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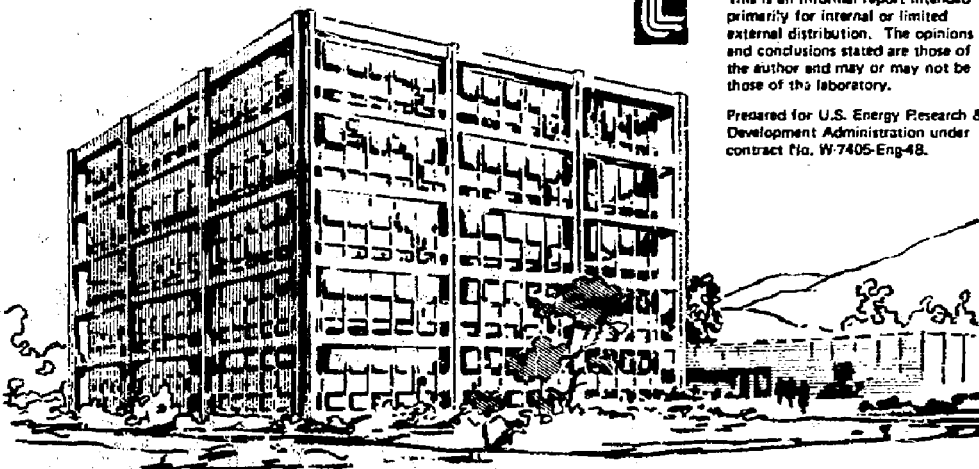
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MEASUREMENT OF RADIATION INDUCED TRANSIENTS IN HYBRID MICROCIRCUITS BY MAGNETIC THIN FILM SENSOR/RECORDERS

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MEASUREMENT OF RADIATION INDUCED TRANSIENTS
IN HYBRID MICROCIRCUITS BY MAGNETIC
THIN FILM SENSOR/RECORDERS*

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ABSTRACT

Magnetic thin film transient current sensor/recorders were modified to make two types of nuclear test measurements, transient currents in hybrid microcircuits and internal electromagnetic pulse (IEMP) fields. The measurements were made possible by the invention of split-domain sensor/recorders which can measure bilateral currents and can be reset and readout on location.

The sensor/recorders were used in two underground nuclear tests and numerous calibration tests in radiation-simulation machines. The data showed that the nuclear environment had negligible effect on the sensor/recorder's operation and the recorded informations on the sensor/recorders were the signals intended to be monitored. Also, the experimental data agreed with the theoretical analysis in controlled experiments.

The data were examined first by on location readout with a magnetic tape viewer and later by Kerr magneto-optic readout in the laboratory. To translate the data into current readings, we reconstructed facsimile data (on each of the sensor/recorders) in the laboratory by current pulses with the same pulse width as the radiation event. An additional check on the accuracy of the data was made by using both the sensor/recorder and the conventional pickup-oscilloscope-camera technique to monitor the same current lead in a simulated radiation environment. Over five runs were made, and the agreement among the two measurement methods was within 25%. The data collectively implied that the measurements were reliable and dependable.

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INTRODUCTION

The magnetic thin film current sensor/recorder^{1,2} is a passive device which responds to the peak current and pulse shape of a transient event. The transient current information becomes a permanent record on the film. The thin film device is small, low mass and reusable. It has been proven to be fast³ (less than 1/2 nanosecond response), radiation hard⁴ and applicable to peak current measurement of both CW and single pulse signals. Two types of thin film sensors are available. The cable-current version, designated "I-sensor" was designed for measurements of currents in cables and other concentrated sources. The other type is the surface-current-density version, the "J-sensor", which was designed for skin-current measurements on surfaces.

The sensor/recorders were initially developed at Lawrence Livermore Lab for pulsed energy measurement and later, the devices were field tested as an EMP measurement device under the sponsorship of the Defense Nuclear Agency and the Air Force weapon Lab. at Kirtland Air Force Base. The present contract with Sandia Laboratories was to apply the sensor/recorders to measure current pulses induced in the hybrid microcircuit boards by nuclear radiations. The severe environment and spatial constraints under which the pulse-current measurements were to be made eliminated all other measurement schemes for technical or economic reasons. A more detailed description of Sandia's requirement will be given in the next section.

The sensor/recorders were used in three experiments: (1) Initial calibration tests in radiation-simulation machines; (2) Underground Nuclear Test I; and (3) Underground Nuclear Test II. In all three experiments, special test circuits were employed (in addition to the actual measurements) whereby the sensor/recorders readouts could be compared to theoretical predictions. Data were obtained in all these experiments. The recorded data in the thin film sensor/recorders survived the nuclear environment and were later translated into pulse-current data by laboratory calibration. The significant findings will be discussed in this report.

SANDIA LABORATORY'S MEASUREMENT REQUIREMENTS

The transient current measurements were to be made on the input-output leads of the hybrid microcircuit boards which were to be used in nuclear radiation environment. The duration of the induced current pulse was expected to be in the range from few nanoseconds to tens of nanoseconds. The input-output leads in a typical microcircuit board were spaced 1/10 of an inch apart and the cross-section dimensions were approximately 5 mil by 10 mil. The circuit boards were stacked in layers with approximately 5 millimeters clearance between them. The spatial constraints and the radiation environment ruled out most active sensors for this type of measurement.

The magnetic thin film sensor/recorders became very attractive for this special application because of small size, radiation resistance, low cost and simplicity for field application. There were some drawbacks, however. The accuracy of the thin film sensors can be established only for each individual case. Being magnetic, the thin film sensors needed special handling during preparation of the experiment and after the test. The sensor/recorders can be disturbed by other magnetic field sources of sufficient strength. The registered information on the film had to be interpreted by laboratory calibration data and the measuring configuration during the test. Also, the thin film sensor/recorders had to be modified significantly before they could meet the Sandia's requirements. In the next section, the new thin film sensor/recorders developed for use in Sandia's experiments will be described.

THE SPLIT-DOMAIN THIN FILM SENSOR/RECORDERS

With reference to our report UCID-16240, in which the principle of operation of the basic thin film sensor/recorders was described, it was obvious that only one direction of current flow could then be detected by any one sensor/recorder. If the current direction was unknown, two sensors magnetized in opposite directions had to be used. The spatial constraint discouraged the use of the two-sensor method for the Sandia experiment. Instead, we developed a new measurement scheme for Sandia's use.

The scheme involved the formation of a 90° domain wall⁵ along the length of the thin film, thus the name split-domain sensor/recorders. Figure 1 shows a split-domain sensor/recorder, positioned for current measurement. Notice that the 90° domain wall splits the once single domain film into two oppositely magnetized domains. With the current carrying conductor positioned immediately below the 90° domain wall, the H field created by the current affects the two domains symmetrically. One can see that either one or the other domain will be switched by the field H, depending on the direction of the current I. When one (or the other) domain is switched, a portion of the 90° wall is displaced, as shown in Fig. 2. We found that the displacement length of the 90° wall can be calibrated to the magnitude of current I. In our previous experiments, we established that the 90° walls were stable and radiation hard, and thus suitable for Sandia's experiment.

In terms of field application, the use of 90° domain wall has many advantages. First of all, the split-domain sensor/recorder can measure current in either directions. Secondly, the 90° domain wall can be visually observed by a simple, passive and inexpensive magnetic tape viewer. This was not true with the single domain sensors. Switching of a domain forms a 180° wall which is very "thin" and does not contain enough magnetic energy to be detected by the magnetic tape viewer. It was quite a drawback when we had to do all the sensor/recorder read-outs in the laboratory by a Kerr magneto-optic technique. With the use of the 90° domain wall, one can do the sensor/recorder examinations before and after the experiment on location. Lastly, the formation of a 90° domain wall on a magnetic film is a simple process. We need only a flash light battery connected to a piece of slit conductor sheet, as shown in Fig. 3, to form 90° domain wall.

The film is laid across the slit and the gradient field created by the current around the slit splits the film into two opposing domains, with a 90° wall formed between them. The "zapper", as the set up was called, can be handheld and operated on location.

RESULTS AND DISCUSSIONS

There were two types of measurements being made in the three tests. The first type was the transient current measurement on the input-output leads of the hybrid circuit devices, or the leads of controlled experimental fixtures where the current magnitudes had been theoretically quantized. The measurements were made in a manner shown in Fig. 1. Typical magneto-optic readouts before and after the measurement are shown in Fig. 4. In special cases, single domain films were used to monitor a few conductors simultaneously.

The other type was internal electromagnetic pulse (IEMP) measurements. The split-domain sensor/recorders were also used. They were placed with their easy axis parallel to the expected IEMP field. By virtue of their positions with respect to the expected IEMP field, we can judge the validity of the theoretical prediction. The IEMP field usually caused "disturbances" on the 90° domain wall but did not cause a clear "displacement" of the 90° wall. Typical magneto-optic readouts of IEMP measurement are shown in Fig. 5. The degree of distortion on the 90° wall can be qualitatively related to the magnitude of the IEMP field. We had not attempted to quantitatively calibrate the IEMP field in Sandia's experiment.

A. Calibration Tests in Radiation Simulation Machines

Before the underground nuclear tests, the split-domain sensor/recorders were tested in the radiation simulators. The majority of the tests centered on Compton-electron related field H_{ϕ} . The sensor/recorders were placed in a magnetically shielded cylindrical tube, as shown in Fig. 6. The sensor/recorders were put at the center (position 1), off center (position 2) and at the periphery (position 3), with their easy axis parallel to the H_{ϕ} field. We expected the H_{ϕ} to be circumferential and stronger at the outer radius of the cylinder. The experimental results agreed with the theoretical expectation. In all cases, the sensor located at the periphery (position 3) always registered the highest degree of disturbance, while the center sensor showed negligible disturbance.

In another calibration experiment the sensor/recorders measurement was compared with a real time measurement by the standard oscilloscope-camera technique. The standard technique monitored the voltage drop across a known resistor during the simulated nuclear transient event. The thin film sensor/recorders were used to measure the induced current on the same lead that connected to the resistor. The recorded information on the sensor/recorder was carefully preserved until it could be recorded by magneto-optic photography. To translate the recorded information (see Fig. 2) into current data, we needed to reconstruct the recording on the sensor/recorder by a current pulse in the laboratory. Since we knew the pulse width of the transient event, we just varied the current amplitude of the pulse until the recording was reconstructed. Please note that the laboratory calibration was a single pulse experiment. The 90° domain wall was reset each time after the pulse. Fig. 7 shows the magneto-optic photographs for the recorded information and the reconstructed recordings at two current levels. The transient event had a 140 ns pulse width and measured by the OSC-camera set up to be approximately 3 amperes. We used 140 ns pulse width at 2 and 3 amperes to reconstruct the recording at the laboratory. We can deduce from Fig. 7 that the sensor/recorder registered a current slightly larger than 2 amperes but definitely smaller than 3 amperes. The discrepancy between the standard OSC-camera technique and the magnetic thin film approach was small enough to be experimentally acceptable. In general, a tolerance limit of $\pm 20\%$ may be applied to our laboratory calibration data.

B. Underground Nuclear Test No. 1

This underground nuclear event was conducted at NTS in the tunnel. It was the first time the sensor/recorders were used to measure transient current in a nuclear event. The sensor/recorders were mounted on the hybrid circuit boards in the laboratory before the entire package was positioned in the tunnel. To minimize the accidental erasure of the sensor/recorders, special handling techniques were employed in protecting the package. Monitoring sensor/recorders were mounted on the outside of the package and they were checked periodically to see if the package had been exposed to unexpected magnetic fields before the nuclear event.

Some of the monitoring sensor/recorders were "re-zapped" on location to examine the intensity of the magnetic field associated with the iron beams within the tunnel. It became evident that had it not been for the on-location re-set and readout capability, the sensor/recorders would find little application in the field.

A total of 22 sensor/recorders were employed. Five of the sensor/recorders were used in a controlled experiment for IEMP measurement. The remainder were used to monitor transient currents in the input-output leads of the hybrid circuit boards. However, most of the sensor/recorders were exposed to IEMP because of the configuration of the package. The measurement results are summarized in Table I.

Type of Measurement	Successful Measurements		Questionable Results
	Above Sensitivity	Below Sensitivity	
IEMP (split-domain sensor/recorders only)	11	6	1
Transient current (split-domain and single-domain sensor/recorders)	5	10	2

TABLE I. Experimental Results from Underground Nuclear Test No. 1

For the IEMP measurement, only the split-domain sensor/recorders were used. A H_{ϕ} field of 1.5 to 2 oersteds (sensitivity of the magnetic film) was required to disturb the 90° domain wall. The magnitude of H_{ϕ} was qualitatively judged by the severity of the disturbance, such as enlargement of the saw-tooth patterns and shifting of the 90° wall from the central position. For the five sensor/recorders in the controlled experiment, the two centrally situated sensors registered no disturbance (below sensitivity) while the three situated toward the periphery showed disturbance. The result agreed with theoretical prediction and thus

added more weight to the other H_{ϕ} measurements. More significantly, all sensor/recorders positioned for H_{ϕ} measurement registered zero 90° wall displacement, implying that the nuclear explosion environment did not affect the magnetic properties of the thin film sensor/recorders. As further proof, we observed 6 of the H_{ϕ} sensor/recorders remained undisturbed during the nuclear event. Those that registered H_{ϕ} field most likely were caused by IEMP and not by heat or mechanical shock or others related to nuclear explosion. The one questionable result was a complete erasure to be explained in the next section.

For the transient current measurements, we had 12 split-domain, 3 single domain and 2 surface current sensor/recorders. The single domain sensor/recorders were larger in dimension and monitored six leads simultaneously. The surface current sensor/recorders had much larger dynamic range than the standard sensor/recorder and thus were used in redundancy to ensure a measurement in case of unexpectedly high induced currents. As shown in Table I, only 5 sensor/recorders encountered transient currents higher than their sensitivity of $\sim 1/2$ amps. Four out of the 5 were split-domain sensor/recorders and their recordings were later calibrated to be above $1/2$ ampere and below 4 amperes, using a 10 ns pulse width. The other was a single domain sensor/recorder, and it registered currents above $1/2$ amperes under each of the 6 leads it monitored. However, the recording had a complicated pattern and required considerable speculation to explain the registered information. Laboratory calibration fixed the upper limit at 3 amperes. The remainder of the sensor/recorders registered no current or less than $1/2$ ampere. The two questionable results included a full erasure and a registration of current opposite to the reference end of the sensor/recorder. We had enough zero current registrations (sixteen) in the experiment to suggest the two unexpected registrations to be caused by improper handling during mounting or in transit.

There remained another question concerning the consistency of the transient current measurements. We mentioned earlier that the two surface current sensor/recorders were used in redundant measurements. They both registered zero current during the test while the split-domain sensor/recorders monitoring the same leads registered currents higher than $1/2$ ampere. There were two possible explanations to the observed discrepancy. The

first was that the sensitivity of the surface current sensor/recorders was known to be lower than the split-domain type and thus failed to register. Unfortunately, the experimental conditions were difficult to duplicate and thus a precise calibration to prove the point was not feasible at this time. The other reason may be the contact problem. The surface current sensor/ recorder was mounted flat on the printed circuit board by double-sided tape, with the printed circuit board leads under it. There was enough separation between the sensor/recorder and the circuit board leads to reduce the transient magnetic field to a level below the sensor/recorder's sensitivity.

C. Underground Nuclear Test No. 2

The No. 2 test was similar to No. 1 test discussed previously and was designed to examine different spectrum of nuclear radiation. All three types of thin film sensor/recorders (the split-domain, single domain and surface-current types) were employed in the test. The test procedures were the same as test No. 1, except that we used 4 ns pulse width to calibrate the registered recordings. The results are summarized in Table II.

Type of Measurement	Successful Measurements		Questionable Results
	Above Sensitivity	Below Sensitivity	
IEMP (split-domain sensor/recorders only)	14	19	3
Transient Current (split-domain and single-domain sensor/recorders)	10	26	6

TABLE II. Experimental Results from Underground Nuclear Test No. 2

A total of 42 sensor/recorders were used in test No. 2 and all were positioned to make transient current measurements. The recorded H_{ϕ} measurements were just "free" data, a bonus to the test. The H_{ϕ} sensitivity for the sensor/recorders was lower for Test No. 2 because of the extremely short pulse width of the induced current. We estimated the H_{ϕ} sensitivity to be 2 to 3 oersteds for Test No. 2. The three questionable results were due to damages to the sensor/recorders during demounting of them from the hybrid circuit boards. For the transient current measurements, the ten registered recordings were calibrated to be between 2 - 7.5 amperes, with the majority grouping around 2-3 amperes. Again, because of the short pulse width (4 ns), the sensitivity for transient current measurement was found to be approximately 2 amperes. Among the 6 questionable results, 3 were due to physical damages and the other three were registering recordings opposite to the reference end of the sensor/recorders. We may attribute the unexpected results to mishandling of the sensor/recorders.

CONCLUSION

We had successfully adapted an experimental magnetic thin film sensor/recorder to make active measurements of transient current and IEMP field in underground nuclear tests. The measurements were made possible by the invention of split-domain sensor/recorders to satisfy the special measuring conditions. With the adoption of the 90° domain-wall configuration, on-location readout by a simple passive magnetic viewer became possible. The on-location readout capability contributed greatly to the successful fielding of the thin film sensor/recorders. The results were unique in the sense that they could not have been obtained by any other methods within reasonable cost and within the state of art of transient measurements.

The data collectively implied that the results were reliable and dependable. The strongest evidence of their reliability was the high percentage of zero (or below sensitivity) registrations among the sensor/recorders employed in the two underground nuclear tests. The sensor/recorders are

passive devices. Thus, there is very little argument other than zero signal (or below sensitivity) to account for a zero registration by the device. It followed that the nuclear explosion environment did not affect the magnetic thin film sensor/recorder's operation, either. Otherwise, there would have been more erroneous recordings instead of zero registrations. We can say that the non-zero recordings (above sensitivity) were most likely the signals we intended to monitor.

The credibility of the data was further heightened by more direct evidence: as we mentioned before, the H_p measurements in the controlled experiment conducted together with the other measurements in underground nuclear test No. 1 agreed with the theoretical predictions. The IEMP experiments conducted in the radiation-simulation machine also agreed with the theoretical analysis. For the transient current measurements, the recordings were quantitatively calibrated by reconstruction technique in the laboratory. A controlled experiment was also conducted in the radiation simulation machine where a real-time measurement of the transient current by the standard OSC-camera technique was made in parallel with the magnetic thin film sensor/recorders. The agreement was within 25% which can be accounted for by the possible variations in the experimental conditions between the controlled experiment and laboratory calibration.

ACKNOWLEDGMENTS

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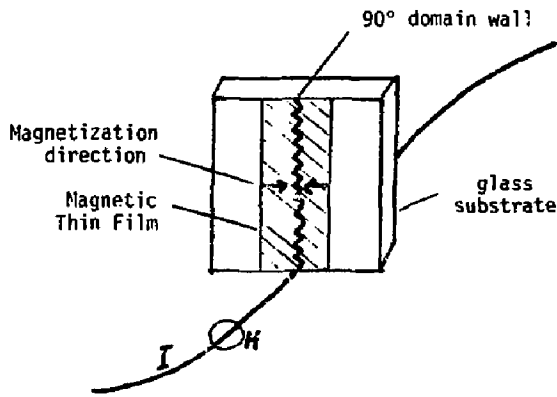


Fig. 1. Measurement of current by Split-domain Thin Film Sensor/Recorder

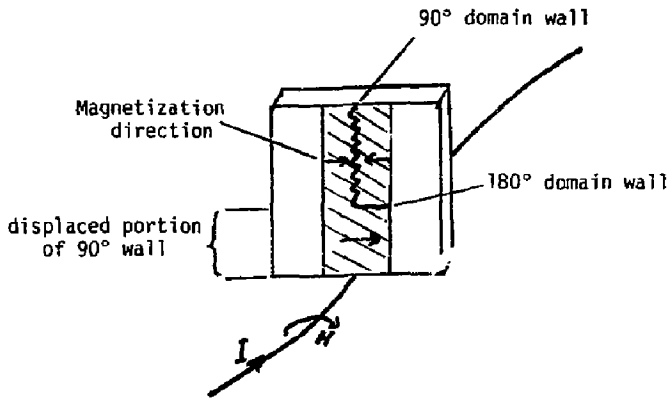


Fig. 2. Displacement of the 90° domain wall by a current

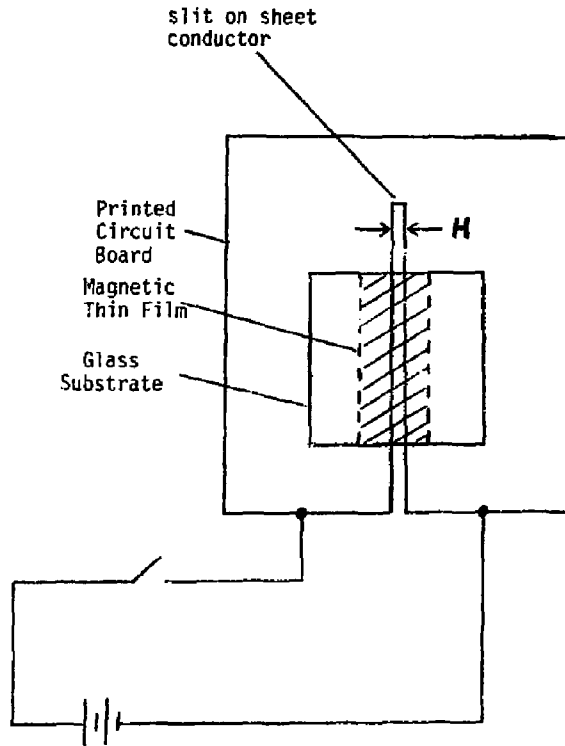
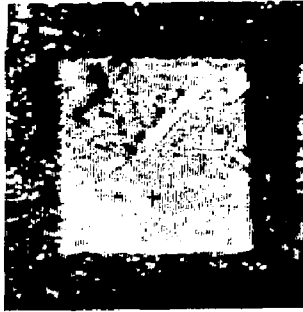


Fig. 3. A "zapper" configuration to form 90° domain wall

single domain sensor/recorder

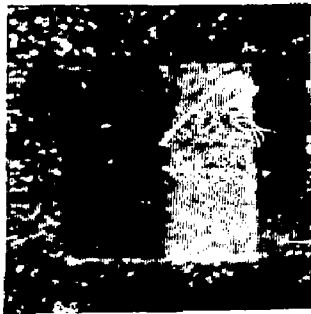


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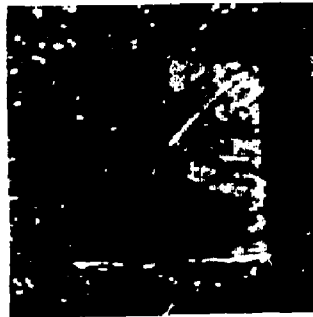


After

split domain sensor/recorder

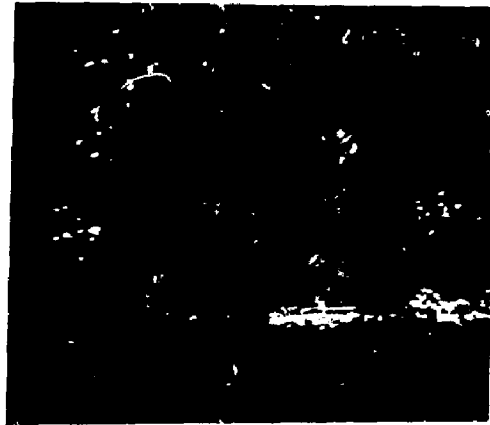


Before



After

Fig. 4. Typical magneto-optic readouts of sensor/recorders before and after measurement



Before



After

Fig. 5. Typical 90° domain wall before and after IEMP measurement

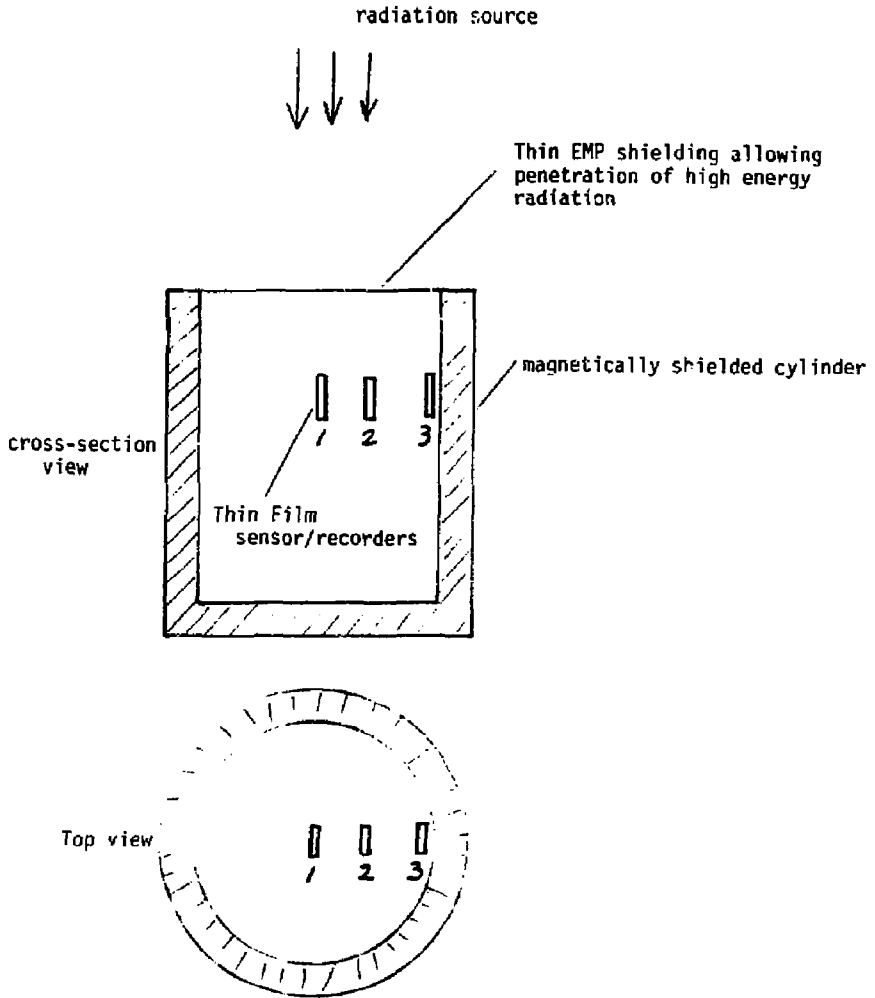
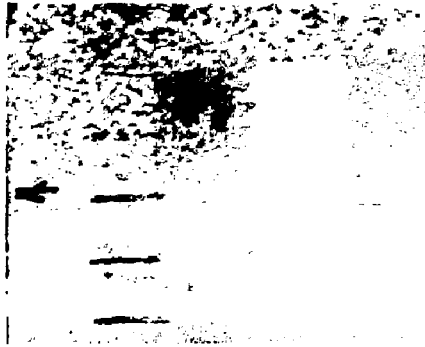


Fig. 6. Magnetically shielded Fixture for Simulated Nuclear Radiation Tests

Simulated Radiation Machine Data



Laboratory Reconstructed data by 140 ns pulse



Fig. 7. Calibration of recorded information with reconstructed recordings

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