 2.6-year half-life and the low energy x-ray emissions, make iron-55 a sensitive long term M50 alloy bearing tag. The use of iron-59, and other irradiation by-product isotopes such as chromium-51 (28-day half-life) as a bearing wear tag will be feasible only for test programs lasting several months.

Subjecting premium bearing quality iron-based alloy steels such as M50, to a neutron flux in a reactor results in the transmutation of various constitutents of the material to radioactive isotopes. The composition of M50 as required by P&WA specification for consumable electrode vacuum melted bearing steels is shown in Table 1.

Of the elements comprising the M50 composition, only iron, chromium, and cobalt convert upon irradiation into radioactive isotopes with a half-life of sufficient duration to be of interest in this program. Table 2 shows the technical details regarding the neutron irradiation of M50 bearing steel.

The half-life of iron-55 is of sufficient duration to permit the decay of the high concentration of iron-59 and chromium-51 isotopes to insignificant levels within 6 months after removal from the reactor. Table 3 shows the decay factors of the various isotopes both 6-months and 5-years after removal from the reactor. Figure 1 depicts the decay of the iron-55. Six months after removal from the reactor, the radioactive atoms are distributed within the bearing material at a concentration range of approximately one radioactive atom for every 10^{10} nonradioactive atoms when the radioactivity levels to be used in the test program rollers are applied.

TABLE 1. CONSUMABLE ELECTRODE VACUUM MELTED BEARING STEEL COMPOSITION M50 PER PWA SPECIFICATION 725

Constituent	Min Weight Percent	Max Weight Percent
Iron	87.92	90.58
Molybdenum	4.00	4.50
Chromium	3.75	4.25
Vanadium	0.90	1.10
Carbon	0.77	0.85
Manganese	-	0.35
Cobalt	-	0.25
Silicon	-	0.25
Tungsten	-	0.25
Nickel	-	0.15
Copper	-	0.10
Phosphorus	-	0.015
Sulfur	-	0.015

TABLE 2. NEUTRON IRRADIATION OF M50 BEARING STEEL

Element:	Nominal Weight Percent In M50	Percent Isotopic Abundance For Activation	Activation Reaction	Cross-Section (Barns)[1]	Half-Life	Gamma Ray Emission (keV)
Chromium	4	4.3	$^{50}Cr\ (n,\gamma)^{51}Cr$	17	28 days	320
Iron	89	0.33	$^{58}Fe\ (n,\gamma)^{59}Fe$	1.01	45 days	143 1098 1290
	89	5.82	$^{54}Fe\ (n,\gamma)^{55}Fe$	2.8	2.6 years	5.9[2] 6.5
	89	5.82	$^{54}Fe\ (n,p)^{54}Mn$	0.68[3]	291 days	5.4[2] 835
Cobalt	0.25 max[4]	100	$^{59}Co\ (n,\gamma)^{60}Co$	37	5.2 years	1170 1330

(1) Thermal neutron cross-section
(2) X-rays
(3) Requires 1 MeV or greater neutron energies
(4) Present in the M50 as a contaminant to a maximum concentration of 2500 ppm

TABLE 3. M50 ISOTOPE DECAY FACTORS

Isotope	Time After Reactor Removal Year		
	0	0.5	5
Iron-55	1.0	0.875	0.264
Iron-59	1.0	0.0623	0.0
Cobalt-60	1.0	0.9362	0.518
Chromium-51	1.0	0.0116	0.0
Manganese-54	1.0	0.659	0.0154

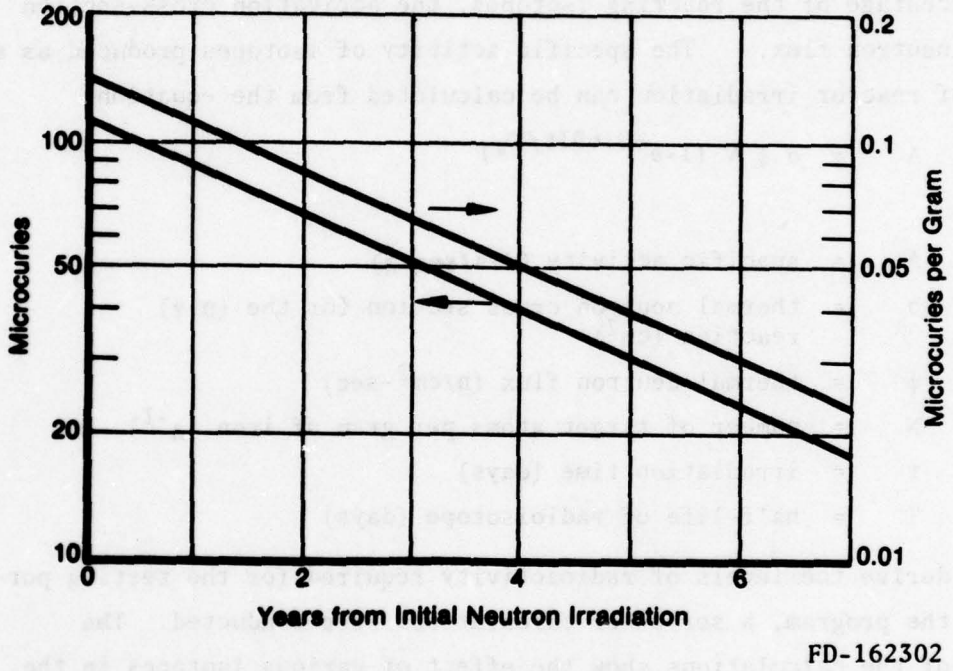

Figure 1. Radioactivity Levels for Program Testing.

The mechanical and chemical properties of the radioactively tagged bearing atoms are identical to those of a nonradioactive bearing; the wear metal debris also maintains pre-irradiation properties. Exposure of the bearing to a neutron flux of 10^{10} neutrons/cm^2 -sec is necessary to induce low-level tagging. The required fluence of 10^{14} neutrons/cm^2 is 10^4 to 10^5 lower than that known to induce changes in the mechanical properties of steel (Reference 7).

b. Neutron Activation Analytical Calculations

A wide range of iron-55 activity, spanning tenths of microcuries to millicuries can be achieved by varying either the neutron flux or the irradiation time of the material. To provide the initial significant

wear identification sensitivity, sufficient iron-55 activity is required to provide wear metal debris measurement capabilities at the one-half part per million range in an engine oil system. Measurement sensitivity parameters are constituted by: (1) the effectiveness of the filtration method used to remove the wear metal debris, and (2) the lower limit of radiation detection provided by the nuclear instrumentation.

The amount of radioactivity induced in bearing material is a function of the weight percent of each element comprising the alloy, the isotope percentage of the reacting isotopes, the activation cross-section and the neutron flux. The specific activity of isotopes produced as a result of reactor irradiation can be calculated from the equation

$$A = \sigma \phi N (1-e^{-0.693t/T_{\frac{1}{2}}})$$

where

A = specific activity (dis/sec-g)

σ = thermal neutron cross section for the (n,γ) reaction (cm^2)

ϕ = thermal neutron flux (n/cm^2-sec)

N = number of target atoms per gram of iron (g^{-1})

t = irradiation time (days)

T = half-life of radioisotope (days)

To derive the levels of radioactivity required for the testing portion of the program, a series of calculations were conducted. The results of the calculations show the effect of various isotopes in the M50 materials and their relative importance as a function of time elapsed, following irradiation. Table 4 illustrates the results. The neutron flux and the ratio of thermal to fast neutrons in these calculations are identical to values previously obtained in the reactor; these values will also be used for the bearing's irradiation during the test program.

The fast decay rates of iron-59, and chromium-51 render these isotopes unimportant 6 months after irradiation. The radiation level of manganese-54 is also insignificant. Iron-55 constitutes 85% of the activity for the typical M50 material subsequent to the 6-month post-irradiation period. The last column in the table shown indicates the extremely small amounts of radioactivity present in the oil system as a result of the radioactive debris. These minute quantities dispersed in a gas turbine oil system are

several orders of magnitude lower than the Nuclear Regulatory Commission's exempt concentration values, and while not expected to pose any health hazards will require sophisticated low-level detection counters to perform debris measurements.

The following assumptions have been made in the calculations in order to determine the radioactivity levels after irradiation:

1) Total mass of the irradiated bearing material = 800 grams (g)
2) The mass of each roller = 25g
3) The iron-55 radioactivity 6 months after reactor removal = 100 microcuries (μCi) per 800g
4) One part per million of debris = 18 mg (5 gal system)
5) Neutron thermal flux = 1.6×10^{10} neutrons/cm^2-sec
6) Thermal to fast flux ratio = 15
7) 7 hr of neutron irradiation

c. Experimental Results

(1) Neutron Irradiation

Roller wear metal debris from a Pratt & Whitney Aircraft turbofan engine roller bearing were irradiated at the Union Carbide swimming pool reactor in Tuxedo, New York during April 1978. Neutron irradiation of the bearing material was undertaken to assess the significance of radioactivity from minor M50 alloy constitutents, specifically cobalt. The irradiation was conducted on six bearing rollers (16 by 16 mm) encapsulated in a 3/4-in. diameter aluminum tube. In addition, fine bearing material debris abraded from No. 4 rollers with No. 600 silicon carbide paper was irradiated. This abraded M50 material was sealed in a separate quartz container. The irradiation was conducted at a thermal flux of 1.6×10^{10} neutrons/cm^2-sec for 157 hr and was completed on 14 April 1978.

TABLE 4. RADIOACTIVE TAGGING — NEUTRON ACTIVATION CALCULATIONS FOR M50 BEARING STEELS[1]

Decay Time (Yr)	Bearing Mass (g)	Iron-55 (μCi)	Iron-59 (μCi)	Manganese-54[2] (μCi)	Cobalt-60[3] (μCi)	Chromium (μCi)	Total System Activity (μCi)	Activity of 1 ppm[4] (μCi)
0	800	115	49	5.9	34.5/4.8	904	1108/1079	0.025/0.024
	1	0.144	0.061	0.007	0.043/0.006	1.13	1.386/1.348	
0.5	800	100	3	3.9	32.3/4.5	9.6	149/121	0.0033/0.0027
	1	0.125	0.004	0.005	0.040/0.0057	0.012	0.186/0.151	
1	800	88	0.19	2.6	30.2/4.2	0.10	121/95	0.0027/0.0021
	1	0.110	0	0.003	0.038/.0052	0	0.151/.119	
5	800	30.3	0	0.01	17.9/2.5	0	48/33	0.0011/0.0007
	1	0.038	0	0	0.022/0.0031	0	0.060/0.041	
Isotope half-life:		2.6 yr	45 days	0.830 yr	5.26 yr	28 days		

(1) 1.6×10^{10} n/cm^{2}sec thermal flux for 7 hr.
(2) Thermal to fast neutron flux ratio = 15
(3) W% cobalt = 2500 ppm max/370 ppm from a material analysis performed during this program
(4) 1 ppm = 0.018g in a 5-gal oil system

Gamma ray spectroscopic measurements of two neutron-irradiated rollers were performed on 17 July 1978, and again 29 September 1978, 93 and 165 days following the removal of the rollers from the reactor. A lithium-drifted Germanium detector was employed; seven distinct gamma ray energy peaks from the irradiated material were apparent. Thermal neutrons produced radioisotopes of iron-59 (1098 and 1290-keV gamma rays) and chromium-51 (320-keV gamma ray), as well as the long half-life cobalt-60 (1170- and 1330-keV gamma rays). In addition, the fast neutron flux produced an 835-keV gamma ray from manganese-54. This 291-day half-life manganese-54 originates from a fast-neutron proton reaction with iron. Figure 2 depicts the spectra for both sets of measurements. The short half-life of chromium-51 and iron-59 is evident. The fast neutron reaction of stable iron-54 which produces radioactive manganese-54 $\left[{}^{54}Fe(n,p){}^{54}Mn\right]$ occurs at neutron energies in excess of 1 MeV. The Union Carbide swimming pool reactor used for the neutron irradiation was estimated to have a fast flux of 1×10^{9} neutron/cm^{2}-sec for an estimated thermal to fast flux ratio of 15.

The decay of radioactive iron-55 occurs through the capture of a K-shell electron with the emission of a 5.9-keV characteristic x-ray from the decay product, as presented in Figure 3. Although iron-55 represents 85% of the radioactivity of the neutron irradiated bearing material (as of the 22 November 1978, assay - 7 months from initial irradiation), 98% of the 5.9-keV x-ray emissions are absorbed within the roller structure itself due to the limited range of the emitted x-ray. To obtain the iron-55 x-ray spectrum milligram quantities of silicon carbide abraded bearing material were dispersed over the surface of a 1-in. diameter planchet, and were positioned in contact with a beryllium window of a sealed argon-carbon dioxide gas proportional detector.

(2) Assay of Neutron Activated Bearing Material

The amounts of radioactive iron-55 and iron-59 per gram of M50 bearing material produced by the 157-hr irradiation are presented in Table 5 as a function of time after removal from the reactor. The radioactivity levels from the actual irradiation are 23 times greater than the irradiation projected for the rig tests in the verification task of the program. The initial irradiation was conducted at a level higher than the minimum required for detection.

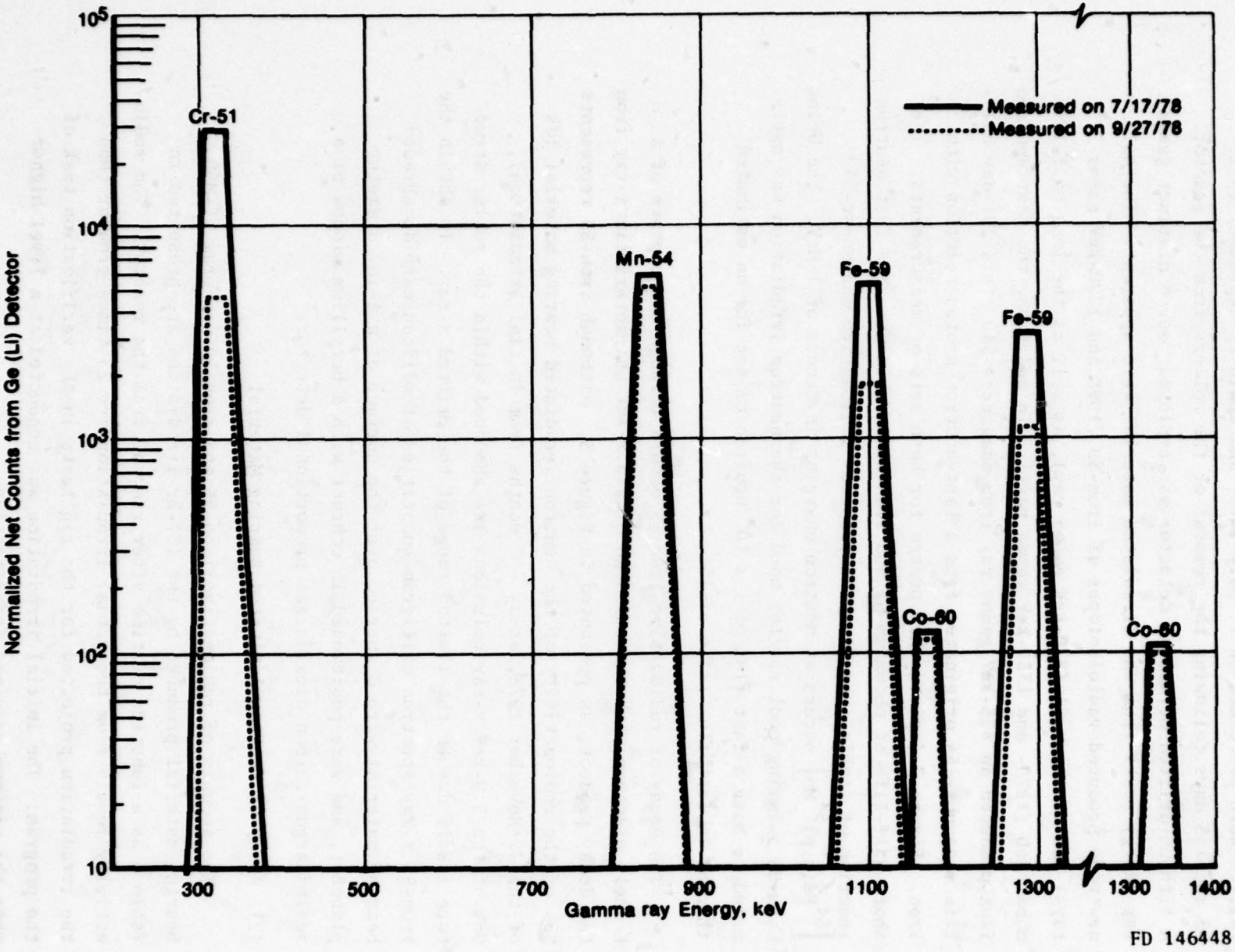

Figure 2. Gamma Ray Spectra From Neutron Activated M50 Roller Bearing Material

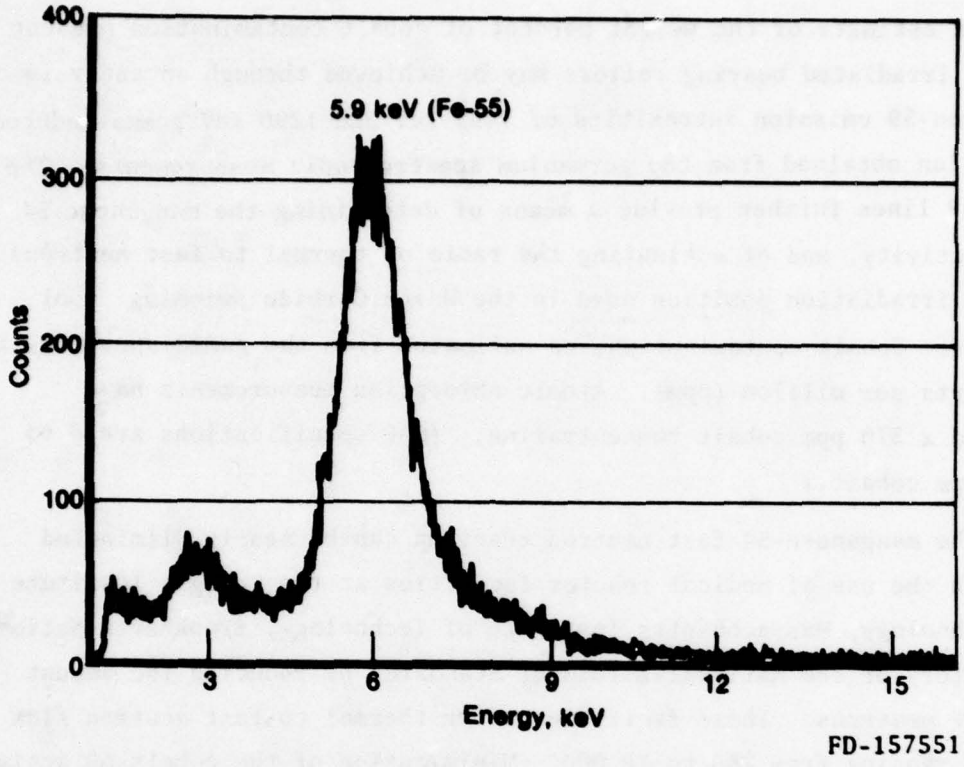

Figure 3. Wear Metal Debris Iron-55 X-ray Spectrum December 78

TABLE 5. M50 BEARING STEEL RADIOACTIVITY DUE TO THE 14 APRIL 1978 NEUTRON IRRADIATION

(157 hr at Thermal Neutron Fluxes of 1.6×10^{10} neutrons/cm^2-sec)

Time After Exposure	Microcuries Per Gram			
	0	½ yr	1 yr	5 yr
Iron-55	3.30	2.90	2.500	0.870
Iron-59	1.40	0.09	0.005	0.000
Cobalt-60(1)	0.14	0.13	0.120	0.080
Manganese-54	0.19	0.12	0.080	0.002
Chromium-51	22.00	0.21	0.070	0.000
Total Activity	27.03	3.45	2.710	0.950

(1) Uses atomic absorption measurements of 370 ppm cobalt in M50 steel.

An estimate of the weight percent of cobalt contamination present in the irradiated bearing rollers may be achieved through an analysis of the iron-59 emission intensities of 1098 keV and 1290 keV gamma-induced radiation obtained from the germanium spectroscopic measurements. The iron-59 lines further provide a means of determining the manganese-54 radioactivity, and of estimating the ratio of thermal to fast neutrons at the irradiation position used in the Union Carbide swimming pool reactor. Cobalt contamination, as estimated from the gamma spectrum, is 100 parts per million (ppm). Atomic absorption measurements have yielded a 370 ppm cobalt concentration. (M50 specifications are 0 to 2500 ppm cobalt.)

The manganese-54 fast neutron reaction can be nearly eliminated through the use of medical reactor facilities at the Georgia Institute of Technology, Massachusetts Institute of Technology, Brookhaven National Laboratory or the National Bureau of Standards by reducing the amount of fast neutrons. These facilities offer thermal to fast neutron flux ratios ranging from 200 to 10,000. Minimization of the cobalt-60 activation, however, can only be achieved through the specific selection of bearings from master melts containing the lowest level of cobalt contamination.

Simulated M50 bearing material wear debris was obtained by abrading bearing surfaces with medium grade silicon carbide paper. Ninety milligrams of this mock wear metal debris were neutron activated with the bearing rollers. Assaying the neutron activated bearing material for the principal iron-55 activity required the counting of milligram quantities. The low energy x-rays are, however, readily absorbed by the wear material itself; the mock debris was, therefore, distributed over the surface of 1-in. diameter aluminum planchets. Model cement dissolved in acetone was used to bind the debris to the planchet surface. Radiation counting was performed using a windowless gas proportional counter. A chemical analysis of irradiated simulated wear metal debris revealed about 38.5% of the debris to be iron, with about 55% of the debris insoluble in hydrochloric acid. The iron component is equivalent to 43.8% bearing material. The insoluble material is silicon carbide abrasive.

The assay results using net count from the tagged material, Figure 4, show that the specific activity of the M50 material consisted of 3.2 μCi/g, 7 months after reactor irradiation. This value was lower than originally calculated estimates due to the use of a neutron flux of 1.6×10^{10} neutrons/cm^2-sec rather than the higher prescribed value of 5×10^{10} n/cm^2-sec. Improved agreement in future neutron irradiations can further be secured through the employment of pure element standards in measurements of the neutron flux intensity for the reactor position used in the irradiation of the bearing. It is estimated that agreement within ±30% is feasible. The assay value was determined assuming that iron-55 was the only radioisotope present. The effects of the beta and x-ray emissions from the other radioactive elements were used to correct the counts to the 3.2-μCi/g assay value.

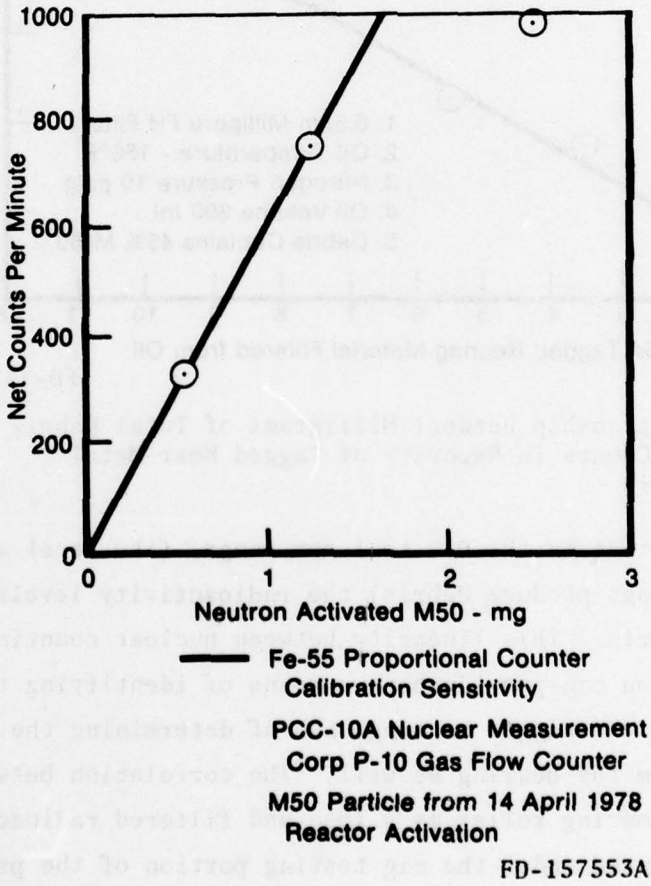

Figure 4. Tagged Bearing Material Assay Results

The nonlinear portion of the 2.4 mg sample results from sample self-absorption incurred by the clustering of the M50 particles on the planchet. Figure 5 includes the total mass of debris, i.e., bearing plus silicon carbide. The presence of the silicon carbide simulates extraneous material, such as metallic debris from other components or nonmetallics such as silicon, which may be present in an engine oil system and which can be trapped on the sampling filter.

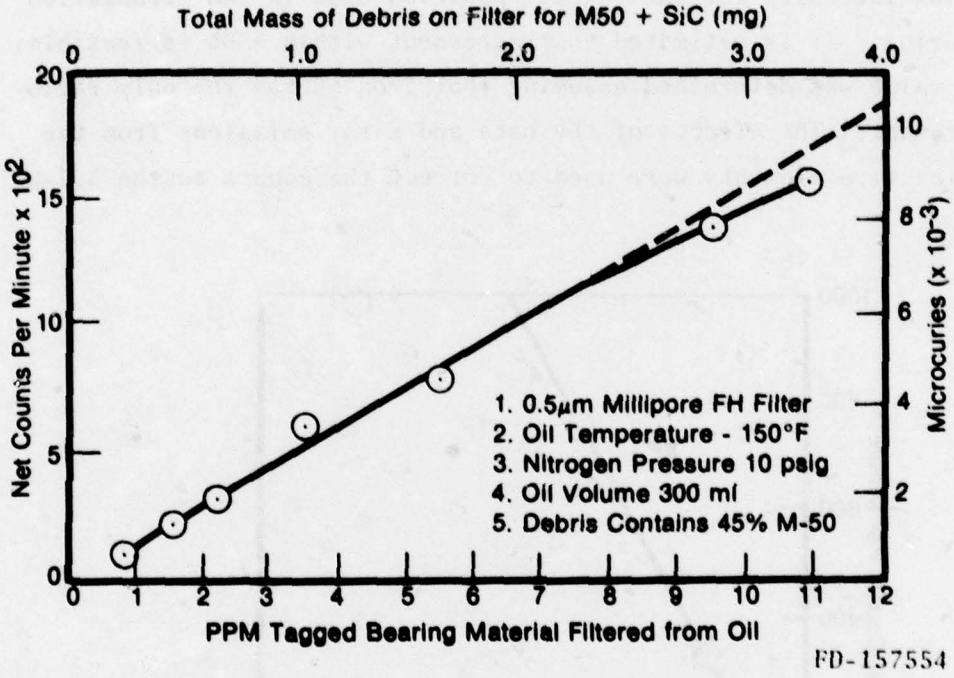

Figure 5. Relationship Betweel Milligrams of Total Debris and Net Counts in Recovery of Tagged Wear Metal Debris

Figure 5 shows that in the 0.5 to 1 ppm range, (the level at which high DN roller bearings produce debris) the radioactivity levels are linear with wear debris. This linearity between nuclear counting and iron parts per million can provide both a means of identifying the presence of debris from the tagged bearing, and of determining the amount of material loss from the bearing as well. The correlation between parts per million actual bearing roller mass loss and filtered radioactive debris will be evaluated under the rig testing portion of the program.

(3) Dose Measurements of the Irradiated Material

To ensure the minimal impact on Air Force maintenance procedures, the quantities of bearing roller radioactivity introduced will be maintained at a level that does not impose any restrictions in handling during roller inspection, bearing assembly, or bearing installation.

On 29 September 1978, the dose rate from 125g of bearing material previously irradiated on 14 April 1978, was measured to examine the characteristics of the irradiated steel and found to be 2.7 millirems (mrem) per hour. These data were obtained at a distance of 7.5 cm from the centerline of an air ionization dose rate meter (Victoreen 440) with the cover off. The 800g of total bearing material to be irradiated for each bearing under Task IV of this program is projected to have an overall dose rate of 0.7 mrems/hr 6 months following removal from the reactor at a comparable measuring distance. Such a decrease in dose level follows from a reduction in the activity of the rollers to be tested when compared to the initial irradiation condition. Table 6 shows the radiation dose rates from the rollers projected at the initiation of the demonstration test, while Table 7 depicts the radiation dose rate from various public sources. To re-emphasize, no handling restrictions will be required for the bearings during the test portion of the program.

TABLE 6
ROLLER BEARING DOSE RATE AT THE INITIATION OF THE DEMONSTRATION TESTING

	Contact (mrem/hr)	3 in. (mrem/hr)	1 ft (mrem/hr)
One Roller	0.2	0.023	0.001
Assembled Bearing	4	0.7	0.2

TABLE 7. RADIATION DOSE RATES AND DOSES FROM COMMON SOURCES

	Dose Rate (mrem/hr)	Dose mrem
Potassium-40 naturally occurring in the body[1]	0.002	20 per yr
Natural background dose at sea level (average)[1]	0.011	100 per yr
3-hr jet-plane flight[1]	0.67	2 per flight
Chest x-ray	—	30 per exposure
Dental x-ray single exposure[2]	—	250-450 per exposure

(1) See Reference 8

(2) See Reference 9

3. KRYPTON-85 DIFFUSION IMPREGNATION

The impregnation of radioactive krypton-85 gas into engine hardware for the purpose of obtaining postoperative measurement of maximum surface temperature distribution has been in use by Pratt & Whitney Aircraft Group since 1968 (References 10, 11, 12, and 13). The majority of the work has involved first- and second-stage turbine blades and vanes; temperature data have been recovered from rig-operated TF30 mainshaft bearings. Maximum temperature data have been recovered from TF30 turbine blades after 150-hr of engine endurance testing. Current laboratory work is aimed at defining the accuracy of the method on JT9D gas turbine mainshaft bearing test pieces over the 250 to 450°F temperature range. Additional work in this area has been reported by other investigators (Reference 14).

The application of krypton-85 to the measurement of wear rates has been attempted with the impregnation of electroplated nickel (Reference 15). A nickel surface was applied in rotary-sliding motion against a surface of nickel-free tool steel. The wear process was then carried out under water in order to prevent the loss of nickel dust. The nickel loss was determined by wet chemical analysis of both the containing water and the steel face. The results revealed an exponential decrease in residual krypton radioactivity as a function of the nickel mass removed from the surface. These measurements demonstrated that the krypton had penetrated to a depth in excess of 3×10^5 Å (1.2×10^{-3} in.) and that the amount of trapped krypton decreased with depth. No attempt was made to measure the radioactivity of the nickel wear metal debris. Work was also reported in this reference regarding the depth of krypton-85 penetration in alloy steel rollers. This was determined by a series of electropolishing and residual radioactivity measurements. The krypton depth was determined to be on the order of 2×10^4 Å (8×10^{-5} in.) and exhibited an exponential decrease with depth, as previously found in the electroplated nickel results.

The 10.6-year half-life of krypton-85 and its nearly pure beta emission of 695-keV energy electron result in a radioactive tag with a minimum radiation hazard, but with sufficient electron energy to produce a measurable wear metal debris tag. The U. S. Nuclear Regulatory Commission (NRC) regulation permits 100 μCi of krypton-85 to be exempted from all NRC

regulation. A neoprene sheet 0.032-in. thick will provide about 95% attenuation of the beta radiation exposure. The 0.4% emission of the 514-keV gamma from krypton-85 is at a low, nonhazardous level.

a. Impregnation Procedure

Impregnation of fifteen 16 by 16 mm bearing rollers was performed at the United Technologies Research Center (UTRC) krypton-85 facility (Figure 6). Introduction of radioactive krypton-85 gas into solids was accomplished by exposing the solid to a high temperature, high pressure krypton environment. Krypton diffusion into the material increases exponentially with temperature, but linearly with pressure and with the square root of time exposure. The thermal diffusion of the krypton was carried into the M50 rollers at 450°F and 320 psia for 267 hr. The krypton gas mixture contained 13.4% krypton-85 gas, while the remaining atmosphere constituted inert nonradioactive krypton gas.

Prior to impregnation, the rollers were solvent cleaned using standard bearing cleaning procedures to remove the oil protective coating and were oxide-passivated by heating in air for 4 hr at 500°F. Seven of the impregnated rollers were new, while eight rollers were previously run in a gas turbine engine environment. The used rollers were also treated electrochemically by following a standard preplating cleaning procedure (alkaline cyanide solution - ENDOX 214) to remove the residual varnish coating.

Radioactive assay subsequent to impregnation revealed a level of 0.5 to 0.8 μCi per new roller and a range of 1.2 to 1.6 μCi per used roller. The higher levels for the used rollers can be attributed to the krypton retention in the residual varnish layer.

When the kryptonated material is reheated to temperatures lower than its previous maximum temperature, no significant activity losses occur. The maximum temperature endured by the kryptonated material must be maintained for a sufficient period to liberate the krypton atoms having

binding energies less than, or within the range of kinetic energy distributions at the maximum temperatures. Thus, in order to thermally "stabilize" the krypton impregnated bearing material for temperatures in excess of those existing for engine oil operating conditions, the rollers were thermally stressed in a 450°F oil bath prior to depth measurements. The stabilization process consisted of subjecting the rollers to twenty-four 4-min heating and cooling cycles. Approximately 10% of the initial krypton radioactivity was lost during this process. Prior work has shown that operating at temperatures lower than 450°F will result in negligible additional gas loss.

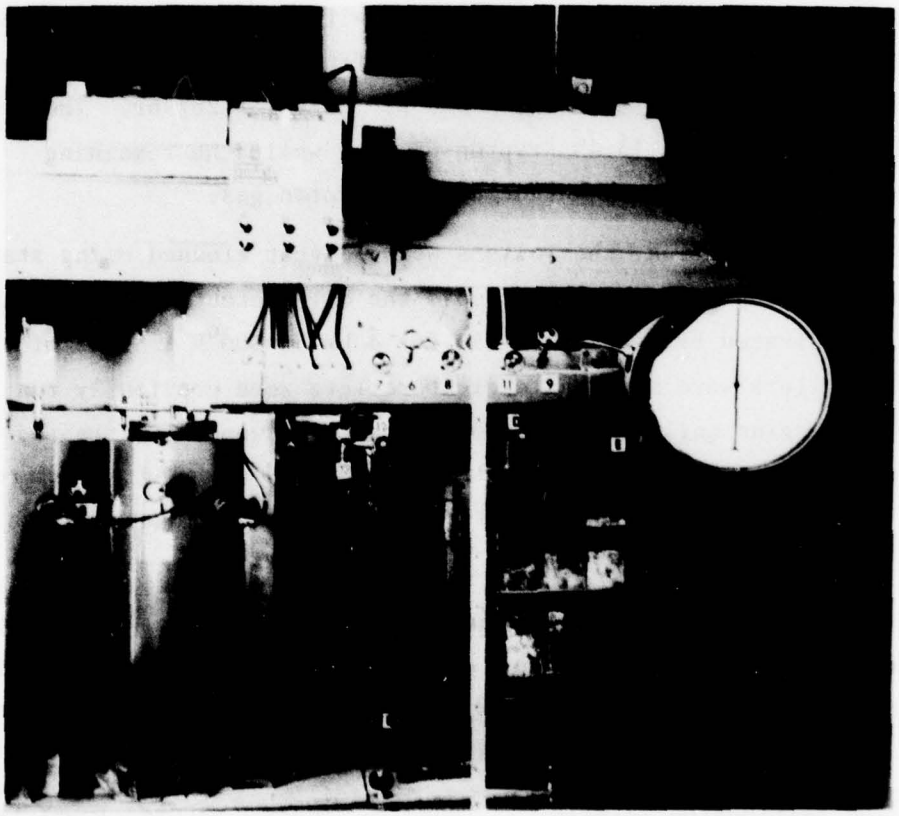

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Figure 6. Radioactive Krypton Impregnation Facility at UTRC

b. Depth Measurements

The depth penetration of the gas, as well as the concentration and distribution of depth into the parent material are dependent upon the nature of the material being impregnated. The trapping sites for the

stable retention of krypton atoms appear to be associated with defect structures in the grain boundaries and intergranular defects of the host material. Chemical and physical properties of the parent material were not found to be altered by the impregnation of the krypton gas into the surface (Reference 14).

The depth of krypton diffusion was measured by sequential abrading and electropolishing removals. Nuclear counting was performed on the end surface area of the various rollers. Two rollers were investigated for each material removal technique. A plastic scintillator coupled to a photomultiplier tube was used to measure the residual radioactivity. The amount of bearing material removed was determined by weighing the rollers before and after each material removal. Figure 7 shows that the fraction of residual (I) activity after material removal divided by the initial activity (I_o), reached the 0.01 level at a depth of about 2 μm (0.08 mils). The abrasive removal depth measurements reached the 0.01 level at a depth of about 1.9 μm. Both the abrasive removal and electropolishing removal data are presented in Figure 7. The 0.001 I/I_o level was determined to be about 3 μm (0.118 mils). Krypton activity at less than the 0.001 $1/I_o$ level would not contribute to bearing tagging detection sensitivity. Measurements of the abraded material removed from the silicon carbide paper confirmed that the krypton was retained in the removed debris.

The electropolishing technique consisted of masking a 0.495 cm^2 area on the roller end and then dipping approximately two-thirds of the roller surface into an insulating lacquer. The roller was then electrically connected to form the anode, a platinum strip providing the cathode. A 10% solution of perchloric acid in methanol constituted the electrolytic solution. The solution was maintained at -10^oF through the use of liquid nitrogen cooling. Electropolishing was performed with an open circuit voltage of 25v DC and about 0.3 amps for periods of both 10 and 25 sec.

Krypton-85 diffusion tagging does not penetrate to a sufficient depth in the M50 bearing material to be applicable to the identification of high-speed roller bearings eccentric end wear. The roller eccentric end wear is restricted to less than 10% of the total surface area of a roller with the wear in this area attaining several mils in depth. Figure 8

shows the wear pattern on a 16-mm roller exhibiting heavy end wear. This wear pattern represents a mass loss of about 12 mg or 0.67 ppm in a 5-gal system. In addition, due to the exponential depth distribution of the krypton gas, a correlation between activity and wear metal debris (parts per million) cannot be accomplished. The krypton tag will solely identify the wear location.

The krypton-85 tagging concept would be applicable for larger surface wear areas in which 0.1 mils of surface depth represents a significant amount of wear.

4. CONCLUSIONS - RADIOACTIVE TAGGING

a. Neutron Irradiation

The neutron irradiation of bearing material is recommended for bearing failure detection tagging procedures. Two isotopes were assessed as possible tags in this program — krypton-85 and iron-55. Of the two, iron-55 was selected for use in radioactive tagging for high speed roller bearings eccentric end wear monitoring. Krypton-85 diffusion tagging was rejected following both a literature survey and experimental testing due to its inefficiency in depth penetration in the bearing material.

In contrast, the radioactivity levels in the neutron-activated iron were uniform throughout the material, and can be established at a specific value. Moreover, the assay of neutron-activated bearing material incorporating iron-55 has revealed a linearity between nuclear counting and the parts per million concentration of iron debris in a lubricating fluid. This provides both a means of recognizing the occurrence of distress in the tagged bearing, and of identifying the amount of material loss from that bearing. This capability is not possible utilizing a krypton tag.

The only major uncertainty of the iron-55 tagging procedure is the by-product generation of cobalt-60 during neutron activation of the bearing steel. It is, however, possible to analytically determine the amount of cobalt-60 so generated, given master-melt information of the bearing steel, irradiation flux, and exposure time. By reducing the cobalt concentration in the original M50 steel used, it is possible to reduce the cobalt-60 dose obtained.

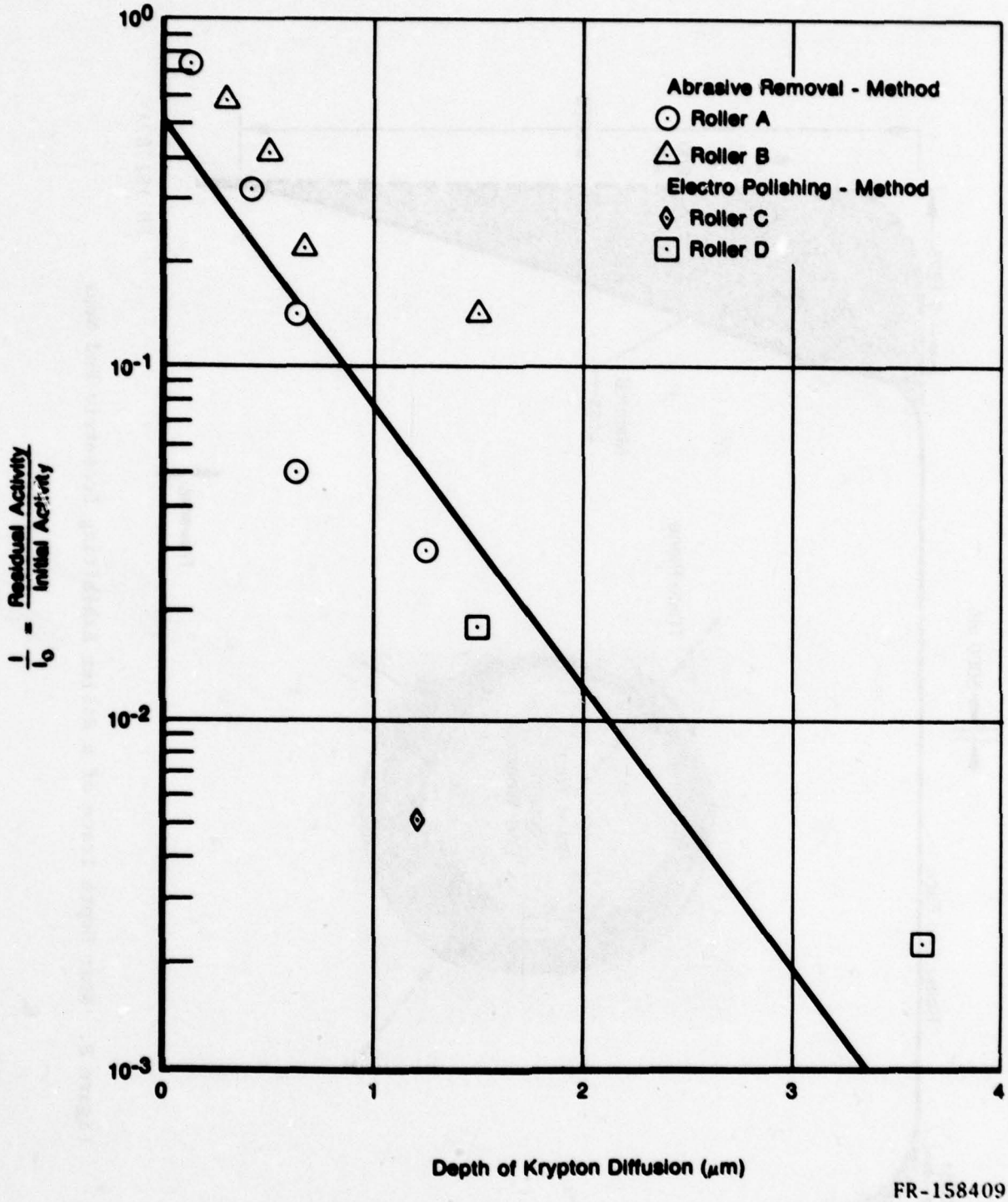

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Figure 7. Krypton-85 Depth Penetration into M50 Bearing Material - Abrasive and Electropolishing Removal Data

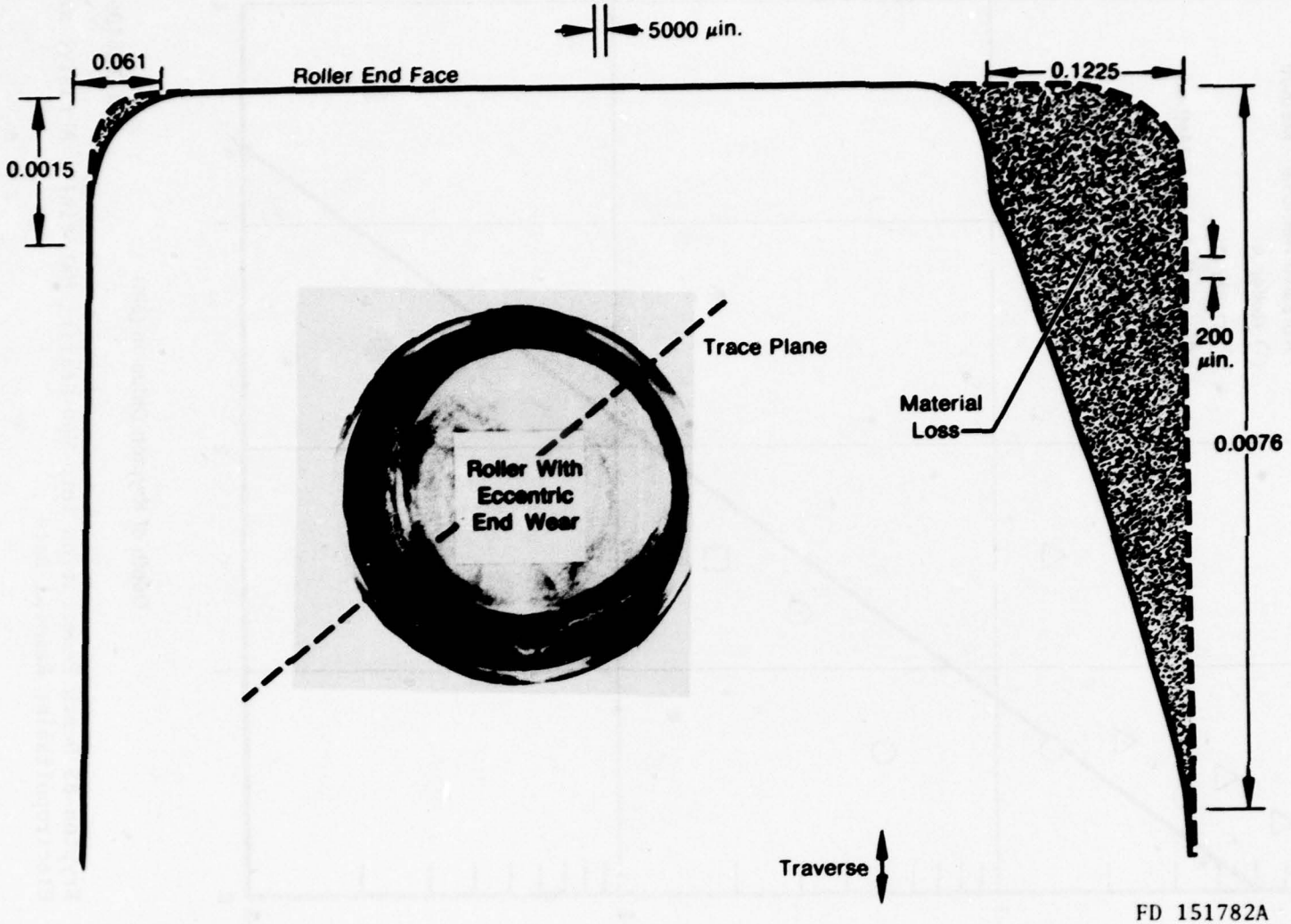

Figure 8. Wear Depth Trace of a Roller Exhibiting Eccentric End Wear

Therefore, as a result of the advantages of the iron-55 isotope noted above, and because of its adherence to all tagging criteria as described in Section I-1, iron-55 has been selected as the radioactive tag best suited for utilization in this program.

SECTION III
DEBRIS RECOVERY

1. GENERAL

The radioactive bearing tagging technique requires separating the wear metal debris from the lubricating fluid. The specific amount of engine oil processed for wear metal debris recovery is dependent upon the required part per million threshold level for detection, the initial level of radioactivity concentration on the tagged roller, the nuclear debris counting system sensitivity, and the radioactive decay time.

Severe roller eccentric end wear from a typical high speed application represents a mass loss of 9 to 15 mg. In a 5-gal oil system, typical of current jet engines, the lower mass loss is equivalent to 0.5 ppm. To provide detectability at the 9-mg eccentric end wear level, a 0.5 ppm debris detection threshold level will be used.

Table 8 illustrates the effect of the recovery efficiency and the amount of oil filtering on the detection capabilities of the radioactive tagging system. The table reflects the following constraints:

1) Iron-55 specific activity after a decay time of 5 yr (0.038 μCi/g, Table 4)

2) One part per million of debris in a 5-gal system is 18 mg of wear

3) A nuclear detection system with a low level of detectability of 2.3×10^{-6} μCi. (See Section IV.)

TABLE 8
WEAR METAL THRESHOLD LEVEL VERSUS SAMPLE SIZE AND DEBRIS RECOVERY EFFICIENCY

Recovery (%)	5 gal (F100 Oil System) (18.9 liters) (ppm)	0.26 gal (1.0 liters) (ppm)	0.13 gal (0.2 liters) (ppm)	0.026 gal (0.1 liters) (ppm)
100	0.003	0.06	0.32	0.64
50	0.07	0.13	0.64	1.29

The Table 8 shows that the 0.5-ppm threshold level can be achieved for 100% recovery of under 130-ml of oil. The threshold level quoted represents the lowest detectability expected due to the reduced radioactivity after 2 half-lives decay of Fe-55 (5 yr). Six months after activation, the 130 ml of oil can detect to a level of 0.15 ppm. The oil sample volume required to achieve 0.5 ppm threshold detection as a function of radioactive decay is shown in Figure 9.

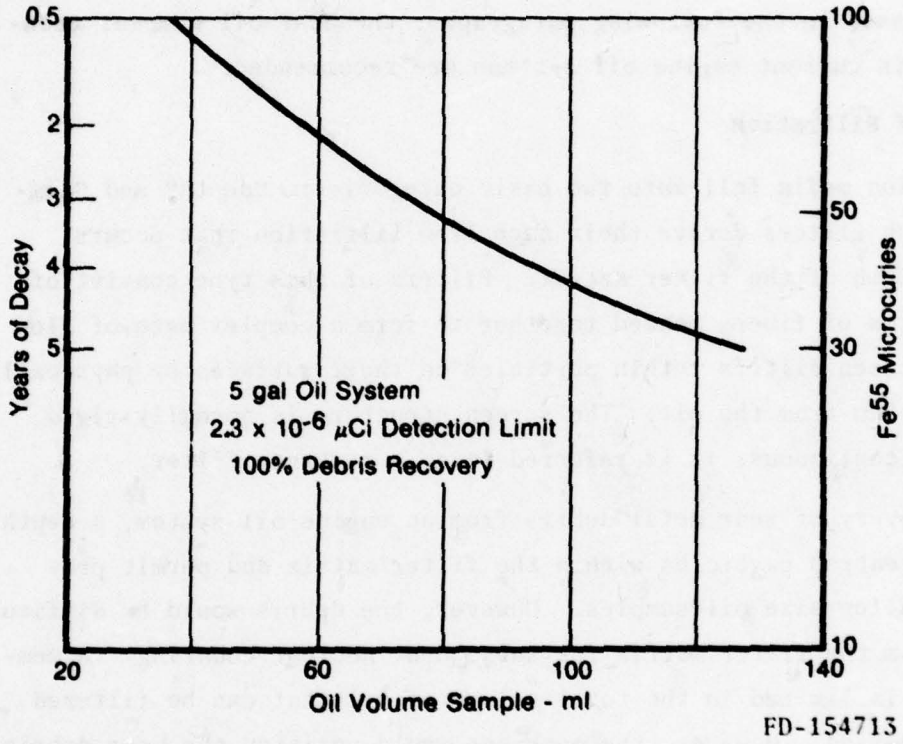

Figure 9. Oil Sample Volume to Achieve 0.5 ppm Debris Measurement Required

2. RADIOACTIVE DEBRIS ANALYSES

An initial evaluation to determine the most practical method of wear metal debris recovery considered procedures such as filtration, centrifuging, and magnetic and solvent extraction. Centrifuging and solvent extraction were rejected because of the limited quantities of oil that could be processed and the complexities involved in processing the oil. Magnetic separation was found to be applicable to gallon size oil samples but filtration was determined to offer the most practical method of debris recovery. Thus, of all the various debris removal techniques

examined, an optimal design appears to consist of either a vacuum or pressure filtration system incorporating a supported membrane filter (Reference 16).

The method used to obtain an oil sample for subsequent radioactive debris analysis must ensure that the sample represents the equilibrium wear metal concentrations existent during the operation of the engine oil system (Reference 17). Details regarding proper oil sampling methods are presented in the wear particles atlas (Reference 18). For the tagging system discussed in the following paragraphs, the SOAP oil removal techniques used in current engine oil systems are recommended.

a. Types of Filtration

Filtration media fall into two basic categories: "depth" and "membrane." Depth filters derive their name from filtration that occurs within the depth of the filter matrix. Filters of this type consist of a random matrix of fibers bonded together to form a complex maze of flow channels. Screen filters retain particles on their surfaces by physically "screening" them from the oil. The screen structure is normally rigid, uniform, and continuous; it is referred to as a membrane filter.

For recovery of wear metal debris from an engine oil system, a depth filter would entrap particles within the filter matrix and permit processing of gallon size oil samples. However, the debris would be difficult to remove from the filter matrix for subsequent nuclear counting. A membrane filter is limited in the total volume of oil that can be filtered in a finite period. However, the membrane would position the wear debris on the filter surface which could then be directly introduced into the nuclear counting system. Due to its high capture efficiency and simplicity of use, membrane filtration has been chosen for wear particle removal. A description of this filtration method follows.

b. Clean Engine Oil

The field application of the tagged mainshaft bearing approach for incipient failure detection necessitates utilization of the least complicated method for removal of the wear metal debris from the engine oil. Membrane filtration using a 47-mm pressure holder (Millipore Corporation

Type XX40 047 40) was selected for laboratory testing (Figure 10). The time necessary to filter 200 ml of clean Mobil Jet Oil II (MIL-23699-B Specification) was measured for applied nitrogen pressures ranging from 5 to 40 psig, Figure 11. The inverse power law relationship of time (T) necessary to filter 200 ml of oil as a function of applied pressure (P) was observed to be $T = aP^{-2/3}$, the value of "a" being a function of the following:

Filter Type	Pore Size (μm)	Temperature (^{o}F)	"a"
Millipore FH	0.5	65	90
Millipore FA	1.0	65	36

From Figure 11 it can be seen that for a 5-min filtration, 70 psig is required for 0.5-micron filtration and 20 psig is required for 1-micron filtration.

Reduction in the amount of time or pressure necessary to filter the oil can be achieved by increasing the oil temperature. For synthetic Type II oil the viscosity decreases from 60 centistokes at 65^{o}F to 18 centistokes at 120^{o}F. Filtration of 200 ml of oil using 0.5-micron pore size membrane filter was performed at 10 psig pressure in about 6 min at the higher temperature. MIL-L-7808 oil used in Air Force gas turbine engines requires shorter filtering times due to its lower viscosity compared to Type II oils.

c. Used Engine Oil

To determine the effects of used engine oil on filtration time and pressure, an engine oil sample was obtained from a P&WA FT 12A-3 gas turbine engine used to drive a compressor at the United Technologies Research Center. Approximately 15 gal of oil were contained in the FT 12A-3 engine; the oil log indicated that the oil had not been changed in 5,000 hr. The oil used in this engine was Exxon Turbo oil 2380. The engine oil system used only metal screen type filtration. The color of the used oil was black.

A 200-ml sample of used oil was first filtered through a 1-micron filter (at approximately 150^{o}F and 10 psig) in about 3 min. Some carbon deposits were trapped on the filter but the filtrate remained black.

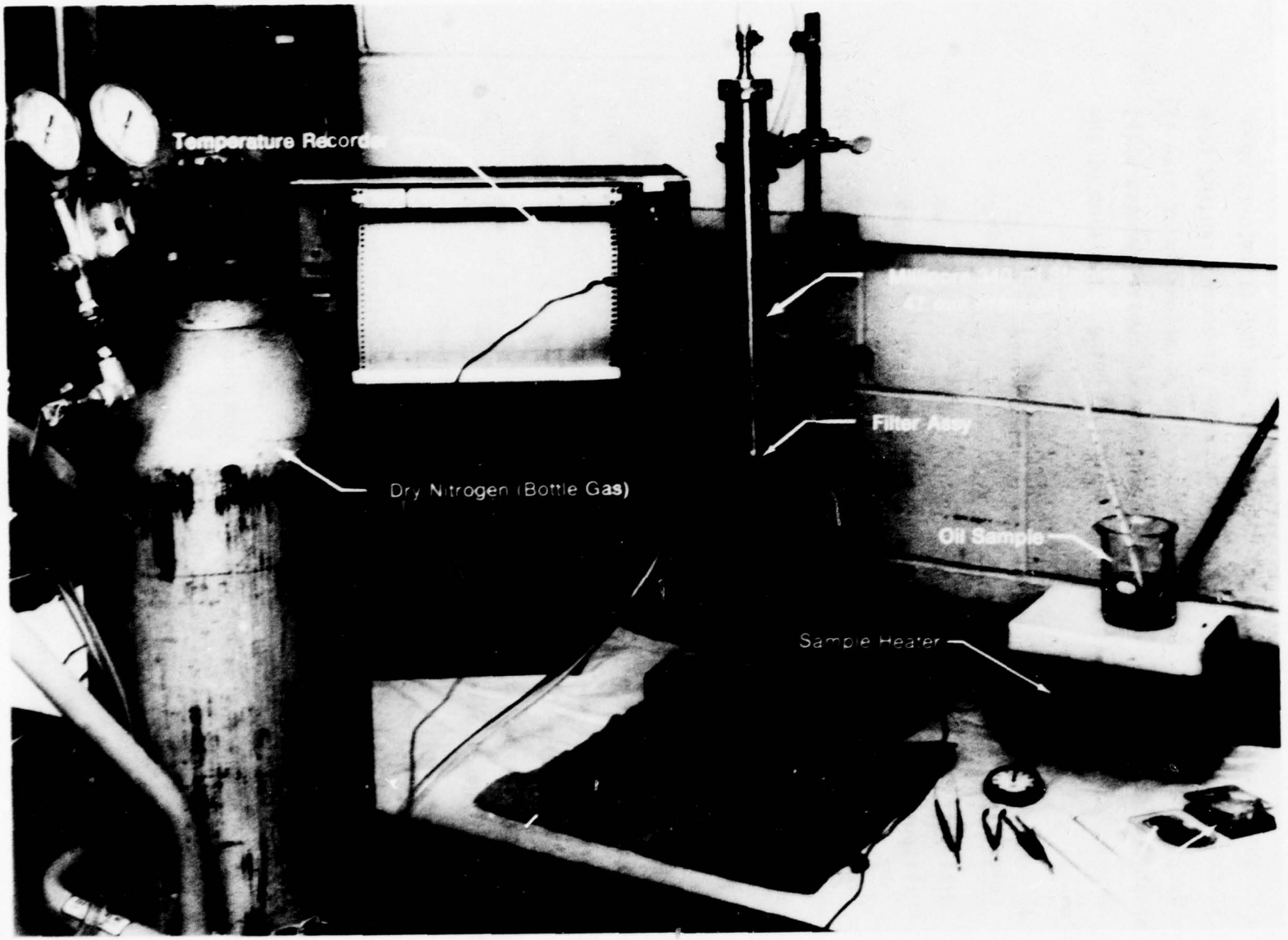

Figure 10. Membrane Filtration System for Wear Metal Debris Removal

The same oil was then filtered through a 0.5-micron filter (at approximately 180°F and 10 psig) in about 3 min. Less black debris was evident although the oil retained its black coloration. This test demonstrated that the absence of filter blockage was expected for used gas turbine engine field oil.

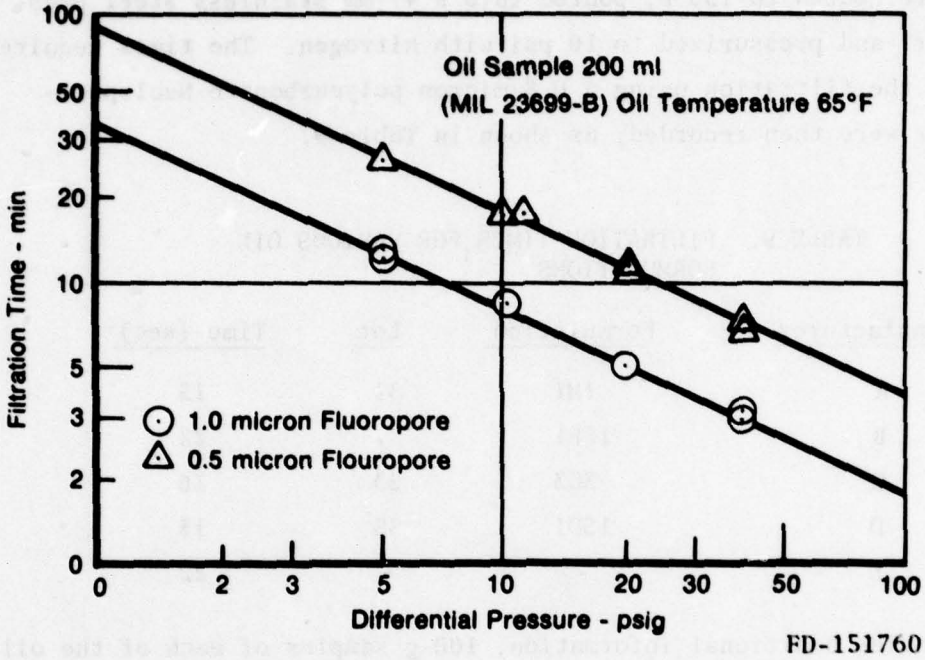

Figure 11. Oil Filtration Time vs Applied Pressure

d. Radioactive Debris Filtering

In order to evaluate the effectiveness of the membrane filter for the recovery of radioactive wear metal debris, various milligram quantites of debris were introduced into 300 ml of Mobil Jet Oil II. A 0.5 μm Flouropore Millipore filter was positioned within a 47-mm pressure holder. Oil temperature was set at approximately 150°F and a nitrogen gas pressure of 10 psig was used. After filtration, the filter was positioned within a gas proportional counter and measured for 1 min. The results, previously shown in Figure 4, Section II, demonstrate a linear relationship between milligram of debris and net counts to about 3 mg or 10 parts per million. For the nuclear counting conditions used, the linearity can be further extended to 100 parts per million by reducing the quantity of oil to 30 ml, thus reducing the amount of wear metal debris in the filter and the self-absorption of the debris.

e. Testing Various MIL-L-7808 Formulations

In order to determine the applicability of membrane filtration to the various manufacturer formulations of MIL-L-7808, 1-qt samples of Humble, Stauffer, Royal and Mobil lubricants were filtered. Fifty-gram samples were heated to 150°F, poured into a 47-mm stainless steel pressure holder, and pressurized to 10 psi with nitrogen. The times required to perform the filtration using a 0.8-micron polycarbonate Nuclepore-type filter were then recorded, as shown in Table 9.

TABLE 9. FILTRATION TIMES FOR VARIOUS OIL FORMULATIONS

Manufacturer	Formulation	Lot	Time (sec)
A	1M1	31	15
B	18E1	7	22
C	3C3	23	26
D	15D1	55	13
E	-	-	22

To provide additional information, 100-g samples of each of the oil types were also filtered using a 0.8-micron Nuclepore filter under the same conditions. The Humble and Mobil lubricants required 20 and 40 sec, respectively. The Mobil Jet Oil II and Stauffer lubricants both required 68 sec. Roughly 60% of the Royal lubricant passed through the filter in about 50 sec, after which the flow subsided to a slow drip.

Further testing using Millipore Fluoropore (polytetrafluoroethylene bonded to a polyethylene net) 0.5 and 1.0-micron filters showed that for the Mobil and Humble lubricants filtration required about two to three times longer than was necessary using the Nuclepore filters. In a 100-g test, about 60% of the Royal lubricant passed through the filter in 95 sec before the flow stopped. Stauffer lubricant was not filterable using the Millipore type filter.

A Schleicher and Schuell pressure filtration pneumatic hand pump with a liquid volume capacity of 50 ml has been used to filter Mobil Jet Oil II. The drawing up of as much as 20 ml of 150°F oil into the cylinder and the subsequent discharging of the oil through a 47-mm Nuclepore

polycarbonate filter required about 60 sec. These various tests suggest Polycarbonate Nuclepore type filters to be the practicable scheme for all formulations of Type I gas turbine engine lubricant.

f. High Gradient Magnetic Separation

In order to minimize the initial radioactivity levels of the bearing material, it is advantageous to process as much of the engine oil as possible for recovery of the tagged wear metal debris. Magnetic separation has demonstrated capability "of removing virtually all of the ferromagnetic wear particles in oil" (Reference 19). The oil is pumped at a flowrate of 1 to 3 gal/min through a filter canister containing a stainless steel wool matrix. The canister, about the size of an automobile oil filter, is enclosed in an electromagnet capable of generating a magnetic field of two kilogauss. The coarse steel wool matrix induces large perturbations in the magnetic field intensity, thereby producing sharp magnetic gradients for trapping the wear debris onto the steel wool.

Removal of the debris from the steel wool matrix would be achieved by circulating an oil solvent through the canister with the power removed from the electromagnet. A membrane type filter would then be used to remove the debris from the solvent. Discussions with magnetic separator manufacturers indicate that laboratory systems would cost upwards of $8000, depending on the technical sophistication and system size. The system would, however, be bulky and would not lend itself to flight line usage. Due to the complications that arise from magnetic separation, this system has been discarded in favor of membrane filtration.

3. CONCLUSION

The radioactive bearing tagging technique requires the separation of the wear metal debris from the lubricating fluid. The low level radioactive debris is filtered out of the oil using membrane filtration in the 0.5 to 1.0 micron range. Filtering duration of under 3 min are projected for samples up to 200 ml of typical Type I MIL-L-7808 gas turbine lubricant.

A polycarbonate Nuclepore membrane filtration is recommended for use in this program due to its high recovery efficiency and its simplicity of use. In addition, membrane filters have the advantage of depositing the wear metal debris on the filter surface, thereby permitting direct incorporation of such debris into a nuclear counting system.

Calculations of the required wear metal debris recovery for a field system using iron-55 as the radioactive tag indicate up to 130 ml of oil will have to be analyzed in order to obtain reliable measurements. The specific amount of oil removed is dependent upon initial tracer activity, debris recovery, decay time, and required part per million threshold level for detection.

SECTION IV

NUCLEAR MEASUREMENTS OF RECOVERED WEAR METAL DEBRIS

1. RADIOACTIVE DEBRIS DETECTION

The amount of induced bearing roller radioactivity required to provide wear metal debris identification is directly dependent upon the lower limit detection accuracy of available nuclear counting instrumentation.

Low level wear debris sample measurements involve the use of techniques that minimize extraneous background. Background counts are principally attributed to environmental radioactivity, cosmic rays, and electronic "noise." Surrounding the detector assembly with 4 in. of lead lined with 0.25 in. of copper will reduce the effects of environmental radioactivity. The positioning of a cosmic ray detector around the sample measuring detector provides a means of identifying cosmic ray counts from radioactive debris counts. The use of anticoincidence circuitry will temporarily block the instrument from responding to the occurrence of a cosmic ray event. The instrument will then respond only to the sample detector counts.

The low-energy 5.9 keV x-ray emissions from iron-55 and the 695 keV beta emissions from krypton-85 require the selection of a radiation detection method which will provide maximum detectibility. Scintillation counting experiences detectibility limitations for these emissions, while gas proportional counting permits higher detection (Reference 20). This higher detectability is critical in obtaining efficient counting sensitivity and background suppression. Gas proportional counters are about 30% efficient for the 5.9 keV x-ray and about 40% efficient for the 695 keV beta ray.

The lowest level of debris detection for this investigation will use the "minimum detectable activity concept" (References 21 and 22), i.e., that activity of a radionuclide which, in a given counting time, increases the reading of the instrument by an amount equal to three times the standard deviation of the background recorded in that time. The significance of background on the lowest level of debris detection is shown in Table 10. The factor increasing the level of detection between the 1 and 40 counts

TABLE 10. COUNTING STATISTICS FOR THE LOWEST LEVEL OF DEBRIS DETECTION

Background (cpm)	Counts (100 min)	Three Sigma Standard Deviation (counts)(1)	Minimum Detectibility Activity (pCi)(2)(3)		Proportional Counter Manufacturer
			Iron-55	Krypton-85	
40	4000	268	14.5	3.0	Nuclear Measurements Corporation
1	100	42.4	2.3	0.48	Canberra Industries(4)

(1) Three Sigma Standard Deviation = $3\sqrt{2X \text{ Background Counts}}$ for 100 min

(2) pCi = 10^{-12} curies = 10^{-6} microcuries = 2.22 disintegrations per minute

(3) Minimum Detectibility Activity is obtained using the following values for detection efficiency and emission fraction:

	Detector Efficiency	Emission Fraction
Iron-55	0.3	0.28
Krypton-85	0.4	1.0

(4) Detector efficiency has been estimated - actual measurement will be made when the system is tested.

per minute (cpm) background is 6.3; it represents the difference between a gas proportional counting system incorporating both lead shielding and anticoincidence methods and one which does not. The 6.3 factor also represents the decrease in the induced bearing roller radioactivity levels necessary to achieve the required level of debris detection.

2. GAS FLOW PROPORTIONAL COUNTING

The proportional counter is an ionization chamber type device in which radiation is detected by the ionization of the contained argon gas by collision with beta particles or by reactions with x-rays (Figure 12). Within the proportional counter the original electrons released by a nuclear event are multiplied by cascade ionization. This cascade ionization results from the electrical field acceleration force produced by a positively charged anode wire. The negative ions that are formed are attracted to the anode wire, and the positive ions are attracted to the cathode housing. The excessive charge on the anode wire is removed by the high voltage supply, resulting in a fast pulse of current through the anode wire. This fast charge pulse is electronically processed to a proportional voltage pulse. Each processed voltage pulse over a set voltage range represents a nuclear event or count.

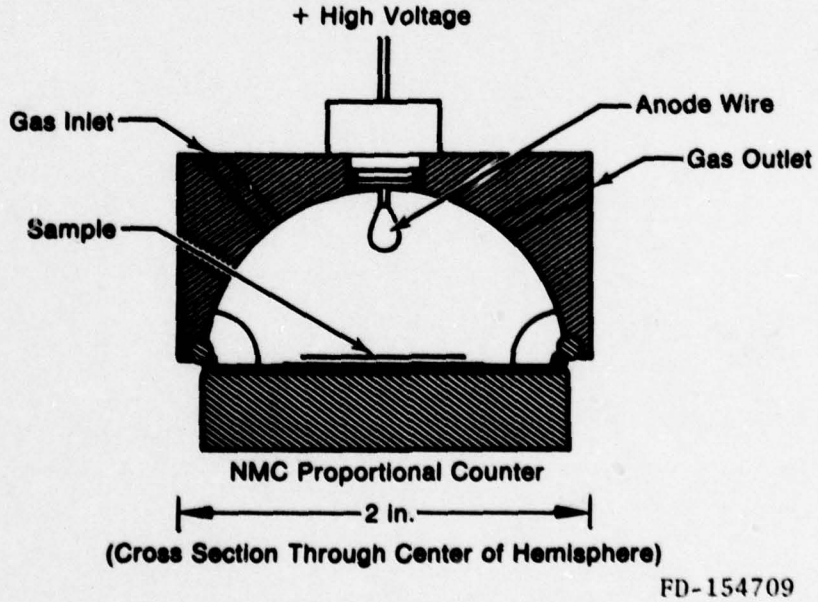

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Figure 12. Proportional Counter Ionization Chamber

The size and shape of the proportional counter determines detector efficiency for a nuclear event. The 5.9-keV x-ray from iron-55 and the 695-keV beta from krypton-85 have been determined for the Nuclear Measurement Corporation detector, Figure 13, to be 0.3 and 0.4 respectively. The Canberra detector, Figure 14, has been assumed to have the same detector efficiency. Testing confirmation will be performed. It should be noted that the background sensitivity is proportional to the volume of the detector, i.e., the smaller the volume the lower the background. There is, therefore, a trade-off between detector efficiency and background sensitivity. The current program is directed towards using off-the-shelf proportional counters. Further work on the optimization of the proportional counter has the potential of improving the detector sensitivity.

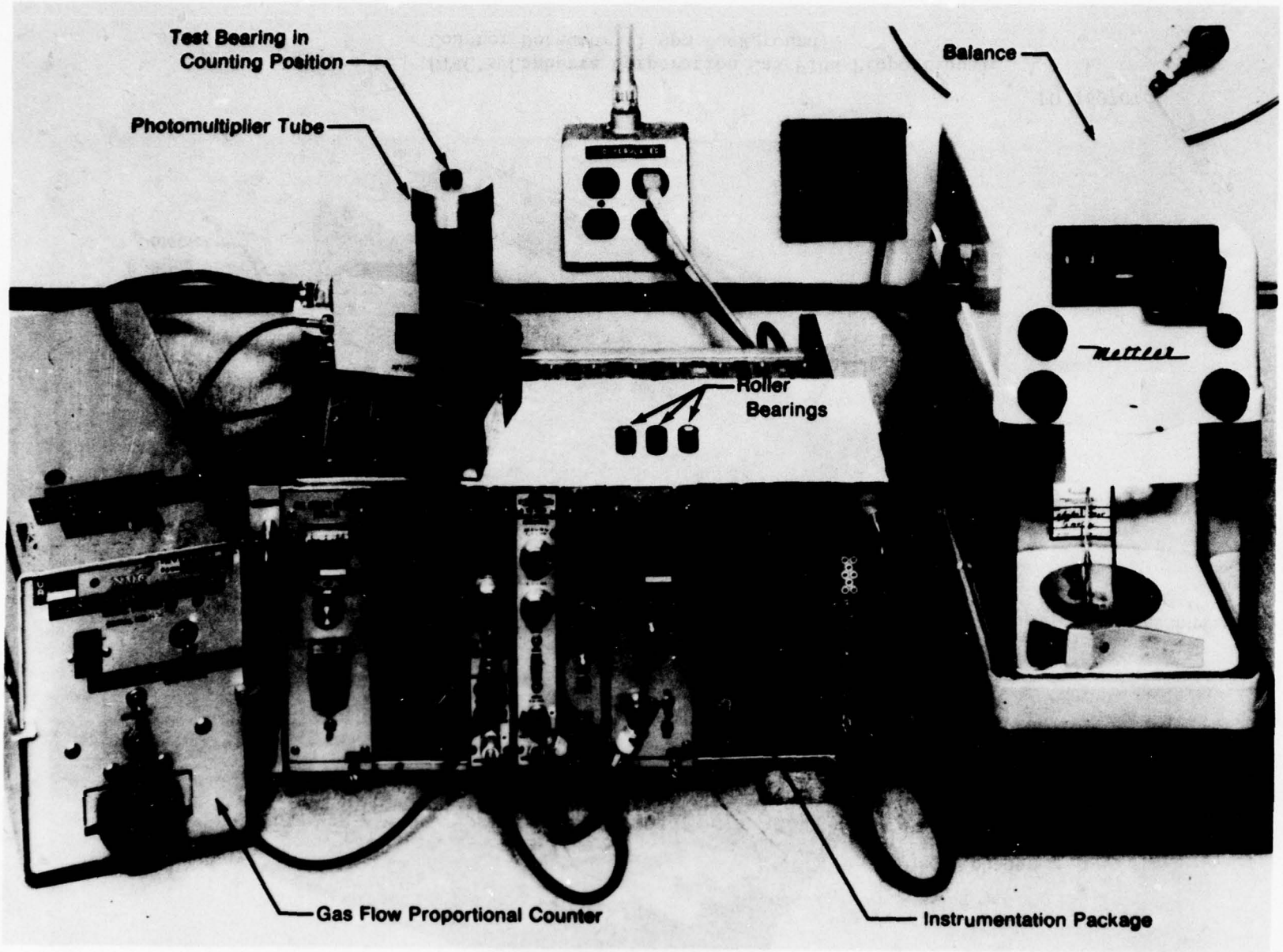

Figure 13. UTRC's Nuclear Measurement Corporation Gas Flow Proportional Counter Detector (40 cpm Background)

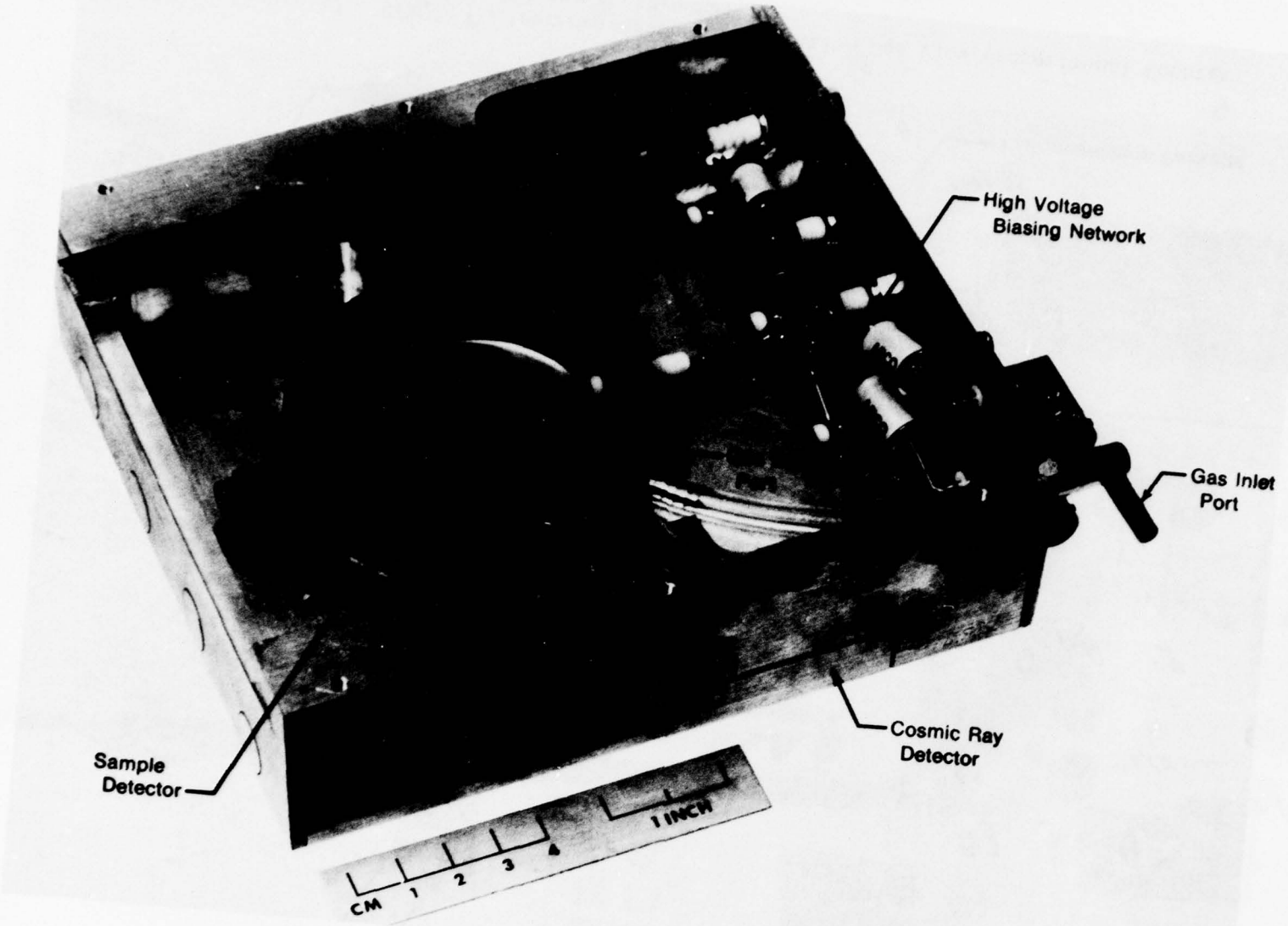

Figure 14. UTRC's Canberra Corporation Gas Flow Proportional Counter Detector (1 cpm Background)

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SECTION V

GOVERNMENT REGULATIONS

An important consideration in the evaluation of radioactive bearing tags is the federal regulatory requirements for the handling and disposal of low level radioactive material. Regulations for the use and possession of radioactive byproduct materials, (i.e., any radioactive material yielded in or made radioactive by exposure to the radiation incident to the process of producing or utilizing special nuclear material, fission of uranium) are promulgated by the U. S. Nuclear Regulatory Commission (Reference 5). Both P&WA and UTRC are licensed in the use of radioactive materials for performing research and development work.

The Nuclear Regulatory Commission provisions exempting the research and development user from compliance with the standard regulations in regard to certain specified quantities of radioactive material exist. These exempt quantities[1] of radioactive material are not considered environmentally significant.

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[1] Exempt quantities are defined in Chapter 30 Paragraph 18 of NRC Rules and Regulations, "Any person is exempt from the requirements of a license to the extent that such person receives, possesses, uses, transfers, owns, or acquires byproduct material in individual quantities each of which does not exceed the quantity set forth in 30.71, Schedule B." In addition, Section 32.19, states that no more than 10 exempt quantities set forth in 30.71, Schedule B, shall be sold or transferred in any single transaction. For the purpose of this requirement, an individual exempt quantity may be composed of fractions of one or more of the exempt quantities in 30.71, provided that the sum of such fractions shall not exceed unity.

The microcuries of radioactivity and the particular radioisotopes used for tagging the bearing rollers 6 months after irradiation approach the exempt category (Table 11), with only cobalt-60 exceeing the exempt quantity levels. The presence of 4.5 μCi of cobalt-60 represents insignificant hazards; i.e., 1 μCi of cobalt-60 is commercially used for spark gas irradiation in electrically ignited fuel burners.

Specific exemptions from the requirements regulation (Section 30.11 and Parts 31-35) may be granted by the Commission upon application of any person or upon its own initiative. The exemptions are authorized by law provided they will not endanger life or property or the common defense and security and are otherwise in the public interest. Part 32 of the regulations "Specific Domestic Licenses to Manufacture or Transfer Certain Items Containing By-Product Materials" prescribes requirements for the issuance of specific licenses to persons who manufacture or initially transfer by-product material for sale or distribution to persons exempted from the licensing requirements. The following (Table 12) lists some of the items being granted exemptions.

In petitioning for an exempt product status, a positive cost benefit relationship must be demonstrated. It must be shown that the product in question is required and that the need for this product cannot be satisfied through the utilization of nonradioactive product material. In addition, an environmental report incorporating appropriate safety analyses and verifying that the product is safe under all possible conditions of use must be compiled and submitted. Reference 23, as well as the NRC rules themselves, details the Environmental Report Requirements.

TABLE 11. EXEMPT QUANTITIES OF RADIOACTIVE MATERIALS

	Schedule B[1] (μCi)	TEST PROGRAM[2] Radioactivity at the start of the test (μCi)	Quantity Comparison Factor[3]	
			Neutron Activation[4]	Krypton Impregnation
Iron-55	100	100	1.00	
Iron-59	10	3.0	0.30	
Cobalt-60[5]	1	4.5	4.5	
Manganese-54	10	3.9	0.39	
Chromium-51	1,000	9.6	0	
Krypton-85	100	26	-	0.26[6]

(1) NRC regulations (30.71)

(2) Activity at the test program occurs 6 months after neutron activation

(3) The quantity comparison factor is the isotope activity/schedule B

(4) Neutron radioactivity values were obtained from Table 4

(5) A cobalt contaminant level of 370 parts per million was assumed.

(6) Individual roller krypton-85 activity was 0.8 μCi.

TABLE 12. SUMMARY OF EXEMPT ITEMS

Radioisotope	Devices	Per Device Microcuries	Schedule B Microcuries
Krypton-85	Electron tubes	30	100
Promethium-147	Self-luminous timepiece	200	10
Hydrogen-3	Marine Compasses	750,000	1,000
Strontium-90	Ion detection Devices	50	0.1
Cobalt-60	Spark gap tubes	1	1

It can be noted that levels significantly higher than the exempt quantities have been exempted.

The only NRC regulation mandated during the installation and realization of the Task IV test program is the affixing of a "CAUTION RADIOACTIVE MATERIAL" tag on the box containing the bearings. During rig operation, the tag will be attached to the rig itself. The radioactivity of the debris generated and collected during the rig testing is of sufficiently low levels to warrant an exempt status from all regulations (NRC Section 30.14 Exempt concentrations, "Any person is exempt from the requirements of a license for material containing byproduct material in concentrations not in excess of those listed in 30.70 Schedule A."). Additionally, inventory control of the radioactively tagged hardware must be maintained.

Both the exempt concentrations and the debris level concentration of the tests undertaken are presented in Table 13.

TABLE 13. EXEMPT CONCENTRATIONS OF RADIOACTIVE MATERIALS[1]

		TEST PROGRAM	
	Schedule A[2] (μCi/ml) or (μCi/g)	μCi/ppm[3] of wear debris	μCi/ml[4] of oil per ppm
Iron-55	8×10^{-3}	2.24×10^{-3}	1.2×10^{-7}
Iron-59	6×10^{-4}	7.20×10^{-5}	3.8×10^{-9}
Cobalt-60[5]	5×10^{-4}	$7.2 \times 10^{-4} / 1.03 \times 10^{-4}$	$3.8 \times 10^{-8} / 5.4 \times 10^{-9}$
Manganese-54	1×10^{-3}	9.0×10^{-5}	4.76×10^{-9}
Chromium-51	2×10^{-2}	2.16×10^{-4}	1.14×10^{-8}

(1) Refers to wear metal debris removed from the bearing and distributed in 5 gal

(2) See Part IV Appendix Exempt Concentrations, NRC Regulations (30.71)

(3) The radioactivity in the oil system per ppm of bearing wear

(4) The radioactive concentration per ml of oil

(5) Max concentration of cobalt in M50 (2500 ppm)/typical concentration (370 ppm).

SECTION VI
BEARING SELECTION

1. SELECTION CRITERIA

Engine modularization achieves goals of reduced maintenance costs and engine down time. The radioactive bearing tagging technique utilizes this modularization by defining an engine diagnostic system that will identify engine bearings with above normal wear rates, thereby reducing the amount of teardown to the specific bearing compartment in which the problem bearing is located. A state-of-the-art operational bearing system which has encountered wear in test stands or field service will be used to evaluate the tagging process.

The F100-PW-100 No. 4 bearing is among the highest DN (bore diameter x-speed) bearing in the Air Force inventory and is inaccessible for inspection or removal without core module teardown. The No. 4 bearing is a 165 mm bore cylindrical roller bearing with an operating DN of 2.2×10^6 that, in conjunction with a thrust bearing, supports the high shaft of the F100 core module. The basic No. 4 bearing geometry is shown in Figure 15. Knowledge of the problem bearing location will reduce the engine operational support costs through a reduction in maintenance cost and engine down time. Figure 16 depicts the location of the No. 4 bearing in the F100 engine. The No. 4 bearing has been selected for this study because it experiences roller wear distress common to other high speed roller bearings. P&WA has amassed extensive knowledge of this bearing's wear characteristics through a comprehensive analytical and rig evaluation program. The proven ability to induce wear through various means on this bearing makes it a cost effective method to evaluate the tagging technique.

2. ROLLER BEARING WEAR

The higher thrust-to-weight ratios required for advanced military aircraft turbine engine designs demand advanced technology bearings. These high technology engines require: (1) high shaft speeds to achieve maximum gas dynamic performance, minimum size, and minimum weight, (2) flexible bearing support structures for lightweight and minimum flowpath obstructions, and (3) large shaft diameters for high bending and

torsional stiffnesses. High DN bearings with high bearing misalignment capability are necessary to meet these engine goals.

The increased engine rotational speeds and the resultant increase in DN levels have intensified the influence of geometric variations on roller dynamics, causing an increase in roller susceptibility to distress. Evidence accumulated in the field and data obtained in development tests have led to the conclusion that roller dynamic behavior at high DN is not fully understood, although recent investigations are providing insight to the problem. Roller instabilities occur frequently in high DN bearings. The characteristic distress mode which identifies roller instability and skewing is rapid eccentric wear on the end surfaces of one or more of the rolling elements of a bearing. Figure 17 shows the eccentric type wear pattern on one end of various rollers in a variety of high-speed environments, the other end having a similar pattern. This condition can exist undetected until bearing malfunction occurs. Evidence accumulated in the field and data obtained in development tests have indicated that roller bearing distress as shown in Figure 17 is common to all sizes of high speed roller bearings and is caused by roller instabilities.

Roller skidding is related to skewing and is apparently influenced by many of the same forces which induce it. When rollers skid, the resulting damage is particularly severe on the rolling contact surfaces and, subsequently, has an adverse effect on bearing durability. Currently, skidding is considered to be of secondary importance, compared to roller end wear. This conclusion is based upon considerable field service experience. Data indicate that the roller end wear malfunction predominates.

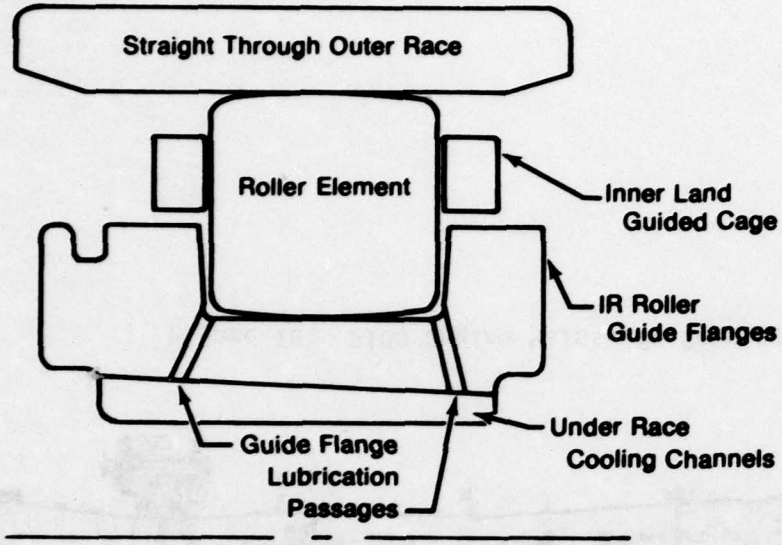
The characteristic distress mode which identifies roller skew is rapid eccentric end wear on some of the rollers. This condition can exist undetected until excessive bearing wear occurs.

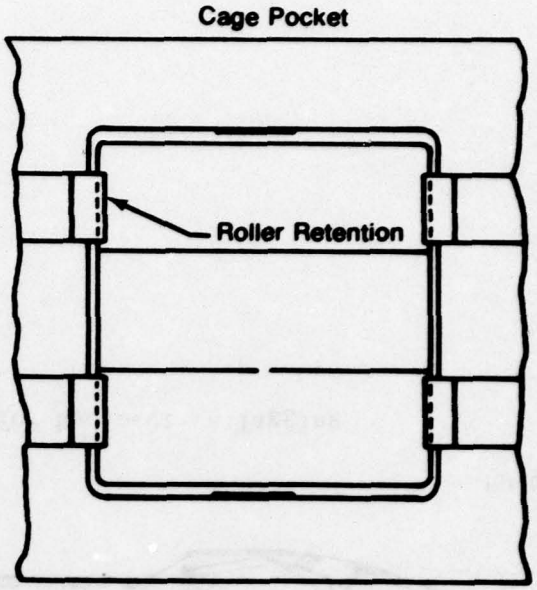
3. MODIFICATION TO THE BEARING FOR ACCELERATED WEAR

The F100 No. 4 bearing rollers will be modified prior to irradiation to ensure the desired distress mode in the rig. Two different levels of wear will be intentionally introduced. Initially eccentric end wear from the rollers will be obtained. Studies at P&WA/Florida have shown that roller unbalance, increased internal clearance, and

geometrical variations such as end clearance, roller-to-guide-rib contact height, and roller dynamics are the most important drivers in high speed roller bearing eccentric end wear. Rig tests have shown that unbalance and large internal running clearances increase the incidence of eccentric end wear.

The eccentric end wear distress progression will be simulated by end wear leading to cage fracture sequence in the second test bearing. This distress level has been duplicated in the rig by modifying the end face of the roller to obtain roller-to-guide-rib contact. The modifications will be made to four rollers in each of the two bearings prior to radioactive tagging.





Inner Race Bore dia:	165 mm
Basic Roller Size, L/D:	16 mm x 16 mm
No. of Rollers:	32
No. of Radial Lube Holes:	2 per Side
Bearing Material:	M50

Cage Material: AMS 6414
Cage Plating: Silver per AMS-2412

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Figure 15. Basic F100 Engine No. 4 Cylindrical Roller Bearing

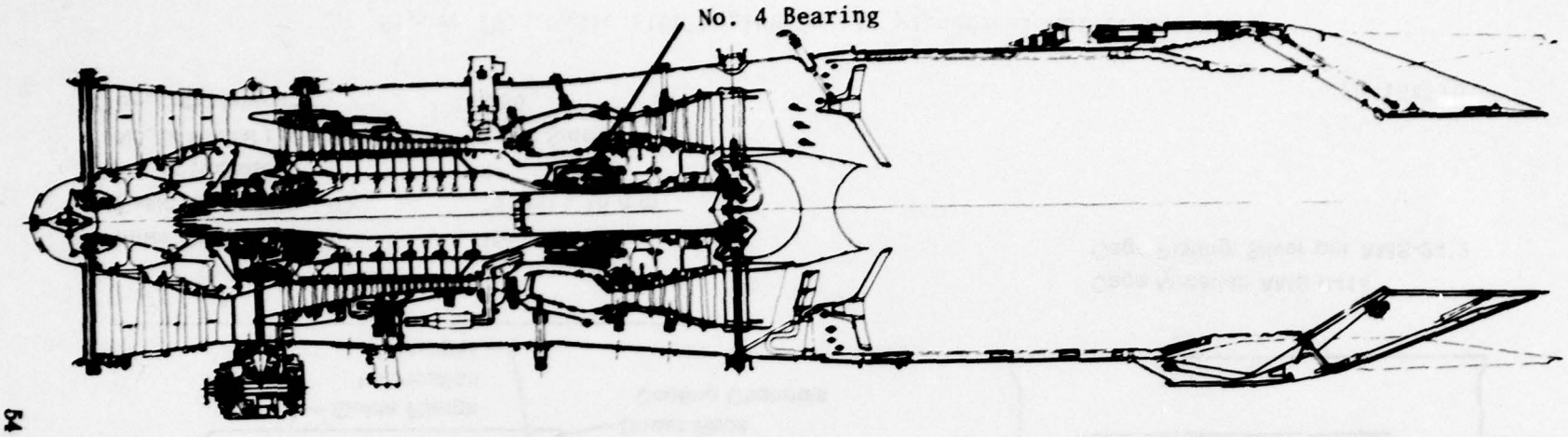

Figure 16. F100 Engine Mainshaft Bearing Proposed for Radioactive Tagging

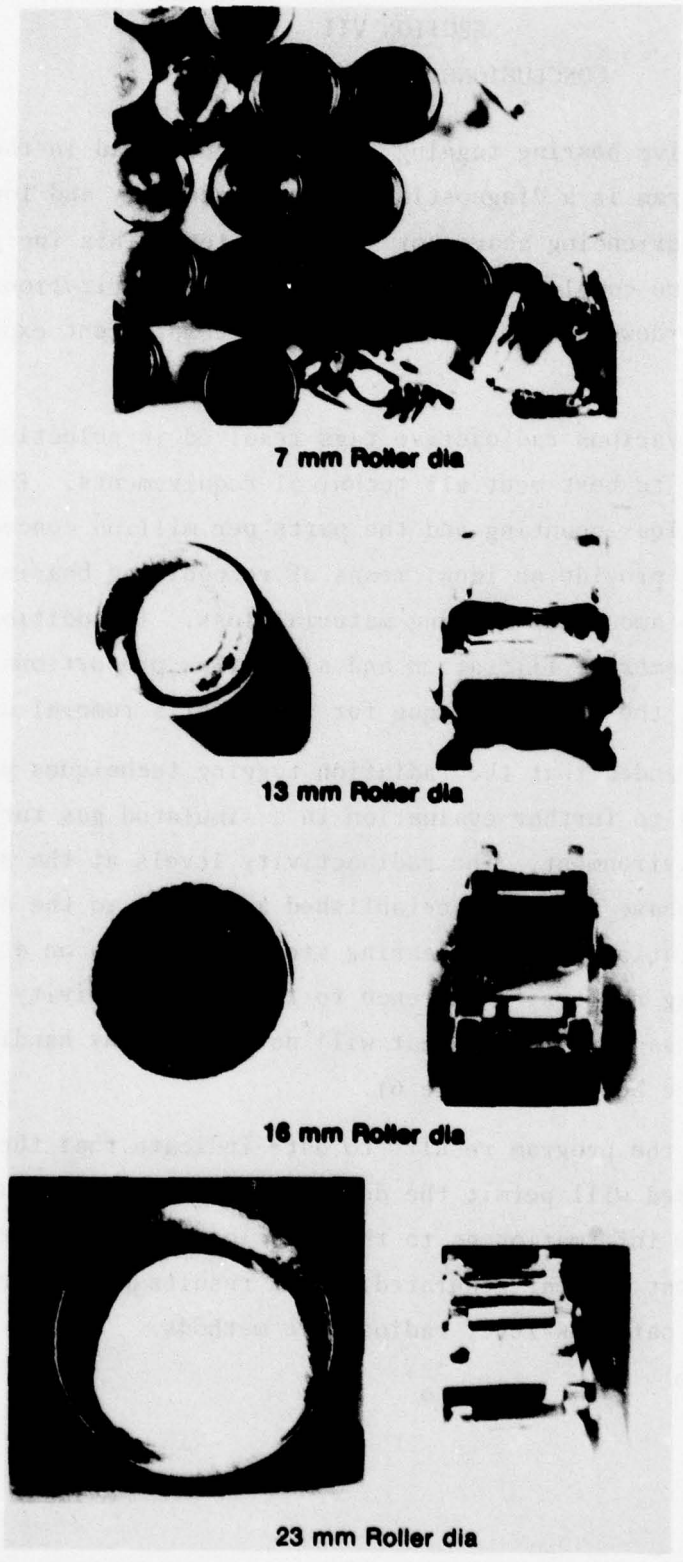

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Figure 17. Application Showing Eccentric End Wear in High Speed Roller Bearings

SECTION VII

CONCLUSIONS/RECOMMENDATIONS

The radioactive bearing tagging technique developed in the first half of this program is a diagnostic system to identify and locate engine bearings experiencing above-normal wear rates. This incipient wear detection technique complements advanced engine modularization by confining engine teardown to the specific bearing compartment experiencing the problem.

Analyses of various radioactive tags resulted in selecting the isotope, iron-55, to best meet all technical requirements. The linearity between nuclear counting and the parts per million concentration of iron-55 in oil provide an ideal means of recognizing bearing distress and assessing the amount of bearing material loss. In addition, it was determined that membrane filtration and a gas flow proportional counting system constitute the best technique for wear debris removal and counting.

It is recommended that the radiation tagging techniques presented here be subjected to further evaluation in a simulated gas turbine engine bearing environment. The radioactivity levels at the start of the rig testing phase should be established according to the neutron activation calculations for M50 bearing steel (Table 4), on a set of F100 No. 4 bearing rollers. Adherence to these radioactivity values will limit the dosage to levels that will not impose any handling limitations on the bearings (Table 6).

In summary, the program results to date indicate that the tagging techniques proposed will permit the detection of incipient bearing failures, provide information as to the location of such distress, and quantify the amount of wear generated. Such results will, moreover, be achieved with safe low-level radioactive methods.

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