RADIATION HARDNESS OF EFRATOM M-100 RUBIDIUM FREQUENCY STANDARD

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ABSTRACT

The effects of nuclear radiation on rubidium gas cell frequency standards and components are presented, including the results of recent tests where a continuously operating rubidium frequency standard (Efratom, Model M-100) was subjected to simultaneous neutron/gamma radiation. At the highest neutron fluence [7.5×10^{12} n/cm^2] and total dose [11 krad(Si)] tested, the unit operated satisfactorily; the total frequency change over the 2½ hour test period due to all causes, including repeated retraction from and insertion into the reactor, was less than 1×10^{-10}. The effects of combined neutron/gamma radiation on rubidium-frequency-standard physics-package components were also studied, and the results are presented.

INTRODUCTION

The use of atomic frequency standards in space during the last decade and the employment of these devices in a growing number of military applications has resulted in continuing efforts to assess and ensure their operation in nuclear radiation environments. In this paper, the focus will be on rubidium gas cell frequency standards in general, and the Efratom, Model M-100, military rubidium frequency standard (RFS) in particular.

This paper is divided into two main parts. The first is a brief review of previous unclassified work in this area, including the effect of total dose and dose rate on an operating RFS and some of its components. The second presents new results that show the effects of neutrons on an operating RFS and certain RFS subsystems and components. These new results are of special interest for military applications that require the use of an RFS in a nuclear radiation environment.

PREVIOUS WORK

Whereas the general principles that govern the effects of nuclear radiation on atomic frequency standards have been enumerated previously,[1] not much has been published that deals with the direct, experimental assessment of these effects for RFS's. Almost all of the previous unclassified work was done by Rockwell International (RI) in conjunction with the NAVSTAR Global Positioning System (GPS). This system uses satellite-borne atomic clocks to provide military navigation of unprecedented accuracy. Most of the clocks used in this system have been built by Rockwell. They are a space-qualified version of the Efratom Model FRK-H RFS and include an Efratom-supplied physics package.

The first radiation test [2,3] of an RFS by Rockwell was carried out in March 1974. In this test, an unmodified, Efratom, Model FRK, commercial RFS was irradiated with a total dose of 10 krad(Si) from a Co^{60} gamma source at a constant rate over a one hour period while the unit was operating. This device, which was not radiation hardened in any way, exhibited a fractional frequency change of $+6 \times 10^{-11}$ due to the irradiation. This frequency increase resulted from a change in the characteristics of the electronics in the servo loop. The fact that the RFS photocell current changed by less than 1% during the irradiation showed that the rubidium lamp, physics package optics, and photocell were essentially unaffected by the radiation.

A second test[2] was carried out by Rockwell on an engineering model of the actual space clock (RFS) to determine the effect of dose rate. This unit was exposed to the maximum dose rate available from the RI flash x-ray facility ($\sim 4 \times 10^8$ rads(Si)/sec). An upper limit of <1 nsec was set on any accumulated phase error due to this dose rate and it was also observed that the radiation had a negligible effect on the physics package.

Samples of glasses that have been used in RFS's were also tested by Rockwell. In these tests[4,5] aluminosilicate[6] and borosilicate[7] glasses were irradiated with up to 1 Mrad total dose from a Co^{60} source. Light transmission at the rubidium resonance-line wavelengths[8] was monitored for cumulative doses of 30 krad, 100 krad, 300 krad, and 1 Mrad. The results for the three samples of each glass type and the two wavelengths[9] are summarized in Fig. 1. At the highest dose of 1 Mrad, the decrease in light transmission was 3.1% and 2.6% for the aluminosilicate and borosilicate samples, respectively.

PRESENT WORK

The purpose of the present work was to assess experimentally the effect of neutron irradiation on an operating, Efratom, Model M-100, military rubidium frequency standard (RFS), and also on certain RFS subsystems and components. This work[10] was carried out in two parts using the General Atomic, Mark F TRIGA reactor in San Diego. The first part tested the complete RFS, and the second part tested RFS subsystem and components. The two tests were conducted one month apart.

IRRADIATION OF OPERATING RFS

The model M-100 RFS used for these tests was an engineering model[11] that differed from a standard production unit only in having a slightly modified frame and thicker-than-normal PC boards. The unit was operated continuously during the entire irradiation test and the following variables were also monitored continuously: the output frequency,[12] the dc output voltage of the photocell amplifier, the servo control voltage to the voltage-controlled crystal oscillator (VCXO), and the baseplate temperature (which varied from 42°C to 47°C during the test).

Irradiation Sequence

The unit was irradiated at four different levels. The irradiation sequence for each level consisted of the following four steps.

1. Attach two dosimeters to the side of the unit receiving the most radiation and insert the unit into the reactor tube.
2. Let the unit run undisturbed, with the reactor off, for 5 - 10 min.
3. Turn on the reactor at a low power level, thereby providing a constant irradiation, and maintain this for approximately 5 min.
4. Turn off the reactor and remove the unit immediately. Remove the two dosimeters and allow the unit to run undisturbed for at least 5 min (retraction period).

After the final irradiation sequence, the power to the unit was turned off for approximately 5 min and the unit restarted, after which it was left running for 45 min.

The purpose of the retraction operation was to minimize the total dose due to gamma radiation that results from the short-lived induced radioactivity of the reactor coolant after the reactor is turned off. In these tests all neutron fluences were expressed in terms of the 1 MeV neutron fluence that would produce the same damage to a silicon sample as the actual neutron fluence, i.e., as 1 MeV-silicon-damage-equivalent fluences.[13]

Test Results

The test data were taken over a four hour period that included a 90 min warmup and a 45 min restart test after completion of all irradiation. Relevant portions of these data have been compressed[14] to fit on a single $8\frac{1}{2}$ x 11 figure (see Fig. 2). Based on the test data, the following observations can be made.

1. The net change[15] in fractional frequency due to all causes [including insertion and retraction] over a 2½ hr period [including irradiation to 7.5 x 10^{12} n/cm^2 and 11.2 krad(Si)] was less than 1 x 10^{-10}.
2. Frequency changes of from -2 x 10^{-11} to -5 x 10^{-11} were produced when the unit was retracted. These frequency changes were most likely due to changes in the orientation of the unit relative to the ambient magnetic field. They were not a result of irradiating the unit.
3. Changes in fractional frequency due to irradiation by combined neutron/gamma radiation were only a couple of parts in 10^{11} for up to 3 x 10^{12} n/cm^2 and 4.4 krad(Si) (levels 1 - 3).
4. Changes in fractional frequency during the last irradiation step [from 3 x 10^{12} to 7.5 x 10^{12} n/cm^2, and from 4.4 to 11.2 krad(Si)] were less than 1x 10^{-10} except for a slow (∿20 s) negative frequency transient of ∿1.5 x 10^{-10} that occurred during the latter portion of the level 4 irradiation.
5. The dc photocurrent dropped drastically due to irradiation but this had only a small effect upon the performance of the unit as a frequency standard.
6. The short-term frequency stability of the unit was degraded by about a factor of two due to the irradiation (levels 1 - 4).
7. After the restart of the unit, subsequent to the level 4 irradiation, the retrace was within 2 x 10^{-11} of the frequency prior to turn off (normal behavior).
8. Over the 2½ hr duration of the test, the VCXO control voltage decreased from 10 V to 9V. For a free-running VCXO not locked to the atomic resonance, this would correspond to a fractional frequency change of approximately +8½ x 10^{-8} which amounts to about one tenth of the electrical trim range of the VCXO.[16]

Decrease of dc Photocurrent

The dc photocurrent was monitored indirectly during these tests by observing the dc output voltage of the photocell amplifier. The photocell is operated in the short-circuit mode and under normal conditions the dc output voltage of the photocell amplifier is proportional to the dc photocurrent. Estimates[10,17] of the change in this dc output due to radiation-induced changes in input offsets, bias voltage and current, show that it is a small fraction of a percent for irradiation by 1 x 10^{12} n/cm^2 and 1.5 krad(Si). This means that the observed decreases in dc output voltage (ranging from 55% to 78%) are due almost entirely to corresponding decreases in dc photocurrent.

At first glance, two mechanisms for this decrease in photocurrent appear

possible. The first of these is a decrease in the intensity of the light incident on the photocell surface. This mechanism would also produce a light shift in the resonance cell. Bench tests to simulate this effect indicate that the light shift is an order of magnitude larger than the observed frequency changes and has the opposite sign. This strongly suggests that changes in light intensity are not responsible for the observed decreases in dc photocurrent. The irradiation tests subsequently carried out on RFS subsystems and components (as will be shown) also support this conclusion. The only mechanism left is photocell degradation. Data[18] on photocell degradation due to nuclear radiation show that for the irradiation levels used here, gamma radiation has little effect but neutrons can produce large decreases in photocurrent of the magnitude observed. As will be discussed later in this paper, direct tests on RFS photocells show clearly that considerable degradation does, in fact, occur.

The main effect of photocell degradation is a deterioration of the short-term frequency stability. Experimentally, a decrease of a factor of two was observed and this is consistent with bench test simulations of the effect.

IRRADIATION OF SUBSYSTEMS AND COMPONENTS

A month after the irradiation of the complete Model M-100 RFS, a second nuclear irradiation test on certain subsystems and components (see Table 1) was carried out using the same reactor under very similar conditions.

SUBSYSTEM IRRADIATION

The two subsystems irradiated were independent and nearly identical, each being comprised of the following M-100 subassemblies (Fig. 3).

1. Photocell-cavity-shield assembly, including cavity-thermostat board.
2. Lamp board and rubidium lamp
3. Power-supply board.

Items 2 and 3 were standard, unmodified, production items. Item 1 was also a standard production item except that the rubidium resonance cell and the Mylar window on the cavity had been removed to allow a completely unobstructed optical path from outside the assembly directly to the active surface of the photocell inside the microwave cavity. Both cavities were heated in the normal way, their temperatures being individually thermostatically controlled and continuously maintained at 75°C. The two assemblies differed only in that the photocells were from different manufacturers (Table 1).

Items 1 and 2 of each subsystem were mounted in the standard M-100 configuration thereby allowing light from each lamp board to be monitored by its

respective photocell. Both subsystem frames were rigidly bolted together so that the entire dual-subsystem unit could be easily inserted into the nuclear reactor for irradiation. Also included as part of this "inboard test fixture" was a standard M-100 servo board that was used to monitor the dc photocurrent of photocell #2 (PC2).

Irradiation Sequence

Like the previous test on the complete M-100, the two subsystems were irradiated at four different levels. The irradiation sequence, which was similar, was as follows.

1. Attach two dosimeters on the side of the unit receiving the most radiation and one dosimeter on the opposite side. Insert the unit into the reactor.
2. Let the unit run undisturbed, with the reactor off, for 5 - 10 min.
3. Turn on the reactor at a low power level, thereby providing a constant irradiation, and maintain this for approximately 5 min.
4. Turn off the reactor and remove the unit immediately. Remove the three dosimeters and allow the unit to run undisturbed for at least 5 min.

Outboard Photocell Test Fixture

Each frame was designed to allow its respective photocell-cavity-shield assembly to be easily removed and then subsequently reinserted into the same position relative to the lamp board. Prior to reactor insertion, each photocell-cavity-shield assembly was removed one-at-a-time and inserted into another test fixture that remained permanently outside the reactor during the entire test period. In what follows, this test fixture will be referred to as the "outboard photocell test fixture." This fixture, which is shown schematically in Fig. 4, consisted of an M-100 lamp board with rubidium lamp, an M-100 servo board, and an M-100 power supply board. The main purpose of this fixture was to provide a stable source of optical radiation for testing each of the two inboard photocells before and after each irradiation level. Since the lamp board, lamp, and power supply board in this fixture were not irradiated, they could be relied upon to provide constant illumination for the duration of the test.

The outboard photocell test fixture had two important modifications that greatly increased its versatility. The first modification allowed sinusoidal modulation of the light beam at the RFS modulation frequency (127 Hz) using the modulation signal from the servo board. The amplitude of this modulation was kept small compared to the dc light level so that the dc measurements were unaffected by it. The purpose of the modulation was to allow determination of the effect of the irradiation on the ac response of the two photocells. The second modification allowed the photocell Thévenin

equivalent shunt resistance[19] (R_S) to be measured[20,21] by insertion of a 100 Ω resistor in series with the photocell. The shunt resistance is an important photocell parameter in our application because its value largely determines[20] the amount of photocell-amplifier additive noise in the vicinity of the RFS modulation frequency which, in turn, influences the short-term frequency stability of the RFS. The shunt resistance must be 1 kΩ or greater for satisfactory operation of the M-100.

In summary, then, the following photocell variables could be monitored using the outboard photocell test fixture: dc photocurrent, ac photocurrent at 127 Hz, and shunt resistance, all under conditions of constant illumination.

Measurement Sequence

Prior to level 1 irradiation, the outboard photocell test fixture was used to characterize both photocells by measuring the dc photocurrent, the ac photocurrent,[22] and the shunt resistance for each.[23] Each photocell was subsequently characterized again between irradiation levels and at the end of level 4.

During the time that the photocells were inserted in the reactor, the dc photocurrent of each was monitored continuously. The current of photocell #1 (PC1) was monitored using the photocell amplifier on the outboard-photocell-test-fixture servo board, and the current of photocell #2 (PC2) using the photocell amplifier on the inboard servo board.

Test Results

Dc Photocurrent The inboard and outboard measurements of dc photocurrent for the two photocells are listed in Table 2 and the outboard results (constant illumination) are plotted in Fig. 5 as a function of neutron fluence and total dose (as measured by the two dosimeters on the side of the unit receiving the most radiation). For the highest cumulative irradiation tested, namely 6.15×10^{12} n/cm^2, the dc photocurrents of both photocells dropped to approximately 40% of the pre-irradiation values. Both photocells exhibited similar dc photocurrent degradation.

Ac Photocurrent The dc and ac photocurrents are compared in Table 3 where it can be seen that the ac photocurrent is degraded to a greater extent than the dc photocurrent.[22] Note that at the highest fluence of 6.15×10^{12}n/cm^2 the normalized ac photocurrents were about 70% of the normalized dc photocurrents.

Shunt Resistance Fig. 6 shows the results for photocell shunt resistance as a function of neutron fluence and toal dose. The Ferranti photocell (PC1) shunt resistance increased slowly with cumulative neutron fluence and total dose. The increase was from an initial value of about 2 kΩ to a final

end-of-test value of about 3 kΩ. The International Rectifier photocell (PC2) showed a different behavior. Its shunt resistance increased slightly at first, starting at 11 kΩ, and thereafter decreased, reaching an end-of-test value of about 6.5 kΩ. In no instance did the shunt resistance for either photocell drop below 2 kΩ as a result of irradiation. Since the requirement for satisfactory RFS operation is 1 kΩ or greater, the effect of the radiation on shunt resistance is of no practical importance for the M-100.

Rubidium Light Source

The test results in Table 2 also show that the M-100 rubidium light source (lamp board and lamp) is virtually unaffected by the radiation even at the highest level of 6.2×10^{12} n/cm^2 and 9.2 krad(Si). This follows from the close tracking of the inboard and outboard values for both photocells. The tracking is not perfect but the differences (up to several percent) that do exist can probably be attributed to small misalignments in the relative positions of the photocell assemblies and the lamp boards from measurement to measurement. (The positioning mechanisms did have some "slop" in them and examination of the insertion/removal processes[24] shows that such misalign- "errors" could have occurred.)

If small light intensity changes of a few percent are occurring, there are several possible mechanisms that might be responsible. For example, radiation-induced offsets in the lamp-thermostat op amp can, in principle, produce changes in lamp temperature. A calculation of the size of this effect for 1×10^{12} n/cm^2 and 1.5 krad (Si) predicts a temperature change of 0.02°C or less. Since a 1°C increase in lamp temperature is required to produce a ∿7% increase in light intensity, this effect is expected to be insignificant.

Changes in light intensity due to effects of nuclear radiation on the lamp oscillator circuitry are also expected to be small but precise calculations are not possible in this case because of a lack of knowledge as to how critical parameters (such as base-emitter impedance) are altered and how the amount and frequency of the rf power delivered to the lamp affect the light output. In any event, it is clear from the experimental results that any changes in light intensity that do occur, do not exceed several percent at most.

COMPONENT IRRADIATION

The optical materials listed as S1 through S5 in Table 1 were also irradiated to determine the effects of simultaneous neutron/gamma radiation on their light transmittance. These are materials that are used in the light paths of Efratom's RFS's.

Transparency Test Fixture

The transparency test fixture is shown in Fig. 7. This fixture contains an RFS rubidium lamp board and lamp which produces rubidium light. The rubidium light is incident upon an interference filter which passes rubidium D_1 resonance light (794.8 nm). The D_1 light is detected by a photocell mounted approximately 5/8" below the filter. Sample transparency is determined by inserting the sample into the light beam and measuring the amount of transmitted light.

The glass samples used were in the form of glass tubes,[25] nominally 2" long. To measure the light attenuation produced by a glass tube, it was positioned as shown in Fig. 7, intercepting all of the D_1 light incident upon the photocell. The mica and Mylar samples were in the form of thin disks (see Table 1) approximately 5/8" in diameter. These disks were glued to a flat aluminum plate, concentric with a 1/2" hole through the plate, as shown in Fig. 8. To measure light attenuation, the plate was inserted into the sample holder slot shown in Fig. 7 (with the glass tube removed). In this configuration, D_1 light could reach the photocell only by passing through the sample.

The mica and Mylar samples could be positioned quite precisely in the test fixture and, in addition, they were of uniform thickness without any obvious optical distortion. This was not the case for the glass samples, each of which had slight irregularities that affected the light transmission due to small variations in reflection and refraction as the tube was rotated about its own axis in the test fixture. To avoid these changes in transmitted light due to this extraneous effect, care was taken during the tests to orient each glass tube in the same way each time it was inserted into the transparency test fixture. This precaution reduced these effects to an insignificant level. (They weren't very large anyhow.) In addition, for each glass sample tested, a nearly identical control was used as a reference. The sample was irradiated in the reactor, the control was not.

Measurement Procedure

Prior to level 1 irradiation the light transmission of each sample and control was measured in the transparency test fixture. The samples, S1 - S5, were then placed behind the inboard test fixture on the carriage that was used to transport the test fixture to the reactor core. The samples remained at this location on the carriage until all irradiation was complete (levels 1 - 4). They were then removed and their light transmission, along with that of the controls, was measured again in the transparency test fixture to determine the effect, if any, of the radiation.

Dosimetry

The dosimeters on the rear of the inboard test fixture (one for each level)

were used to determine the cumulative neutron fluence to the optical samples. This amounted to 2.7×10^{12} n/cm^2, compared to the corresponding figure for the front of the inboard test fixture of 6.2×10^{12} n/cm^2 (plus 9.2 krad(Si) total dose, 98% of which is due to gamma radiation). The difference in these neutron fluences can be attributed mostly to scattering of the incident neutrons by the test fixture. Since the gamma radiation is attenuated very little by the test fixture, the cumulative gamma dose to the glass is expected to be $\sim$9 krad(Si).

Test Results

The transparency test fixture was observed to be stable to a few tenths of a percent over the more than three hour duration of the optical sample test. It is therefore expected that changes in sample light transmission of $\lesssim$1% could have been detected. The observed changes in light transmission for all samples and controls (after vs. before, and sample vs. control both before and after) were of the order of a few tenths of a percent with the exception of the Schott 8436 glass where the after vs. before readings for the transmitted light were -1.2% and -1.0% for the sample and control, respectively. The fact that both sample and control showed nearly identical 1% decreases is most likely due to a short-term fluctuation in the test apparatus rather than to any change in sample or control transparency. It is therefore reasonable to conclude that, to within the experimental uncertainty of several tenths of a percent, no radiation-induced transparency changes occurred for any of the optical materials tested.

SYNTHESIS OF RESULTS

In the tests carried out on the complete Model M-100 RFS, it was concluded that the decrease in the dc photocurrent due to irradiation was due almost entirely to photocell degradation. This conclusion is supported by the results of RFS subsystems and components, namely, the constancy of the light output from the lamp board during irradiation, the absence of any radiation-induced changes in the transparency of the optical materials,[26] and, of course, the degradation of the two photocells tested.

Photocell Degradation

The dc photocurrent of the complete RFS tested is plotted against neutron fluence in Fig. 5 assuming that the illumination of the photocell remained constant during the test (a good assumption, as pointed out above). The photocell used in this unit was neither an IR nor a Ferranti photocell but rather one manufactured by Silicon Sensors, Inc.. Consequently, the significance of Fig. 5 is that there are considerable variations in photocell degradation from one manufacturer to the next. For the three curves shown, the max/min variation ranges from 1.5 at 6.5×10^{11} n/cm^2 to 2.0 at 6.5×10^{12} n/cm^2. It is highly significant that for the worst degradation

shown, the complete M-100 still operated satisfactorily.[27]

EXTRAPOLATION TO HIGHER RADIATION LEVELS

The results obtained in the two parts of this investigation are based on neutron irradiation up to 7.5 x 10^{12} n/cm^2 and 6.2 x 10^{12} n/cm^2, respectively. Since data points were also taken at lower fluences, a straightforward extrapolation to at least 1 x 10^{13} n/cm^2 is possible for certain portions of the RFS.

Transparency of Optical Components The optical materials tested received a maximum fluence of 2.7 x 10^{12} n/cm^2 which is estimated from the front/rear dosimetry data to correspond to a fluence of 5 x 10^{12} n/cm^2 to a complete RFS. At this level of irradiation, no change in transparency was observed and the experimental uncertainty sets an upper limit on changes in light transmission of a few tenths of a percent. It therefore seems unlikely that a fluence of 1 x 10^{13} n/cm^2 to an RFS will produce significant darkening of any of the optical materials. Independent data on the effects of neutron fluences of 1 x 10^{13} n/cm^2 and greater for glass and mica also support this view.[28]

As regards the glass alone, there is additional direct evidence that it can withstand neutron irradiation in excess of 10^{15} n/cm^2. During the Rockwell Efratom rubidium lamp investigation for the Global Positioning System (GPS),[29] in which one of us (T.C.E.) was directly involved, a number of rubidium lamps were neutron activated as part of a program to determine the quantity of rubidium in rubidium lamps. The first step in the activation process is to irradiate the filled lamp (less base) with neutrons. This was done in the General Atomic TRIGA, Mark I reactor[30] in San Diego. Lamps were typically irradiated simultaneously with a $\sim$2 x 10^{15} n/cm^2 of 1 MeV-equivalent neutrons and $\sim$7 Mrad gamma total dose.[10] The irradiated lamps were made of Corning 1720 glass and Schott 8437. Schott 8437 is very similar to the Schott 8436 glass that Efratom presently uses in all its RFS lamps (both are alkali-resistant borosilicate glasses).

Several of the irradiated lamps were used in Rockwell/Efratom GPS rubidium clocks that are in GPS satellites presently orbiting the earth. The glass of these lamps had a slight yellowish cast after irradiation but there were no indications during acceptance testing that they performed in any way that was different from an unirradiated lamp.[31]

Photocell Degradation Extrapolation of the normalized dc photocurrent for the IR photocell to 1 x 10^{13} n/cm^2 using Fig. 5 gives a value of $\sim$40%. Assuming that the normalized ac response is $\sim$60% of the normalized dc response gives a normalized ac response of $\sim$25% at 1 x 10^{13} n/cm^2. This is low but nevertheless adequate since the complete M-100 tested showed satisfactory operation for about a factor of two lower value at 7.5 x 10^{12} n/cm^2

using the Silicon Sensors photocell.[27]

Electronics The hardness of the electronics at 1 x 10^{13} cannot be extrapolated from our results and will require an additional hardness assessment at this level.

SUMMARY AND CONCLUSIONS

Seperate tests were conducted on an Efratom, Model M-100, military, radiation-hardened, rubidium frequency standard (RFS), and on certain RFS subsystems and components by subjecting them to combined neutron/gamma radiation from a nuclear reactor. The results of these tests allow the following conclusions to be drawn.

Complete RFS

1. The Model M-100 RFS, which was operated continuously during the test, performed satisfactorily up to and including the highest radiation levels tested [7.5 x 10^{12} n/cm^2 and 11 krad(Si)]. Over the 2½ hr duration of the test, the overall frequency change due to all causes (including insertion into and retraction from the reactor) was less than 1 x 10^{-10}.
2. As a result of irradiation of the unit at the highest level, the short-term frequency stability decreased by about a factor of two. The tests conducted show that this decrease was due to a degradation of the performance of the photocell in the unit. This result is of particular significance since the photocell used in this unit showed the greatest degradation of the three photocells irradiated. In the future, use of either Ferranti or IR photocells should result in the unit meeting its original short-term stability spec even after irradiation to 7.5 x 10^{12} n/cm^2 and 11 krad(Si).[32]
3. The free-running VCXO frequency (had the VCXO not been locked to the atomic resonance) was shifted by only about one tenth of its electrical trim range due to the irradiation. For this reason there is no danger of the control voltage being shifted beyond the control limits due to irradiation, or the unit failing to reacquire lock when turned off and then turned on again.
4. After the final irradiation of the unit, it was turned off for five minutes and then turned on again. Retrace was within 2 x 10^{-11} of the frequency prior to turn off (normal performance).

Subsystems and Components

5. Samples of all materials used in the optical paths of Efratom rubidium frequency standard (RFS's) were tested for radiation-induced changes in the optical transmission of rubidium D_1 resonance light (at 794.8 nm). For simultaneous neutron fluences and total doses up

to 2.7×10^{12} n/cm^2 and ∿9 krad(Si), respectively (corresponding to ∿5 x 10^{12} n/cm^2 and ∿9 krad(Si) to a complete RFS), no changes in the optical transmission of any of the materials were observed, to within the experimental uncertainty of a few tenths of a percent. Transmission measurements for rubidium D_2 light (780.0 nm) were not made, but because of the close proximity of the D_1 and D_2 spectral lines (∿15 nm separation) it is quite unlikely that D_2 transmission behaves in a different manner than D_1 transmission. This latter conclusion is also supported by measurements of total light intensity from rubidium lamps operating in the same radiation environment (see below).

6. The experimental results for two rubidium lamps, lamp boards, and power supply boards, all continuously operating in a nuclear radiation environment, can be used to set an upper limit on radiation-induced changes in the total light output of an Efratom RFS rubidium light source. For the highest irradiation level tested (6.2 x 10^{12} n/cm^2 and 9.2 krad(Si) total dose), this limit amounts to several percent and corresponds to the experimental uncertainties in the measurements. In addition, calculations based on the known behavior of electronic components under irradiation make it virtually certain that changes in light intensity due to radiation-induced changes in lamp-oven temperature are significantly less than one percent.

7. Rubidium lamps made by Efratom were neutron activated to determine their rubidium fills for the GPS program. During neutron activation these lamps received a neutron fluence in excess of 10^{15} n/cm^2 and a gamma dose of ∿7 Mrad. (These radiation levels are ∿300x and ∿600x greater, respectively, than those used in our tests.) Subsequent to neutron activation these lamps passed GPS acceptance testing and there were no indications that they operated in any way that was different from that of an unirradiated rubidium lamp. Six of these lamps are now in GPS satellites orbiting the earth. Of these six, the one that has been turned on is still operating satisfactorily after two years.

8. Two different RFS photocells were tested for degradation after simultaneous exposure to neutrons and gamma radiation (see Fig. 5). For the highest radiation levels of 6.2 x 10^{12} n/cm^2 and 9.2 krad (Si), the dc photocurrents dropped to approximately 40% of their initial, pre-irradiation values (under conditions of constant illumination with unfiltered rubidium light).

9. The ac photocurrents of the two photocells due to light modulation at 127 Hz (the RFS modulation frequency) were also measured under the same conditions and were found to degrade somewhat more rapidly than the corresponding dc photocurrents (see Table 3). At the highest irradiation level, the ac photocurrents, normalized to the pre-irradiation values, amounted to ∿70% of the corresponding normalized dc photocurrents.

10. The photocell shunt resistances were also measured and found to be

affected by simultaneous neutron and gamma irradiation (see Fig. 6), but even at the highest irradiation level (6.2×10^{12} n/cm^2 and 9.2 krad(Si) total dose) the shunt resistances of both photocells were in excess of 3 kΩ. Since the shunt resistance must be 1 kΩ or greater for satisfactory M-100 operation, shunt resistance changes due to irradiation at up to 6.2×10^{12} n/cm^2 and 9.2 krad(Si) are of no importance for the M-100.

11. Straightforward extrapolation of the results of this paper indicates that the physics package optical components and photocell are most likely hard at neutron fluences of 1×10^{13} n/cm^2. The hardness of the electronics at this level of irradiation is presently unknown and requires a seperate assessment.

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6. Corning 1720 glass, 0.11 cm thick sample
7. Corning 7070 glass, 0.16 cm thick sample
8. 794.8 nm (D_1) and 780.0 nm (D_2)
9. All readings for 780.0 nm and 794.7 nm were the same to within 0.1%
10. Thomas C. English and Henry Vorwerk, "M-100 Radiation Hardness Test," Parts 1 and 2 (Efratom Systems Corporation Internal R & D Reports, May 1982 and November 1982, respectively; unpublished.)
11. S/N E-002. It came off the assembly line in November 1981. The frame and PC board modifications mentioned were originally intended to improve the mechanical rigidity.
12. Measured against an Efratom, Model FRT-H, RFS using a Tracor, Model 527A Frequency Difference Meter.
13. For the test reactor used, a neutron fluence of 10^{12} n/cm^2 also results in a total radiation dose of 1.5 krad(Si). Of this total dose, only 2% is due to neutrons, the remainder being due to gamma radiation that is present with the neutrons. All other types of radiation (e.g., α, β) are negligible.
14. In order to fit the data on one 8½ x 11 figure, part of each of the following were omitted from Fig. 2: Initial warmup prior to level 1 sequence retraction period for each level, restart data. Also not shown in Fig. 2 are transient frequency changes that occur during a one minute interval when the unit is retracted, and later when it is reinserted into the reactor.
15. y(end of 2½ hr) - y(beginning of 2½ hr) where y = fractional frequency offset from reference.
16. The crystal used in the M-100 is an unswept, AT cut, third overtone, 10 MHz quartz crystal manufactured by Colorado Crystal

17. "Hardness Assessmant of the Efratom Rubidium Frequency Standard, Model M-100" (Consultant's report to Efratom dated July 24, 1979, available on request.)

18. H.Y. Tada and J.R. Carter, Jr., Solar Cell Radiation Handbook, JPL Publication 77-56 (NASA & JPL, Nov. 1, 1977), Figs. 3.6, 3.18 and p. 3-49.

19. "Silicon Photovoltaic Detectors and Detector/Amplifier Combinations" (EG&G Electro-Optics Application Note D3011B-1, 1 August 1975).

20. T. English, "Noise Sources in the FRK Photocell and Photocell Amplifier, Part 1" (Efratom Systems Corp. Internal R & D Report, 1 August, 1978).

21. For normal operation of the photocell in the short-circuit current mode, the shunt resistance can be computed from

$$R_S(\Omega) = 100\ \Omega \times \frac{i}{(i - i_0)}$$

where i_0 = dc photocurrent without series resistor

i = dc photocurrent with series resistor

22. Due to the complexity of the test and the time factor (the unit was radioactive after the first irradiation and could only be handled for a very short period between irradiations) the ac photocurrent was not measured between levels 1 and 2, or between levels 2 and 3.

23. When a photocell-cavity-shield assembly was inserted into the outboard photocell test fixture for characterization, the photocell's dc and ac photocurrents were measured using the photocell amplifier on the fixture's servo board. Since this servo board was not irradiated, its performance could not be affected in any way by nuclear radiation.

24. The insertion/removal processes mentioned here refer to the insertion/removal of a photocell-cavity-shield assembly relative to an inboard or outboard lamp board.

25. Flat glass plates would have been more desirable but they were not conveniently available.

26. The samples of optical materials were at ambient temperature when irradiated, whereas in an RFS they operate at elevated temperatures. However, it was not convenient in these tests to irradiate the samples at temperatures above ambient.

27. Efratom no longer uses Silicon Sensors photocells in any of their RFS's due to the low shunt resistance of these devices.

28. Ref. 5, Ch. 11.

29. This investigation began in February 1979 and continued through 1981.

30. This reactor is different than the TRIGA, Mark F reactor used in the RFS irradiation experiments.

31. No "before-and-after" tests of light transmission were performed on these lamps.

32. A typical M-100 has a short-term stability (σ_y) that is a factor of two better than spec. Using either a Ferranti or IR photocell should reduce the deterioration of short-term stability due to irradiation from a factor of two to about a factor of 1½.

TABLE 1

OPTICAL MATERIALS USED IN RFS COMPONENT IRRADIATION TEST

Item	Description [a]	RFS Function [b]	Used in Efratom RFS Model(s) [c]
PC1	Silicon solar cell, International Rectifier P/N 49-2835, 1.0 O.D.	Photodetector	A
PC2	Silicon solar cell, Ferranti MS11B, 1.0 O.D.	Photodetector	A
S1	Transparent mica window, 0.5 D. X 0.004 thk	Lamp oven window	A
S2	Transparent Mylar window, 0.5 D. X 0.003 thk	Microwave cavity window	A
S3 [f]	Corning 7740 [d] glass tube, 1.0 D. X 0.060 wall	Rb resonance cell [e]	M-100, FRK
S4 [f]	Schott 8435 glass tube, 0.875 D. X 0.065 wall	Rb lamp	A
S5 [f]	Corning 1720 glass tube, 1.0 D. X 0.070 wall	Rb resonance cell	M-1000

[a] All dimensions in inches.

[b] Dimensions in RFS may differ somewhat from that of irradiation sample.

[c] A denotes all models: M-100, FRK, M-1000.

[d] Pyrex (trade name of Corning Glass).

[e] Cells produced in Munich use Schott Duran 50 glass which is nearly identical to Corning 7740 glass (Pyrex).

[f] For samples S3, S4, S5, controls (designated S3C, S4C, S5C) were also used for comparison. The samples were irradiated, the controls were not.

TABLE 2

EFFECT OF IRRADIATION ON DC PHOTOCURRENTS

Measurement Point [a]	Normalized dc Photocurrent, I/I_o (%)			
	PC1 (International Rect.)		PC2 (Ferranti)	
	Inboard [b]	Outboard	Inboard [c]	Outboard
BL1	100	100	100	100
AL1	81	78	85	91
BL2	80		90	
AL2	75	73	81	86
BL3	75		82	
AL3	58	56	64	70
BL4	57		68	
AL4	38		40	
AL4 + 1 hr	40	37	43	44

[a] BL1 = before level 1 irradiation
AL1 = after level 1 irradiation, etc.

[b] Uses outboard servo board

[c] Uses inboard servo board

TABLE 3

COMPARISON OF AC AND DC PHOTOCURRENTS [a,b]

Measurement Point [c]	dc Photocurrent I/I_o(%)		ac Photocurrent i/i_o(%)		ac Photocurrent as % of dc Photocurrent	
	PC1	PC2	PC1	PC2	PC1	PC2
BL1	100	100	100	100	100	100
AL3/BL4	56	70	39	57	69	81
AL4 + 1hr	37	44	23	34	63	76

[a] Normalized to pre-irradiation values

[b] Outboard measurements

[c] BL1 = before level 1 irradiation
AL3 = after level 3 irradiation, etc.

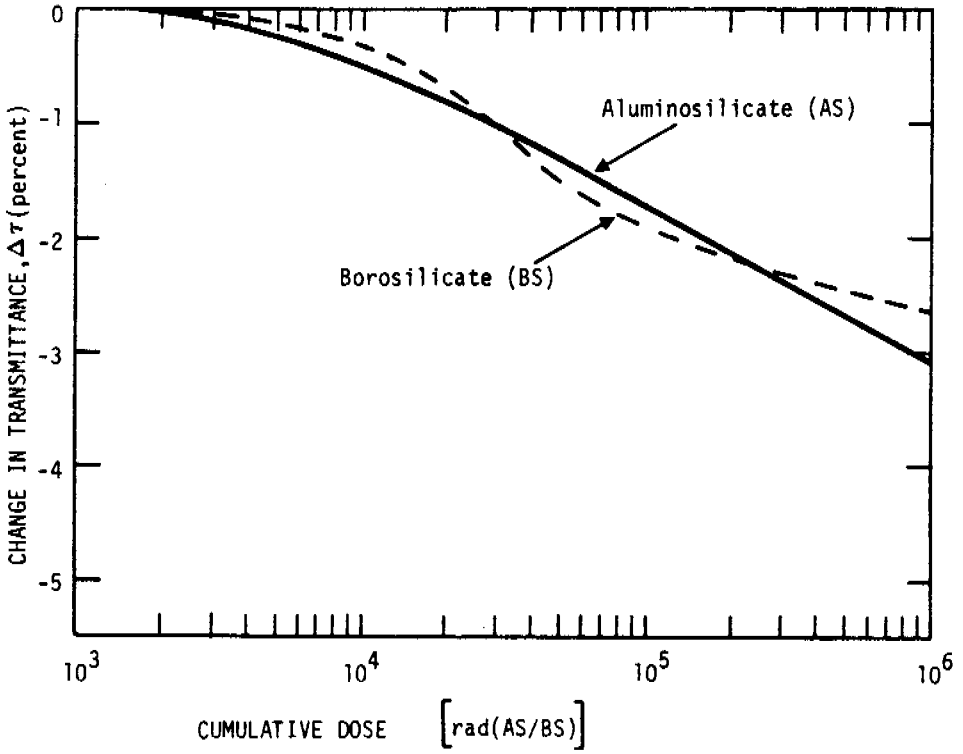

FIGURE 1. Nominal change in transmittance as a function of total dose for two glasses.

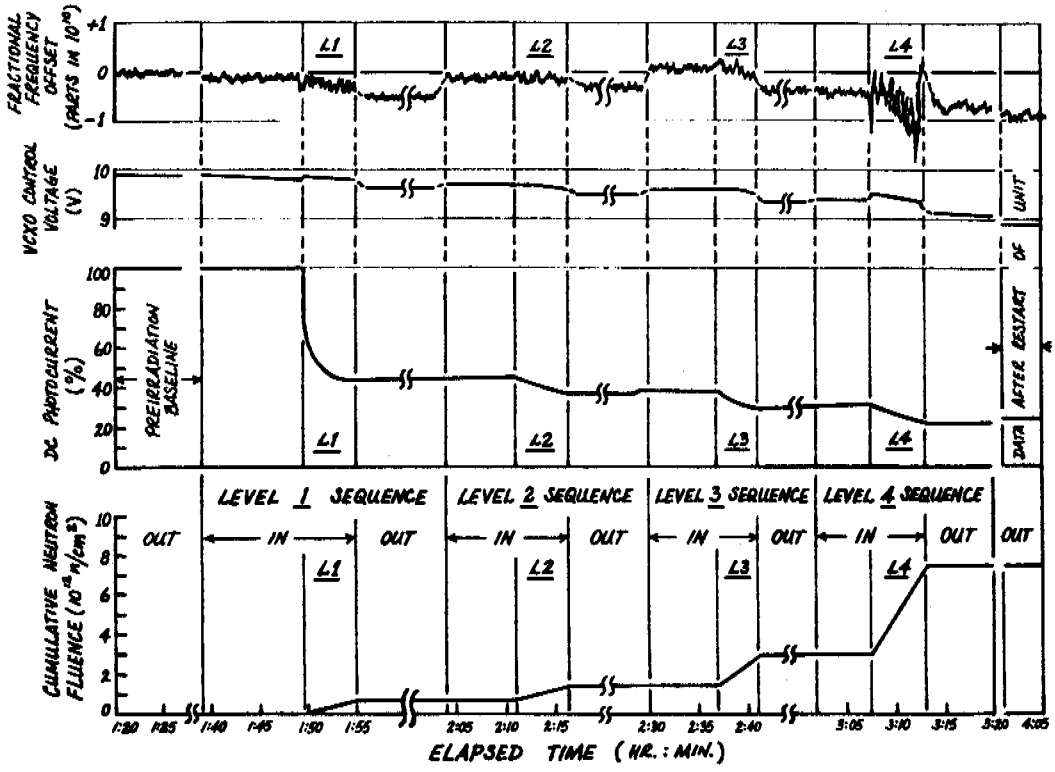

FIGURE 2. Effect of combined neutron/gamma radiation from a nuclear reactor on an operating Efratom M-100 rubidium frequency standard.

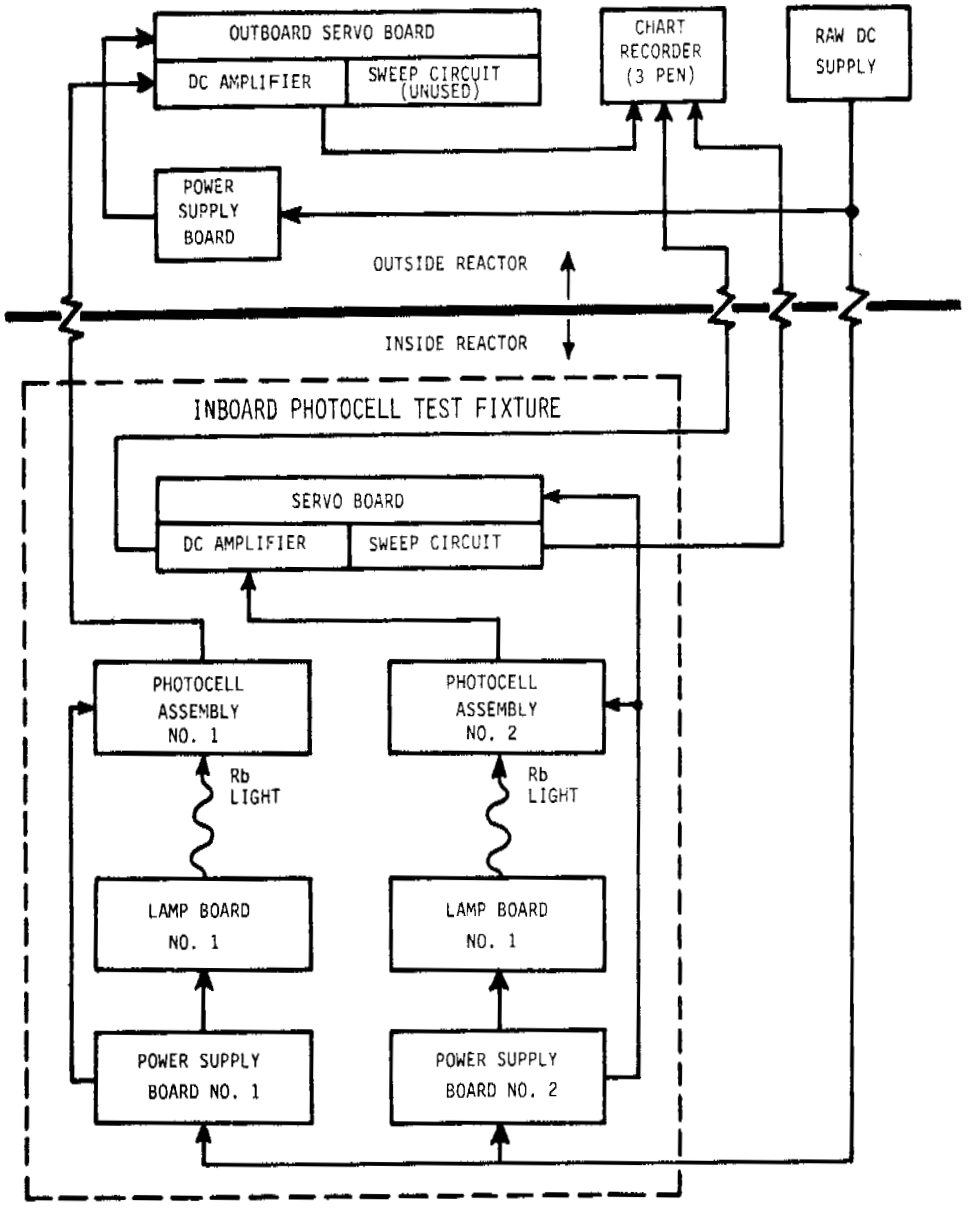

FIGURE 3. Block diagram of inboard photocell test fixture and associated test equipment.

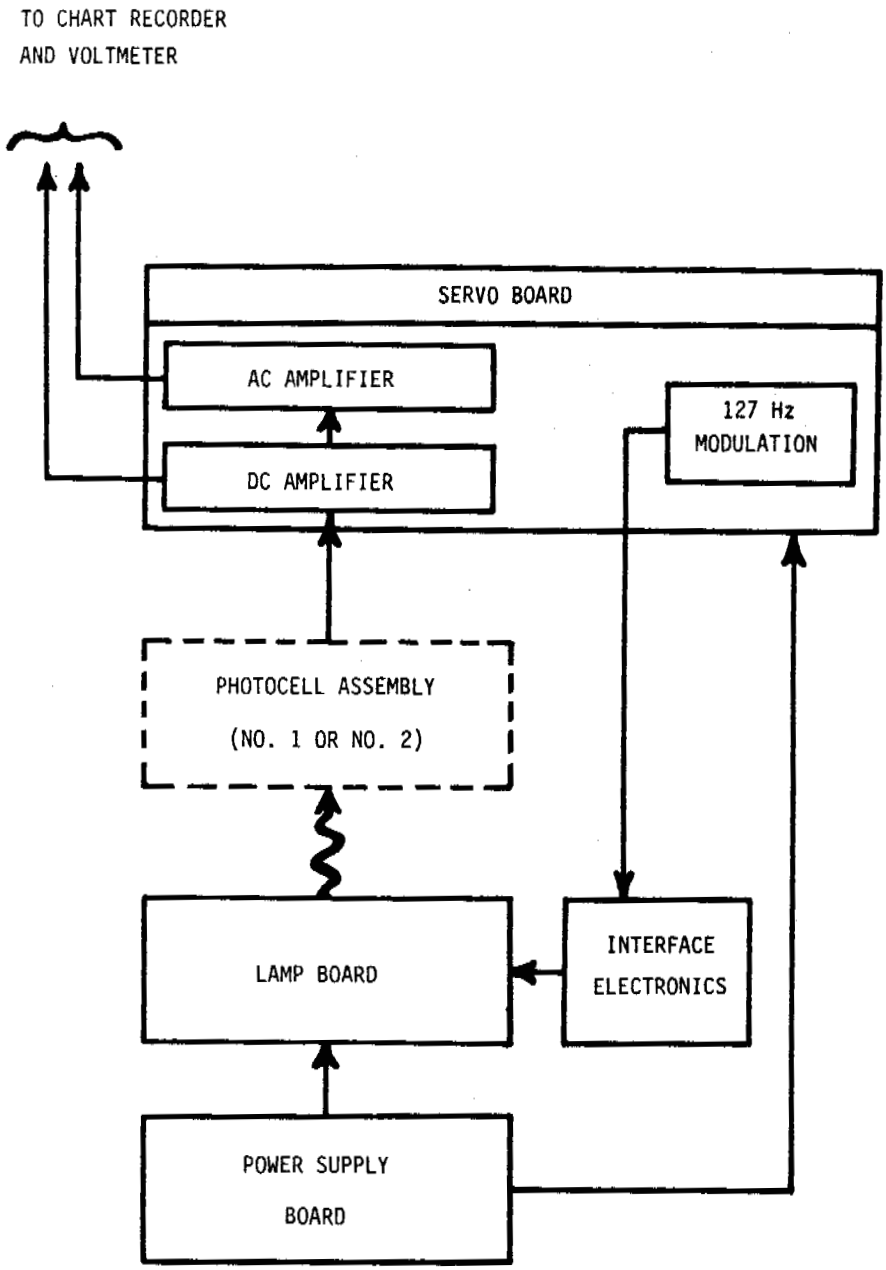

FIGURE 4. Block diagram of outboard photocell test fixture.

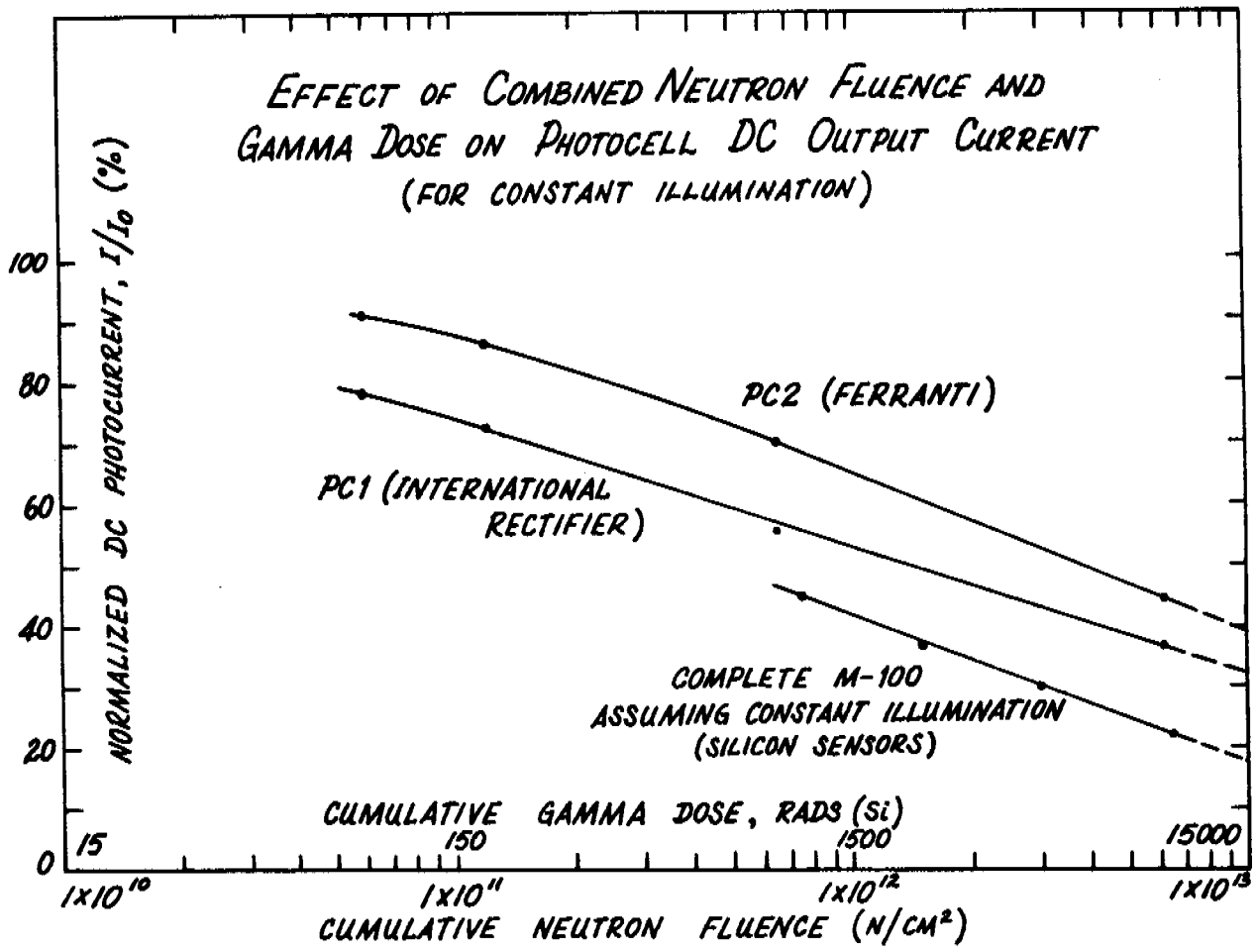
EFFECT OF COMBINED NEUTRON FLUENCE AND
GAMMA DOSE ON PHOTOCELL DC OUTPUT CURRENT
(FOR CONSTANT ILLUMINATION)
NORMALIZED DC PHOTOCURRENT, I/I0 (%)
100
80
60
40
20
0
PC2 (FERRANTI)
PC1 (INTERNATIONAL
RECTIFIER)
COMPLETE M-100
ASSUMING CONSTANT ILLUMINATION
(SILICON SENSORS)
CUMULATIVE GAMMA DOSE, RADS (Si)
15
150
1500
15000
1X10^10
1X10^11
1X10^12
1X10^13
CUMULATIVE NEUTRON FLUENCE (N/CM^2)

FIGURE 5

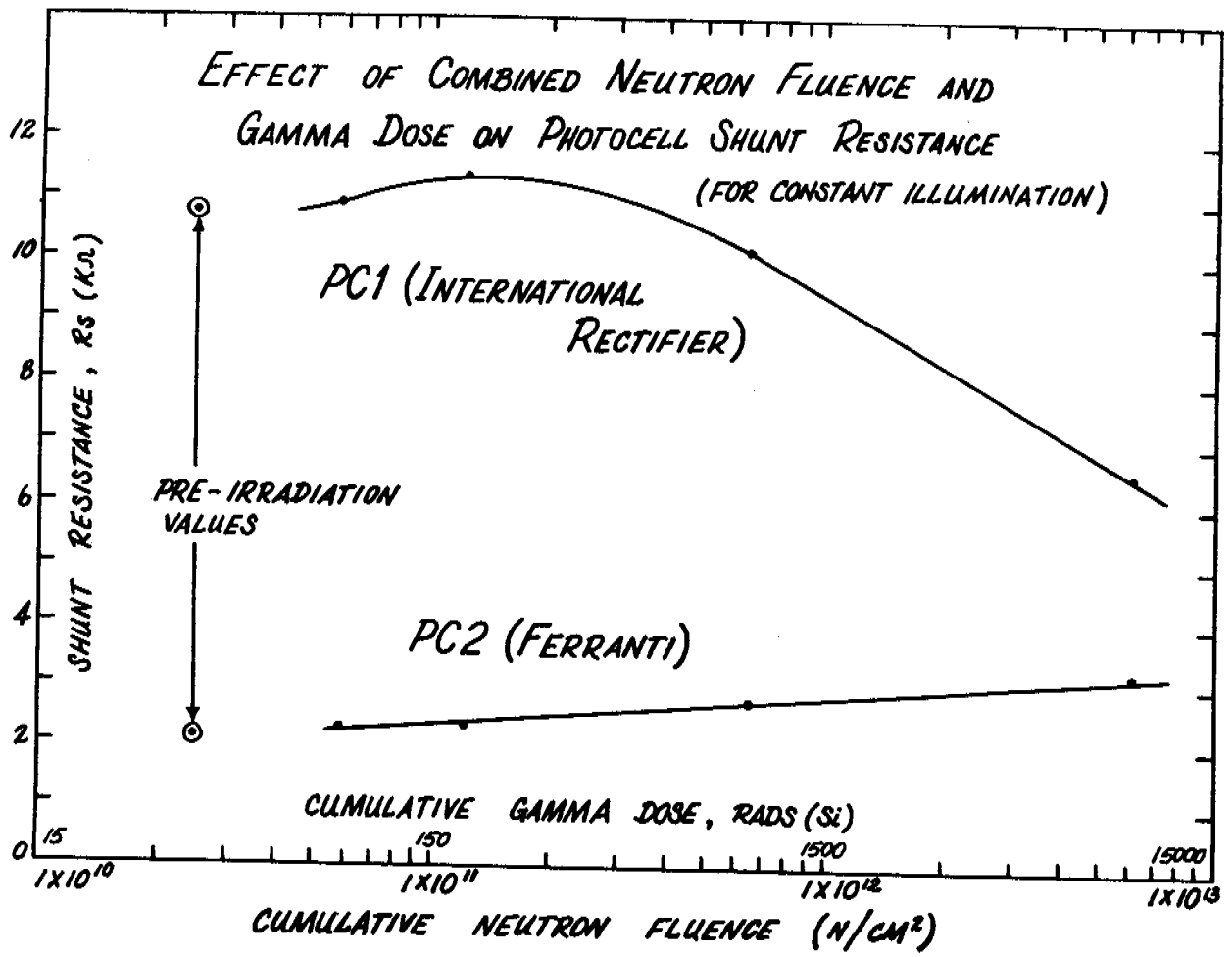
EFFECT OF COMBINED NEUTRON FLUENCE AND
GAMMA DOSE ON PHOTOCELL SHUNT RESISTANCE
(FOR CONSTANT ILLUMINATION)
PC1 (INTERNATIONAL RECTIFIER)
PC2 (FERRANTI)
PRE-IRRADIATION VALUES
SHUNT RESISTANCE, Rs (KΩ)
0
2
4
6
8
10
12
CUMULATIVE GAMMA DOSE, RADS (Si)
15
150
1500
15000
1X10^10
1X10^11
1X10^12
1X10^13
CUMULATIVE NEUTRON FLUENCE (N/CM²)

FIGURE 6

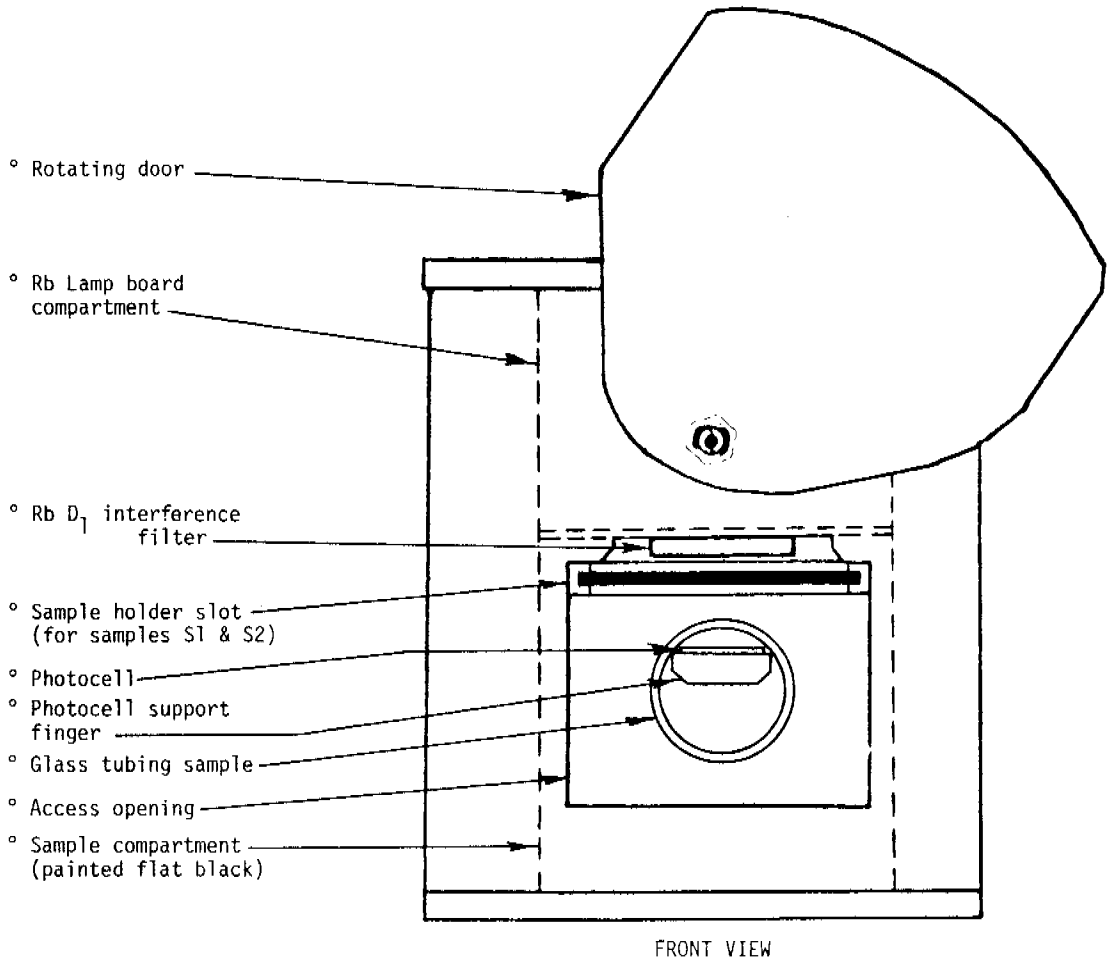

FIGURE 7. Transparency test fixture.

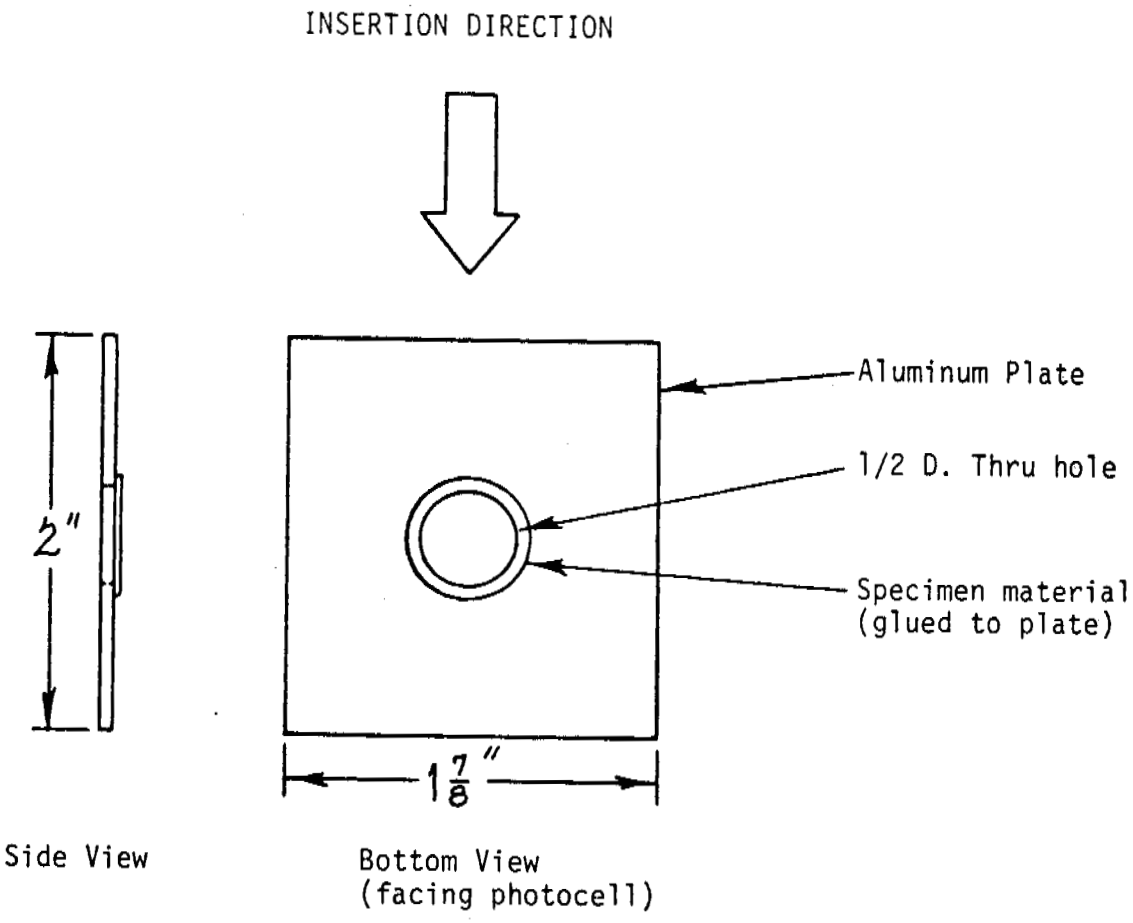

FIGURE 8. Sample holder used for samples S1 and S2.

QUESTIONS AND ANSWERS

None for Paper #28