

NEUTRON-INDUCED FAILURE TESTS OF 3300-V IGBTs FOR THE SPALLATION NEUTRON SOURCE ACCELERATOR*

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Abstract

The RF transmitters for the 1-GeV Spallation Neutron Source (SNS) linear accelerator are powered by 15 converter-modulator stations. Each converter-modulator provides pulses up to 11 MW peak power with a 1.1 MW average power to a multiple-klystron load. A low-voltage switching network, comprised of three sets of four IGBTs in an 'H-bridge' configuration, is used to generate the 20 kHz drive waveform components for the three step-up transformer primaries. This setup brings the total number of 3300-volt semiconductor IGBTs operating within the accelerator at 180. When biased to operating voltages of 1500 V or greater, all IGBTs are inherently sensitive to neutron interactions caused by background cosmic ray radiation.

The project described used neutrons produced by proton spallation (with a similar spectrum as cosmic ray neutrons) to gain knowledge of failure mechanisms of the SNS IGBTs. These tests were performed using the highly accelerated neutron flux generated at the Weapons Neutron Research facility at the Los Alamos National Laboratory.

The results of these experiments have shown the existence of a critical threshold voltage that lies within the operational range beyond which the IGBTs are no longer effective. This threshold varied with each brand of IGBT tested. Statistical failure times have also been projected for all brands of IGBT tested under normal biased operation with the SNS accelerator given natural neutron flux in Oak Ridge, TN.

HIGH POWER IGBTs IN THE SNS ACCELERATOR

The RF transmitters for the 1-GeV Spallation Neutron Source (SNS) linear accelerator are powered by 15 converter-modulator stations. Each converter-modulator provides pulses up to 11 MW peak power with a 1.1 MW average power to a multiple-klystron load, as required for the acceleration of the beam.

A low-voltage switching network, comprised of three sets of four Insulated-Gate Bipolar Transistors (IGBTs) in an 'H-bridge' configuration, is used to generate the 20 kHz drive waveform components for the three step-up transformer primaries in each converter-modulator. This setup brings the total number of IGBTs operating at any time to 180.

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The operation of each of these IGBTs can be interrupted by random collisions with cosmic-ray-produced neutrons when subjected to the high electric field (collector-emitter voltages) required for their operation. Because of the H-Bridge design, conduction of one IGBT caused by random neutron interaction at the time the opposite IGBT is normally conducting will cause a direct discharge of all capacitor bank energy through both IGBTs, causing a disastrous failure, or a 'shoot-through' fault, as shown in Figure 1.

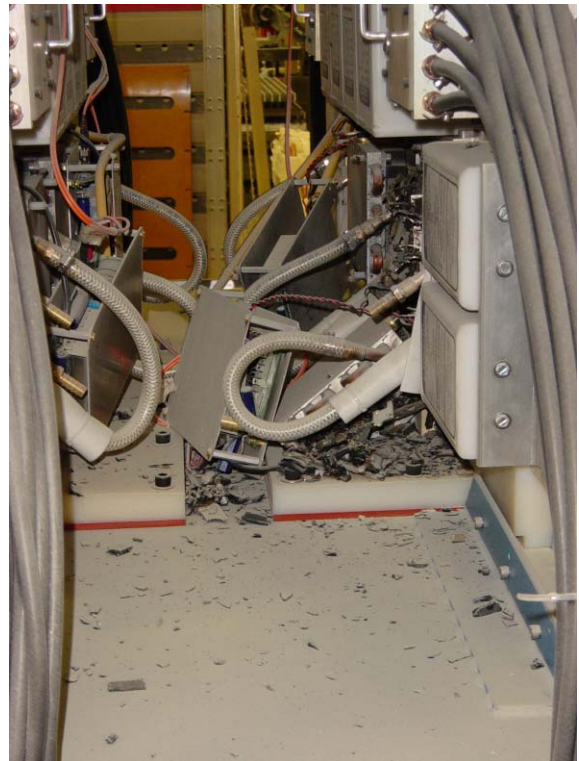


Figure 1: Example of IGBT failure during recent acceptance tests.

Any such interruption will take down the entire accelerator, causing costly down time for the entire facility.

The converter-modulator is designed to not permit accidental turn-on of adjacent IGBTs. A random turn-on, however, caused by a high-energy cosmic neutron will not be detected. The current passing through each IGBT is also monitored, and the control system is designed to shut down all power and discharge the capacitor bank if an anomaly is detected. However, because of its reactive

nature, this system will not protect the IGBTs, but merely avoid secondary damage.

It was therefore imperative that the impact of random neutron interactions with various IGBT systems and a predicted failure behavior be studied in depth.

COSMIC-RAY-INDUCED NEUTRONS AND HIGH-POWER SEMICONDUCTORS

Solar and galactic cosmic rays collide with nuclei in Earth's upper atmosphere and create a shower of subatomic particles, including neutrons. A small percentage of these neutrons can penetrate the atmosphere and reach low altitudes, where they can interfere with operating semiconductor electronics. These effects are noticeable especially for miniature devices on one end and high-power semiconductors on the other.

In high-power devices, such as the SNS IGBTs, a neutron interaction with the semiconductor material produces one or more charged particles, which are accelerated by the high electric field and create secondary charged particles, causing a particle avalanche which allows the device to draw large currents and be destroyed. The failure rate increases dramatically above a critical threshold voltage that is significantly lower than the rated voltage of the device.

Weapons Neutron Research (WNR) Facility: The ICE House

Because neutrons are produced at the WNR LANSCE Facility by the same basic process as in the atmosphere (proton spallation), the neutron spectrum is similar to the neutron spectrum produced by cosmic rays in the atmosphere, as shown in Figure 2.

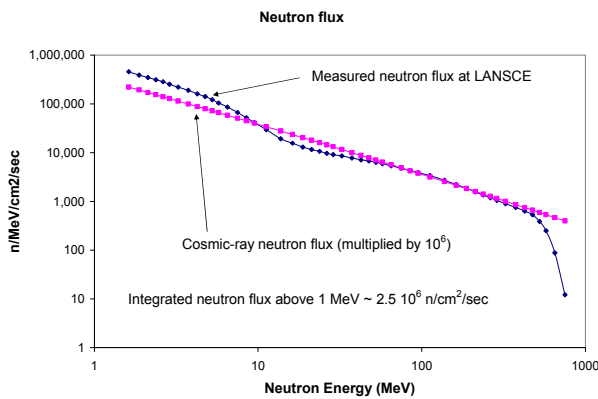


Figure 2: A graphical comparison of cosmic neutron spectrum vs. LANSCE spallation-produced spectrum.

Because ICE House beam intensity is approximately 10^6 times greater than the flux at aircraft altitudes, one hour of testing is equivalent to over 100 years of natural flux testing. The neutron beam used for these experiments consists of 625-microsecond pulses at 100 Hertz and covers an 8-cm diameter area, enough to shower an entire IGBT uniformly. Thanks to the design of the testing facility at WNR, all IGBTs tests were

performed in air within easy reach of data acquisition equipment.

TEST SETUP AND DATA ACQUISITION

The objective of the experiment was to use neutrons produced by proton spallation (similar to the process taking place in the atmosphere by cosmic rays) to gain knowledge of failure mechanisms of the SNS IGBTs at a highly accelerated neutron flux.

During the experiment, we monitored and recorded:

- leakage current, collector-emitter voltage, heat sink temperature, neutron beam energy;
- the time to failure for identical IGBTs at a full range of collector-emitter voltages;
- the time to failure (single effect gate rupture) for different manufacturers' IGBTs subjected to different operational voltages;
- current spikes as precursors to gate rupture, using current detectors and digital oscilloscopes.

The IGBTs being tested were placed directly into the path of the neutron beam, and a voltage differential applied between the collector-emitter gap of up to 3000 V, simulating normal operation. All parameters and data were monitored continuously and stored into a hard disk for later reduction.

The neutron flux was monitored using a thin film detector as well as directly by monitoring the neutron interactions inside the IGBT. Figure 3 displays a direct measurement of the neutron interaction inside the semiconductor (top trace) and signals from the monitoring chamber (bottom trace), which was used statistically to predict neutron density.

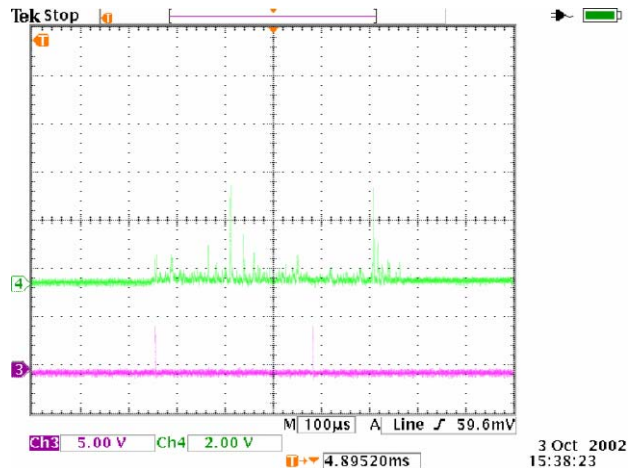


Figure 3: A direct measurement of neutron interactions inside the IGBT (top) and the detector chamber (bottom).

When charges caused by one or more interactions were accelerated by the electric field, starting an avalanche, a noticeable drop in power supply voltage and a corresponding rise in current were observed, signaling the shorting of the IGBT and its final failure. In these experiments, the power supply was current limited, limiting the physical destruction of the IGBT, but at full

operational current, the damage created would closely resemble that pictured in Figure 1.

The IGBTs tested were multiple elements of the following types:

- Dynex Semiconductor DIM1200ESM33-A000,
- Mitsubishi CM1200HB-66H,
- EUPEC FZ 1200 R 33 KF2,
- EUPEC FZ 1200 R 33 KL2 and KL2 ENG.

TEST RESULTS

Failure curves were obtained for each device by monitoring the time to failure at increasing bias voltages. Multiple IGBT test subjects showed great consistency, providing a minimum failure voltage above which the field across the emitter-collector gap is large enough to accelerate randomly-created charges to avalanche speed, destroying the device. An example of one such failure curve is shown in Figure 4. These findings indicate that during operation above this threshold the IGBTs are susceptible to random cosmic neutron interactions.

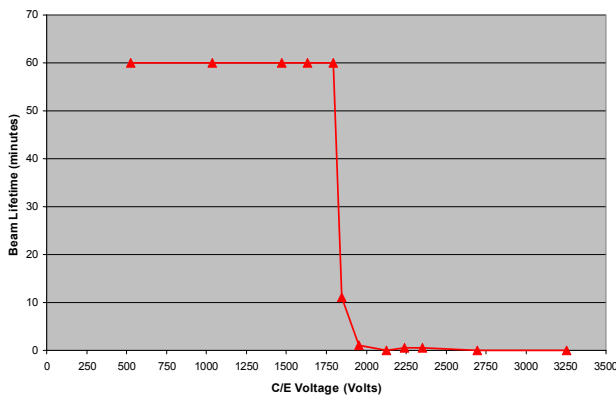


Figure 4: A failure curve for one of the brands of IGBTs tested.

Similar tests were performed while the IGBT cooling plate was artificially heated to normal operational temperature (60°C). No difference was observed in the resulting failure curve.

Consistent failure curves were obtained for all types of IGBTs available, and specific thresholds were obtained for each, all within a bias voltage range of 1500 V to 2300 V, well within their operational specifications.

Lifetime Projections for SNS-Specific Operation

Given the known neutron flux in the WNR beam, its ratio with the flux of natural cosmic-ray induced neutrons, and the average flux at the SNS site in Oak Ridge, Tennessee, lifetime predictions were obtained to assist in the maintenance procedures and expectations.

When the converter-modulator capacitor banks are charged, the IGBTs are biased to full voltage and susceptible when not switching. Since regular IGBT operation for all SNS Converter-Modulators takes place at up to 1,200 V, there are no expectations of reliability problems, as long as the voltage stays below the knee of the curve.

However, during a typical pulse, because of the H-bridge design for the IGBT switching network, each IGBT is biased to twice the voltage for periods of 25 microseconds (or less), at 20 kHz, during each 1.3 ms SNS 60-Hz pulse. During regular, full-power (5-MW klystron) operation, the duty factor for exposure to potential neutron damage at 2400V is 3.9%. In other words, every 100 minutes of normal pulsed operation the IGBTs get 3.9 minutes of double-voltage exposure.

From the data obtained in these experiments, lifetime expectancies of each IGBT during normal SNS pulsed operation ranged between 13 and over 2500 calendar days. This means that, with the best device tested, reliability calculations project that, due to the multiple converter-modulators having multiple IGBTs, a random failure is expected statistically about every 90 calendar days, unrelated to ageing of the devices or any other failure mechanisms.

CONCLUSIONS

The failure curve for the lifetime vs. voltage was established for each available IGBT. The failure rate increases very dramatically past a certain voltage within the operational range.

It was established that the IGBT device least susceptible to cosmic-ray induced neutrons is the EUPEC KL2. Based on these results, SNS IGBT selection has already been changed to the KL2.

Statistical lifetime projections for normal operations of the SNS accelerator were obtained, given no other failure modes.

REFERENCE

B. Takala, S. A. Wender, "Accelerated Neutron Testing of Semiconductor Devices", <http://int.lanl.gov/orgs/nmt/news/index.shtml>.