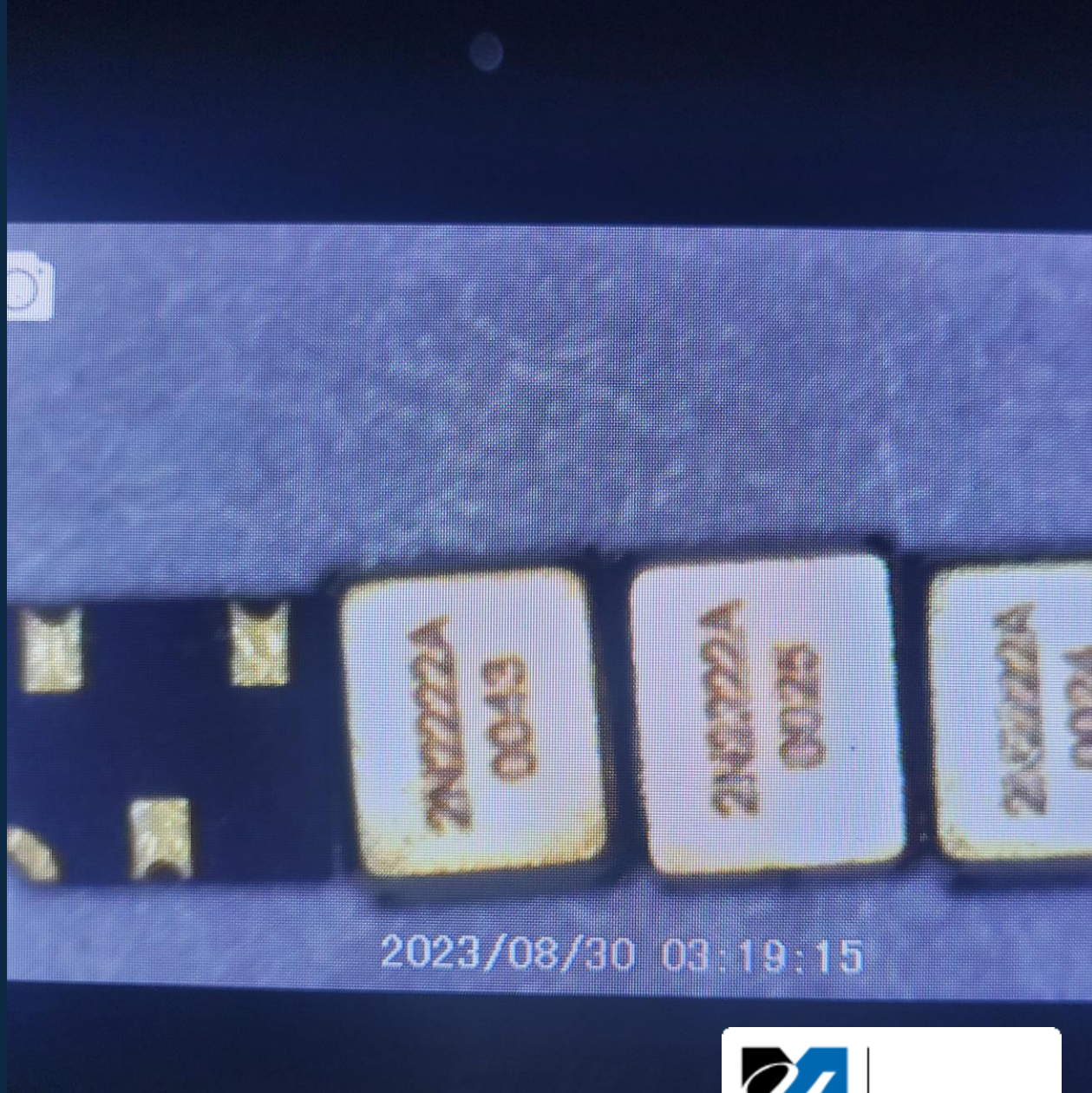


2N2222A and 2N2222AUB Transistors as 1 MeV(Si) Equivalent Neutron Fluence Monitors

Characterization and interfacility validation of transistor gain degradation correlated to 1 MeV (Si eq.) damage

University of Massachusetts Lowell Research Reactor

James Frye, Daniel Gill, and Thomas Regan (presenter)



UML Research Reactor and Fast Neutron Irradiator



Original semiconductor application

Designed to irradiate 12-inch silicon wafers for minority-carrier lifetime control for Fairchild Semiconductor.

Reactor

1 MW thermal
Open-pool MTR plate-fuel design
Licensed in 1974
Renewed in 2022 for 20 years
LAR for 2MW Operations slated for Q1 2027

Fast Neutron Irradiator

Sample capacity: $30 \times 30 \times 15$ cm
1 MeV equivalent flux: approximately 10^{11} n/cm²·s
Fast-to-thermal flux ratio: greater than 4000:1
Neutron-to-gamma ratio: 7×10^9 n/cm² per rad

The FNI provides a predominantly fast-neutron field for displacement-damage testing of electronics. For example, a “typical” $1E12$ 10^{11} n/cm² (1 MeV in Si) the associated gamma (Ionizing Dose) is less than 150 Rad (Si)

Project objective

Establish damage constants for TO-18 and surface-mount 2N2222A populations, then test whether they reproduce independently measured 1 MeV(Si) equivalent neutron fluence across different facilities.

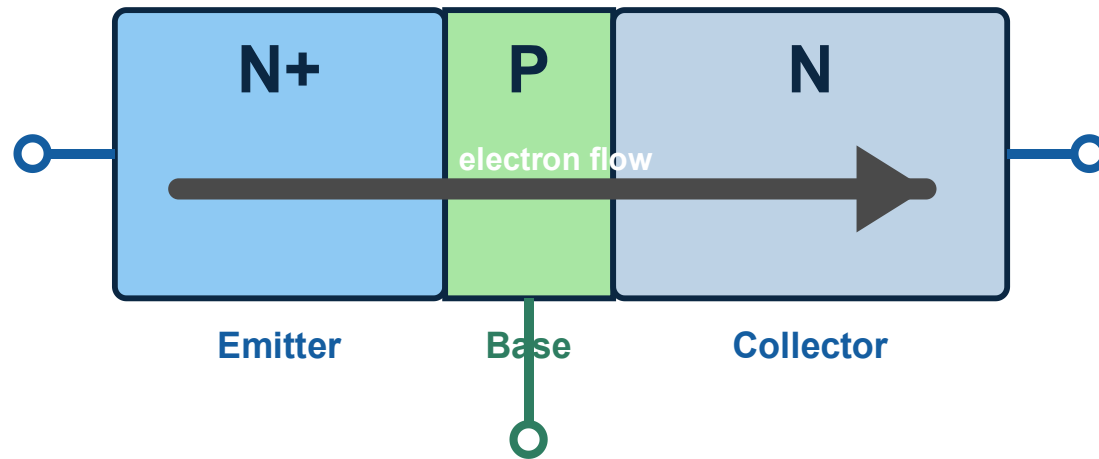
Reference exposure	Device response	Facility check	Broader comparison
SNL ACRR	Change in hFE	UMLRR FNI	Other neutron sources

The TO-18 population provided the tighter reference response. The AUB devices remain a promising compact alternative, but their damage constant requires verification across batches and irradiation geometries.

Reference method: ASTM E1855-20

NPN transistor current gain

NPN bipolar junction transistor



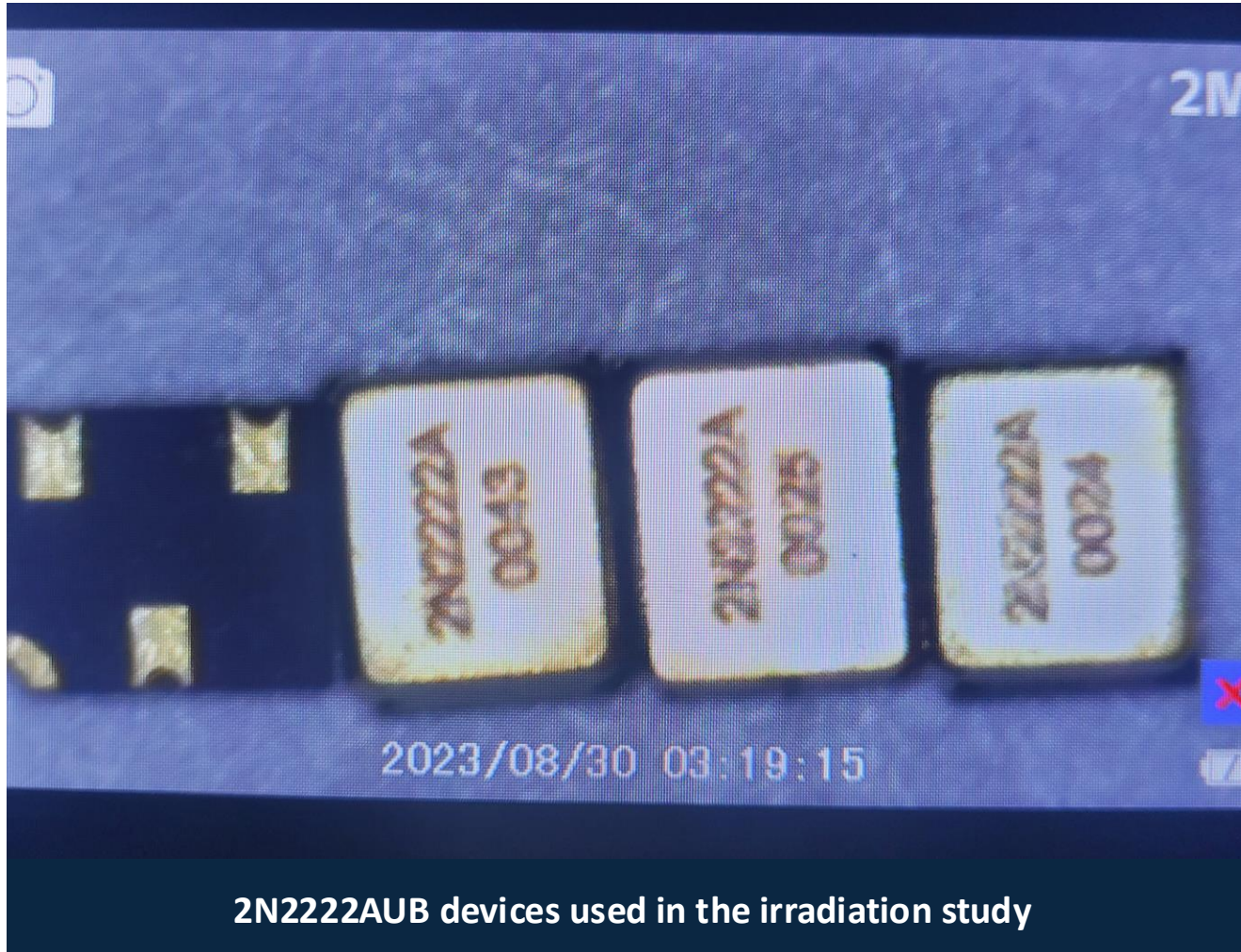
A small base current controls a larger collector current

$$I_C \approx h_{FE} \times I_B$$

Fast-neutron displacement damage creates recombination centers in the silicon. The base current required for the same collector current increases, so h_{FE} decreases.

The measurable quantity is the change in reciprocal current gain.

TO-18 reference and AUB qualification question



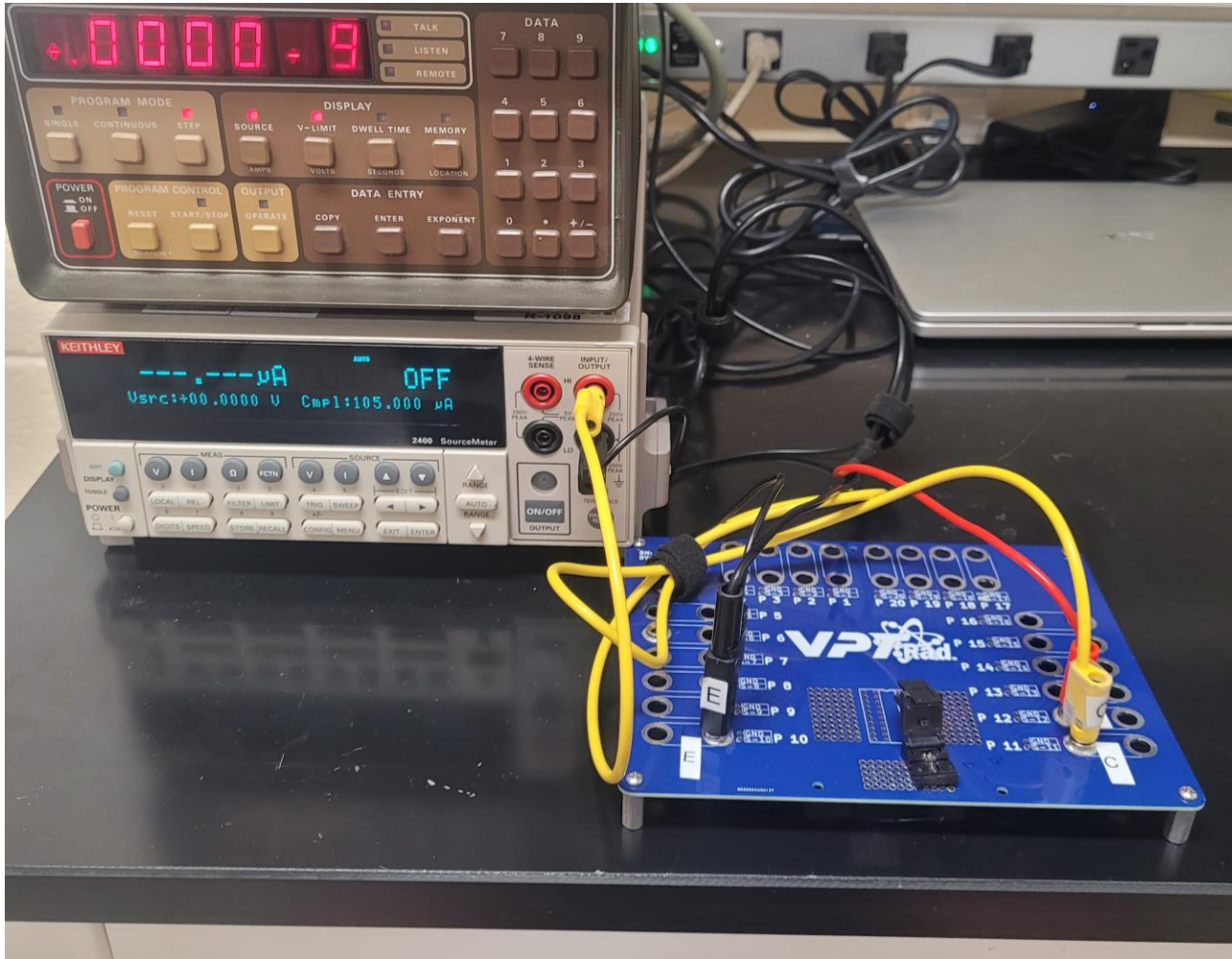
Initial-gain distribution

TO-18 devices showed a 15.1% initial-gain range. The AUB population showed a 37.3% range and distinguishable batch-dependent damage constants.

Dosimetry role

The TO-18 devices provide the reference response. AUB devices offer a smaller package and lower annealing recovery, but require confirmation that one damage constant transfers between production batches.

Initial characterization and device traceability



300 devices

150 metal-can 2N2222A

150 surface-mount 2N2222AUB

Permanent device identification

The manufacturer laser-marked each DUT with a unique identifier. Individual devices must remain traceable through baseline measurement, irradiation, annealing, and post-test hFE measurement.

180 °C recovery anneal

Before UMLRR validation, selected devices were annealed at 180 °C for 24 hours and measured after cooling. Durable laser identification preserved device-level traceability.

TO-18 devices provided the tighter baseline population; AUB variability remained measurable by batch.

Reference irradiation and annealing

Completed reference exposure

Sandia National Laboratories ACRR

**Target: 1×10^{13} n/cm², 1 MeV(Si) equivalent
SNL nickel and sulfur dosimetry uncertainty:
4.5%**

Post-exposure annealing

TO-18 and selected AUB groups were annealed at 80 °C for 2 hours before final gain measurements. The AUB population recovered approximately 5% on average, compared with about 30% expected for TO-18 devices.

Previous work utilizing this test method found the device identification and marking were difficult due the annealing conditions needed to “re-set” the transistors recovering a portion of the induced damage from the neutron irradiation.



Controlled-temperature furnace used for device conditioning

Measured damage constants

Reciprocal gain change

$$1/h_{FE} - 1/h_{FE,0} = K\tau \Phi 1 \text{ MeV(Si)}$$

TO-18 reference

$K = 1.34 \pm 0.08$
 $\times 10^{-15} \text{ cm}^2/\text{n}$
11% below ASTM nominal

AUB batch 1

$K = 1.24 \pm 0.08$
 $\times 10^{-15} \text{ cm}^2/\text{n}$
17% below ASTM nominal

AUB batch 2

$K = 1.07 \pm 0.07$
 $\times 10^{-15} \text{ cm}^2/\text{n}$
29% below ASTM nominal

ASTM nominal $K \approx 1.50 \times 10^{-15} \text{ cm}^2/\text{n}$. Reported uncertainties are one standard deviation.

Combined measurement uncertainty

1

SNL reference fluence

Nickel and sulfur dosimetry standard deviation: 4.5%

2

Damage-constant scatter

TO-18: 3.94% AUB: 4.46%

3

Collector-current effect

Approximately 1.0%; source-meter accuracy is negligible

4

Combined standard uncertainty

TO-18: 6.1% AUB: 6.4%

Root-sum-square

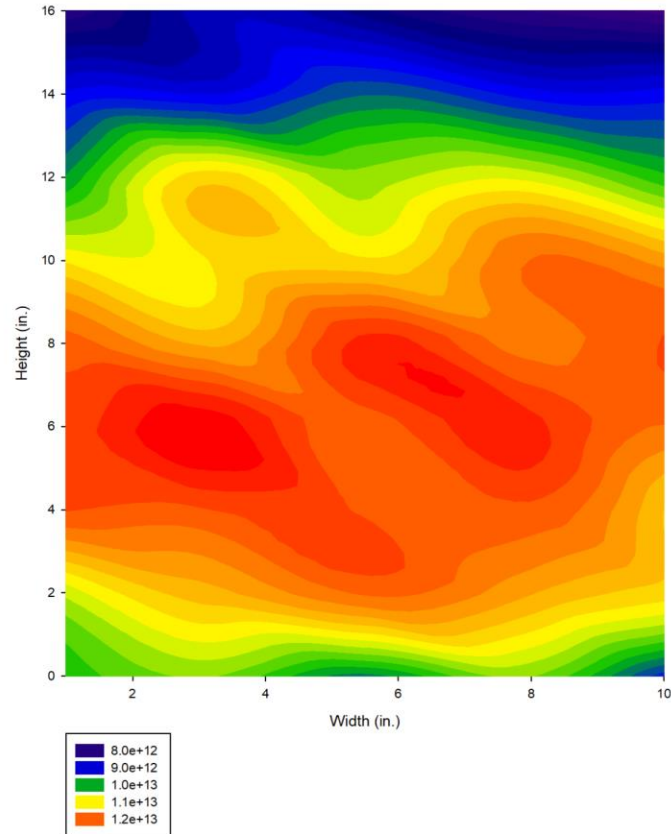
$$\sigma_{\text{total}} = \sqrt{(\sigma_{\Phi}^2 + \sigma_{\text{stat}}^2 + \sigma_{\text{current}}^2)}$$

The SNL fluence and device-population scatter dominate the total.

Values represent one standard deviation. No coverage factor has been applied.

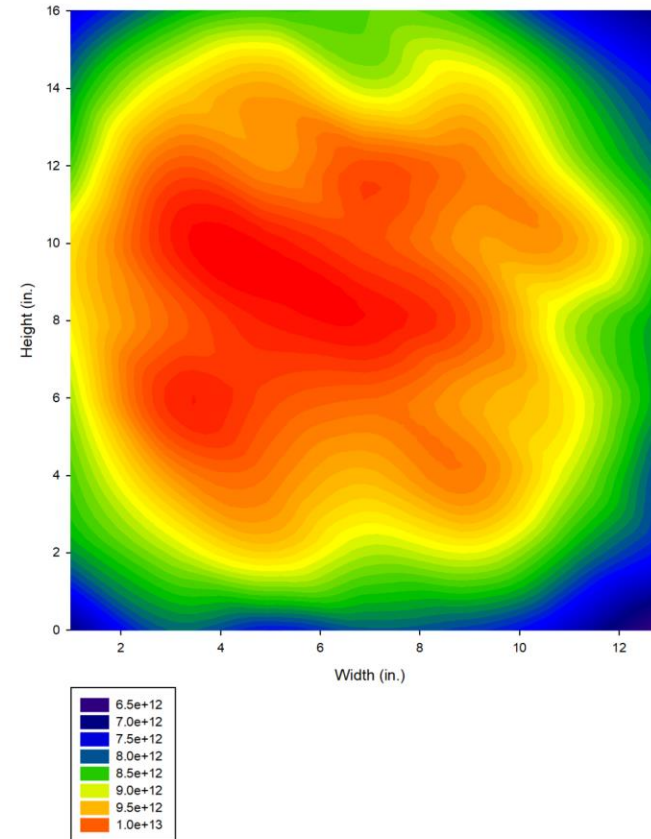
FNI fast-neutron field

FNI Heat Map (Front)



Front

FNI Heat Map (Back)



Back

34%

TO-18
measured
flux decrease

The transistor result follows the field broadening from the inner to outer irradiation position.

MCNP predicted a 36% decrease, only two percentage points above the TO-18 measurement. MIL-STD-883/750 TM1017 allows for a generous $\pm 20\%$ divergence from the targeted exposure level

Beamport fast-neutron profile

A second UMLRR irradiation location provides a substantial fast-neutron field at a much lower rate than the FNI.

Normalized flux at 1 MW (10^8 n/cm²·s)

Beamport dosimeter	Normalized flux at 1 MW
Position 1	7.62×10^8 n/cm ² ·s
Position 2	6.74×10^8 n/cm ² ·s
Position 3	6.84×10^8 n/cm ² ·s

Test conditions

900 kW reactor power
14,040 s irradiation
Three transistor dosimeters

Measured profile

Mean fluence: 8.93×10^{12} n/cm²
Mean flux at 900 kW: 6.36×10^8 n/cm²·s
Normalized flux at 1 MW: 7.07×10^8 n/cm²·s
Relative scatter: 6.8%

The beamport extends the characterized UMLRR range to a flux approximately 140 times lower than the nominal FNI field.

Repeat UMLRR validation against sulfur dosimetry

A repeat FNI irradiation tested whether the batch-1 AUB damage constant transferred to a second AUB population.

Average discrepancy in repeat UMLRR irradiation (%)

Dosimetry comparison	Average discrepancy
TO-18 versus sulfur-32	5.4%
AUB versus sulfur-32	4.2%
TO-18 versus AUB	1.2%

Average fluence

Sulfur-32: $1.10 \times 10^{13} \text{ n/cm}^2$

TO-18: $1.14 \times 10^{13} \text{ n/cm}^2$

AUB: $1.13 \times 10^{13} \text{ n/cm}^2$

Agreement

TO-18 versus sulfur: 5.4%

AUB versus sulfur: 4.2%

TO-18 versus AUB: 1.2%

The repeat run supports $K = 1.24 \times 10^{-15} \text{ cm}^2/\text{n}$ for the tested AUB batch, while earlier batch variation remains part of the qualification question.

AFRRI second-source validation

The Armed Forces Radiobiology Research Institute reactor provided an independent neutron field to test transferability beyond the SNL baseline.

Exposure configuration

Exposure Room 1 lead-cave configuration

Reactor power: 200 kW

Experiment position: 70 cm

Transistor target: 1×10^{13} n/cm²

Independent dosimetry

Sulfur activation measurements were converted to 1 MeV(Si)-equivalent fluence using the AFRRI MCNP spectrum model.

Reported 1 MeV(Si) benchmark

$$6.04 \times 10^9$$

n/cm²·s measured silicon-equivalent flux

AUB location

$$1.04 \times 10^{13} \text{ n/cm}^2$$

This second-source irradiation provided an additional benchmark for the transistor method and for AFRRI's experimental and computational models.

Expanding irradiation-rate requirements

The required neutron exposure rate is moving in opposite directions for different user communities.

Lower flux

Electronics users increasingly request lower exposure rates to reproduce low-rate environments and provide finer control of accumulated fluence.

Challenge: extend the characterized field to lower rates without losing dosimetric accuracy.

Intense neutron fields

Electronics intended for fusion reactor systems require high-flux, high-fluence testing to determine whether response saturation or cumulative neutron damage causes functional failure.

Challenge: provide sufficiently intense sources with representative spectra and defensible dosimetry.

A transferable transistor dosimetry method helps compare facilities across this widening range of exposure conditions.

Follow-on cross-particle validation

Use the same characterized 2N2222AUB dosimeters to test whether NIEL scaling remains consistent across neutron energy and particle type.

1 MeV(Si)

Reference neutron damage

Established transistor baseline

14 MeV

D-T fusion neutrons

Contrast monoenergetic fusion-
neutron response

20–70 MeV

Protons

Correlate proton displacement
damage in silicon

Cost connection

Direct proton testing is expensive. A validated neutron-to-proton NIEL correlation could support lower-cost screening before final proton qualification.

Acceptance challenge

Some European programs require direct proton evidence or testing aligned with where systems will operate and may not accept NIEL equivalence alone.

Current evidence and remaining qualification work

1

Reference calibration completed

SNL established package-specific damage constants and uncertainties

2

UMLRR field independently checked

TO-18 measurements agreed with sulfur dosimetry and MCNP

3

AUB transfer demonstrated once

The repeat UMLRR run produced 4.2% agreement with sulfur dosimetry

4

Additional AUB qualification required

Test more production batches and control stacking and self-shielding geometry

Technical conclusion

The TO-18 is the defensible reference monitor. The AUB is a compact candidate whose transferable damage constant still needs confirmation.

In a recent test, the TO-18 behavior was determined to have been corrupted resulting in a significant increase in apparent measured sensitivity

Next comparisons: AFRRI, additional reactors, D-T fusion neutrons, and 20–70 MeV protons.

Sandia National Laboratories

Annular Core Research Reactor

Reference irradiation and associated dosimetry used to establish the 1 MeV(Si) baseline response of the transistor populations.

Armed Forces Radiobiology Research Institute

Reactor and dosimetry teams

Second-source irradiation, sulfur activation dosimetry, and modeled spectral data used for interfacility validation and as an additional benchmark for AFRRI's experimental and computational models.

The authors gratefully acknowledge both teams for making the interfacility comparison possible.