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WL-TR-94-2015

STRAIN MEASUREMENT IN TURBINE ENGINES

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FINAL REPORT FOR 07/01/88-01/01/89

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THIS IS A SMALL BUSINESS INNOVATION PROGRAM REPORT (SBIR) PHASE 1

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THE GOAL OF THIS PROJECT WAS TO DESIGN AND TEST STRAIN GAGES BASED ON ATTENUATION OF POSITRONS EMITTED IN THE RADIOACTIVE DECAY OF NEUTRON-POOR NUCLIDES. THIS NEW TYPE OF STRAIN GAGE HAS THE ADVANTAGES OF CONVENTIONAL MOUNTED GAGES, BUT WITH A MUCH HIGHER TEMPERATURE RANGE, NO ADHERENCE PROBLEMS, AND NO ELECTRICAL OR FIBER-OPTIC CONNECTIONS. THIS TYPE OF WIRELESS GAGE WOULD BE IDEAL FOR ADVANCED, HIGH-TEMPERATURE TURBINE ENGINES, AND PARTICULARLY FOR ROTATING PARTS.

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SECTION 1
EXECUTIVE SUMMARY

1.1 DESCRIPTION OF RESULTS

Testing of static tensile strain was performed on activated strips of copper, titanium, and steel to determine whether radiometric effects due to elongation of the material could be reliably used to remotely indicate mechanical strain in engines. Several radiation effects were considered, including gamma ray attenuation in the activated strips, attenuation of annihilation photons originating within the strip, and positron attenuation measured by detecting annihilation events occurring external to the strips. As expected, this latter method was found to be most responsive and clearly feasible for the desired gauging applications.

Phase I work concentrated on selection of suitable materials, nuclides, activation techniques and configuration for a radionuclide sensor system. All configurations were based on the concept of remotely measuring small changes in mechanical strain in high temperature systems by detecting changes in some form of attenuation. A prototype strain gauge based on positron attentuation was constructed, *and tested for feasibility;* limits of accuracy, reproducibility and temperature dependence were evaluated. The following specific objectives were accomplished during this test:

- A minute embedded positron source configuration was found to be the most promising sensor design because it does not require bonding or mounting to the measured surface.
- This configuration was tested to determine limits of accuracy, resolution, and reproducibility, particularly in the presence of vibration, cyclic stress, and elevated temperature.
- Three representative materials, specifically copper, titanium, and steel, were chosen for testing and analysis.
- Of various methods considered for producing carefully shaped positron sources, Van de Graaff bombardment was selected for its precision, reproducibility, and relatively low cost.
- Testing indicated sizeable linear changes in detected counting rate over a large range of strain for both steel and titanium. These were highly reproducible in all but one case, where a slight hysteresis was noted.
- Results were evaluated along with cost estimates to support a conclusion of technical and commercial feasibility.

1.2 SUMMARY OF CONCLUSIONS

Apparent attenuation changes associated with static strain were larger than expected based on simple geometric considerations of shape change, suggesting the possibility of electronic effects on transport of positrons to the surface or in escaping from the surface. Resulting sensitivity was more than sufficient to insure feasibility of wireless strain readings using very small sources, less than 10 microcuries each, produced in steel and titanium. Potential strain resolution for the configurations tested was estimated to be better than 0.001% over the elastic range.

Counting statistics sufficient for 1% resolution in counting rate were achieved in less than two minutes of data collection, allowing source strengths which do not require licensing. High-speed electronics would be required for intervals less than about 10 seconds.

Common structural metals were found to be easily activated to suitable positron emitters. Most alloys and ceramics contain at least one suitable trace component.

Small effects due to temperature and cyclic fatigue were also indicated. Careful configuration of the source depth should minimize the impact of these effects on strain measurements. Conversely, other configurations could enable thermometry and possibly monitoring of fatigue microcracking.

1.3 SUMMARY OF RECOMMENDATIONS

Positive results and potential advantages strongly warrant further bench testing and laboratory development, including production of detailed calibrations for turbine wheel material and tests with varying depths of activity to optimize sensitivity. Spin pit tests are needed to confirm Phase I conclusions and eliminate potential problems. Eventual full-scale testing in a gas turbine engine should be planned either in a ground test cell or in flight.

Some potential concerns unique to high temperatures should also be isolated and investigated prior to actual engine testing. These are related to possible permanent changes in material properties which may affect average mass density of the attenuating material. Preliminary results of this program and theoretical estimates indicate that these should be negligible, but specific testing is needed to confirm these evaluations.

Additional work is also recommended to explore alternative gauge designs such as attachment of attenuating cover slips over the activated zone. It should be possible to configure designs to focus on fatigue and thermometry, and to measure strain along selected axes by surface texturing or coatings.

1.4 CONTRACT STATEMENT OF WORK

The following summarizes major tasks accomplished under this contract:

TASK 1 - REVIEW OF MATERIALS PROPERTIES
TASK 2 - SELECTION OF POSITRON SOURCES
TASK 3 - EVALUATION OF SENSOR GEOMETRY
TASK 4 - PROTOTYPE STRAIN GAUGE DESIGN
TASK 5 - CONSTRUCTION OF PROTOTYPE STRAIN GAUGE
TASK 6 - TESTING OF STRAIN MEASUREMENT CAPABILITY
TASK 7 - EVALUATION OF FEASIBILITY
TASK 8 - REPORTING

1.5 MAJOR PROGRAM ACCOMPLISHMENTS

Tests with representative structural materials, steel, titanium, and copper, demonstrated that precise measurements of mechanical strain can be made by a simple configuration which detects attenuation changes in a signal from a small subsurface positron emitter. The combination of accuracy, short counting times, and very small source activations make this simple design feasible and attractive for application to high-temperature rotating components of advanced gas turbine engines.

Because the source activation in this configuration is an integral part of the monitored component material, questions of adhesion and sensor integrity or survival are eliminated. Detection of annihilation events occurs external to the engine or test pit, so the gauge functions without wire or optical fiber connectors. Electronic components are thus isolated from harsh environments.

Test results indicate that a positron strain gauge will produce reliable, repeatable, linear responses over a much broader range of temperature and strain than any current type of strain gauge. As with other strain gauges, prolonged readings may be affected by accumulated cyclic fatigue damage, and by stress levels that exceed the elastic limit or cause creep.

Sensitivity to strain was also found to be much greater than would be predicted by simple geometric assumptions. This suggests that tensile strain causes significant changes in electronic transport properties, because apparent attenuation was changed by more than could be attributed to simply moving material out of the path of transmission. It is known, for example, that positrons on the surface of conductors will spontaneously leave the surface, unlike ordinary negative electrons which generally accumulate on the surface unless the metal's "work function" is overcome. Strain appears to somehow enhance positron transport to (or exiting from) the surface.

SECTION 2
TECHNICAL BACKGROUND

2.1 STRAIN GAUGES

Conventional strain gauges are versatile devices with application to many mechanical quantities in addition to tensile, compressive or shearing strain. Pressure, moments, heat, acceleration, displacement, vibration, and structural changes can all be deduced from strain, so strain gauges are often incorporated into transducers specially designed to measure derived quantities.

The most common types of strain gauges depend on linear variance of electrical resistance measured by a Wheatstone bridge circuit. Piezoresistive alloys, semiconductors or other materials such as carbon are arrayed in fine grids which are bonded to a backing or carrier matrix which is in turn bonded to the surface to be monitored. Strain is transmitted through the carrier to the electrically sensitive grid.

These small, low-cost gauges are only moderately affected by temperature changes over their operating range, and they can be highly directional. Fiber optic devices share many of these same properties with the advantage of not suffering from stray noise pickup. However, requirements for either electrical or fiber optic leads complicate applications of conventional gauges to rotating parts. At temperatures above 1000°F, other problems develop as response varies, sensitivity vanishes and bonding becomes extremely difficult.

2.2 POSITRON ATTENUATION

The goal of this project was to design and test strain gauges based on attenuation of positrons emitted in the radioactive decay of neutron-poor nuclides. This new type of strain gauge has the advantages of conventional mounted gauges, but with a much higher temperature range, and no electrical or fiber optic connections. Consequently, this wireless gauge is ideal for advanced, high-temperature turbine engines, and particularly for rotating parts.

Positrons (positively charged electrons) are emitted in beta decay of nuclides having an excess of protons (lack of neutrons). An example positron emitter is cobalt-56 which is made by proton bombardment of Fe-56. In comparison, stable cobalt has an atomic mass of 59. Co-60 has an excess of neutrons and decays by beta-minus emission.

Positrons, like their negative counterparts, are quickly slowed down and absorbed in dense matter, although the most energetic from radioactive decay will travel up to about 18 feet in air. When they stop, positrons combine with electrons in matter and mutually annihilate. The characteristic annihilation gamma rays (511 keV) are much more penetrating than the positrons themselves and can easily be detected through moderate shielding.

Although easily attenuated in matter, positrons scatter repeatedly as they slow in matter, whereas photons of comparable energy tend to scatter only once or twice before disappearing through photoelectric absorption. This difference creates an important advantage for positrons in detecting strain. Because annihilation photons have the same energy regardless of positron path, a detector efficiently registers positrons even though they have diffused around corners or through mazes. Transport therefore resembles diffusion of a gas with small holes or cracks creating significant effects and resulting in sensitivity to material conditions.

In contrast, gamma rays lose energy if they scatter, so detected photopeaks only count gamma rays that penetrate without deflection. Transmission is not enhanced by opening microscopic voids or channels unless they follow the line-of-sight path between source and detector.

2.3 POSITRON GAUGE DESIGNS

Several possible strain gauge designs can be based on the unique properties of positrons. A simple example configuration is shown in Figure 2-1. Annihilation gamma rays detected away from the shield and source indicate relative opening or closing with the component strain along a particular axis. Larger sources can be used if rapid changes must be detected. Size and shape can be varied to adapt the system to any size or directional strain requirement including transverse to the orientation of the shield mounting. For example, shear can be measured by orienting motion of the gap transverse to the line between points of attachment as shown in Figure 2-2.

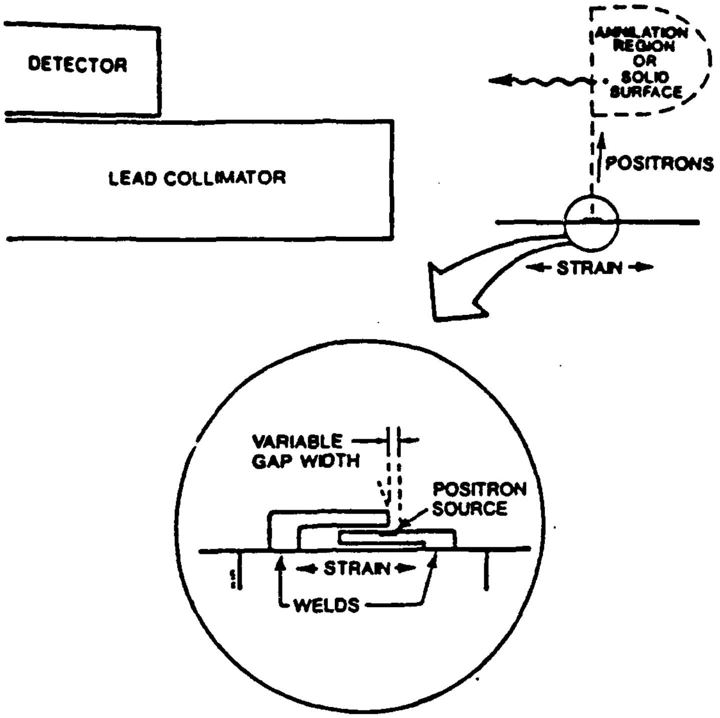


FIGURE 2-1. EXAMPLE WIRELESS STRAIN GAUGE CONFIGURATION BASED ON SHIELDING OF A POSITRON SOURCE.

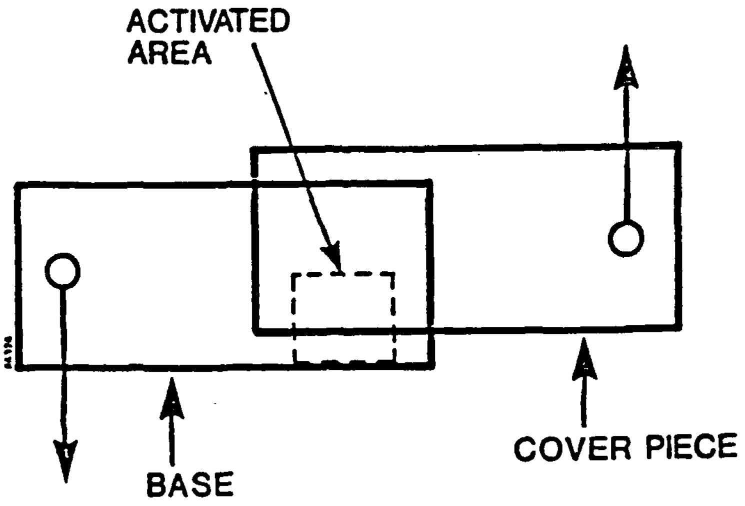


FIGURE 2-2. TOP VIEW OF STRAIN GAUGE CONFIGURATION FOR MEASURING SHEAR STRAIN.

Although these designs are "wireless," they still require attachment of at least a shielding foil to the monitored surface. The rugged simplicity of foil attenuators does allow high-temperature bonding techniques, such as spot welding or brazing, which might not be feasible for fiber optic or electronic devices. However, an even simpler design is to allow the original surface material itself to function as the attenuator for an embedded positron source which can be generated inside the part by particle accelerator bombardment leaving the original material structure intact. This is the approach shown in Figure 2-3 which was was selected as the basis for prototype gauge design and testing. Estimates of net decrease in attenuation were based on the assumption that materials contract about 30% transversely for a given elongation due to simple tensile strain, as shown in Figure 2-4.

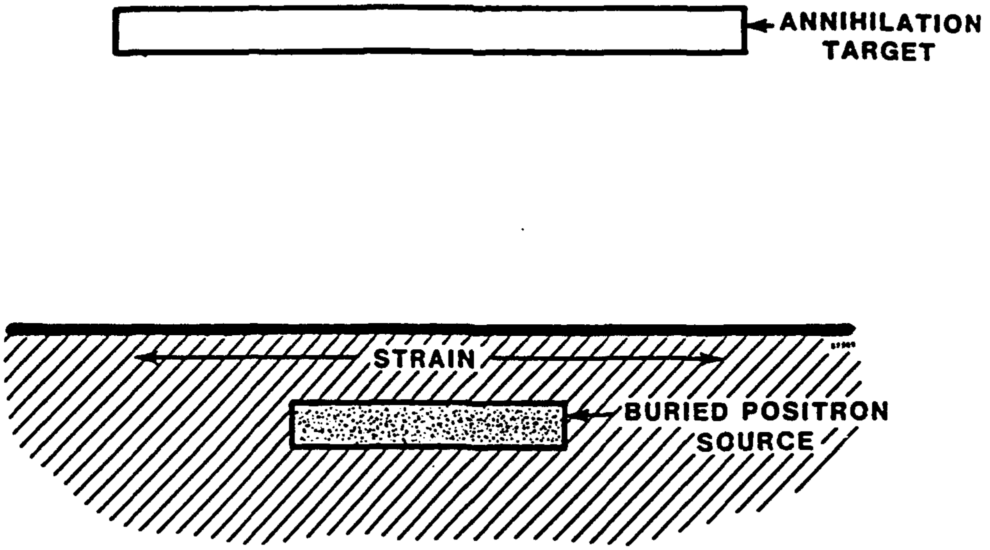
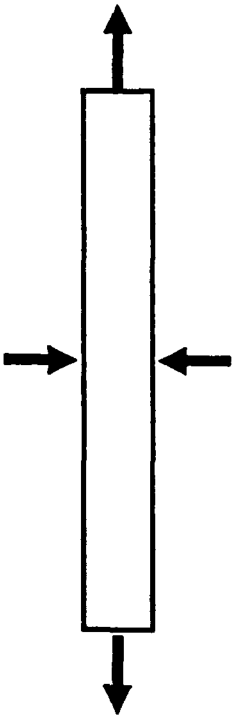


FIGURE 2-3. SCHEME FOR MEASURING STRAIN USING AN ACCELERATOR-PRODUCED, BURIED SOURCE. The detector would be positioned and collimated to detect annihilation photons from the external target which could be the walls of an engine or a set of stationary blades in a turbine, etc.



Contraction about 30% of elongation results in net decrease of attenuation by surface layer

FIGURE 2-4. POISSON'S RATIO.

SECTION 3

EXPERIMENTAL PROCEDURE

Three representative materials, copper, titanium, and steel, were selected for testing. Although pure copper is not a likely structural material for engines, it was selected as a common alloying element, often used in combination with aluminum or nickel. In these materials three distinct nuclides were produced by proton bombardment. The copper strip was activated to Zn-65, titanium to V-48, and the steel produced Co-56. These three nuclides (with Na-22) represent all of the positron emitters with half-lives sufficient for monitoring and with atomic numbers less than 33. This includes a wide variety of common industrial materials including Fe, Ni, Cu, Al, Mg, Ti, and Cr, which can be activated to produce at least one of these four nuclides.

Positrons from Zn-65 have an extremely low branching ratio of 1.7% which made it appropriate for testing lower limits for source strength. An average of 59 decay events, each producing a gamma ray at 1115 keV, are required for a single positron emission. For the 10 microcurie sources used in these tests, the maximum measured positron counting rate for Zn-65 was extremely low, less than 1 count per second. This resulted in poor counting statistics, and long data collection intervals.

Consequently, the counting rate fluctuated due to normally subtle background effects and showed an unreliable strain dependence for copper. This is not because copper has intrinsically unique mechanical properties. Instead, this demonstrates the need for a positron source with a sufficient branching ratio and source size to avoid loss of effective signal-to-noise ratio.

Measurements were made in both "reflection" and "transmission" geometry, with the detector shielded or unshielded from the source, respectively. Photographs of the experimental arrangement are shown in Appendix A. With an unshielded source, the counting rate was dominated by annihilation events occurring inside the strip. Strain was expected to decrease annihilation events, thus reducing the counting rate. This effect was subtle, and could not be resolved in these tests.

Greatest sensitivity was achieved with the detector shielded from the source as shown in Figure 3-1, so the counting rate was due exclusively to annihilation events occurring on a solid surface simulating an engine wall, or in the intervening air. Even small changes in the number of escaping positrons becomes significant in this configuration, leading to a sensitive response.

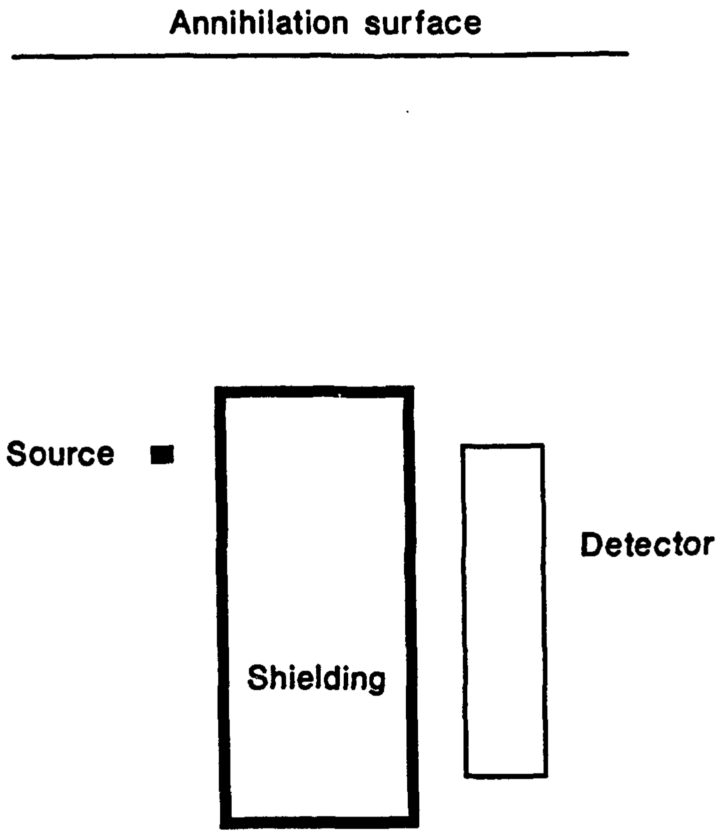


FIGURE 3-1. DETECTOR ARRANGEMENT.

Most positrons generated in the subsurface source were stopped by the material in the strip. Ones that escaped the strip into the chamber continued to scatter until they came to rest and annihilated, usually on the solid wall. A fraction of the resulting gamma rays were then detected by a sodium iodide detector shielded from a direct view of the source. This approach was found to be very sensitive to strain, because of the severe attenuation by the strip material.

Temperature dependance of this approach was also tested by placing steel strips in an oven and heating them. The detector was placed outside the oven and again shielded from direct view of the source. The oven itself served as a simulated engine chamber, on the walls of which the positrons annihilated. Temperature was measured using a dissimilar metal coil thermometer and a resistance probe thermometer.

The coil thermometer incorporated into the oven was found to be innacurate at room temperature, so its readings were noted but used only as a reference. Reliable temperature readings were recorded using the resistance thermometer. When the oven's thermostat was changed to a new setting, the system was left for several hours to reach thermal equilibrium. Once this was reached, a series of count rate and temperature measurements were taken and averaged before the next temperature increase.

An informal fatigue test was also performed to determine effects of cyclic loading on measurement accuracy and sensitivity. The activated steel strip was placed in the simulated engine chamber and the unstressed count rate determined. The strip was then bent repeatedly to generate visibly obvious discoloration and creasing. The strip was placed back in the chamber in the exact same position and the count rate measured.

SECTION 4
RESULTS

Strain testing with steel and titanium strips yielded particularly promising, linear sensitivity of annihilation counting rates. An applied mass was increased from zero to 1.9 kg corresponding to 0.017% strain for steel samples, and up to 24.55 kg for both titanium and copper corresponding to 0.024% strain and 0.182% respectively. Counting rate for steel varied as shown in Figure 4-1. In Figure 4-2 the applied load was first increased to 1.9 kg or 0.0093% strain, and then returned to zero to determine reproducibility. Figures 4-3 and 4-4 show comparable results for titanium.

Each plotted point represents the mean of five to ten individual readings of five minutes counting each. Error bars indicate the sample standard deviation of the mean for each averaged set of readings. Copper readings were not reliable nor reproducible because of "noise" which obscured any possible strain dependence.

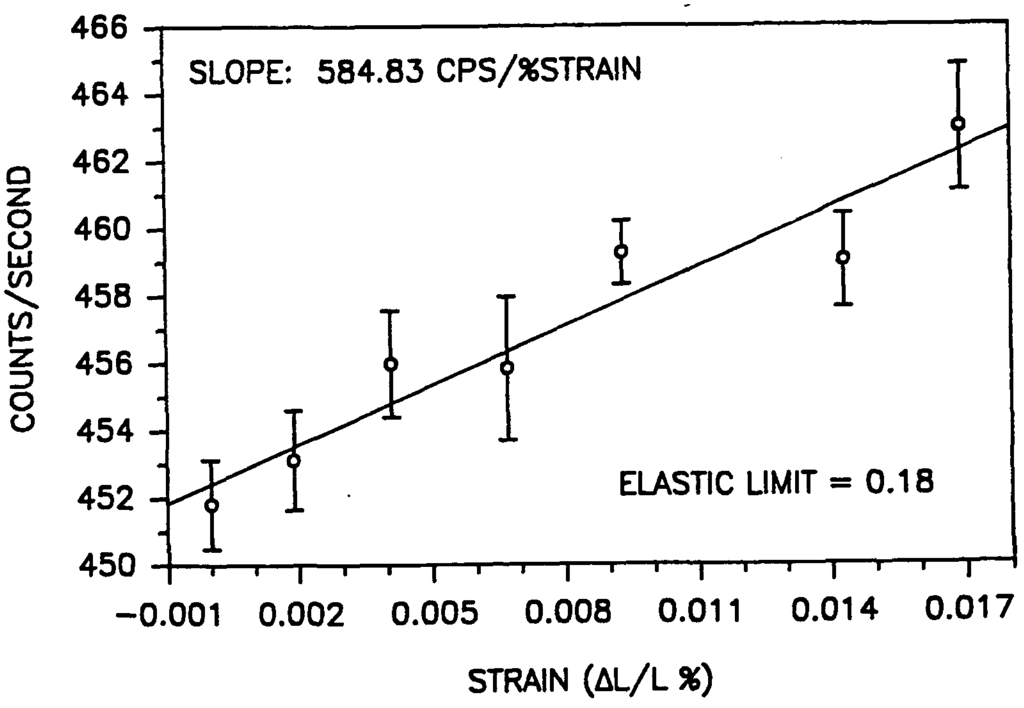


FIGURE 4-1. PLOT OF RESULTS WITH STEEL.

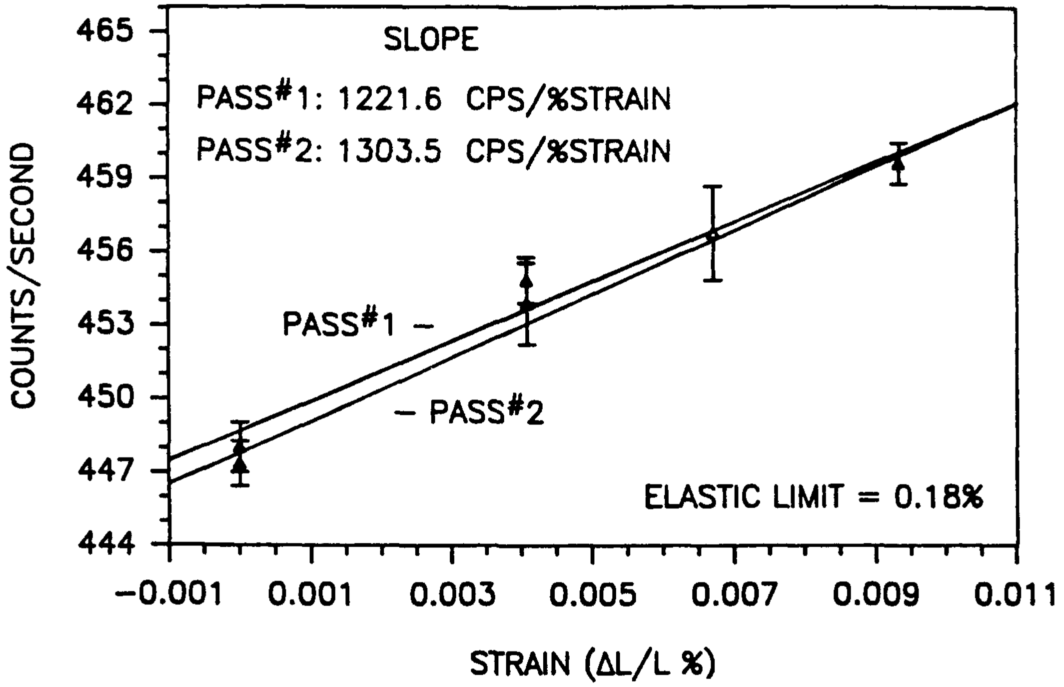


FIGURE 4-2. REPRODUCIBILITY STUDY FOR STEEL.

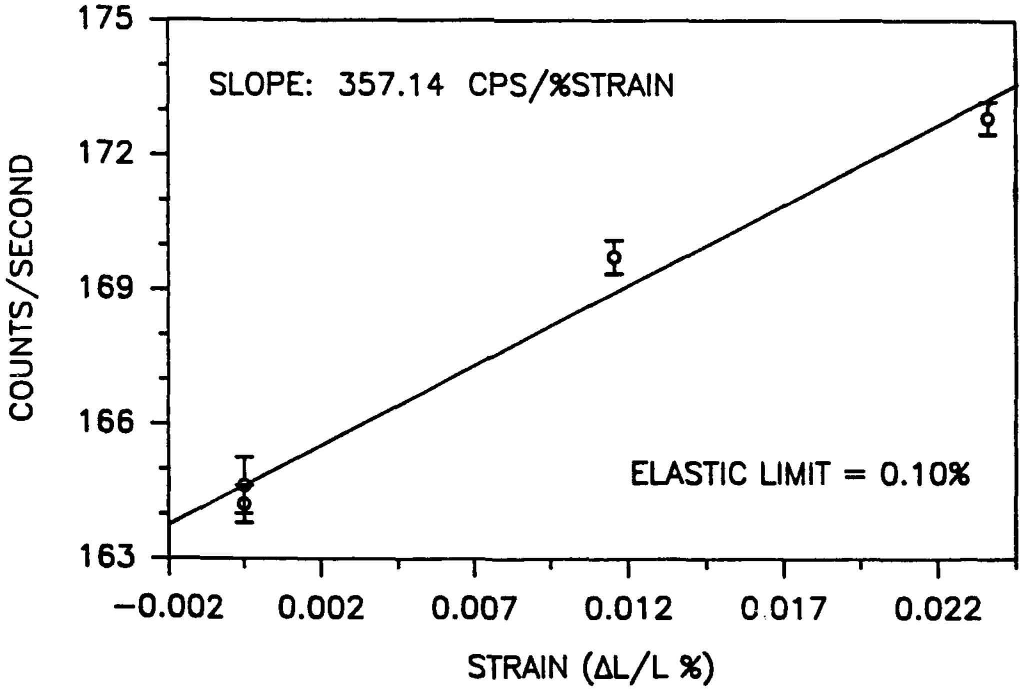


FIGURE 4-3. PLOT OF RESULTS WITH TITANIUM.

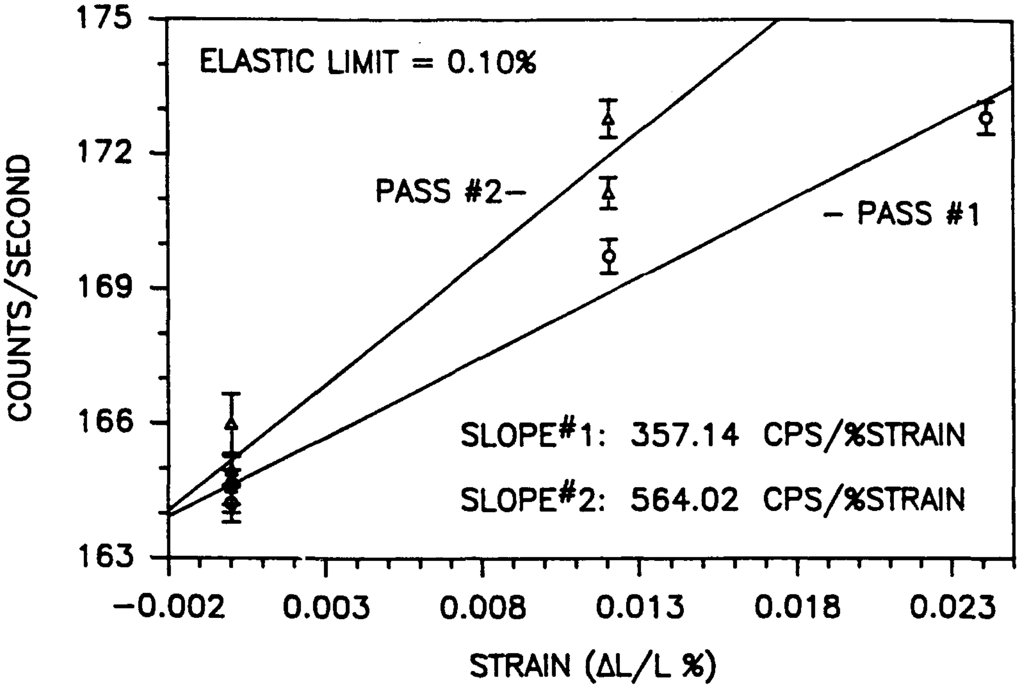


FIGURE 4-4 TITANIUM REPRODUCIBILITY STUDY.

The X-axis of these plots is labeled with deduced strain calculated from the applied mass using the defining formula for strain:

$$\Delta L/L = F/YA$$

where F is the applied weight, A is the measured cross-sectional area of the strip (1.21 mm^2 for steel and 5.94 mm^2 for titanium), and Y is a published value of Young's modulus of 9.1×10^{10} $kg/msec^2$ for steel and 16.8×10^{10} $kg/msec^2$ for titanium (CRC Handbook of Chemistry and Physics).

As shown in the preceding figures, annihilation signals from the simulated engine chamber were linearly dependent upon applied strain. This dependence was demonstrated to be generally reproducible except for one series of tests with titanium which deviated by about 0.005% strain at the maximum load tested, which was estimated to be 25% of the elastic limit. This may be due to hysteresis, creep, or some undiagnosed effect.

These two series of readings were performed several days apart, so the geometry may have changed in the interim. Because the unstrained counting rates coincide, it does not appear to be due to detector drift. Tests with small DC voltages applied to both the source strip and annihilation wall indicated that atmospheric electricity or conductivity did not significantly change the apparent attenuation.

In similar tests varying temperature from 20° to 340°C, counting rate changed by about 0.5%, indicating a possible slight thermal expansion dependence. Statistical variation was negligible within experimental error, so this temperature effect is not conclusive. Temperature range tested was not large enough to evaluate thermal effects in proposed engine environments up to 1200°C, and this issue should be investigated further.

Generally ambiguous results of testing with copper demonstrated the need for positron sources with branching ratios of greater than 1%. This will provide a sufficiently strong positron signal while eliminating the need for dangerously large sources. There are several positron sources with sufficiently high branching ratios which can be produced from common construction materials (Figure 4-5).

NUCLIDE	MATERIAL	B.R.	E MAX MeV	1/2 LIFE DAYS	MIN. STRAIN %
Co-56	Fe,Ni,Cu	0.20	1.459	77.7	.005
Co-58	Fe,Ni,Cu	0.15	0.47	70.91	.001
Na-22	Al,Mg	0.91	0.545	2.6 yrs	.001
Rh-102	Pd,Ag,Cd,Sn	0.19	1.29	206.0	.004
V-48	Ti,Cr,Fe	0.49	0.698	15.98	.002

FIGURE 4-5. RECOMMENDED POSITRON SOURCES.

SECTION 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

These tests demonstrated the feasibility of remotely measuring strain in high temperature mechanical systems by directly detecting signal modulations caused by changes in attenuation resulting from elongation of the monitored part. Because this approach presented the most potential technical problems at the start of the test, its success implies that other, more obvious strain gauge designs involving combinations of mounted carriers and attenuating cover slips would also be feasible.

Changes in apparent attenuation found to be associated with controlled static strain levels were larger than predictions based on simple geometric considerations of shape change during strain. This suggests several possibilities, including electronic effects on transport of positrons to the surface or in escaping from the surface due to strain. This might allow the use of positrons to investigate other material properties associated with conductivity.

Observed sensitivity of counting rate to strain was more than sufficient to insure feasibility using very small sources, less than 10 microcuries gauge. Copper sources (Zn-65) should also be feasible with larger activity levels, although in most cases there are several practical advantages to avoiding larger sources. Potential strain resolution for the materials and depths of activity tested was estimated to be better than 0.001% over the elastic range.

Poisson counting statistics governing random variation in the measured counting rate require at least 10,000 counts under the annihilation photopeak at 511 keV to insure 1% resolution in counting rate. For steel and titanium samples in the laboratory configuration using a 3-inch x 3-inch detector, this was achieved in less than 2 minutes of data collection. Comparable collection intervals should be possible in a spin rig or engine, although an additional attenuation factor may be present due to the engine walls between the annihilation surface and the detector.

If these or even longer intervals are acceptable, source strengths needed would be so low that licensing would definitely not be required. On the other hand, shorter intervals can be achieved by increasing source strength or sacrificing counting rate resolution. To maintain 1% statistics in intervals less than about 10 seconds would require more rapid counting rates than the system in these tests could handle. Such counting rates could be generated by a combination of larger sources, larger volume, multiple detectors, and optimal geometry, but high-speed electronics would be required to process the incoming signals.

Common structural metals were found to be easily activated to suitable positron emitters. Most alloys, ceramics, and composites contain at least one suitable trace element, as was indicated in the table of target elements in Figure 4-5.

Small effects on counting rate caused by temperature and cyclic fatigue were also detected in these tests, but only barely for temperature. Careful configuration of the source depth should minimize or eliminate the impact of these easily correctable effects on strain measurements. Conversely, other configurations of depth or shielding could enable thermometry, directional strain measurements and possibly monitoring of fatigue microcracking.

5.2 RECOMMENDATIONS

Positive test results obtained in Phase I and potential advantages of this technique strongly warrant further bench scale laboratory testing and development including production of detailed calibrations for turbine wheel material and tests with varying depths of activity to optimize sensitivity to strain.

Certainly field tests or small scale demonstrations should be conducted in a spin pit to confirm conclusions and eliminate problems prior to working with an actual engine. Positron gauges should obviously be combined with other currently available devices to correlate readings to the limit possible in overlapping ranges. Eventual full scale testing in a gas turbine engine should be planned either in a ground based test cell or even in flight.

Some potential concerns unique to engine environments with a combination of high temperatures, stress, and vibration should also be isolated and investigated prior to actual engine testing. These are related to possible permanent changes in materials properties cause by diffusion of the activated source nuclide, or recrystallization and other changes which may affect the average mass density of the attenuating material.

Diffusion constants in pure materials are typically measured using radioactive tracers applied to the surface or created in the surface by accelerator bombardment. However, few such diffusion properties have been measured for specific alloys. Preliminary results of this program and estimates based on similar combinations of elements indicate that these effects should be negligible, even in operating engines, but specific testing of diffusion is needed to confirm these evaluations.

Additional work is also recommended to explore alternative gauge designs such as attachment of attenuating cover slips over the activated zone. Cover slip designs, such as that shown in Figure 2-1, would be intrinsically directional. It should also be possible to configure attenuation effects to focus on fatigue microcracking and thermometry, and to measure strain along selected axis by surface texturing or coatings. Cyclic loading effects in particular should be investigated to allow more precise strain measurements, but also for the potential of monitoring and evaluating fatigue in structures.

APPENDIX A

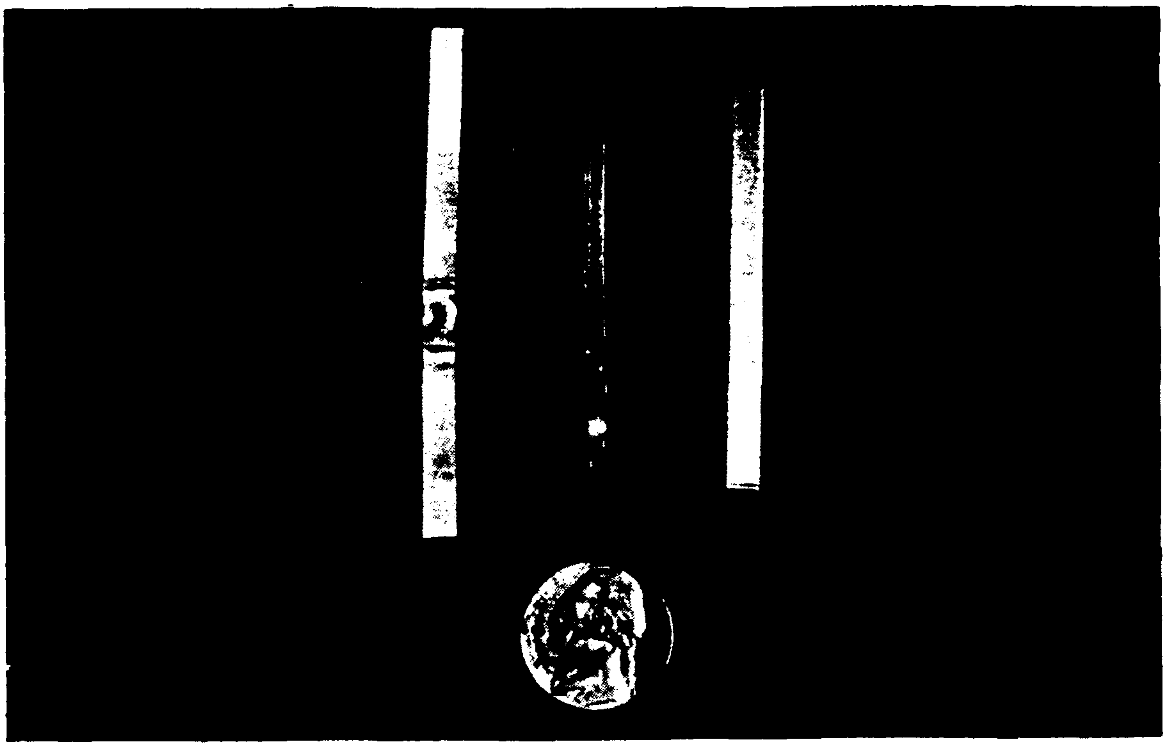


FIGURE A-1 ACTIVATED STRIPS OF STEEL, COPPER, AND TITANIUM (left to right). Deformation at ends of strips is due to clamping in test rig. Discoloration near center of strips is due to carbon tacking, a common vacuum effect of the activation process which does not affect material properties.

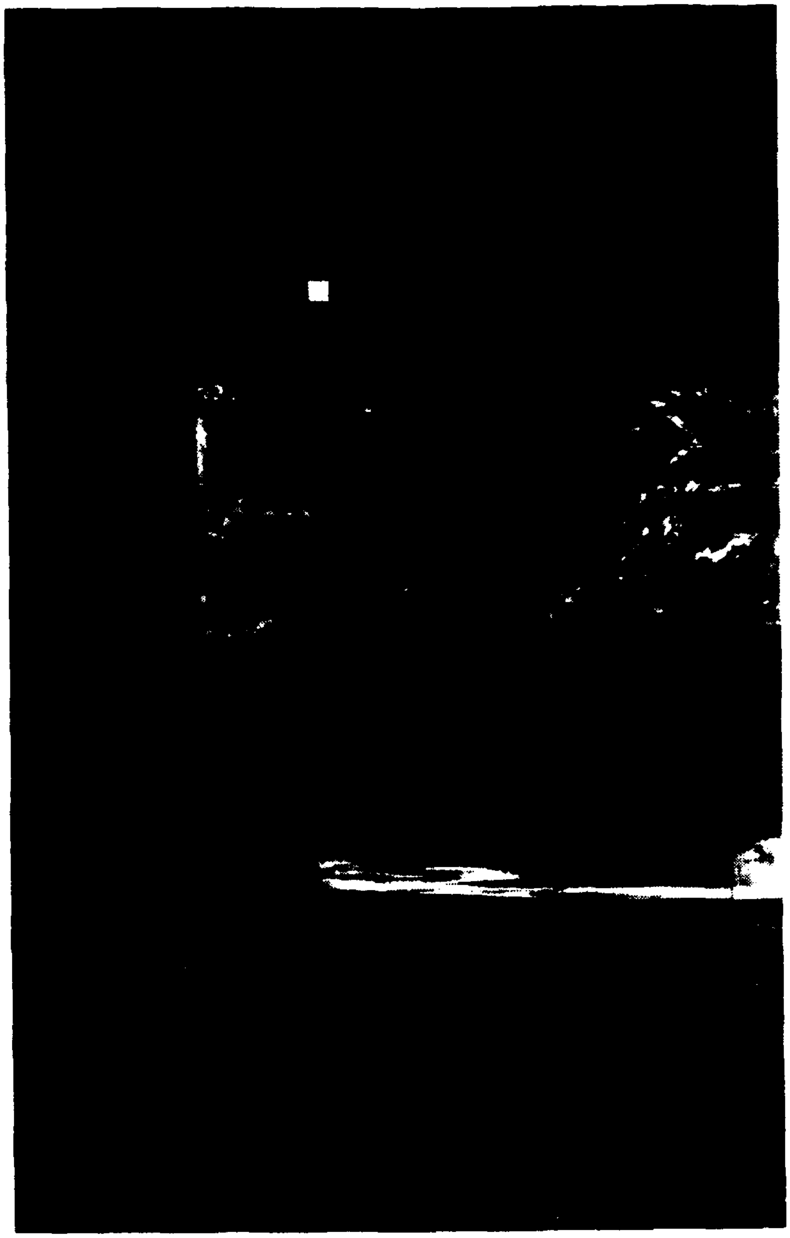


FIGURE A-2 CONFIGURATION FOR MEASURING ANNIHILATION EVENTS IN ENGINE CHAMBER. Detector is shielded from source.

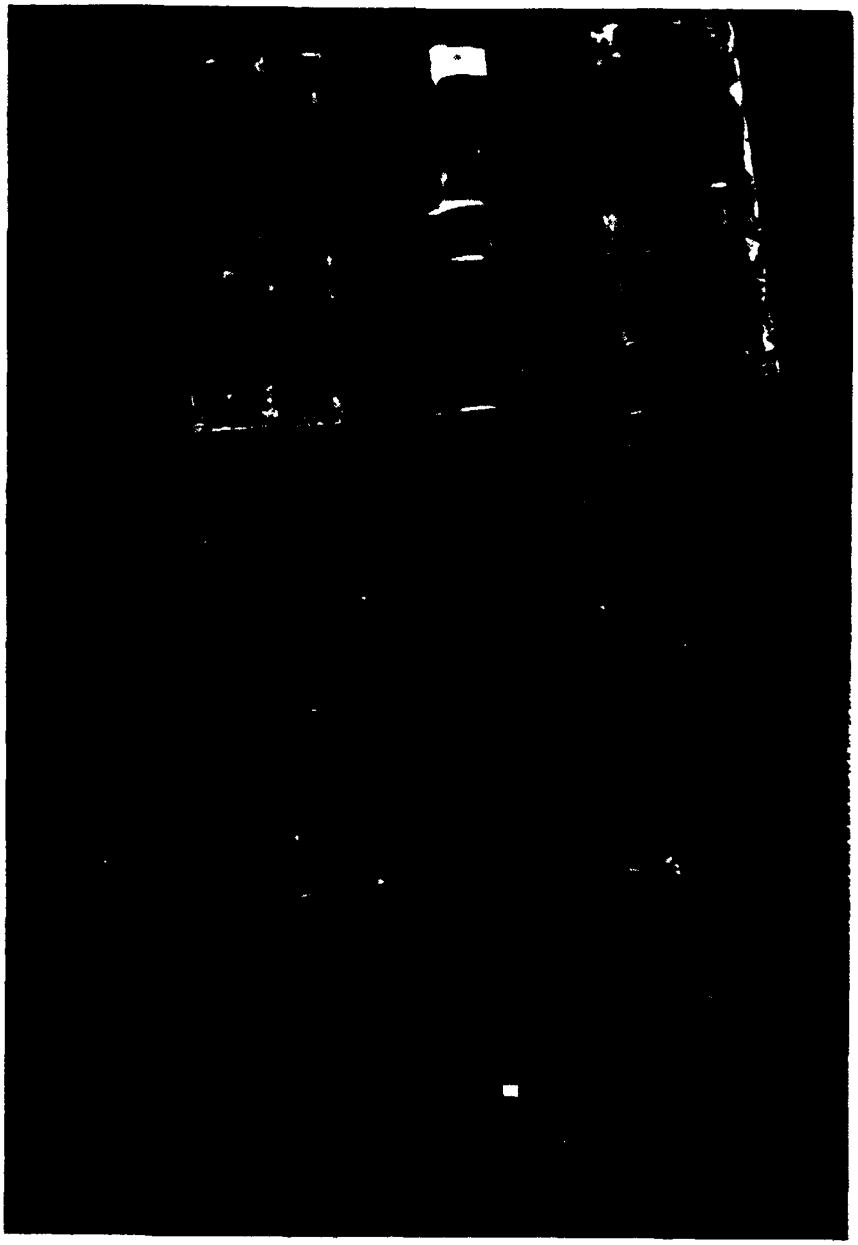


FIGURE A-3. CONFIGURATION FOR DIRECT MEASUREMENT OF STRIP ATTENUATION. Detector is collimated to view source and not engine chamber.

FIGURE A-4. STRAIN GAUGE TEST RIG WITH DETECTOR SHIELDED TO VIEW ANNIHILATION EVENTS ON ALUMINUM PLATE IN FOREGROUND (SIMULATED ENGINE WALL).

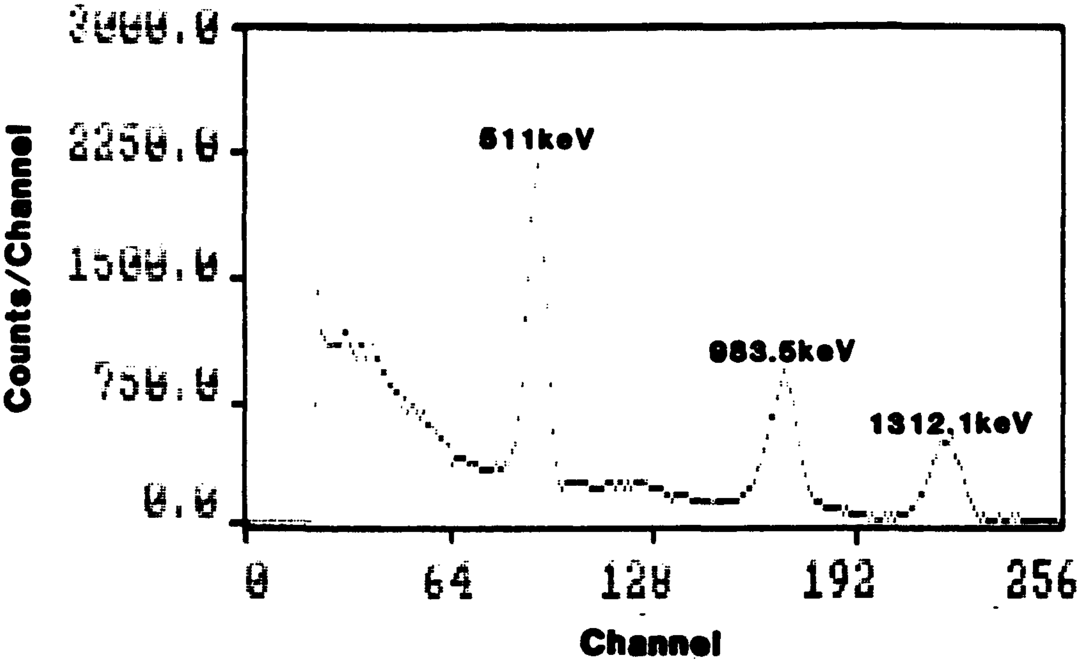


FIGURE A-5. SPECTRUM OF V-48 STRIP. Channel number corresponds to gamma ray energy, with 511 keV peak due to positron annihilation indicated .

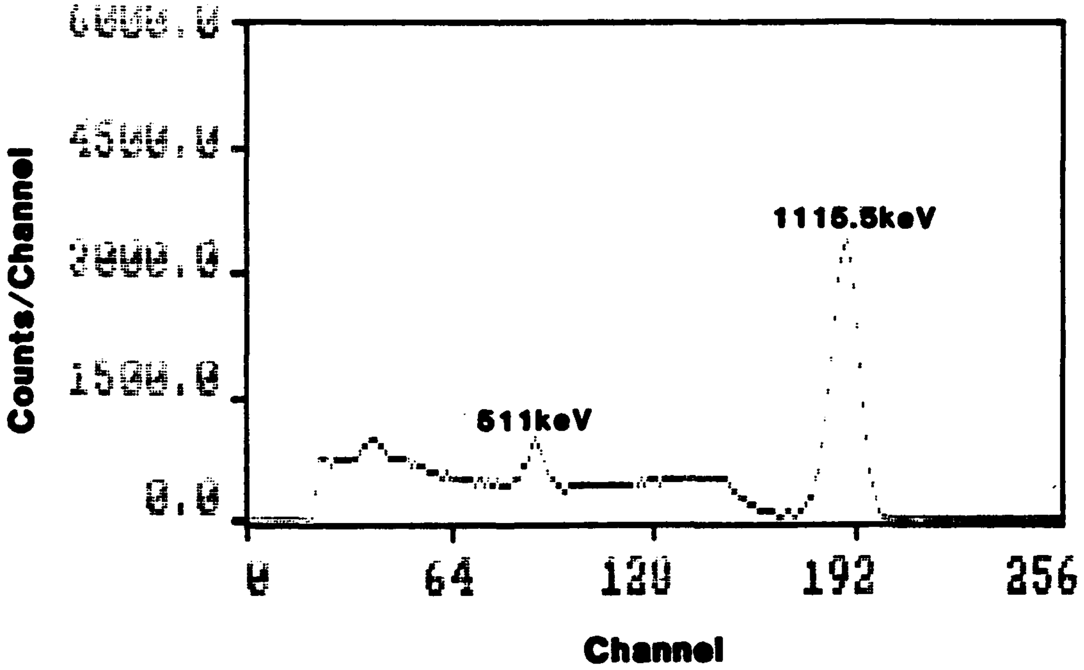


FIGURE A-6. CHARACTERISTIC SPECTRUM OF Zn-65 STRIP. Note the relatively small 511 keV peak due to the low branching ratio of Zn-65.

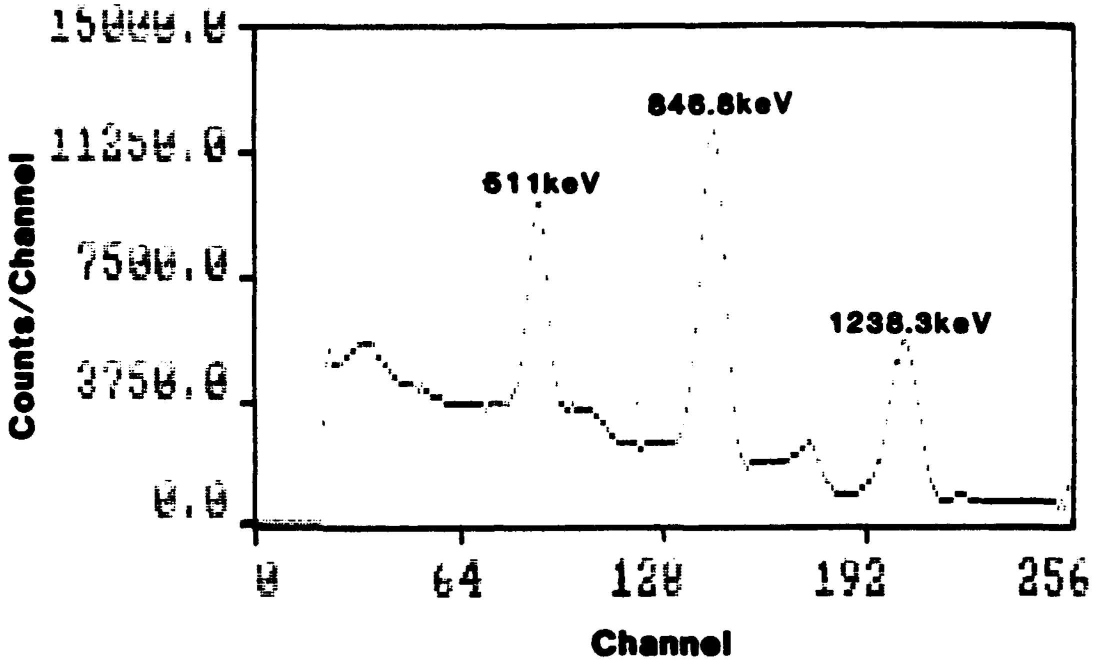


FIGURE A-7. SPECTRUM FROM Co-56 STRIP SHOWING CHARACTERISTIC GAMMA RAYS.

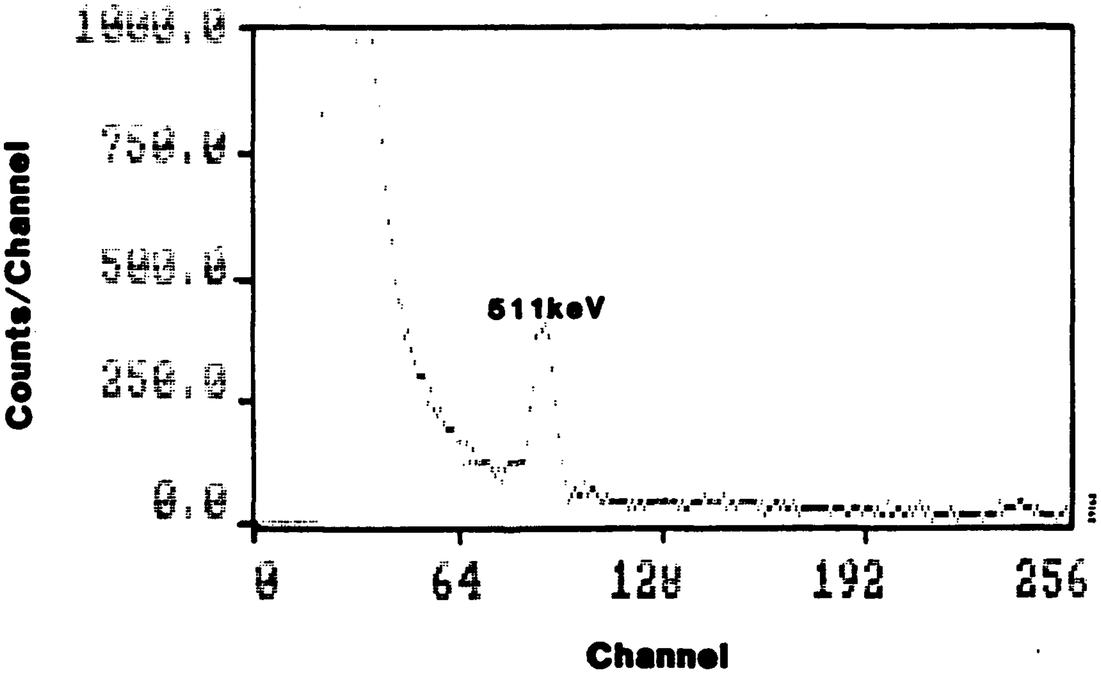


FIGURE A-8. Co-56 STRIP WITH DETECTOR SHIELDED TO VIEW ENGINE CHAMBER. 846.8 and 1238.3 keV gamma rays are shielded, leaving the 511 keV peak from positron annihilation.