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Studies of radiation damage equivalence have been conducted in four different neutron environments by using silicon transistors with gain-bandwidth products covering the range from 1 MHz to 2 GHz and power ratings covering the range from 200 mW to 115 W. The neutron environments were obtained from two TRIGA reactors, a fast-burst reactor, a 14-MeV generator, and a Californium 252 fission source. Experimentally, damage factors were obtained by comparisons of changes in the reciprocal of the common-emitter dc gain as a function of measured fluences. The damage factor was the

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slope of the resulting curve. Corrections were made for the fraction of total damage associated with gamma radiation effects. The ratios of the slopes of the data from the different irradiation facilities give an indication of spectral differences among the facilities. These ratios do not appear to be strong functions of collector current or of the transistor type.

The experimental data were compared with theoretical calculations of displacement damage as defined by the damage curves of Messenger and of Holmes. The ratio of 14-MeV generator to fast-burst reactor damage is less than predicted theoretically; the ratio of fast-burst reactor to TRIGA reactor is higher than calculated. Uncertainties in the parameter and dosimetry measurements could account for some of the observed differences, but the uncertainty in the spectra content of the reactors is probably the major contributor.

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## 1. INTRODUCTION

Semiconductor devices exposed to the same total fluence at different reactors or neutron sources incur different degrees of damage because of the dependence of damage on neutron energy. Because of the difficulties and inaccuracies inherently associated with spectrum measurements and because of a lack of readily available 14-MeV neutron sources, it is important to measure the relative damage factors in silicon devices for the various reactors and sources used for testing electronic equipment and components and compare them with the calculated relative damage factors obtained from published damage curves. These comparisons give the design engineer added confidence that his test results can be related to applicable nuclear radiation requirements.

Available radiation sources, normally pulsed reactors, are used to simulate weapon and space radiation environments. However, they do not always produce the intensity, the time sequence, or the energy spectra of the intended environment. Furthermore, they frequently differ from each other. These factors emphasize the need for a good understanding of how components, particularly silicon semiconductor devices because of their widespread use, incur different degrees of damage in different radiation test environments. Relative damage-factor experiments on transistors were conducted at a TRIGA reactor at the Diamond Ordnance Radiation Facility (DORF), Harry Diamond Laboratories, Adelphi, MD; a GODVIA-type, fast-burst reactor at the Army Pulse Reactor Facility (APRF), Ballistic Research Laboratories, Aberdeen, MD; the Insulated Core Transformer (ICT) deuterium-on-tritium 14-MeV neutron generator at the Lawrence Livermore Laboratory, Livermore, CA; and a Californium 252 fission neutron source at the National Bureau of Standards (NBS), Gaithersburg, MD. An additional comparison was made between the DORF TRIGA reactor and the Armed Forces Radiobiology Research Institute (AFRRI) TRIGA reactor in Bethesda, MD.

Damage equivalence studies in semiconductor devices[1-4] and in semiconductor materials[5] have been done at facilities similar to DORF and APRF. Also, methods have been developed for using 14-MeV neutrons as a standard so that the damage created by any spectrum can be designated in terms of a 14-MeV equivalance.[1,6] The results of these studies show that there are differences between the calculated and measured equivalences. The calculations indicate that a TRIGA reactor (DORF) and a fast-burst reactor (APRF) should be relatively equal in the amount of damage created, but the measurements show that the APRF neutron output is about 50 to 100 percent more damaging than DORF's. This discrepancy may be due to a difference in the scattering of the initial fission spectrum. Because the DORF TRIGA reactor is water moderated, its energy spectrum should be degraded more than that of the air-surrounded fast-burst rector (APRF). Unfortunately, energy spectral measurements are difficult to make, but it is reasonable to assume that the DORF spectrum in the experimental area is more degraded than that used in the calculations and that the APRF spectrum may be slightly harder.

[1] *J. M. McKenzie and L. J. Witt, Conversion of Neutron Spectra to Their 14-MeV Equivalences, IEEE Trans. Nucl. Sci., 19 (December 1972), 194.*

[2] *F. N. Coppage, Experimental Neutron Damage Equivalences Utilizing Device Parameters, IEEE Trans. Nucl. Sci., 20 (December 1973), 349.*

[3] *M. L. Green and R. K. Thatcher, Preparation of a Standard Technique for Determination of Neutron Equivalence for Bulk Damage in Silicon, IEEE Trans. Nucl. Sci., 19 (December 1972), 200.*

[4] *F. N. Coppage, The Influence of Dosimetry in Earlier Damage Equivalence Ratios, IEEE Trans. Nucl. Sci., 22 (1975), 2336.*

[5] *H. J. Stein, Energy Dependence of Neutron Damage in Silicon, J. Appl. Phys., 38 (1967), 204.*

[6] *J. M. McKenzie, Method to Determine the Relative Damage Produced in Semiconductors by Different Neutron Sources, Sandia Laboratories, Albuquerque, NM, SC-M-72 0133 (February 1972).*

## 2. DAMAGE EQUIVALENCE

The experimental data are evaluated in terms of displacement damage as defined by Messenger[7] and Holmes et al.[8] These references give damage equivalence curves as a function of neutron energy. Holmes utilizes the displacement-energy transfer cross section, which for convenience is normalized to 96 MeV·mb, the cross section near 1 MeV. Messenger used points at 1 and 14 MeV from Smits and Stein's[9] data and used a saturating extrapolation between 1 and 14 MeV and a linear extrapolation from 1 MeV down. This amounts to a smoothing out (averaging) of Holmes' curve (fig. 1). The theoretical damage equivalence is obtained by using these curves and the spectra of interest. First, calculate the 1-MeV equivalences, and then take the ratios of these to get the relative damage of the two different sources. The spectra used for the TRIGA is the leakage spectrum in water 2 cm beyond the outer periphery of the core.[10] The fast-burst reactor spectrum was calculated for the APRF by Oak Ridge National Laboratory (ORNL) with the ORNL multigroup transport theory techniques.[*] The Californium 252 has a pure fission spectrum, and the 14-MeV generator is essentially monoenergetic. The DORF and APRF spectra are shown in figure 2. Table I lists the various calculated damage equivalence ratios and the 1-MeV equivalence.

The experimental damage equivalence is obtained by taking the ratio of the damage factors obtained at the different neutron sources. The damage factor ($Kt_b$) is defined by the following equation:[11,12]

$$\Delta \frac{1}{h_{FE}} = \frac{1}{h_{FE\phi}} - \frac{1}{h_{FEO}} = Kt_b\phi , \quad (1)$$

where

$h_{FE}$ = common-emitter dc gain,

$h_{FE\phi}$ = common-emitter dc gain at neutron fluence $\phi$,

$h_{FEO}$ = initial common-emitter dc gain,

$K$ = energy dependent damage constant ($cm^2$/neutron·s),

$t_b$ = base transit time (s),

$\phi$ = neutron fluence > 10 keV (energy/$cm^2$).

Equation (1) is a simplification of that given by Messenger and Spratt.[11] The damage constant, K, is actually a function of emitter current, but reaches a minimum at a current density[12,13] of about 100 A/$cm^2$. This is the current density at which most transistors show peak current gain.

To eliminate the errors associated with differences in base transit time and the influence that such differences have on damage in tran-

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[7] *G. C. Messenger, Displacement Damage in Silicon and Germanium Transistors, IEEE Trans. Nucl. Sci., 12 (April 1965).*

[8] *R. R. Holmes, J. P. Mitchell, D. K. Wilson, and W. H. vonOulock, Weapons Effects Studies, II, Radiation Effects on Interceptor Electronics, Bell Telephone Laboratories, Whippany, NJ (October 1970).*

[9] *F. M. Smits and H. J. Stein, Energy Dependence of Neutron Damage in Silicon-Experimental, Bull. APS, Series 2, 9, No. 3 (March 1964), 289.*

[10] *G. B. West, Calculated Fluxes and Cross Sections for TRIGA Reactors, General Atomic, San Diego, CA (August 1963), 49.*

[11] *G. C. Messenger and J. P. Spratt, The Effects of Neutron Irradiation on Germanium and Silicon, Proc. IRE, 46 (June 1958), 1038.*

[12] *F. Larin, Radiation Effects in Semiconductor Devices, John Wiley and Sons, Inc., New York (1968).*

[13] *R. K. Thatcher, ed., TREE Handbook, 2nd ed., Defense Nuclear Agency, Washington, DC (1967).*

[*] *A. H. Kayi, U. S. Ballistic Research Laboratories, Aberdeen Proving Ground, MD, private communication.*

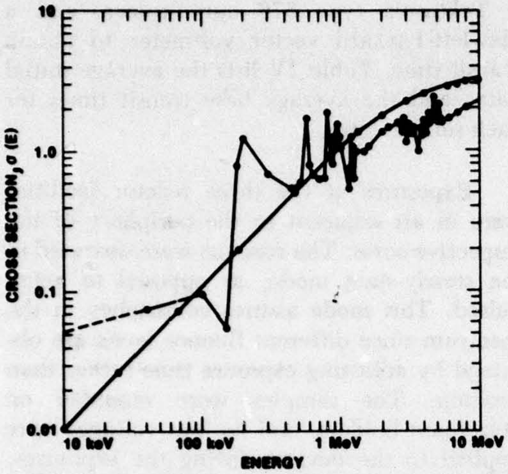


**Figure 1. Relative neutron damage curves (sources: Messenger (smooth curve) and Holmes).**

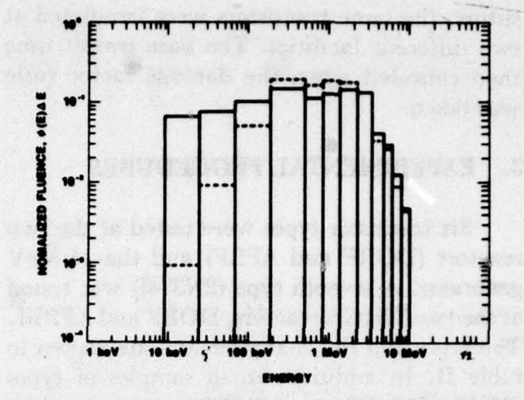


**Figure 2. Neutron spectra at Diamond Ordnance Radiation Facility (—) and Army Pulse Reactor Facility (--).**

**TABLE I. CALCULATED DAMAGE EQUIVALENT RATIOS FOR NEUTRON ENERGY SOURCES**

| Source[a] | Ratio | |
|---|---|---|
| | Holmes[b] | Messenger[c] |
| APRF/DORF | 1.17 | 1.13 |
| 14 MeV/DORF | 2.89 | 3.19 |
| 14 MeV/APRF | 2.46 | 2.81 |
| 14 MeV/Cf 252 | 2.12 | 2.12 |
| Cf 252/DORF | 1.36 | 1.50 |
| Cf 252/APRF | 1.16 | 1.32 |
| AFRRI/DORF | 1.00 | 1.00 |
| | 1-MeV equivalence | |
| 14 MeV | 2.50 | 3.23 |
| Cf 252 | 1.18 | 1.52 |
| APRF | 1.02 | 1.15 |
| DORF | 0.87 | 1.02 |
| AFRRI | 0.87 | 1.02 |

[a] *APRF = Army Pulse Reactor Facility, Ballistic Research Laboratories, Aberdeen, MD.*
*DORF = Diamond Ordnance Radiation Facility, Harry Diamond Laboratories, Adelphi, MD.*
*14 MeV = 14-MeV neutron generator, Lawrence Livermore Laboratory, Livermore, CA.*
*Cf 252 = Californium 252 fission neutron source, National Bureau of Standards, Gaithersburg, MD.*
*AFRRI = Armed Forces Radiobiology Research Institute, Bethesda, MD.*

[b] *R. R. Holmes, J. P. Mitchell, D. K. Wilson, and W. H. vonOulock, Weapons Effects Studies, II, Radiation Effects on Interceptor Electronics, Bell Telephone Laboratories, Whippany, NJ (October 1970).*

[c] *G. C. Messenger, Displacement Damage in Silicon and Germanium Transistors, IEEE Trans. Nucl. Sci., 12 (April 1965).*

sistors, the same transistors were irradiated at two different facilities. The base transit time then canceled when the damage factor ratio was taken.

## 3. EXPERIMENTAL PROCEDURES

Six transistor types were tested at the two reactors (DORF and APRF) and the 14-MeV generator. A seventh type (2N3741) was tested at the two TRIGA reactors, DORF and AFRRI. The types and the characteristics are shown in table II. In addition, small samples of types 2N930, 2N1486, and 2N3055 were tested at NBS. The various combinations of exposures are listed in table III. For example, devices numbered 11 to 20 (second sequence) were exposed twice to 14-MeV neutrons, twice at DORF, then twice more to 14-MeV neutrons, and finally twice at DORF.

All transistors were characterized by using a Teradyne T-241 automated transistor tester, a Tektronix type 576 curve-tracer, and a Hewlett-Packard vector voltmeter to obtain transit time. Table IV lists the average initial gains and the average base transit times for each sample lot.

Exposures at the three reactor facilities were in air adjacent to the periphery of the respective cores. The reactors were operated in the steady-state mode, as opposed to being pulsed. This mode assures consistency in the spectrum since different fluence levels are obtained by adjusting exposure time rather than position. The samples were mounted on Styrofoam holders, and no bias voltages were applied to the devices during the exposures. After the exposures, no measurements were made for at least 1 hour to allow the annealing to stabilize. Sulfur dosimeters were used during each exposure to obtain the neutron fluence. The fluences above 10 keV were then obtained from the results of reactor mapping programs, during which the plutonium-to-sulfur ratios

**TABLE II. TRANSISTOR TYPES AND CHARACTERISTICS USED IN EQUIVALENT DAMAGE TESTS**

| Type | Power (W) | Gain-bandwidth product (MHz) | Collector current (max) (A) |
|---|---|---|---|
| 2N2857 | 0.20 | 1900[a] | 0.040 |
| | | 1000[b] | |
| 2N2222 | 0.50 | 250[c] | 0.80 |
| 2N930 | 0.30 | 30[c] | 0.030 |
| | | 120[b] | |
| 2N5320 | 10[d] | 50[c] | 2.0 |
| 2N1486 | 25[d] | 1.20 | 3.0 |
| | 1.7 | 0.60[b] | |
| 2N3055 | 115[d] | 0.010[c,e] | 15.0 |
| | 6.0 | 0.80[b] | |
| 2N3741 | 25 | 4[c] | 1.0 |

[a] *Maximum.*
[b] *Minimum (JAN).*
[c] *Minimum.*
[d] *Infinite heat sink.*
[e] *Common-emitter cutoff frequency.*

TABLE III. SEQUENCE OF EXPOSURES TO TRANSISTOR LOTS

| Test sequence | Lot No. | Device No. | Facility (No. of exposures)[a] | | | |
|---|---|---|---|---|---|---|
| First | 1 | 1 to 10 | APRF (2) | 14 MeV (1) | APRF (2) | |
| (2N2857, | 2 | 11 to 20 | DORF (2) | 14 MeV (1) | DORF (2) | |
| 2N2222, | 3 | 21 to 30 | 14 MeV (3) | DORF (1) | | |
| 2N930) | 4 | 31 to 40 | 14 MeV (1) | DORF (1) | | |
| | 5 | 41 to 50 | 14 MeV (1) | APRF (2) | | |
| | 6 | 51 to 60 | DORF (2) | APRF (3) | DORF (2) | |
| Second | 7 | 1 to 10 | 14 MeV (4) | | | |
| (2N930, | 8 | 11 to 20 | 14 MeV (2) | DORF (2) | 14 MeV (2) | DORF (2) |
| 2N5320, | 9 | 21 to 30 | 14 MeV (2) | APRF (2) | 14 MeV (2) | APRF (2) |
| 2N1486) | 10 | 31 to 40 | DORF (4) | | | |
| | 11 | 41 to 50 | APRF (4) | | | |
| Third | 12 | 1 to 5 | DORF (2) | 14 MeV (2) | DORF (2) | |
| (2N3055) | 13 | 11 to 15 | APRF (2) | 14 MeV (2) | APRF (2) | |
| | 14 | 16 to 20 | APRF (4) | | | |
| | 15 | 21 to 25 | 14 MeV (2) | DORF (2) | | |
| Fourth | 16 | 1 to 10 | DORF (4) | AFRRI (2) | | |
| (2N3741) | 17 | 11 to 20 | DORF (4) | AFRRI (2) | | |
| | 18 | 21 to 30 | DORF (4) | AFRRI (2) | | |

[a] *APRF* = *Army Pulse Reactor Facility, Ballistic Research Laboratories, Aberdeen, MD.*
*14 MeV* = *14-MeV neutron generator, Lawrence Livermore Laboratory, Livermore, CA.*
*DORF* = *Diamond Ordnance Radiation Facility, Harry Diamond Laboratories, Adelphi, MD.*
*AFRRI* = *Armed Forces Radiobiology Research Institute, Bethesda, MD.*

TABLE IV. AVERAGE INITIAL GAINS AND AVERAGE BASE TRANSIT TIMES FOR TRANSISTOR LOTS

| Lot[a] No. | Gain | Base transit time | Gain | Base transit time | Gain | Base transit time |
|---|---|---|---|---|---|---|
| | 2N2857 | | 2N2222 | | 2N930 | |
| | (at 5 mA) | ($\times 10^{-12}$ s) | (at 10 mA) | ($\times 10^{-12}$ s) | (at 6 mA) | ($\times 10^{-12}$ s) |
| 1 | 110 | 64 | 140 | 345 | 300 | 855 |
| 2 | 114 | 62 | 143 | 341 | 296 | 864 |
| 3 | 114 | 65 | 115 | 378 | 327 | 795 |
| 4 | 106 | 65 | 150 | 322 | 297 | 810 |
| 5 | 76 | 85 | 110 | 355 | 291 | 850 |
| 6 | 110 | 65 | 144 | 356 | 305 | 815 |
| | 2N930 | | 2N5320 | | 2N1486 | |
| | (at 3 mA) | ($\times 10^{-12}$ s) | (at 100 mA) | ($\times 10^{-11}$ s) | (at 100 mA) | ($\times 10^{-9}$ s) |
| 7 | 317 | 740 | 140 | 127 | 107 | 163 |
| 8 | 324 | 740 | 143 | 112 | 108 | 158 |
| 9 | 257 | 790 | 136 | 131 | 86.4 | 155 |
| 10 | 266 | 800 | 137 | 125 | 82.2 | 170 |
| | 2N3741 | | | | | |
| | (at 500 mA) | ($\times 10^{-9}$ s) | | | | |
| 16 | 61.4 | 3.93 | | | | |
| 17 | 52.5 | 3.67 | | | | |
| 18 | 55.1 | 2.84 | | | | |

[a]*No data for lots 12 to 15.*

were measured. Neutrons with energies below 10 keV are considered insignificant in the damage curves; 10 keV is a convenient cutoff energy because of the large increase in capture cross section for plutonium at this energy.

Exposures at the 14-MeV generator also were in air 3.5 cm in front of the tritium target. To assure a uniform exposure, the devices and the dosimeters were mounted at the edge of a plastic disk 15 cm in diameter and 0.6 cm thick, which was rotated in the 14-MeV neutron field.

Exposures at the Californium 252 source were made in air at precisely measured distances from the source. No dosimetry was needed since this source is used as a standard.

## 4. NEUTRON DOSIMETRY

Fluence measurements were made for all irradiations at the 14-MeV generator, in the exposure room at the DORF TRIGA and AFRRI TRIGA reactors, and at the fast-burst reactor (APRF). No dosimetry was done at the Californium 252 source. This source is used as a standard and is well mapped. Rather than use of dosimetry, precise measurements are made between the source and the transistor chip.

The reaction $^{19}F(n,2n)^{18}F$ was used to monitor the 14-MeV generator irradiations. Actually, the energy was approximately 14.3 MeV, and a cross section of $58 \pm 3$ mb was used for the reaction. This comes about since the neutron energy varies as a function of the angle relative to the deuterium beam axis and varies from 14.9 MeV at 0 deg to 13.4 MeV at 180 deg. The samples were located at 75 deg to the incident beam direction.

Teflon ($CF_2$) in the form of a disk 0.31 cm thick was used as the source of $^{19}F$ to monitor the 14-MeV irradiations. When the Teflon is irradiated with neutrons having energies in excess of 10 MeV, the monoisotope $^{19}F$ undergoes an (n,2n) reaction to produce 110-min half-life $^{18}F$. The $^{18}F$ is a positron emitter. The positron is annihilated in adjacent matter, and two 0.511-MeV gamma rays are emitted in coincidence in opposite directions. These gamma rays were detected by a coincidence counter by counting scintillations from face-to-face sodium iodide crystals when the positrons were annihilated in Lucite between the crystals.[6] The Lucite also served to accurately position either a Teflon dosimeter or a calibration source between the crystals.

To calibrate the position counter, an NBS certified $^{22}Na$ source was mounted in a Lucite disk 2 cm thick between the sodium iodide crystals. The $^{22}Na$ source emitted in coincidence a 1.274-MeV gamma ray and a positron. On a nanosecond time scale, the resulting annihilation radiation was in coincidence with the 1.274-MeV gamma ray.

Neutron fluence measurements above 10 keV at the reactors were based on methods developed by Hurst et al.[14] The fluence in each irradiation was directly measured with the $^{32}S(n,p)^{32}P$ reaction. This (n,p) reaction had an effective low-energy threshold of 3 MeV. The sulfur fluences were then converted to total fast neutron fluence by multiplication by a previously determined ratio of greater than 10-keV neutrons to greater than 3-MeV neutrons. For irradiations at APRF, the ratio is 7.28; at DORF, the ratio is 7.45; at AFRRI, the ratio is 6.4.

Although passive dosimeters were used for all neutron fluence measurements, three different measuring systems were used. The (n,2n) reaction in fluorine used to monitor 14-MeV neutrons has a different cross section and requires a different radioactivity detection system

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[6] *J. M. McKenzie, Method to Determine the Relative Damage Produced in Semiconductors by Different Neutron Sources, Sandia Laboratories, Albuquerque, NM, SC-M-72 0133 (February 1972).*

[14] *G. S. Hurst, J. A. Harter, P. M. Hensley, W. A. Mills, M. Slater, and P. W. Reinhardt, Techniques of Measuring Neutron Spectra with Threshold Detectors, Rev. Sci. Instrum., 27 (1956), 153.*

than the (n,p) reaction in sulfur, used as the monitor at DORF, AFRRI, and APRF. Furthermore, in the reactor measurements, the beta radioactivity of the sulfurs was evaluated on separate counting systems, each calibrated in a different manner. All of these differences manifest themselves as uncertainties in the data.

The neutron fluence measurements are the abscissas of graphs that depict changes in the electronic parameters with radiation. Accordingly, bias errors associated with different methods or different calibrations directly affect the relative damage observed among these neutron fields. In particular, when parameter degradation is a linear function of fluence, the slope of the line is changed by these errors. Such a change can lead to an incorrect estimate of the ability of the neutron field to create damage. Therefore, there is a direct correlation between the uncertainty of sulfur-monitored fluences and the relative amounts of damage induced during irradiation testing in the four non-14-MeV neutron fields, even though those fields were supposedly correlated with precise 14-MeV dosimetry with careful electronic measurements.

Table V lists the uncertainties assigned to the dosimetry at the reactors and the 14-MeV generator and the uncertainties assigned to device measurements. These were then used for deduction of the resultant uncertainties in the damage factors obtained from data at either reactor or the 14-MeV source and the uncertainties in the ratios of relative damage factors.

## 5. RESULTS

Figures 3 through 17 show typical data from which the damage factors were obtained. These curves were corrected for damage as a result of a high gamma radiation content in the

**TABLE V. ASSIGNED UNCERTAINTIES**

| Measurement | Uncertainty (± %) |
|---|---|
| Reactor dosimetry | |
| Cross section | 10 |
| Neutron spectra | 15 |
| Neutron spectra (calibration) | 7 |
| Reproducibility | 8 |
| 14-MeV dosimetry | |
| Cross section | 5 |
| Reproducibility | 3 |
| Device measurements | |
| $h_{FE}$ | 2 |
| $\Delta \frac{1}{h_{FE}}$ (av) | 8 |
| Damage factor | |
| Reactor | 24 |
| 14-MeV generator | 10 |
| Equivalence ratio | |
| Reactor to reactor | 34 |
| 14-MeV generator to reactor | 26 |
| Reactor to reactor (relative to 14-MeV generator data) | 15 |

DORF radiation environment. It has been shown that neutron (n) and gamma ($\gamma$) damage can be added as[15,*]

$$\Delta \frac{1}{h_{FE(n+\gamma)}} = \Delta \frac{1}{h_{FE(n)}} + \Delta \frac{1}{h_{FE(\gamma)}} . \quad (2)$$

The higher frequency transistors showed significant degradation at the gamma doses associated with the particular neutron fluence. The required corrections were 8 percent for the 2N2222 transistors and 30 percent for the 2N2857 transistors. The other transistors needed no correction. The APRF, 14-MeV generator, and Californium 252 gamma fields were significantly less than those at DORF and AFRRI, and no corrections were required.

The data shown in figures were not corrected for differences in base transit time, and the spread, as shown by the vertical bars, is large for some devices, on the order of ±20 percent. The vertical bars reflect one-sigma variations about the average value of $\Delta 1/h_{FE}$. When the data were normalized for base transit time, this variation was reduced to 5 to 8 percent. Figures 13 and 14 show examples of this reduction.

Although the annealing was allowed to stabilize for 1 hour after irradiation before measurements were made, some annealing took place thereafter. Over 1 or 2 weeks (the maximum time between exposures at two different facilities), this extra annealing may amount to 3 or 4 percent. Corrections were made for this extra annealing although it did not affect the damage factor. Figures 4 to 6 show an example of this.

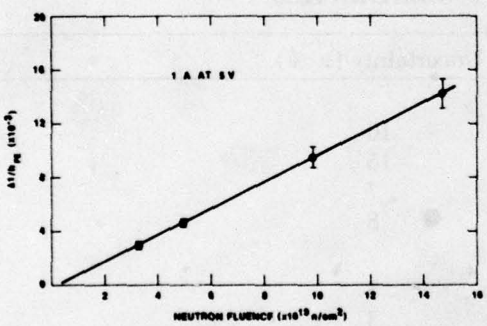


**Figure 3. Damage curve of transistor type 2N3055 at Californium 252 source.**

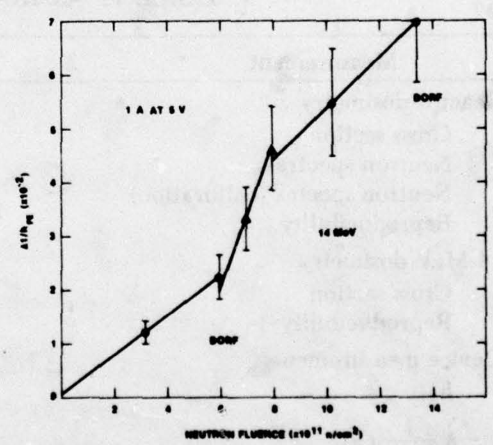


**Figure 4. Damage curves of transistor type 2N3055 at TRIGA reactor (●) and 14-MeV neutron generator (▲).**

[15]*B. D. Shafer and R. A. Burghard, Evaluation of Combined Radiation Effects to Transistors, Sandia Laboratories, Albuquerque, NM (July 1971).*

**P. A. Trimmer and D. Bassett, Combined Neutron and Gamma Effects at DORF, Harry Diamond Laboratories, R-280-75-1 (January 1975).*

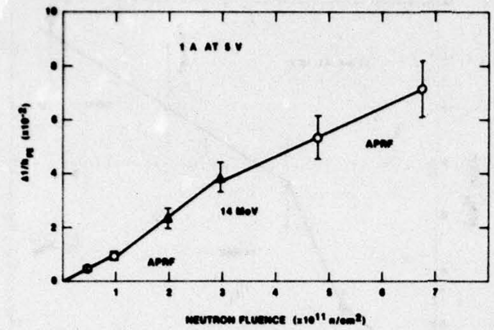


**Figure 5. Damage curves of transistor type 2N3055 at fast-burst reactor (○) and 14-MeV neutron generator (▲).**

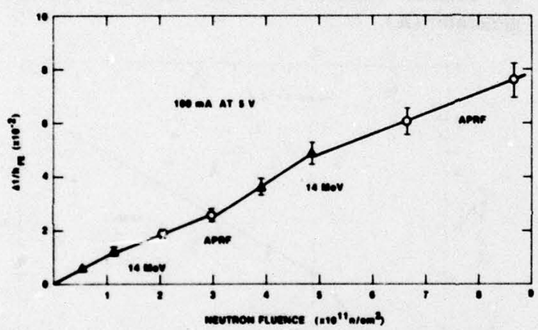


**Figure 6. Damage curves of transistor type 2N1486 at fast-burst reactor (○) and 14-MeV neutron generator (▲).**

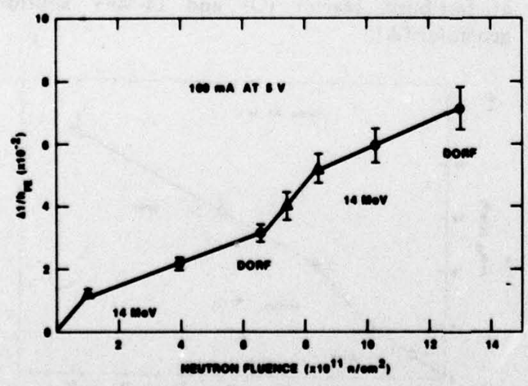


**Figure 7. Damage curves of transistor type 2N1486 at TRIGA reactor (●) and 14-MeV neutron generator (▲).**

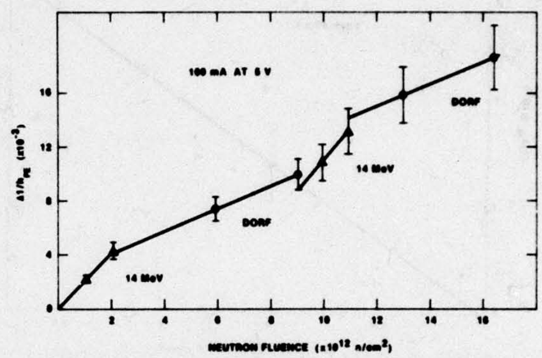


**Figure 8. Damage curves of transistor type 2N5320 at TRIGA reactor (●) and 14-MeV neutron generator (▲).**

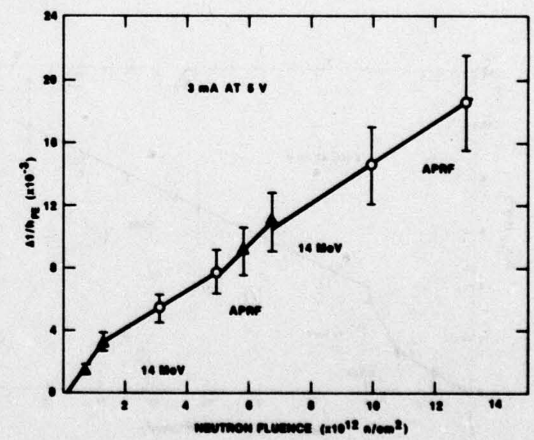


**Figure 9. Damage curves of transistor type 2N930 at fast-burst reactor (○) and 14-MeV neutron generator (▲).**

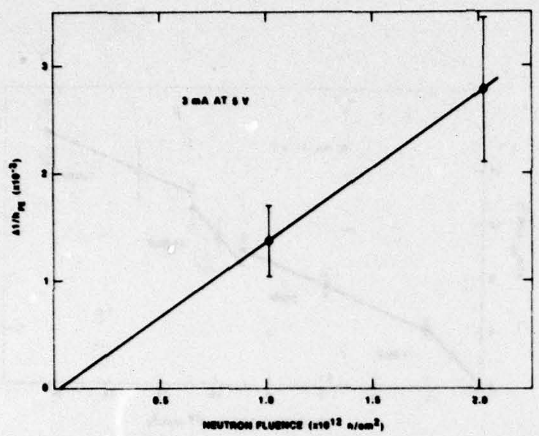


**Figure 10. Damage curve of transistor type 2N930 at Californium 252 source.**

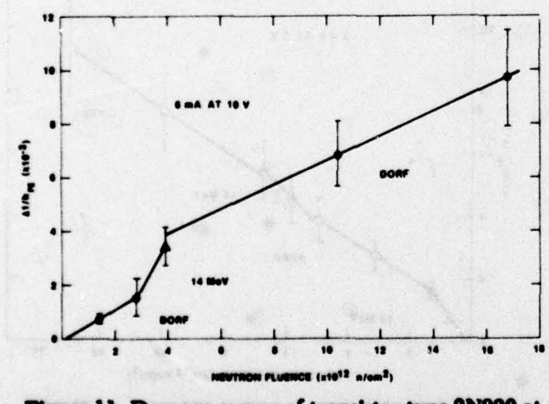


**Figure 11. Damage curves of transistor type 2N930 at TRIGA reactor (●) and 14-MeV neutron generator (▲).**

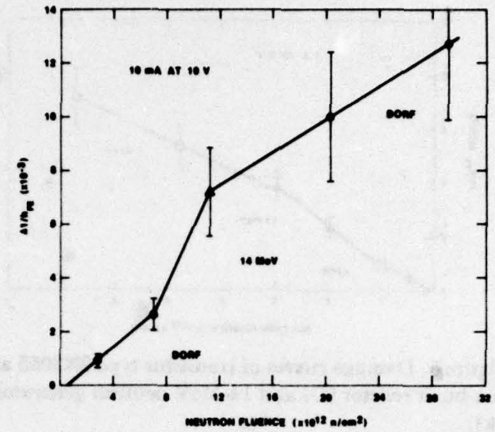


**Figure 12. Damage curves of transistor type 2N2222 at TRIGA reactor (●) and 14-MeV neutron generator (▲).**

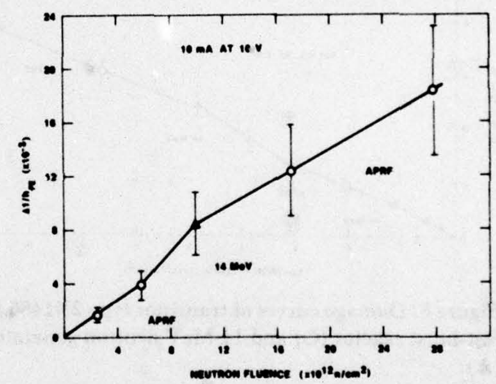


**Figure 13. Damage curves of transistor type 2N2222 at fast-burst reactor (○) and 14-MeV neutron generator (▲).**

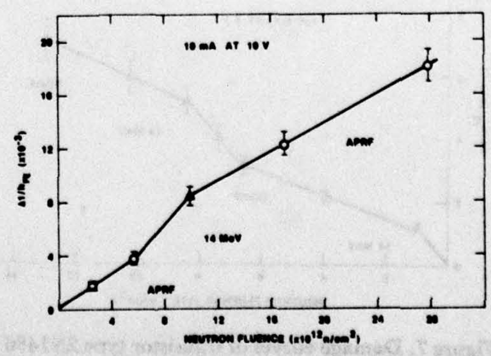


**Figure 14. Damage curves shown in figure 13 with base transit time normalized.**

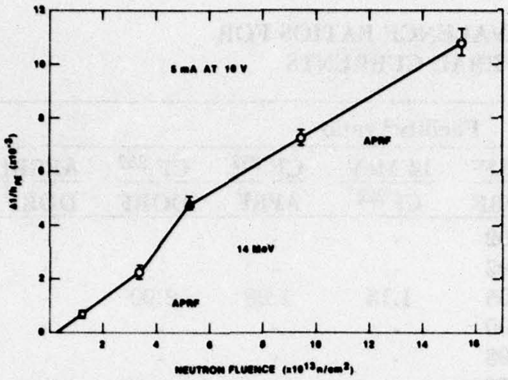


**Figure 15. Damage curves of transistor type 2N2857 at fast-burst reactor (○) and 14-MeV neutron generator (▲).**

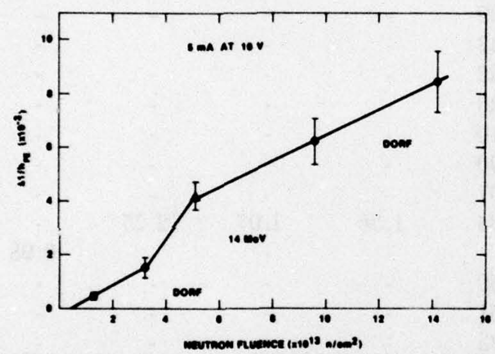


**Figure 16. Damage curves of transistor type 2N2857 at TRIGA reactor (●) and 14-MeV neutron generator (▲).**

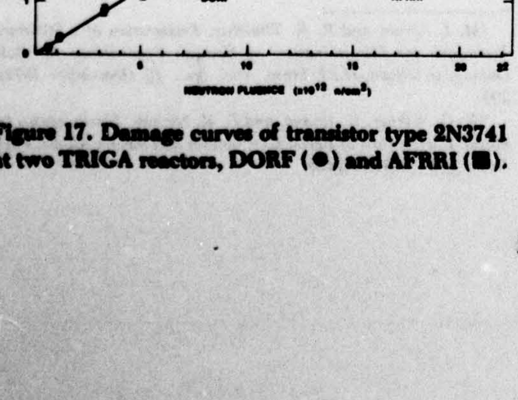


**Figure 17. Damage curves of transistor type 2N3741 at two TRIGA reactors, DORF (●) and AFRRI (■).**

Table VI (p. 16) shows the damage factor ratios for all the transistor types at several different currents. The uncertainties for each ratio are listed at the head of each column. These uncertainties are a combination of several factors as shown in section 4. Dosimetry is the major source of uncertainty, which comes about mainly due to lack of knowledge of the spectra. The final correlation between neutron sources is a ratio of ratios, and therefore the uncertainties propagate and become large.

Another source of uncertainties is in the semiconductor ($h_{FE}$) parameter measurements and the variation in the damage constant found for a transistor by using equation (1). The $h_{FE}$ measurement uncertainty is 2 percent, and the damage constant uncertainty is 8 percent.

## 6. DISCUSSION

The calculated damage ratios (table I) indicate that DORF and APRF should be about equal. However, the data show APRF to be much more damaging per unit fluence. Coppage[3] reports ratios ranging from 1.52 to 2.20 for similar reactors. Our Californium 252 results are interesting in that they indicate that APRF and the Californium 252 source are about equal. The calculated 1-MeV equivalences of the two sources are nearly equal by Holmes' curve. Since the Californium 252 spectrum is well known relative to the DORF spectrum, this calculation implies that the DORF spectrum is softer than originally thought. The ratio of 14-MeV generator to Californium 252 source is lower than expected and appears to get lower for the higher power transistors. Also, the ratio of 14-MeV generator to APRF is lower than calculated, whereas the ratio of 14-MeV generator to DORF is high for the low-power or high-frequency 2N2857, 2N2222, and 2N930 and low for the 2N5320 and 2N1486. The 2N3055 ratio is about right.

[3]*F. N. Coppage, Experimental Neutron Damage Equivalences Utilizing Device Parameters, IEEE Trans. Nucl. Sci., 20 (December 1973), 349.*

## TABLE VI. DAMAGE EQUIVALENCE RATIOS FOR TRANSISTORS AT SEVERAL CURRENTS

| Transistor type | Current (mA) | Facility[a] ratio | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 14 MeV[b] / APRF | 14 MeV[b] / DORF | APRF[c] / DORF | 14 MeV / Cf 252 | CF 252 / APRF | CF 252 / DORF | AFRRI / DORF |
| 2N930 | 0.01 | 1.55 | 3.13 | 2.02 | - | - | - | - |
| | 1 | 1.60 | 3.07 | 1.92 | - | - | - | - |
| | 3 | 1.79 | 3.67 | 2.05 | 1.75 | 1.06 | 2.00 | - |
| | 6 | 1.73 | 3.46 | 2.00 | - | - | - | - |
| | 10 | 1.64 | 3.24 | 1.98 | - | - | - | - |
| 2N1486 | 1 | 1.49 | 2.50 | 1.68 | - | - | - | - |
| | 10 | 1.55 | 2.56 | 1.65 | - | - | - | - |
| | 100 | 1.51 | 2.84 | 1.88 | 1.45 | 1.05 | 1.94 | - |
| 2N2222 | 0.01 | 1.33 | 3.30 | 2.49 | - | - | - | - |
| | 1 | 1.41 | 3.23 | 2.29 | - | - | - | - |
| | 10 | 1.52 | 3.54 | 2.33 | - | - | - | - |
| | 50 | 1.49 | 3.46 | 2.32 | - | - | - | - |
| 2N2857 | 0.01 | 1.82 | 4.11 | 2.26 | - | - | - | - |
| | 1 | 1.79 | 3.77 | 2.10 | - | - | - | - |
| | 5 | 1.97 | 3.72 | 1.90 | - | - | - | - |
| | 10 | 1.79 | 3.70 | 2.07 | - | - | - | - |
| 2N3055 | 1000 | 1.65 | 3.04 | 1.84 | 1.36 | 1.07 | 2.25 | - |
| 2N3741 | 500 | - | - | - | - | - | - | 0.98 |
| 2N5320 | 1 | 1.57 | 2.50 | 1.59 | - | - | - | - |
| | 10 | 1.57 | 2.53 | 1.61 | - | - | - | - |
| | 100 | 1.49 | 2.72 | 1.83 | - | - | - | - |

[a] *14 MeV* = *14-MeV neutron generator, Lawrence Livermore Laboratory, Livermore, CA.*
*APRF* = *Army Pulse Reactor Facility, Ballistic Research Laboratories, Aberdeen, MD.*
*DORF* = *Diamond Ordnance Radiation Facility, Harry Diamond Laboratories, Adelphi, MD.*
*Cf 252* = *Californium 252 fission neutron source, National Bureau of Standards, Gaithersburg, MD.*
*AFRRI* = *Armed Forces Radiobiology Research Institute, Bethesda, MD.*

[b] *±26% uncertainty.*

[c] *±34% uncertainty.*

The results of the tests compared with the calculation can be interpreted two ways. (1) The DORF spectrum is softer than indicated and the 14-MeV neutrons are not quite as damaging as predicted. (2) The APRF and the Californium 252 source are harder than indicated. The first alternative is the more likely since the Californium 252 spectrum and similarly the APRF spectrum are well known. For the DORF spectrum to be softer than thought is not hard to rationalize since considerable scattering is involved. The 14-MeV generator damage equivalence is not so easy, however. Wikner et al[16] reported a 14-MeV generator/TRIGA ratio of approximately 2.2 for minority carrier lifetime degradation in silicon. This number is also lower than calculated in table I. Green and Thatcher[3] also

[3] *M. L. Green and R. K. Thatcher, Preparation of a Standard Technique for Determination of Neutron Equivalence for Bulk Damage in Silicon, IEEE Trans. Nucl. Sci., 19 (December 1972), 200.*

[16] *E. G. Wikner, H. Houye, and D. K. Nichols, Elastic versus Inelastic Energy Loss of Recoil Germanium and Silicon Atoms, Phys. Rev., 136 (1964), A1428.*

reported a fission-to-fusion ratio (1.7) that was lower than calculated.

Van Antwerp and Youngblood[17] have reported results that show considerable change in damage cross section for small changes in neutron energy near 1 MeV. For example, a 1.630-MeV neutron is more damaging than a 14-MeV neutron, whereas a 1.157-MeV neutron is much less damaging. Therefore, small differences in the fluence at critical energies could cause differences in the damage to transistors even though the total fluence were the same. One would expect the differences to average out, however.

Table VII compares the low current ratios and the high current ratios as listed in table VI. Some of the ratios in table VII are greater than 1, and some are less, with no apparent trend. Therefore, it appears that the damage equivalence ratios are not a function of current.

[17] *W. R. van Antwerp and J. E. Youngblood, Calculated and Measured Displacement Damage in Silicon for Monoenergetic Neutrons, IEEE Trans. Nucl. Sci., 24 (1977), 2521.*

## 7. CONCLUSION

Seven types of silicon transistors were tested at four different neutron sources so that the damage equivalence relationship could be determined between the sources. These sources included a water-moderated reactor (TRIGA), a bare-critical assembly, a 14-MeV generator, and a Californium 252 source. If the Californium 252 source is considered the standard, then the TRIGA and the 14-MeV generator were found to be less damaging than calculated relative to the bare-critical assembly and the Californium 252 source.

The major disagreement with theoretical calculation and the one most important to Army users was the damage equivalence ratio of the two reactors (bare-critical assembly and water-moderated reactor), which was about 2.1 for low-power transistors and about 1.7 for high-power transistors. The predicted equivalence was about 1.1. A possible basis for this disagreement could be the large uncertainties from the cross-section, spectra, reproducibility, and parameter measurements. Another possible basis (not detailed in this report) is that the damage curves are obtained from bulk silicon displacement damage and may not apply directly to transistor damage.

**TABLE VII. RATIOS OF LOW CURRENT RATIOS (TABLE VI) WITH HIGH CURRENT RATIOS FOR TRANSISTORS**

| Type | Ratio of facility[a] ratio | | |
|---|---|---|---|
| | $\frac{\text{Low}}{\text{High}}$ for $\frac{\text{14 MeV}}{\text{APRF}}$ | $\frac{\text{Low}}{\text{High}}$ for $\frac{\text{14 MeV}}{\text{DORF}}$ | $\frac{\text{Low}}{\text{High}}$ for $\frac{\text{APRF}}{\text{DORF}}$ |
| 2N930 | 0.95 | 0.97 | 1.02 |
| 2N1486 | 0.99 | 0.88 | 0.89 |
| 2N2222 | 0.89 | 0.95 | 1.07 |
| 2N2857 | 1.02 | 1.11 | 1.09 |
| 2N5320 | 1.05 | 0.92 | 0.87 |

[a] *14 MeV = 14-MeV neutron generator, Lawrence Livermore Laboratory, Livermore, CA.*
*APRF = Army Pulse Reactor Facility, Ballistic Research Laboratories, Aberdeen, MD.*
*DORF = Diamond Ordnance Radiation Facility, Harry Diamond Laboratories, Adelphi, MD.*

The transistors used in these tests are types of recent interest and cover a frequency range pertinent to today's technology. The reactors produce the very environments used to simulate weapons radiation, and these test results (based on standard device measurements) should be of interest in practical system-hardening applications. Furthermore, the study is, in itself, an inquiry as to how well one can establish damage equivalence between different irradiation environments. The results indicate the need for better dosimetry and detailed investigation of a broader scope of devices, which would include integrated circuits and a wider variety of transistors and diodes.

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