Radiation & Thermal Cycling Effects on Gallium Nitride and Silicon Carbide Power Transistors

Richard L. Patterson, NASA GRC

Jean-Marie Lauenstein & Megan Casey, NASA GSFC

Leif Scheick, JPL

Ahmad Hammoud, Vantage Partners LLC

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SCOPE OF WORK

- A NEPP (NASA Electronic Parts and Packaging) collaborative effort among NASA Centers to address performance and reliability of new COTS (Commercial-Off-The-Shelf) power devices based on wide bandgap semiconductor for use in space harsh environment

- Test and evaluate performance of emerging GaN (Gallium Nitride) & SiC (Silicon Carbide) power devices under the exposure to radiation and thermal cycling

- Document results and disseminate findings

TECHNICAL APPROACH:

- Identify and acquire candidate power devices
- Perform parametric evaluation
- Subject devices to radiation exposure representative of mission environment
- Perform long-term thermal cycling on survived parts
- Determine effects of radiation and temperature cycling on performance of devices
- Address reliability, determine risk factors, and identify mitigation techniques for device use in space missions

Accomplished/Ongoing Work

- ***Radiation Testing (GSFC/JPL)***
  - TID (Total Ionization Dose)
  - SEE (Single Event Effect)

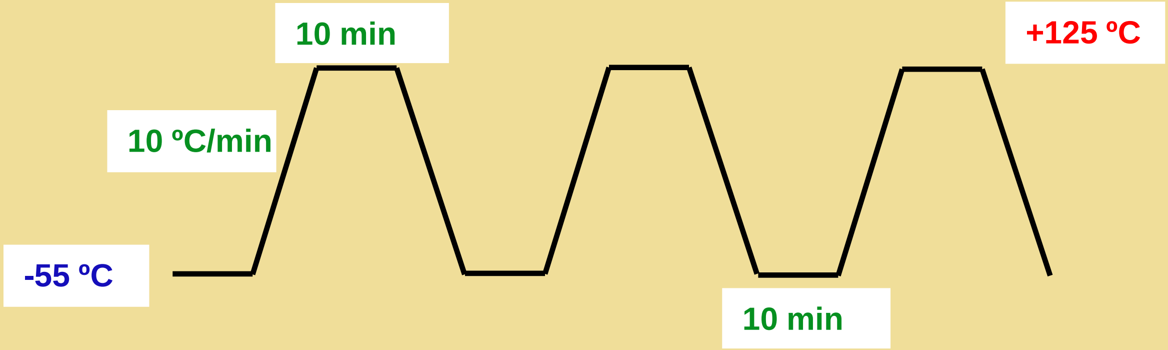
- ***Thermal Cycling (GRC)***
  - Control (Un-irradiated) Samples
  - Irradiated Parts
  - Long-Term

- ***Wide Bandgap Devices***
  - First Generation GaN FETs (EPC) from JPL
  - SiC MOSFETs (Cree) from GSFC
  - Second Generation GaN FETs (EPC) from JPL

Thermal Cycling

At NASA Glenn Research Center (GRC)

- Cycling Profile:
  - Total # of Cycles 1000
  - Temperature rate of change: 10 ºC/min
  - Temperature range: -55 ºC to +125 ºC
  - Soak time at extreme temperatures: 10 min
- Repeat measurements on devices during cycling
- Perform measurements after conclusion of cycling activity



Test Setup

Parameters Investigated:

- I-V Output Characteristics
- Gate Threshold Voltage, V_{TH}
- Drain-Source On-Resistance, $R_{DS(on)}$
- Pre, during, & post-cycling, measurements at selected temperatures

Equipment Used:

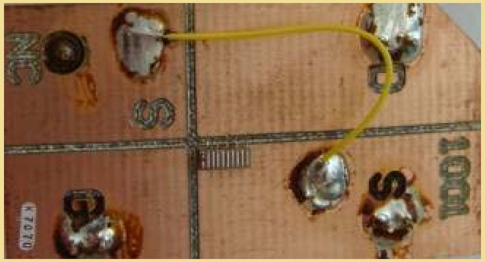
- SONY/Tektronix 370A Curve Tracer
- Keithley 238 Source-Measure-Units
- LN-cooled Sun Systems Chamber

First Generation GaN FETs

Irradiated by JPL at TAMU

- **Efficient Power Conversion, EPC1001, GaN transistors grown on Si wafer; http://www.epc-co.com**
- **Passivated-die form with solder bumps**

Sample die mounted on test structure



# of Parts	Device Label	Condition	Ion	Energy (MeV)	LET (MeV•cm^2 /gm)	Range (µm)	Dose (rad (Si))
1	K7063	Irradiated	Au	2342	84.7	122.9	22718
1	K7064	Irradiated	Xe	1569	98.8	124.5	8301
1	K7044	Irradiated	Xe	1569	50.9	124.5	7886
1	K7065	Irradiated	Xe	1569	98.8	124.5	15838
4	K7068-K7071	Control (un-irradiated)					

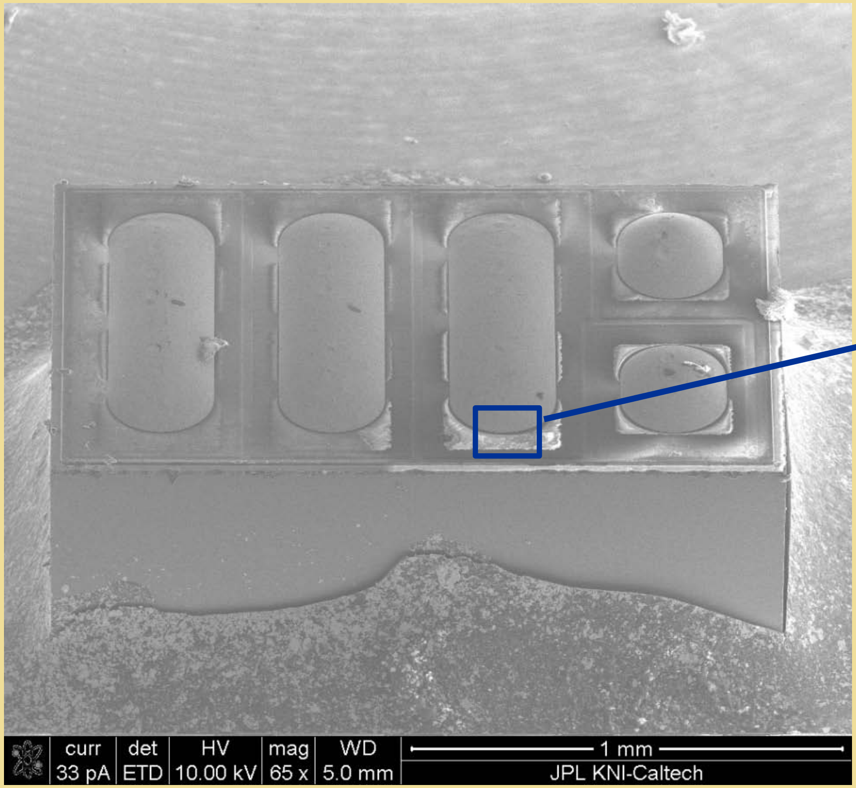
EPC1001 Enhancement-Mode GaN Power FETs

Manufacturer's Specifications

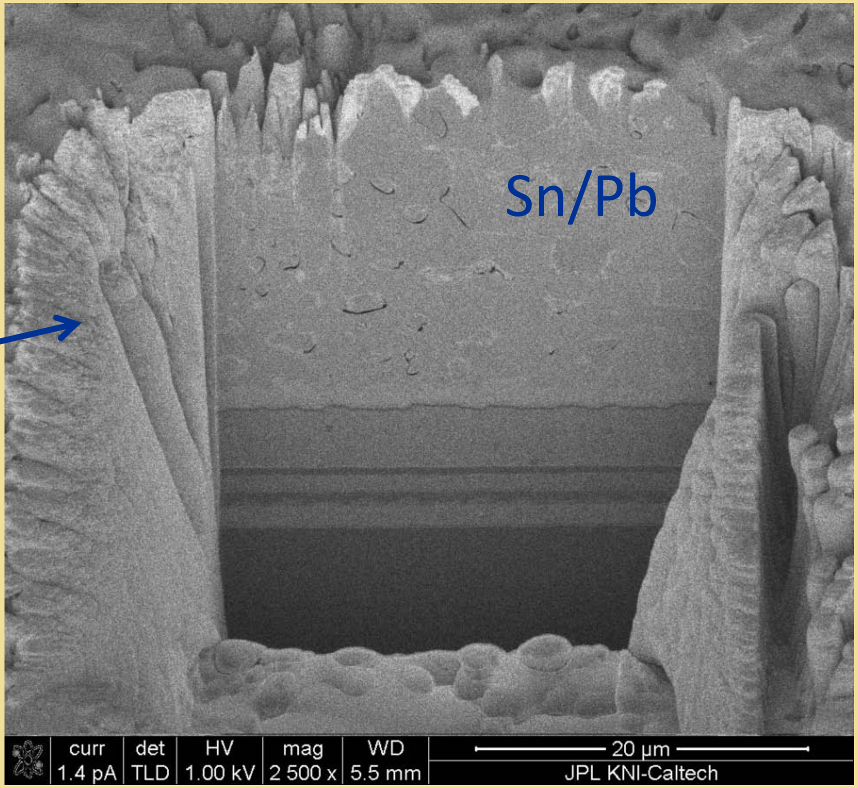
Part #	EPC1001
Drain-Source Voltage, V_{DS} (V)	100
Gate Threshold Voltage, V_{TH} (V)	1.4 @ $V_{DS} = V_{GS}$, $I_D = 5$ mA
Drain Current, I_D (A)	25
Drain-Source On Resistance, $R_{DS(ON)}$ (mΩ)	5.6 @ $V_{GS} = 5V$, $I_D = 25$ A
Operating Temperature, T_J (ºC)	-40 to +125
Package Type	Passivated-Die with Solder Bumps

Focused Ion Beam and SEM Cross-Section of EPC GaN FETs

SEM Micrograph, 65X , 52 deg. Tilt



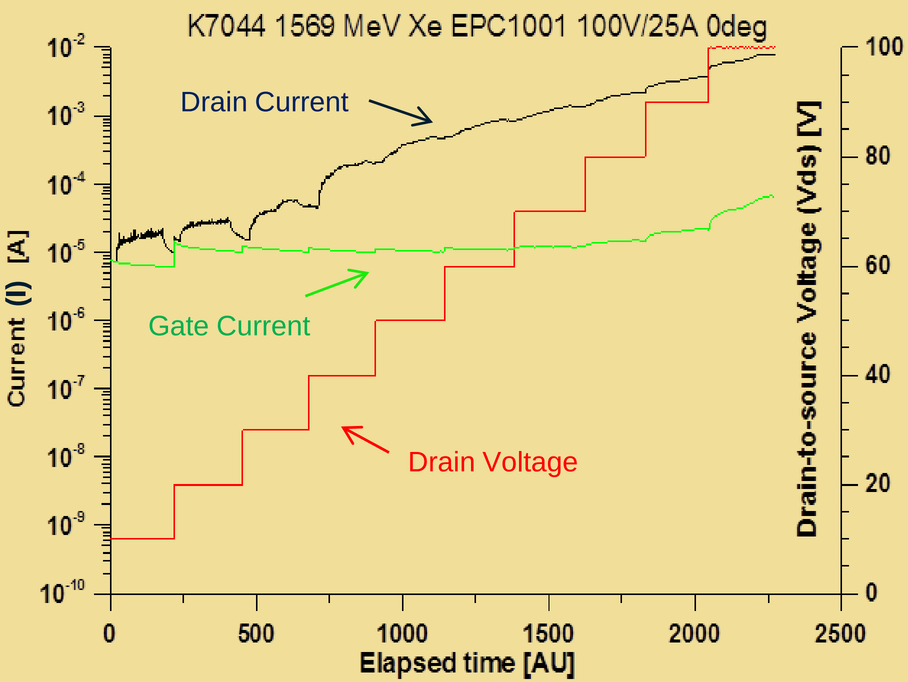
SEM Micrograph after FIB Cut, 2500X, 52 deg. Tilt

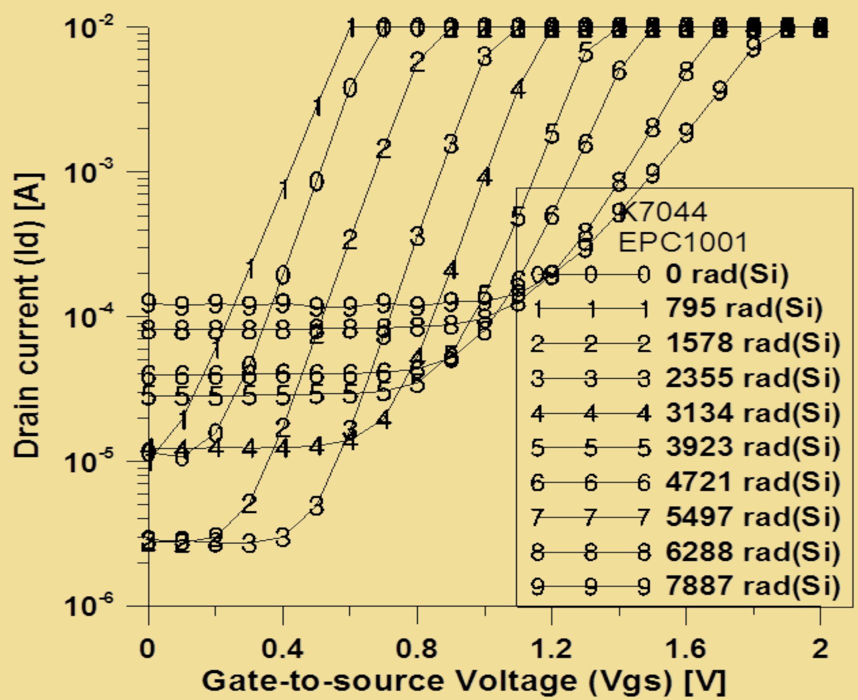


RADIATION DATA
from JPL

- Devices were irradiated under bias at increasing drain biases
- Transfer curves were measured between irradiations
- Devices still functioned but were well out of spec after irradiation

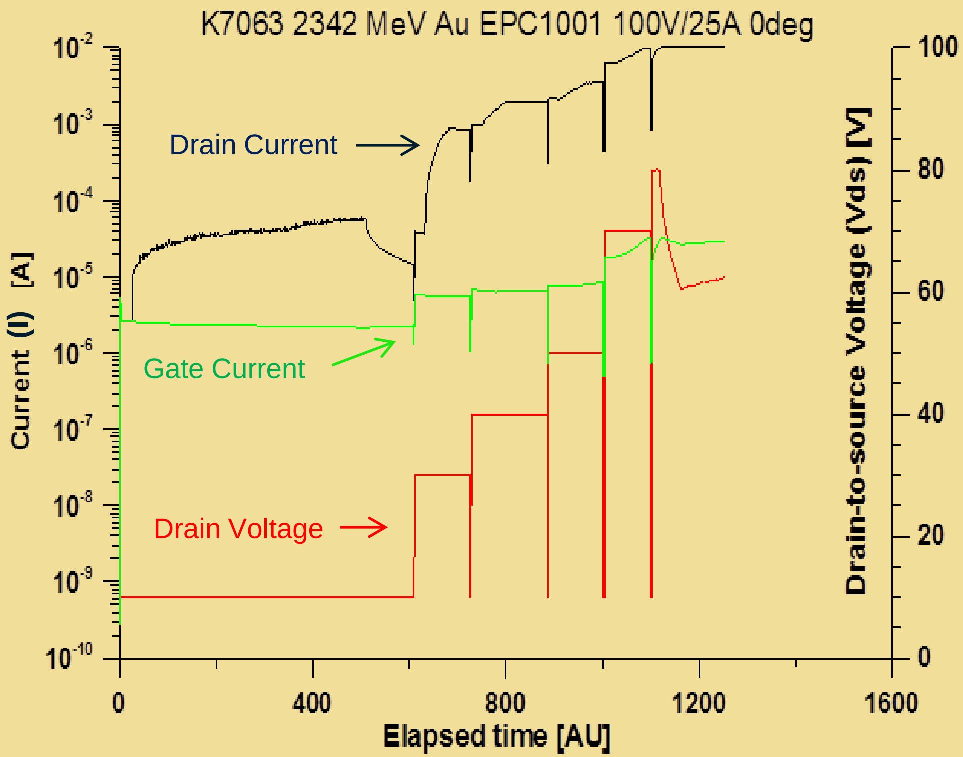
Device K7044 (EPC1001 First Gen GaN FET irradiated with Xe to 7.9 krad (Si))

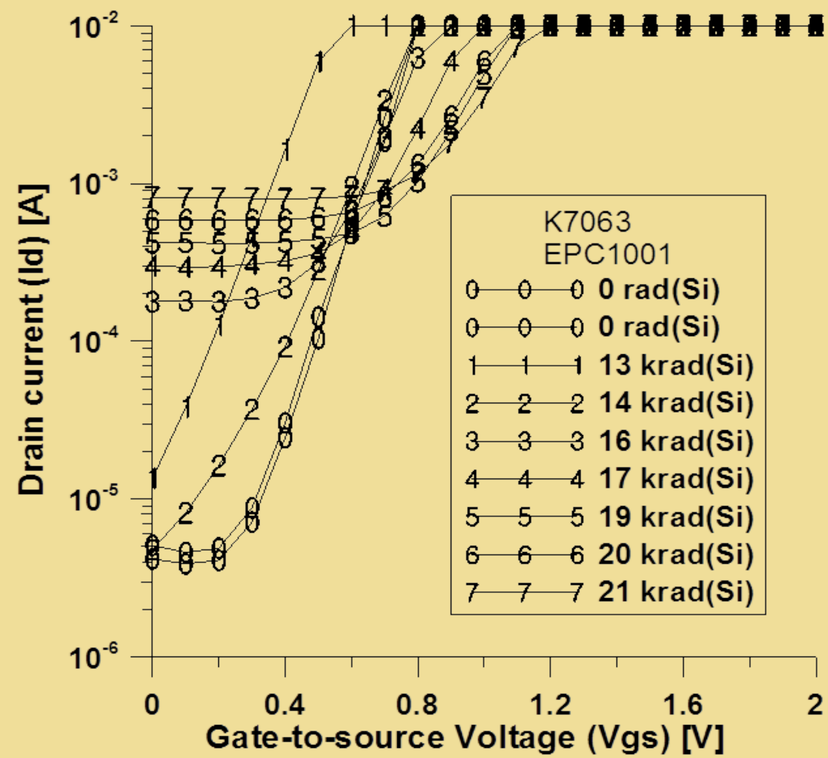




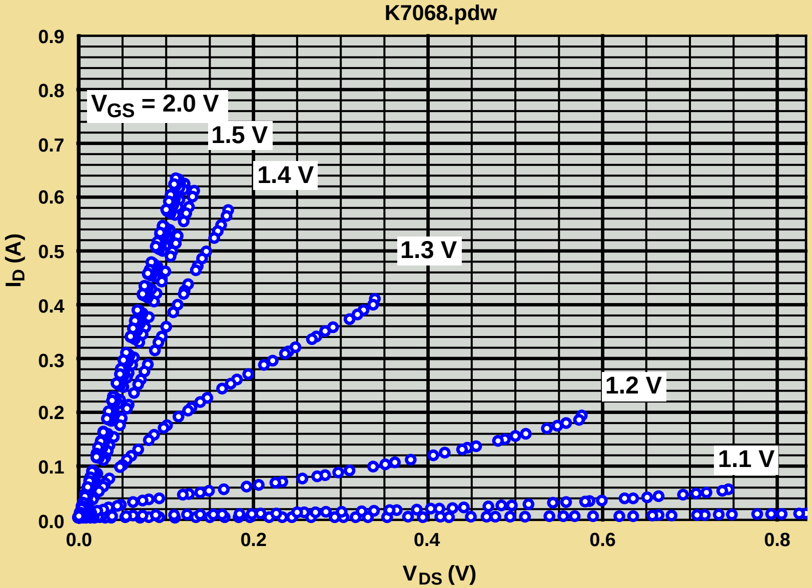
RADIATION DATA
from JPL

Device K7063 (EPC1001 First Gen GaN FET irradiated with Au to 27.7 krad (Si))

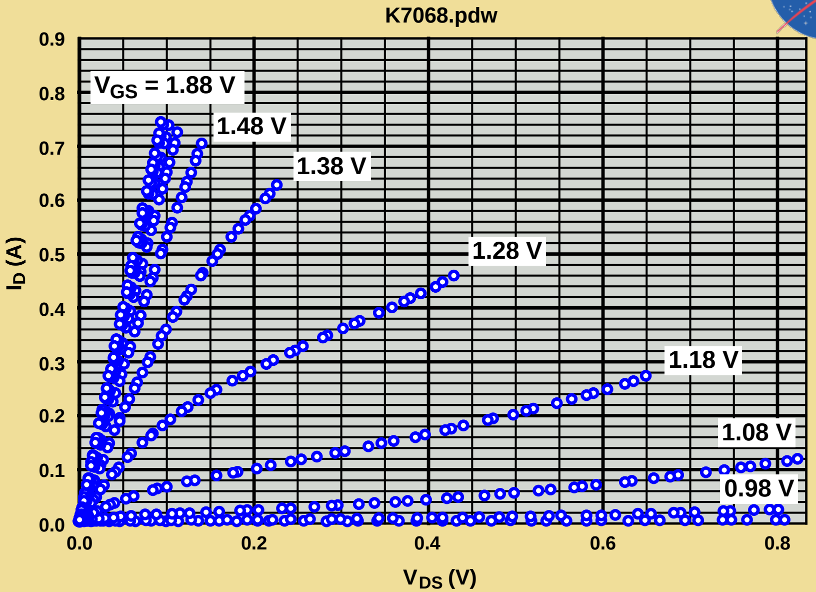




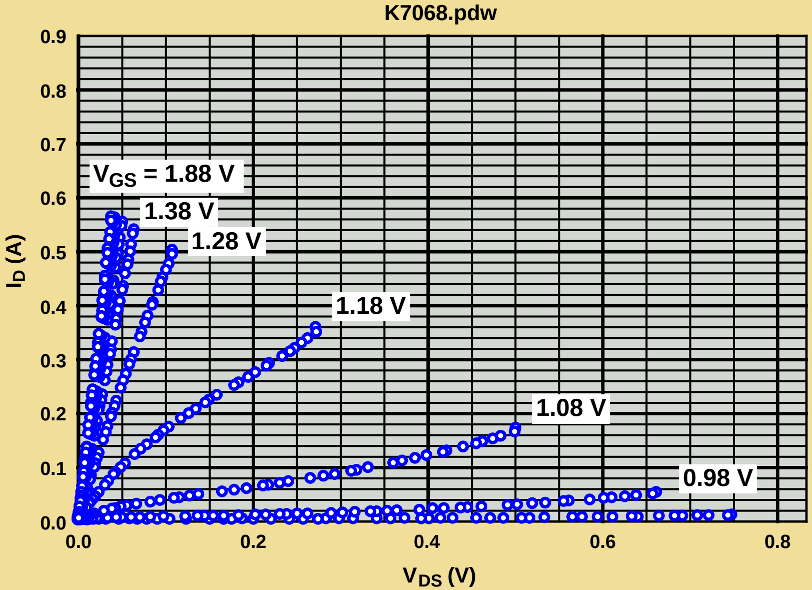
I-V Curves for K7068 control (un-irradiated)



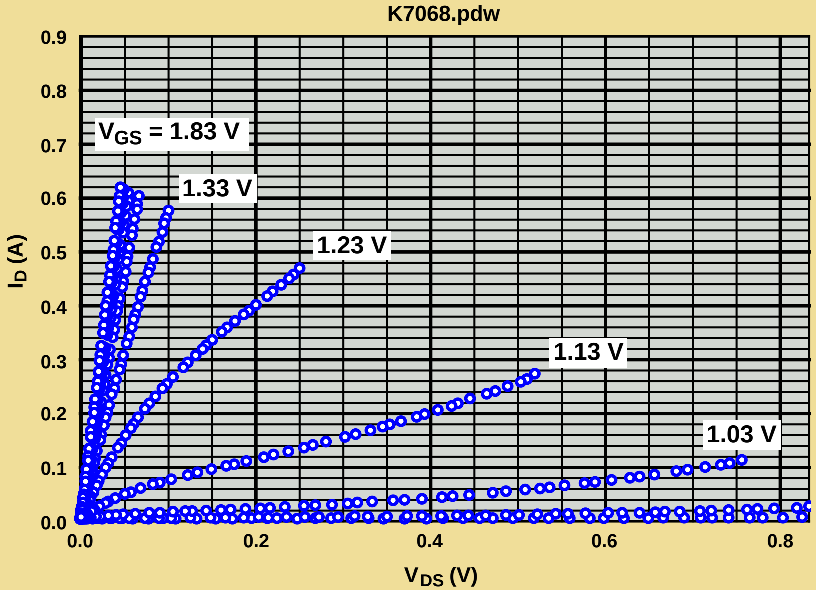
Pre-Cycling



After 500 Cycles

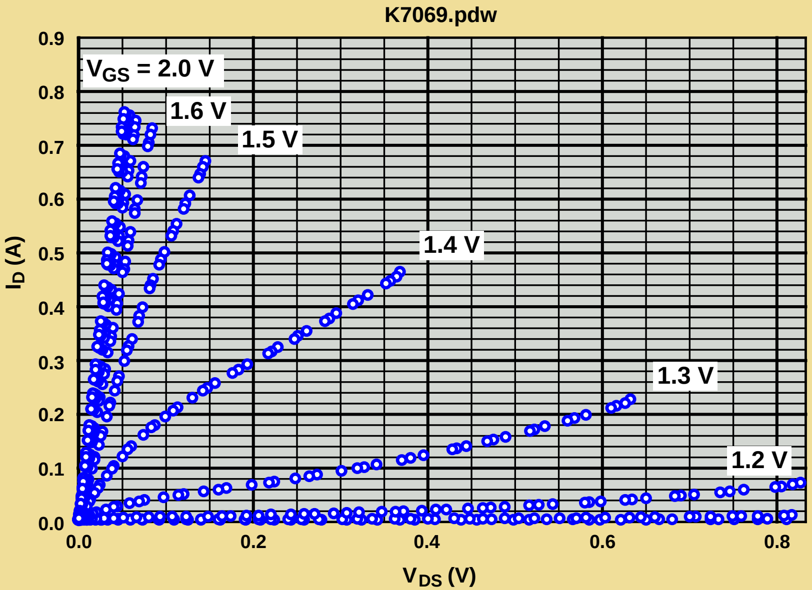


After 824 Cycles Transconductance Increase

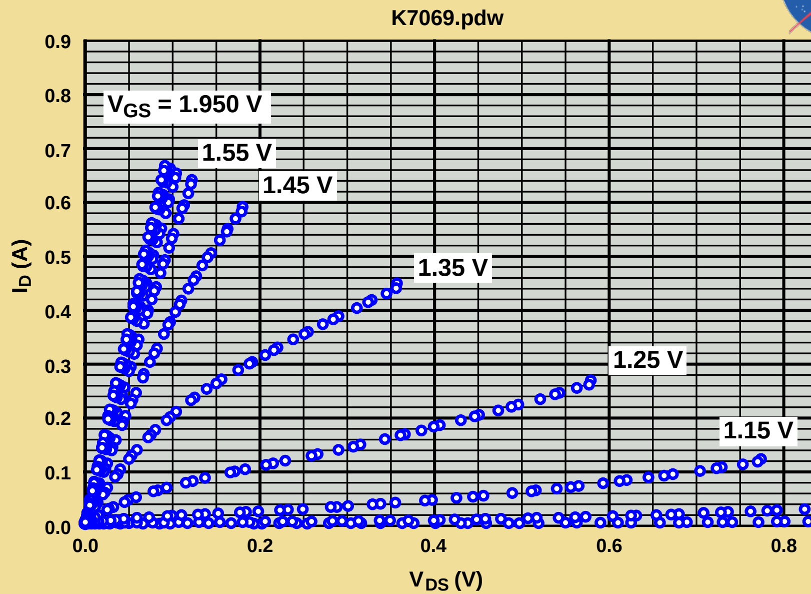


After 1000 Cycles Similar to 824 Cycles

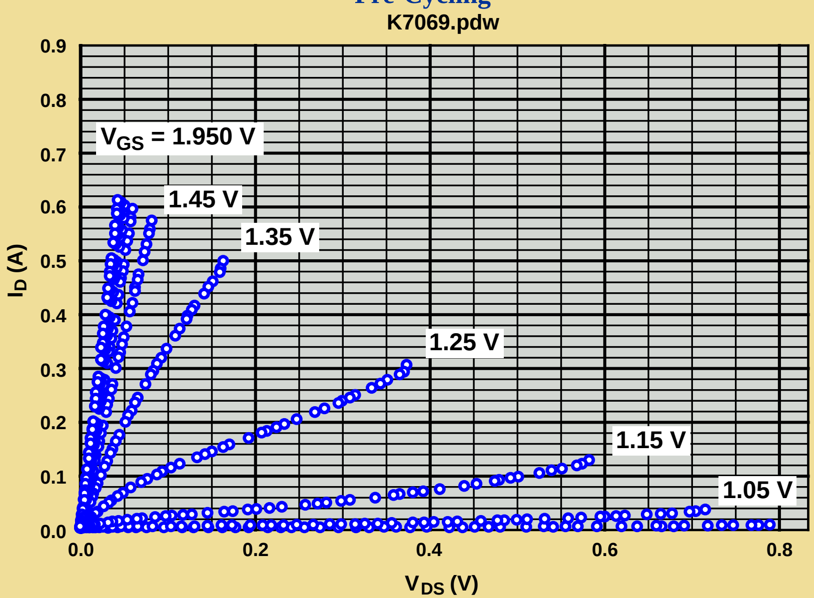
I-V Curves for K7069 control (un-irradiated)



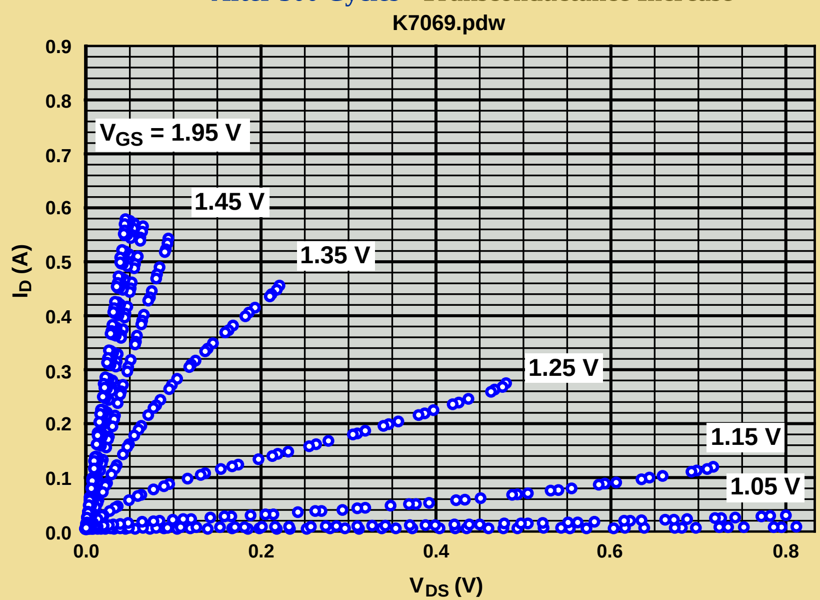
Pre-Cycling



After 500 Cycles Transconductance Increase

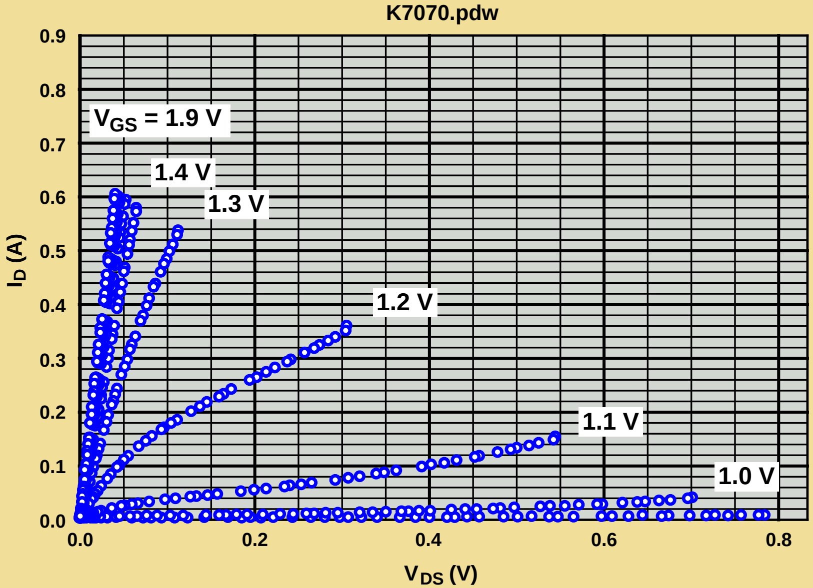


After 824 Cycles More Transconductance Increase

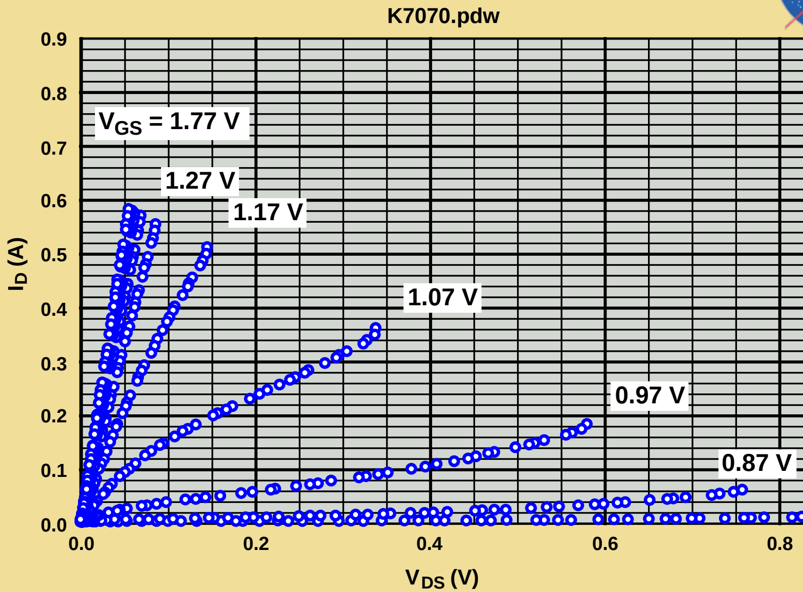


After 1000 Cycles Drop in Transconductance

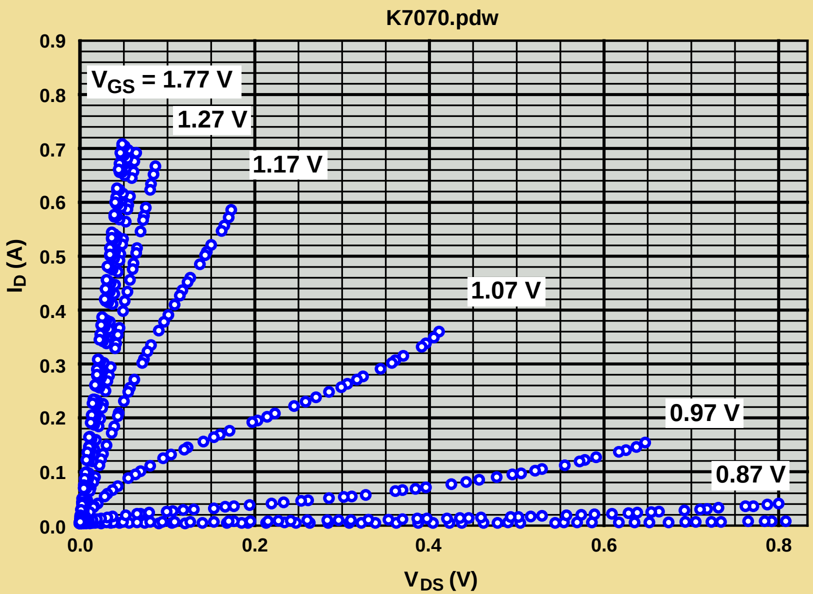
I-V Curves for K7070 control (un-irradiated)



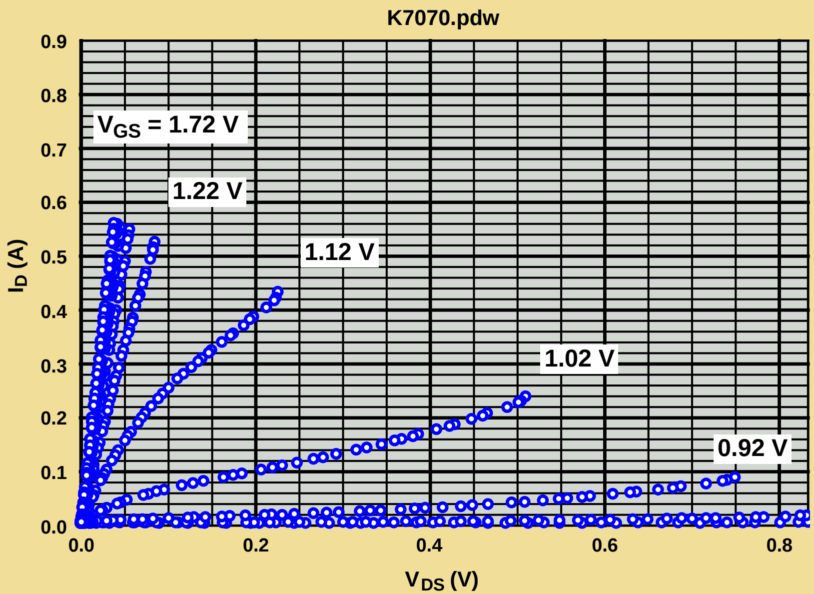
Pre-Cycling



After 500 Cycles Transconductance Increase

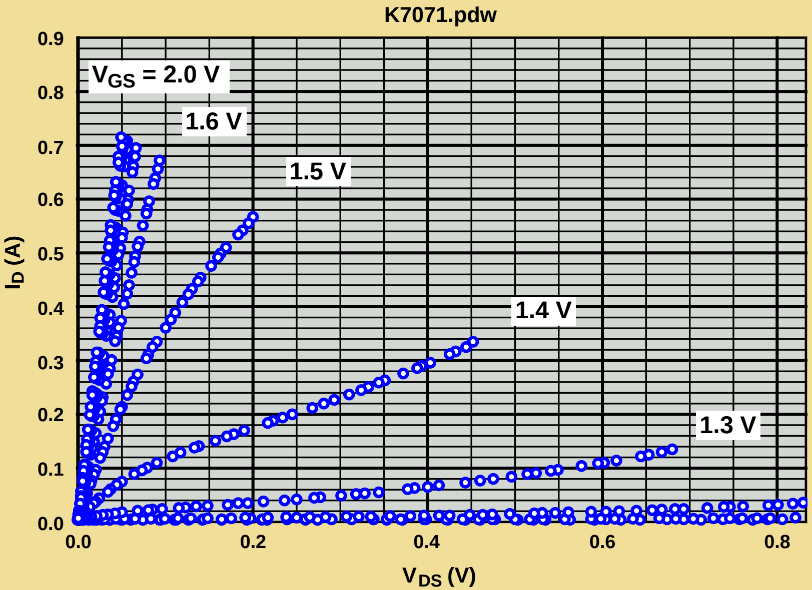


After 824 Cycles

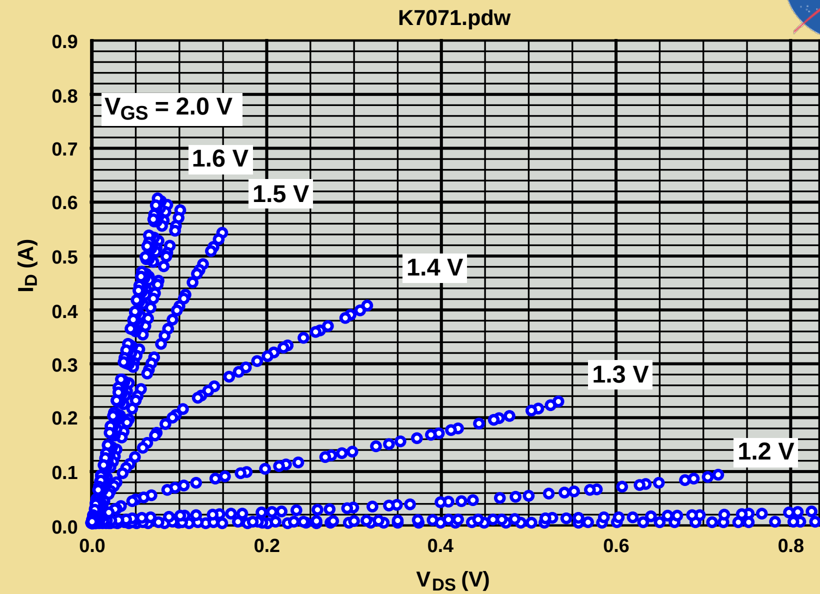


After 1000 Cycles

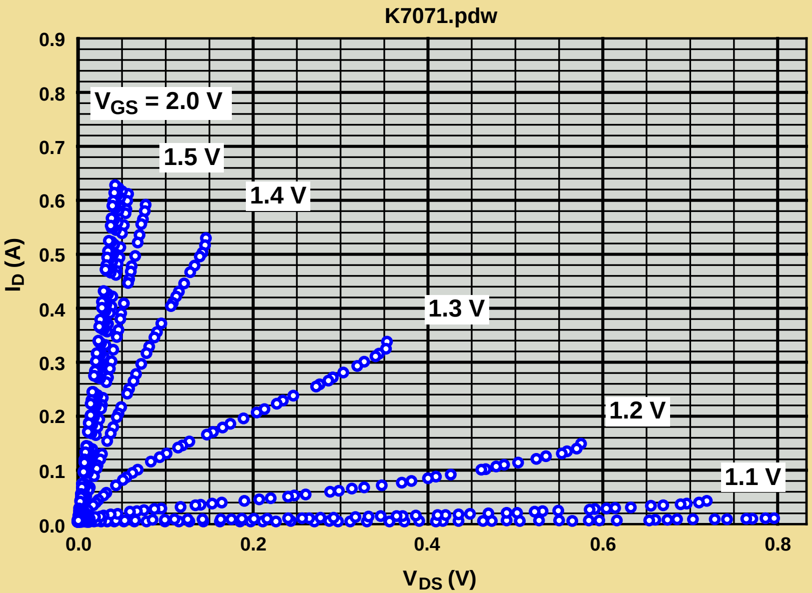
I-V Curves for K7071 control (un-irradiated)



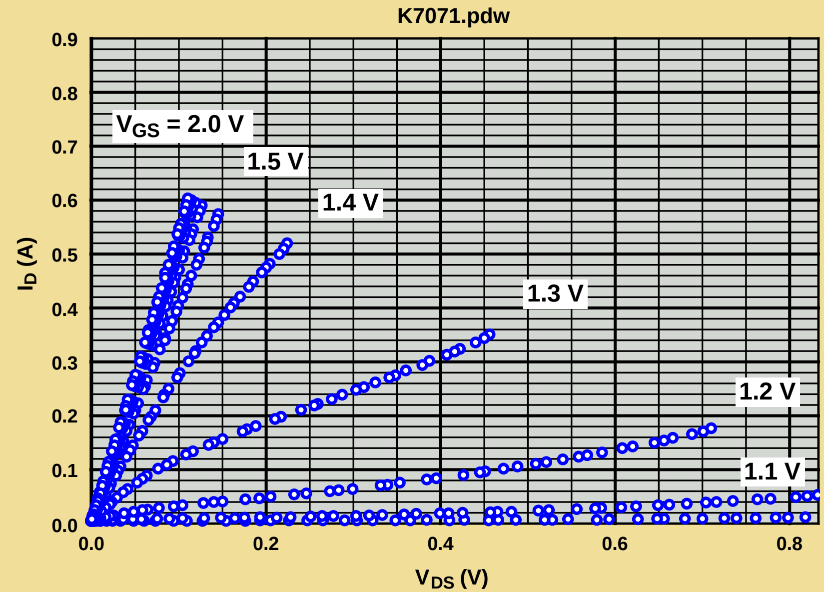
Pre-Cycling



After 500 Cycles Transconductance Increase

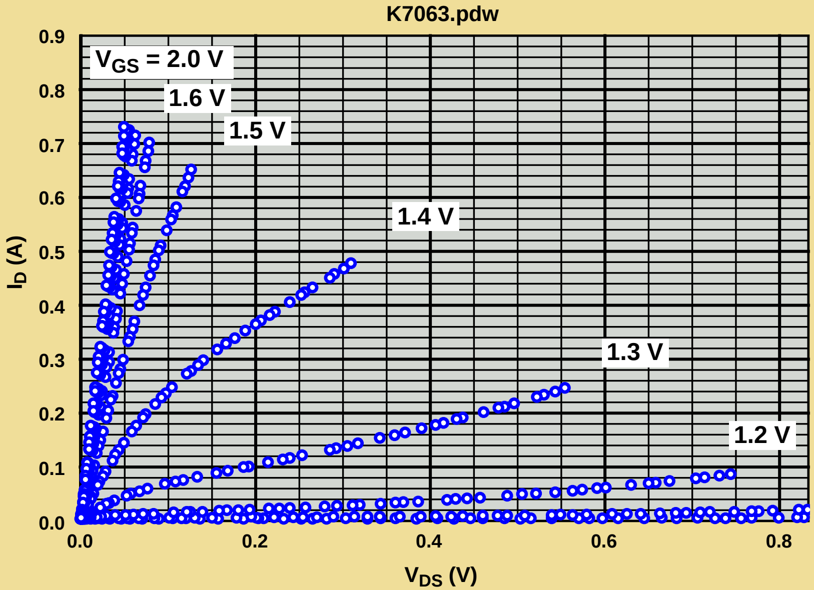


After 824 Cycles More Transconductance Increase

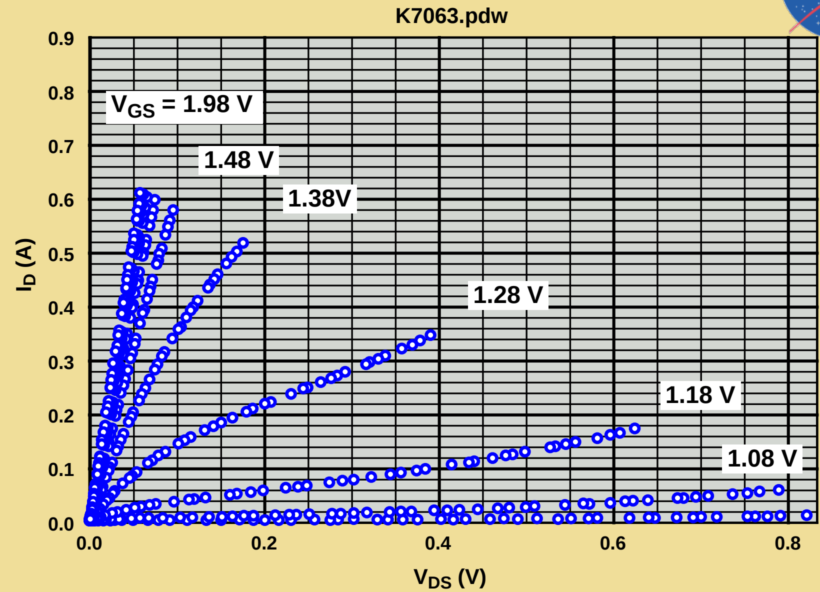


After 1000 Cycles Drop in Transconductance

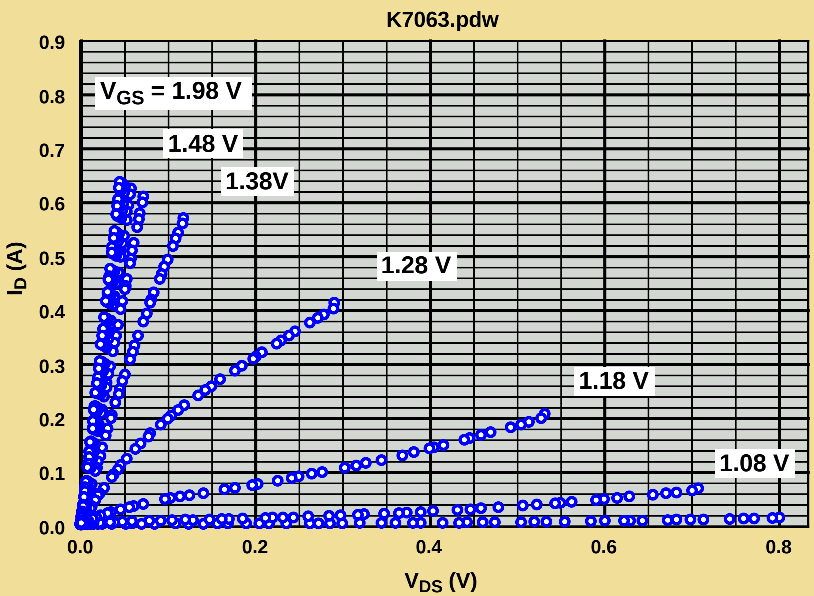
I-V Curves for K7063 (irradiated, Au ions, 22.7 krad (Si))



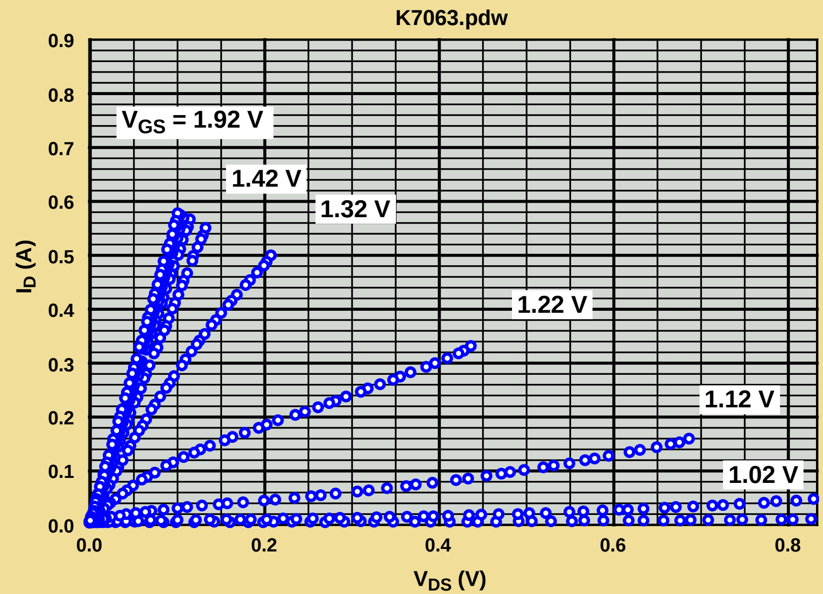
Pre-Cycling



After 500 Cycles Transconductance Increase

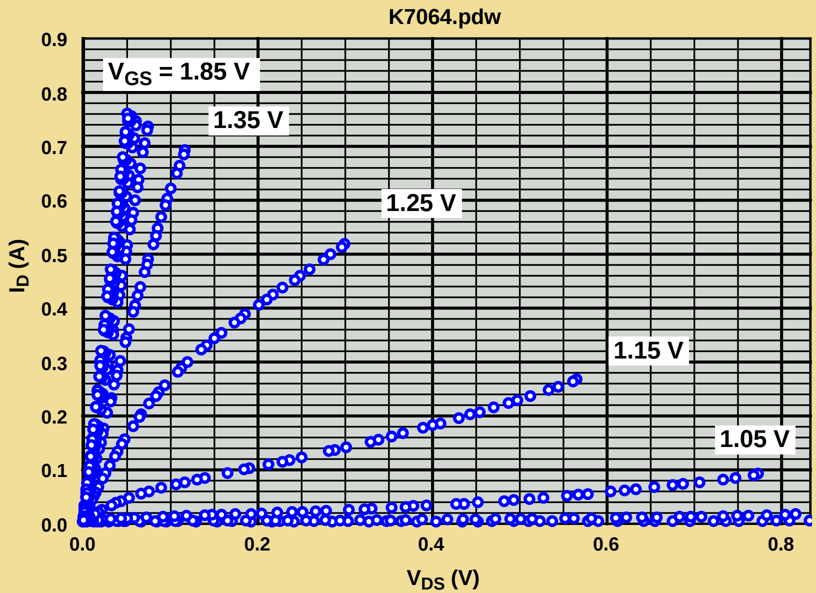


After 824 Cycles

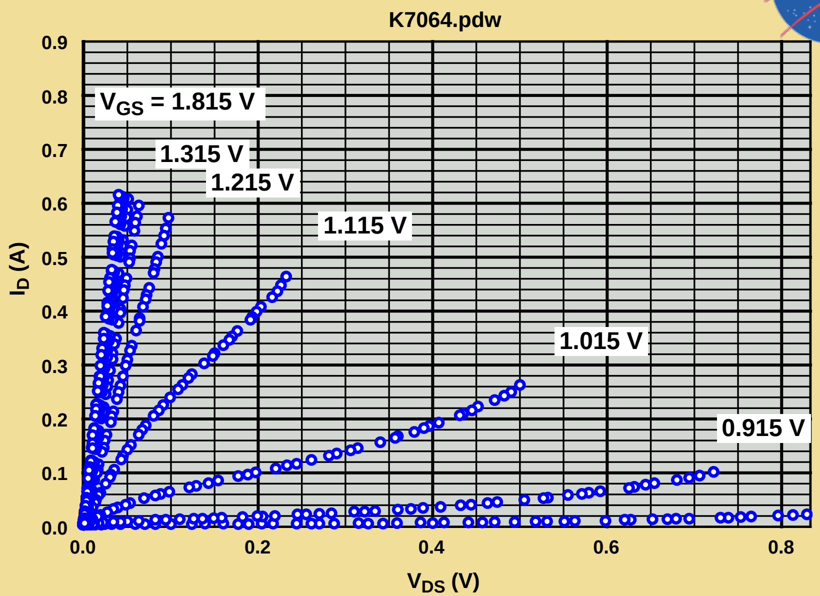


After 1000 Cycles

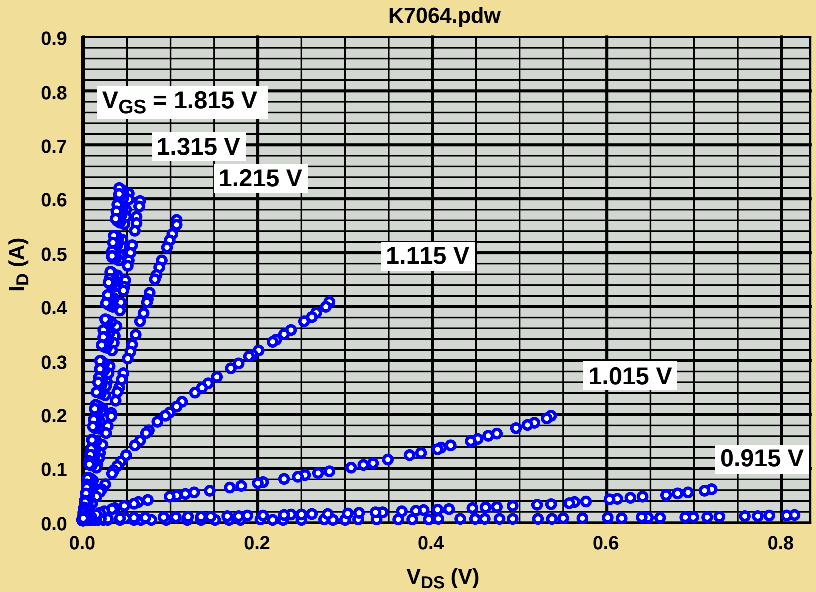
I-V Curves for K7064 (irradiated, Xe ions, 8.3 krad (Si))



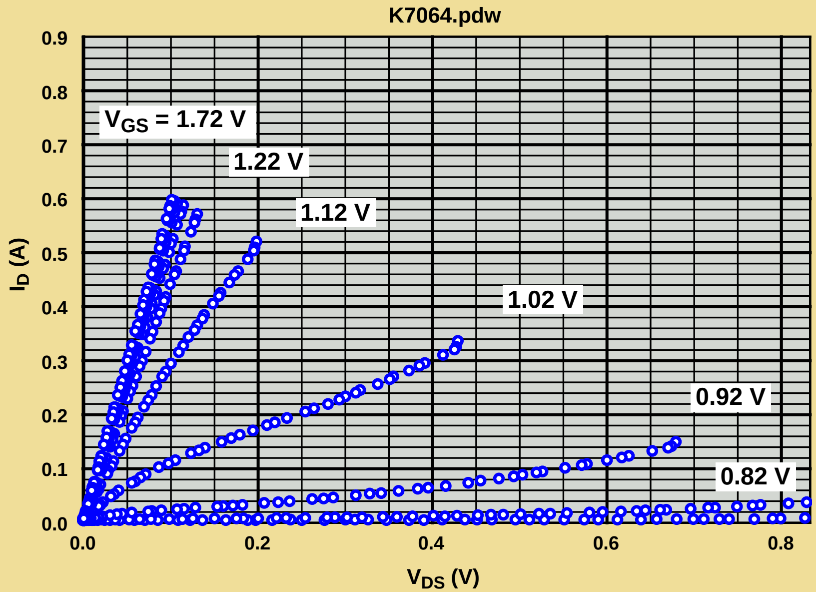
Pre-Cycling



After 500 Cycles

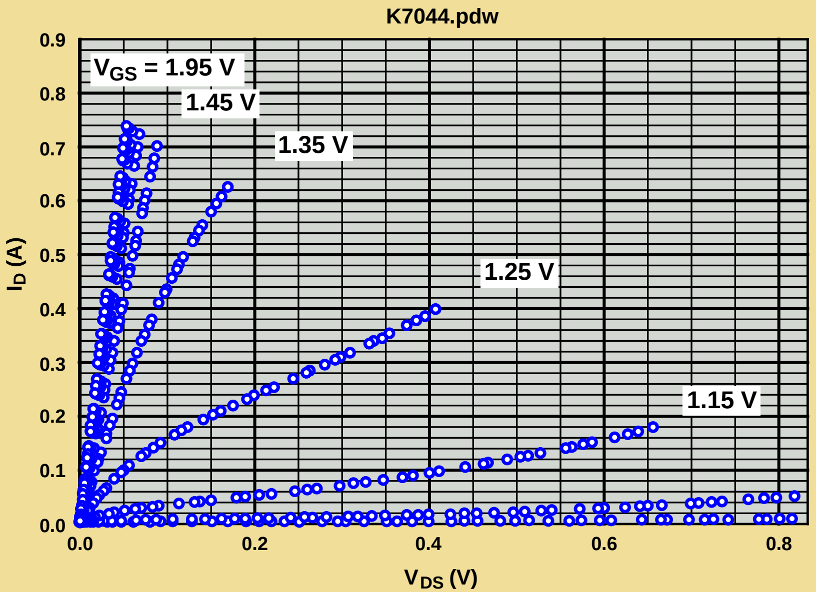


After 824 Cycles

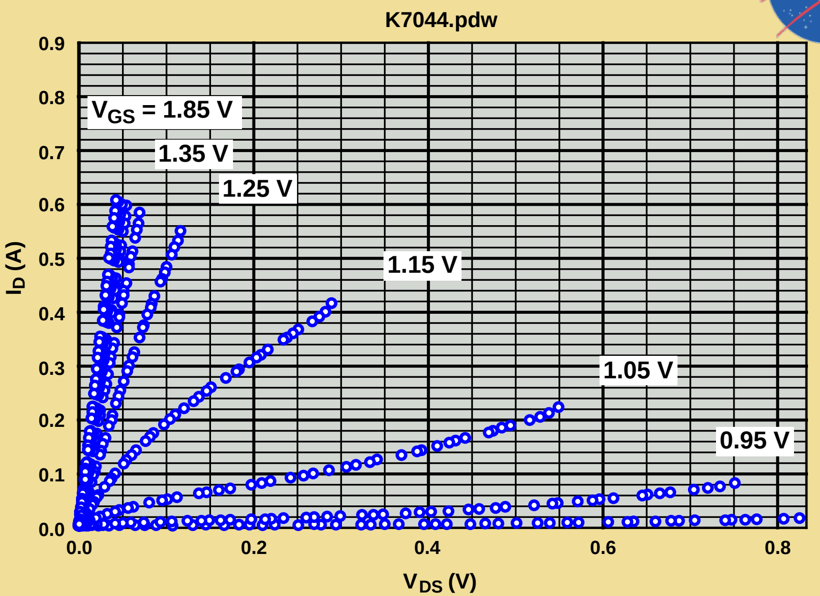


After 1000 Cycles

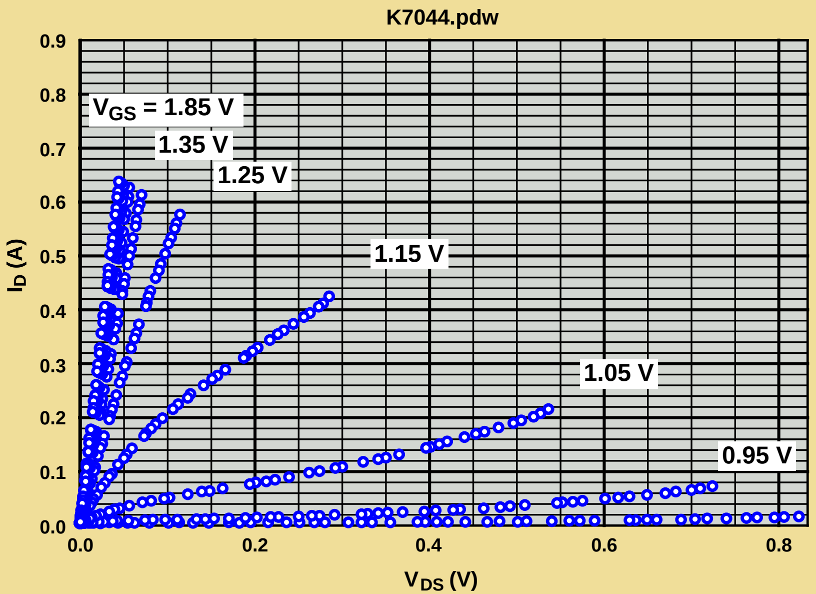
I-V Curves for K7044 (irradiated, Xe ions, 7.9 krad (Si))



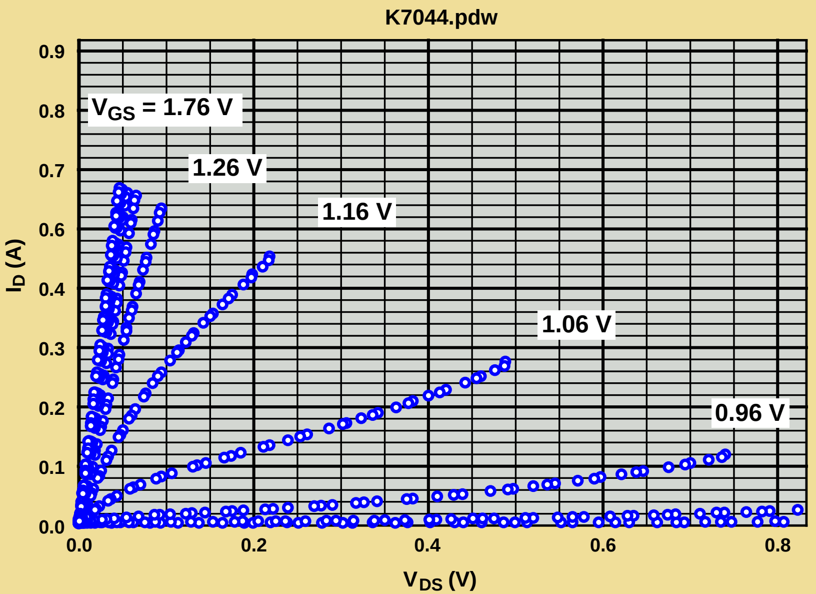
Pre-Cycling



After 500 Cycles Transconductance Increase

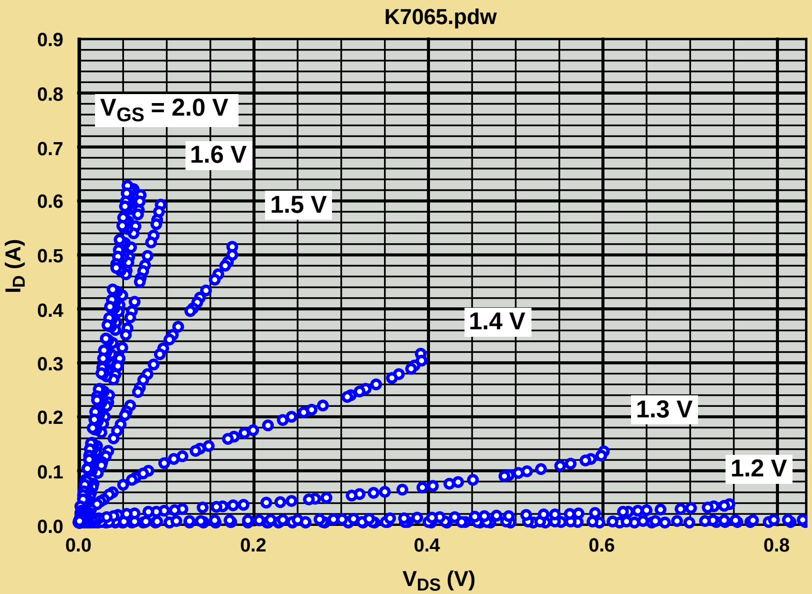


After 824 Cycles

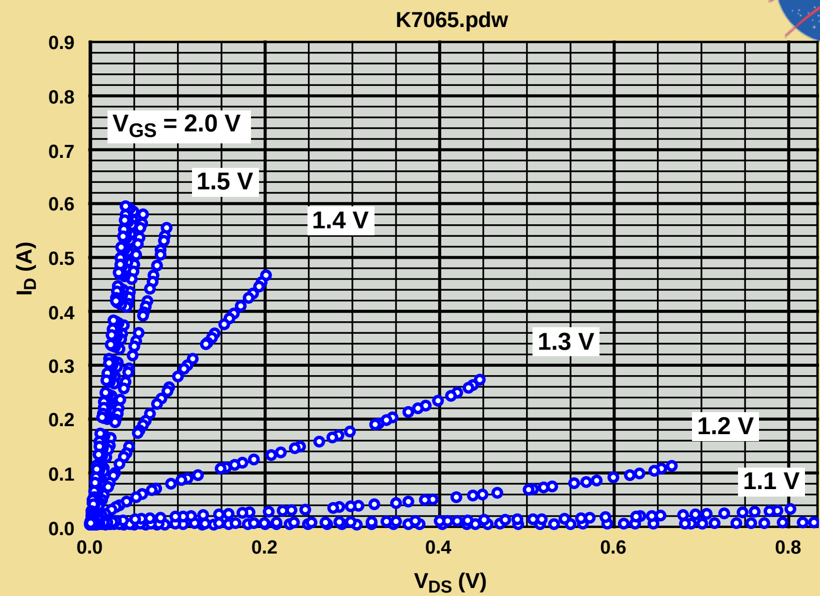


After 1000 Cycles

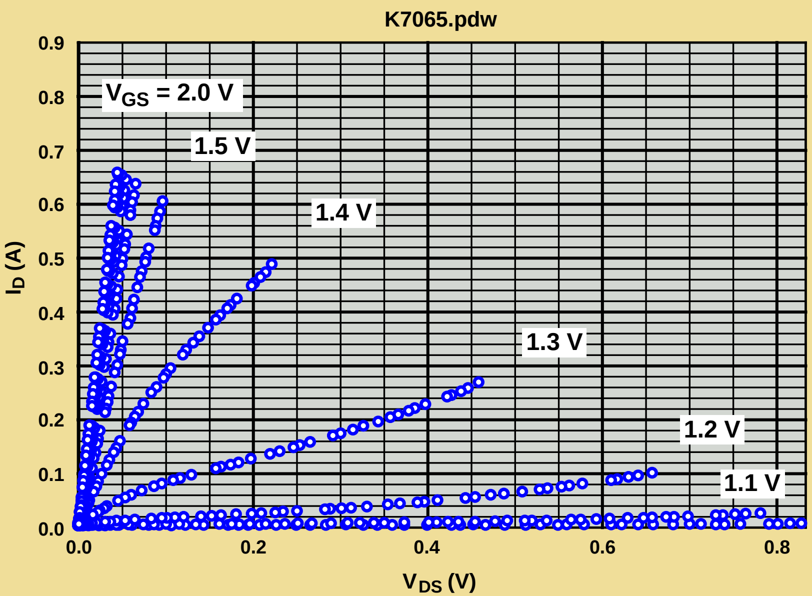
I-V Curves for K7065 (irradiated, Xe ions, 15.8 krad)



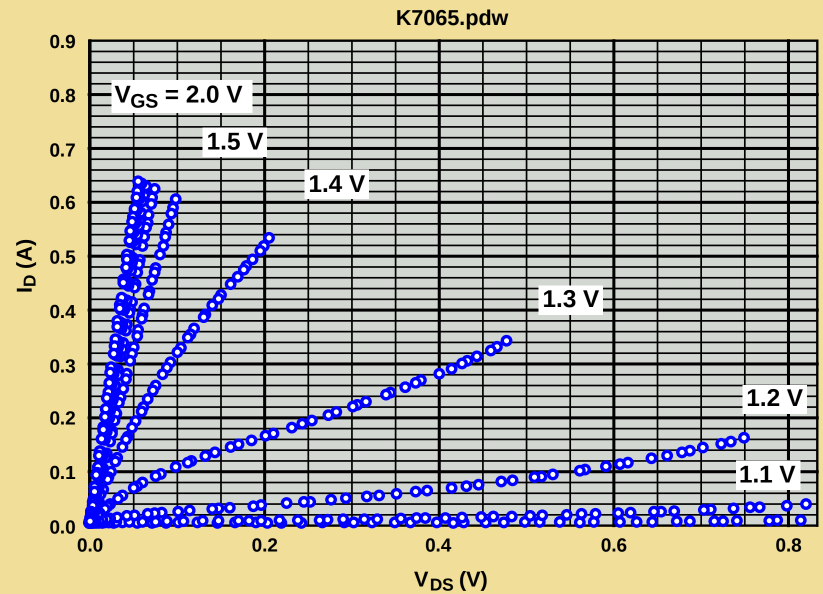
Pre-Cycling



After 500 Cycles Transconductance Increase

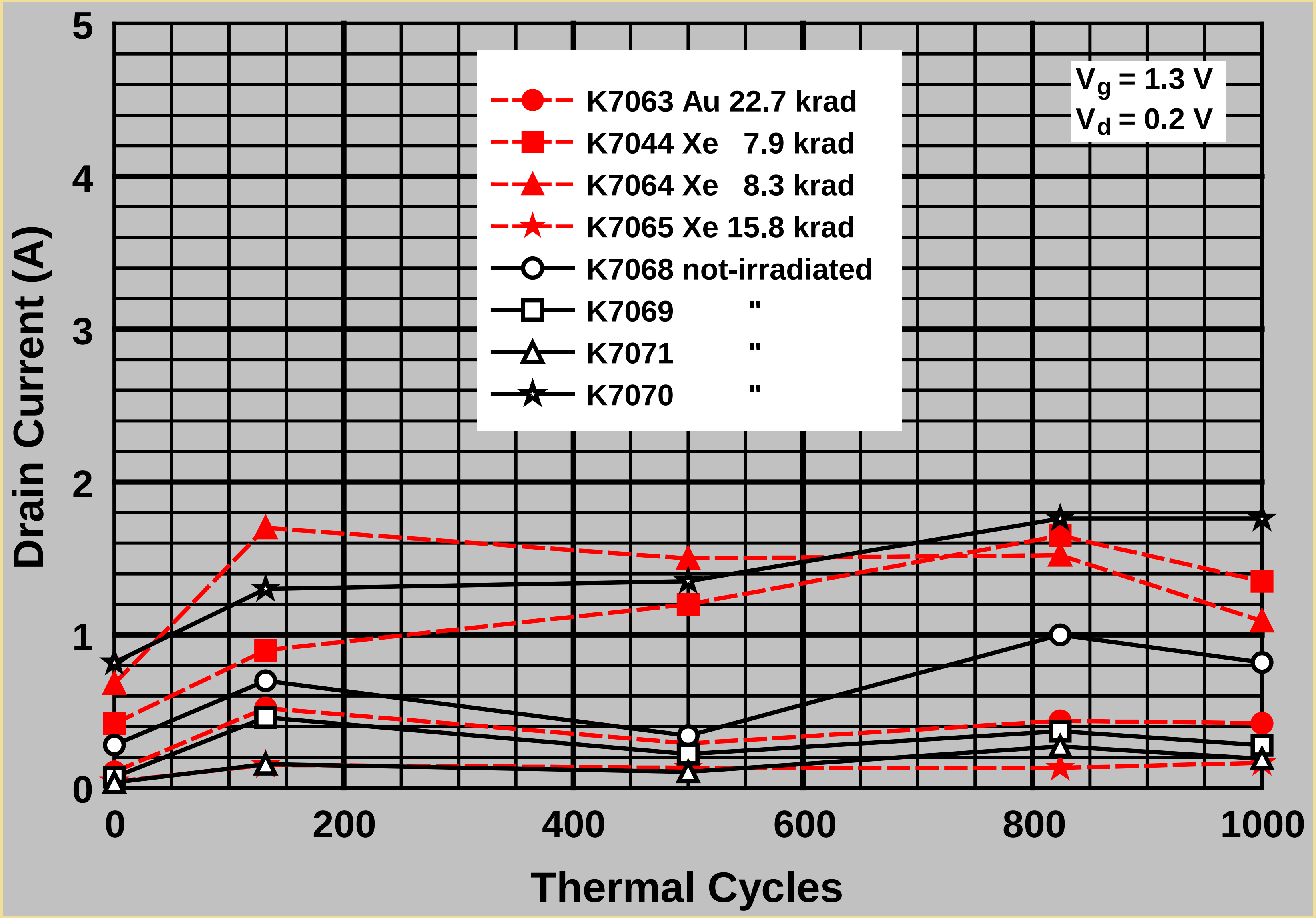


After 824 Cycles

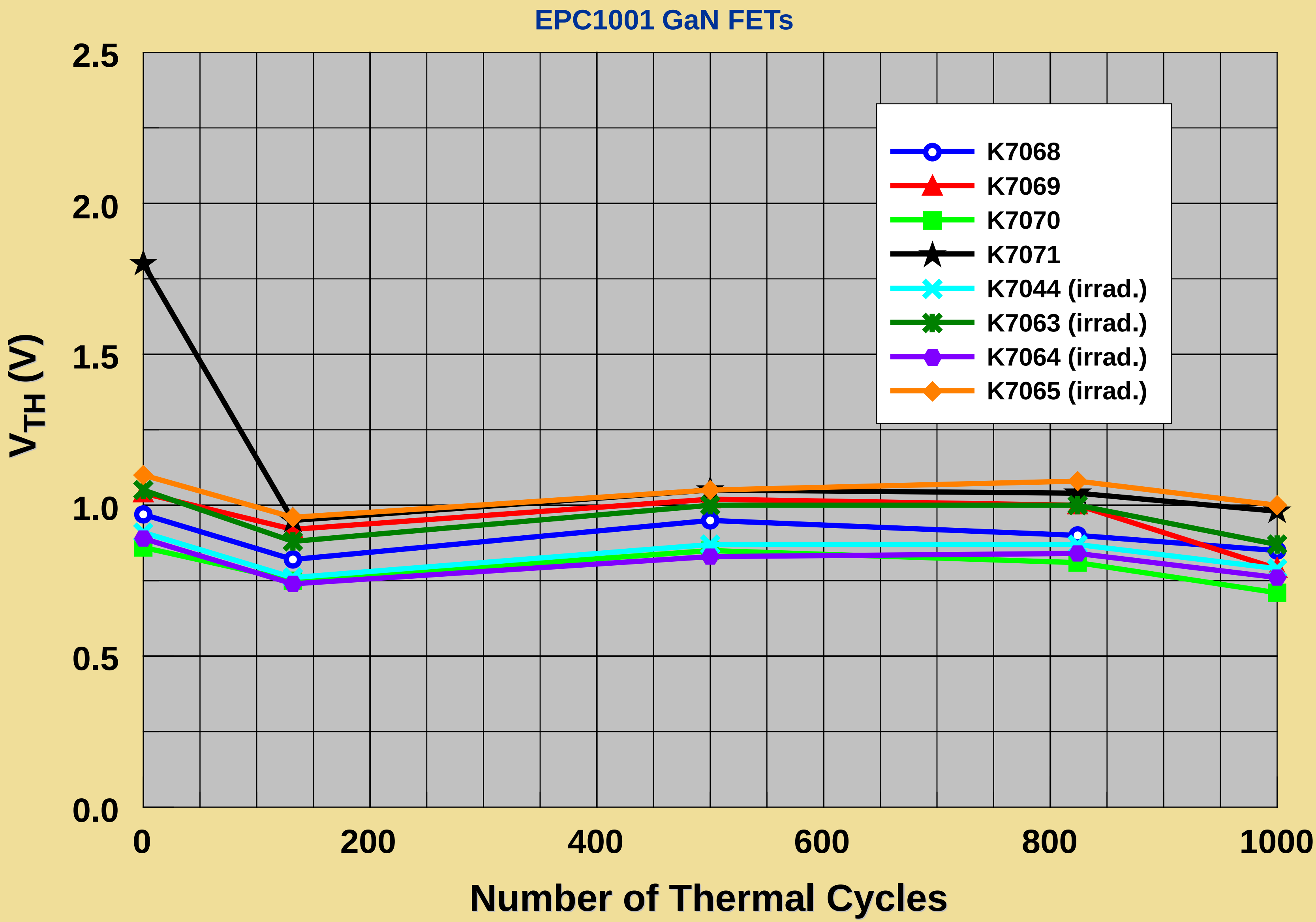


After 1000 Cycles

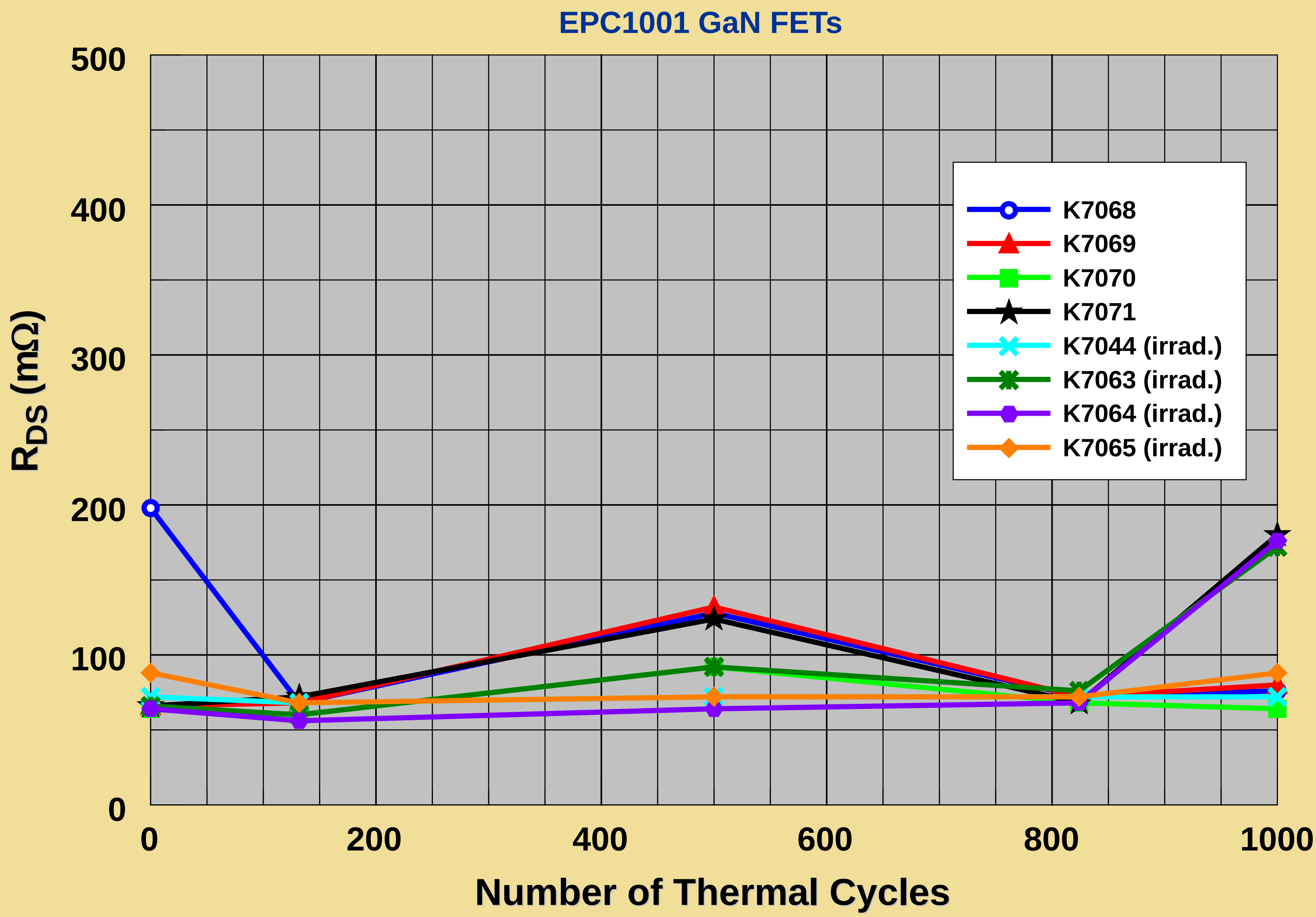
Drain Current of EPC1001 GaN FETs to 1000 Thermal Cycles



GATE THRESHOLD VOLTAGE, V_{TH}



Drain-Source On Resistance, $R_{DS(ON)}$



OBSERVATIONS

- All eight GaN FETs remained functional after exposure to radiation followed by 1000 thermal cycles between -55 & +125 ^{0}C
- Main impact of radiation was increase in leakage current of devices
- Thermal cycling seemed to introduce inconsistent variation in I-V characteristic curves of the GaN FETs; notably in their transconductance
- V_{TH} of tested devices experienced an initial decrease with cycling but seemed to level off after exposure to about 130 cycles; possibly due to thermal conditioning
- For the $R_{DS(ON)}$ data, at 1000 thermal cycles the values of $R_{DS(ON)}$ occurred in two distinct clusters. A two-sample t-test ($p<0.005$) showed that the means of the clusters were different. The cause of the two distinct clusters is not known, but further investigation should probably wait until the second generation of the devices is tested.

SiC Power MOSFETs

Irradiated by GSFC at GSFC REF

- **Cree Z-FET transistor, part # CMF20120D**
- **http://www.cree.com**

Part #	CMF20120D
Drain-Source Breakdown Voltage, $V_{(VBR)DSS}$, (V)	1200
Gate Threshold Voltage, V_{TH} (V)	2.5
Drain Current, I_D (A)	33
Drain-Source On Resistance, $R_{DS(ON)}$ (mΩ)	80
Operating Temperature, T_C (°C)	-55 to +125
Package	Plastic TO-247-3

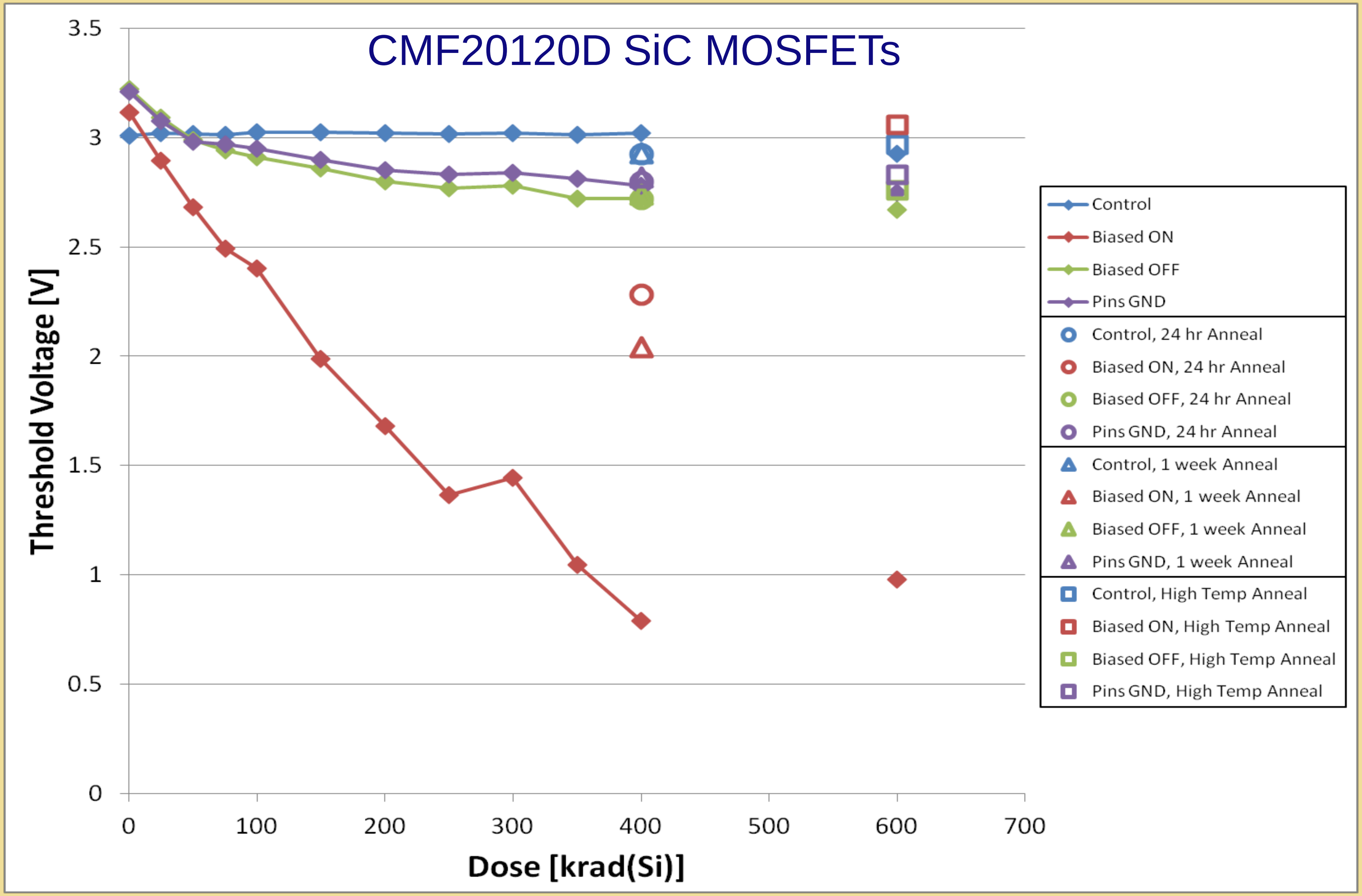
Radiation Testing

CMF20120D SiC MOSFETs

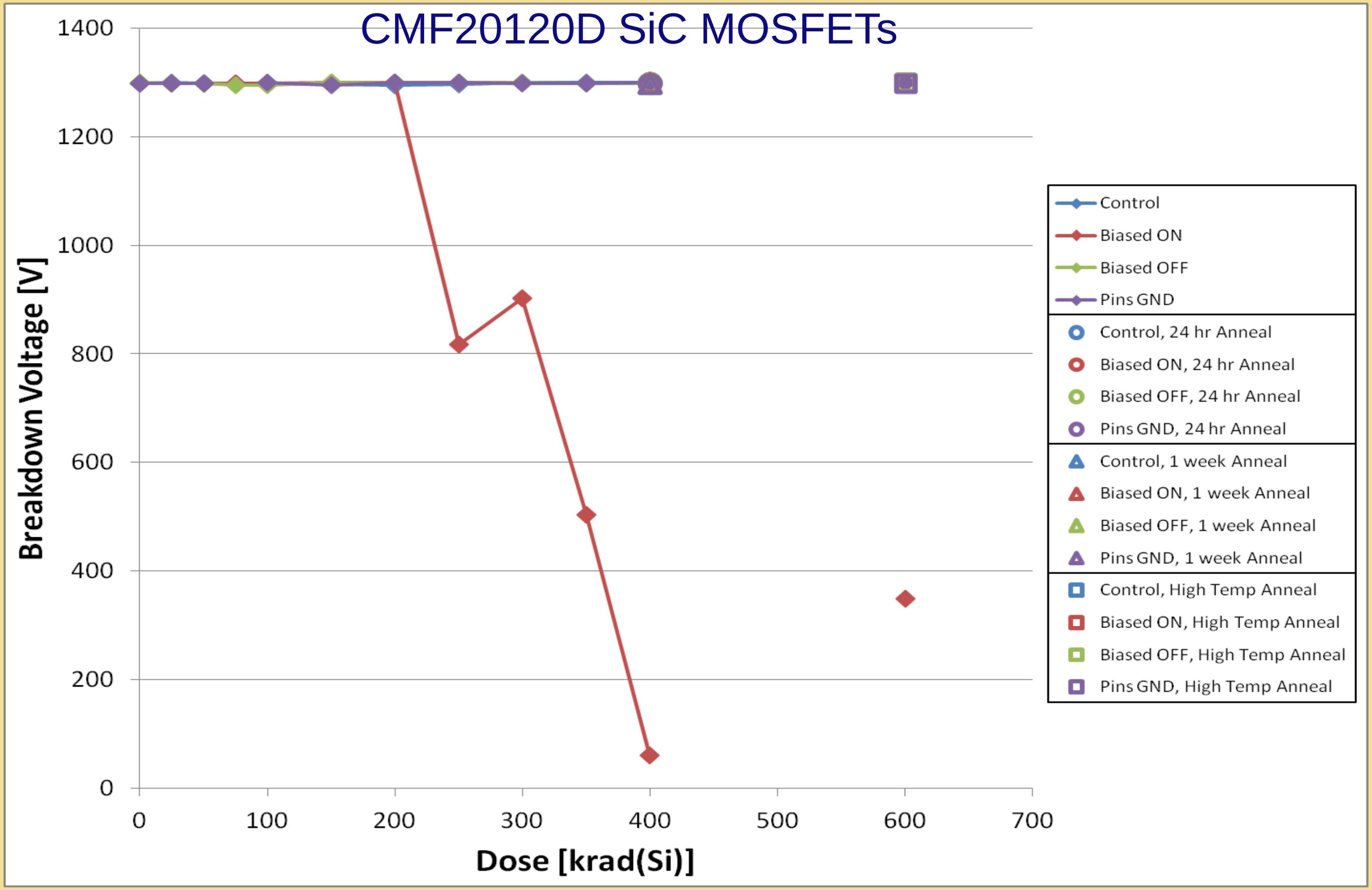
- Radiation done using Cobalt-60 source for a total dose of 600 krad (Si)
- Damage Criteria: gate threshold voltage shifted below 1V, or turn-on delay time increased by more than 200%
- Thermal annealing after 400 krad (one week at RT) and after 600 krad (one week @ 100 °C) per MIL-STD-883

Device Label	Condition
2	Control
5	Control
4	Irradiated, Biased ON: Vgs = 20V, Vds = 0V
7	Irradiated, Biased OFF: Vgs = 0V, Vds = 900V
9	Irradiated, GRND: Vgs = 0V, Vds = 0V

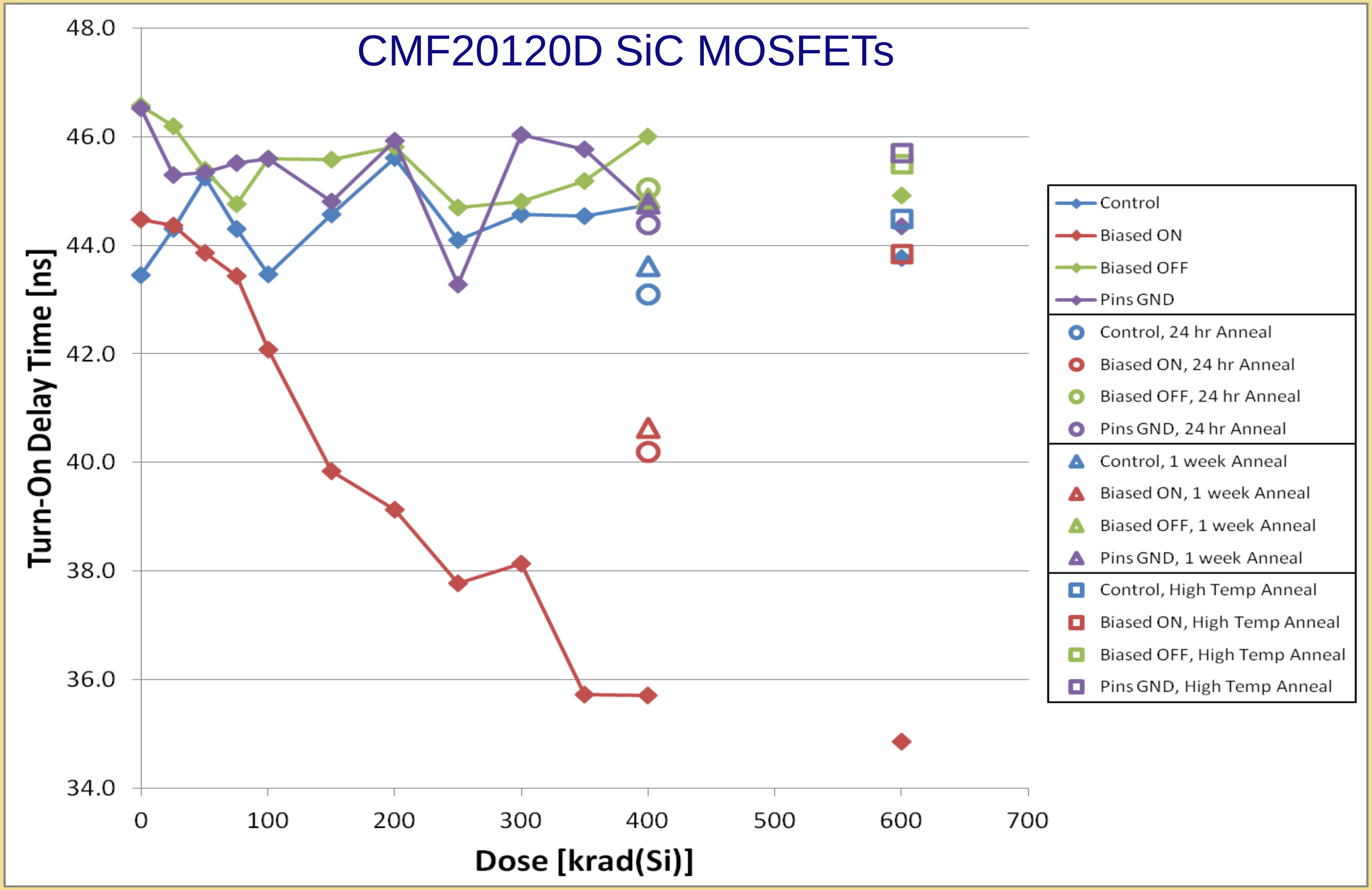
Threshold Voltage



Breakdown Voltage

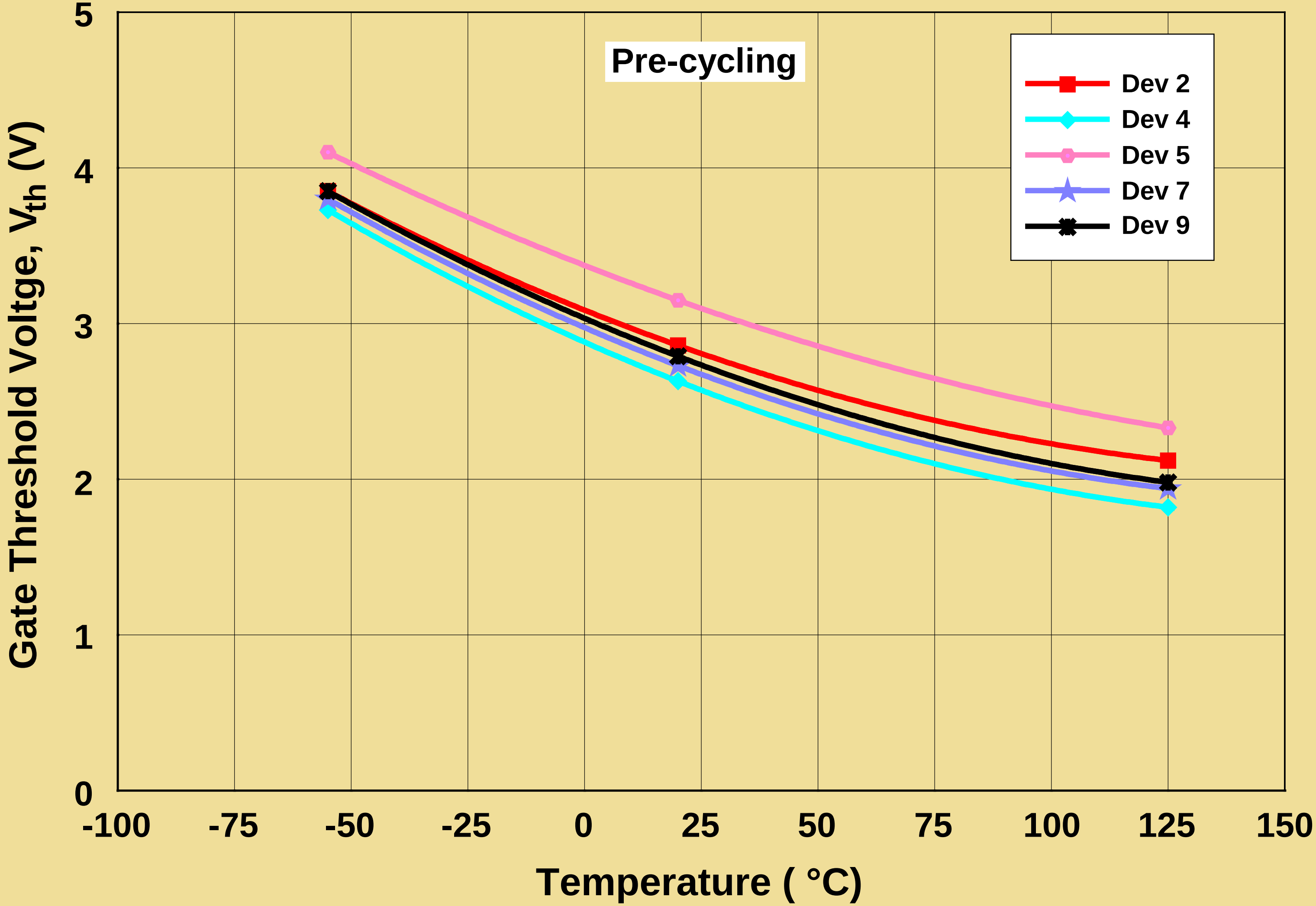


Turn-on Time Delay



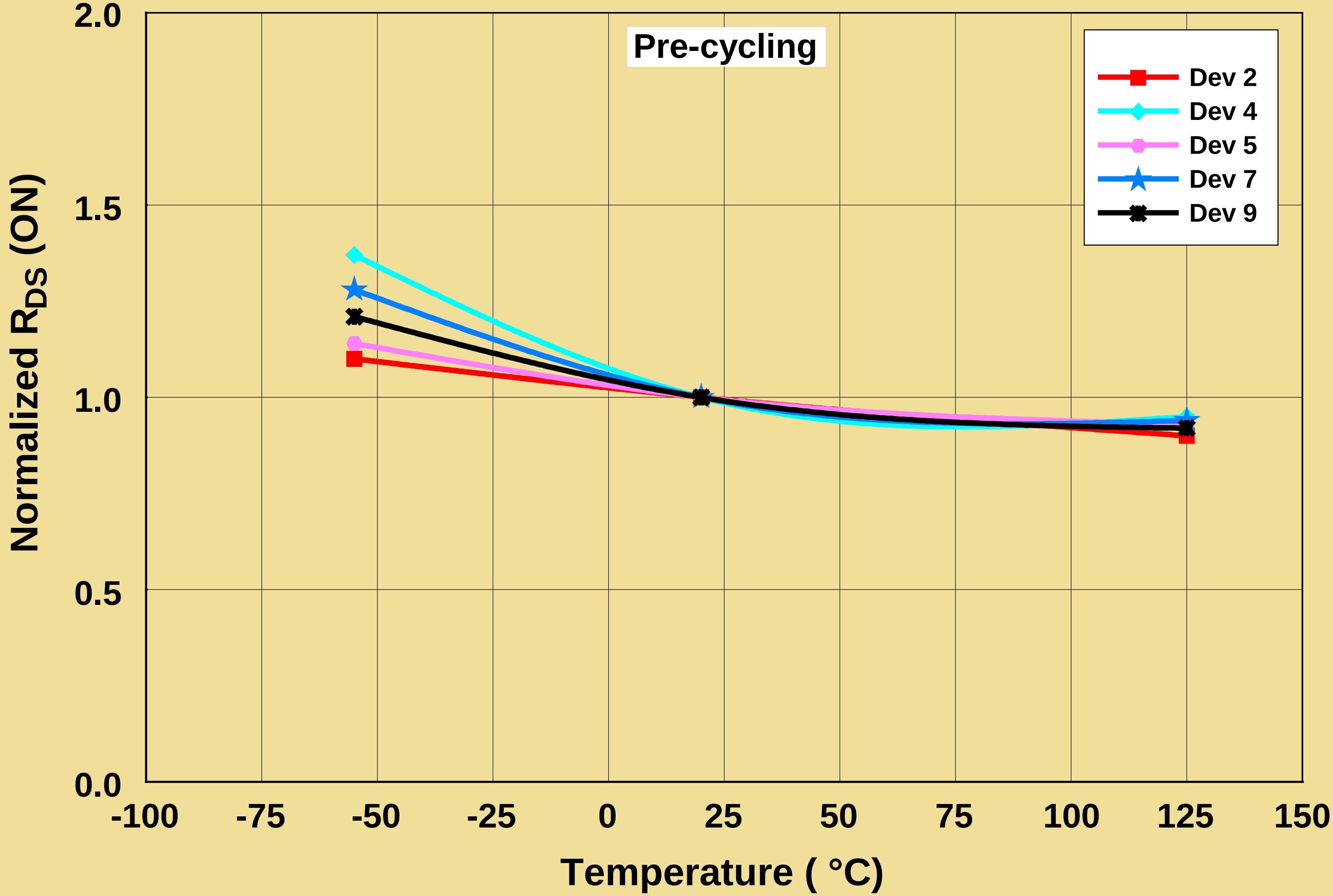
Threshold Voltage

CMF20120D SiC MOSFETs

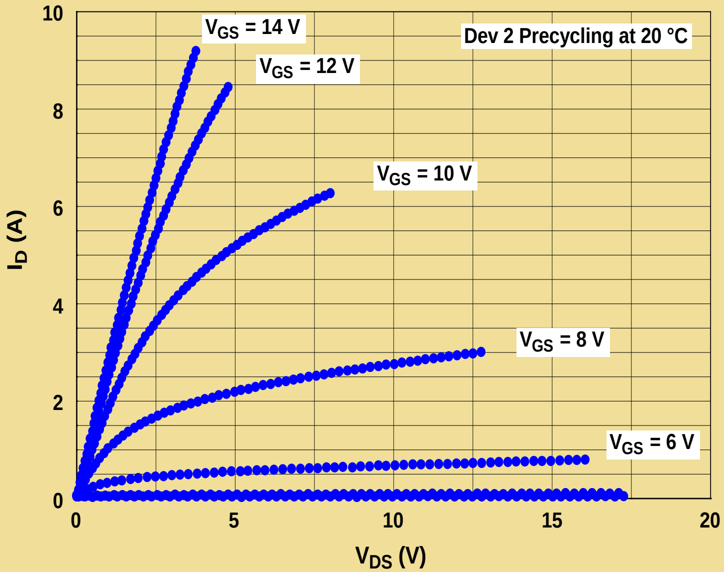


On-State Resistance

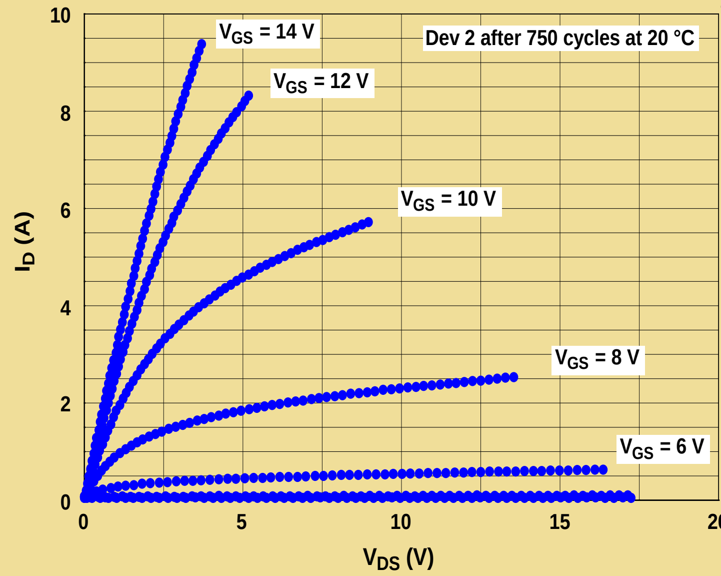
CMF20120D SiC MOSFETs



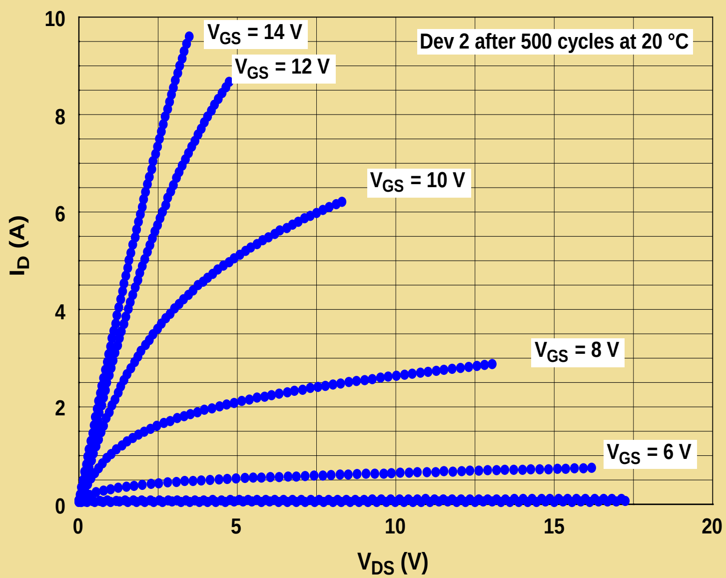
I/V Curves (SiC Dev 2, un-irradiated)



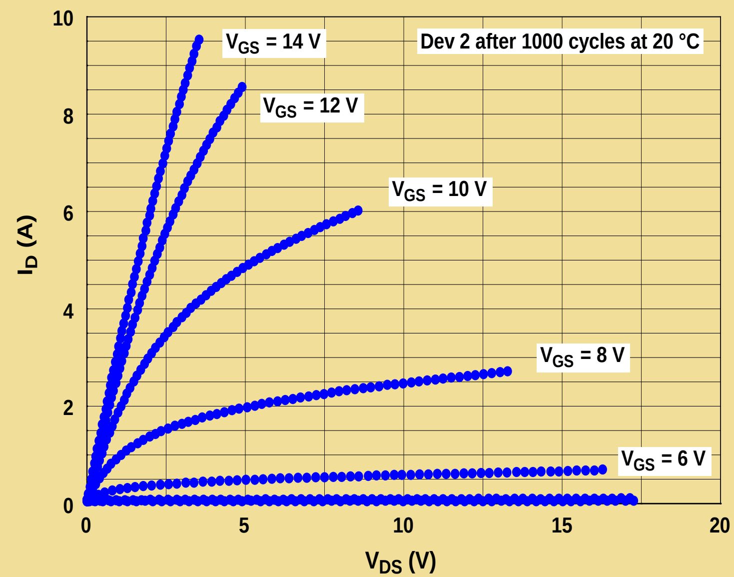
Pre-cycling



After 750 cycles

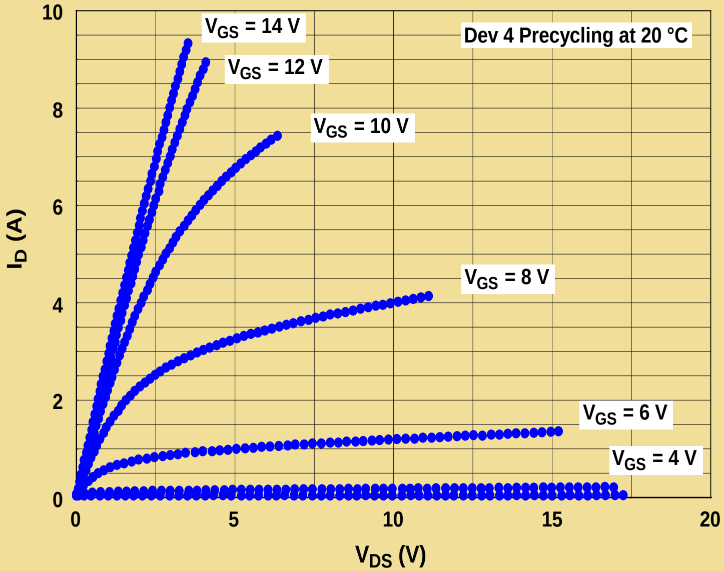


After 500 cycles

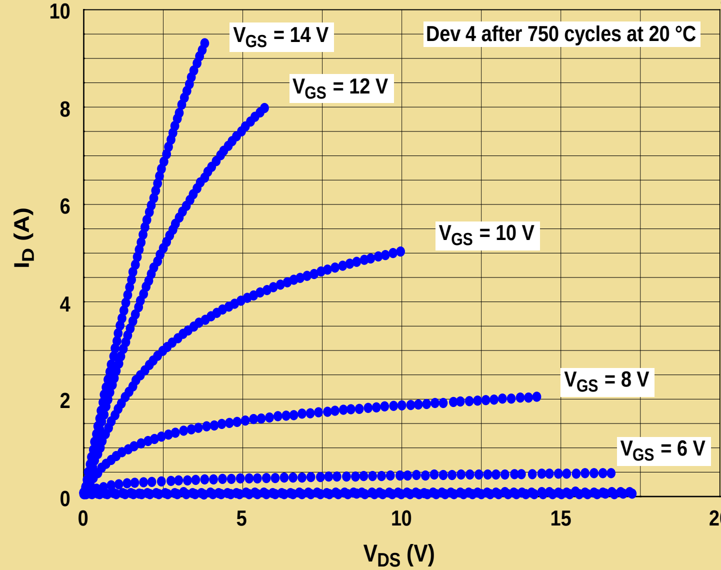


After 1000 cycles

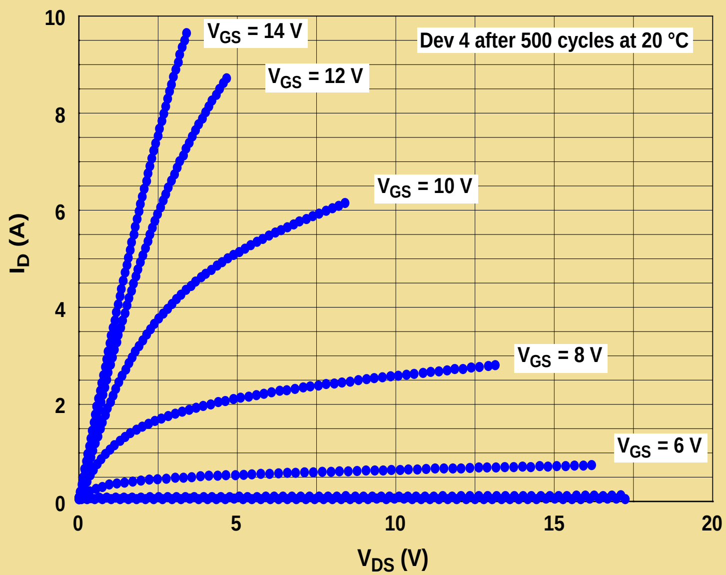
I/V Curves (SiC Dev 4 Biased ON, irradiated)



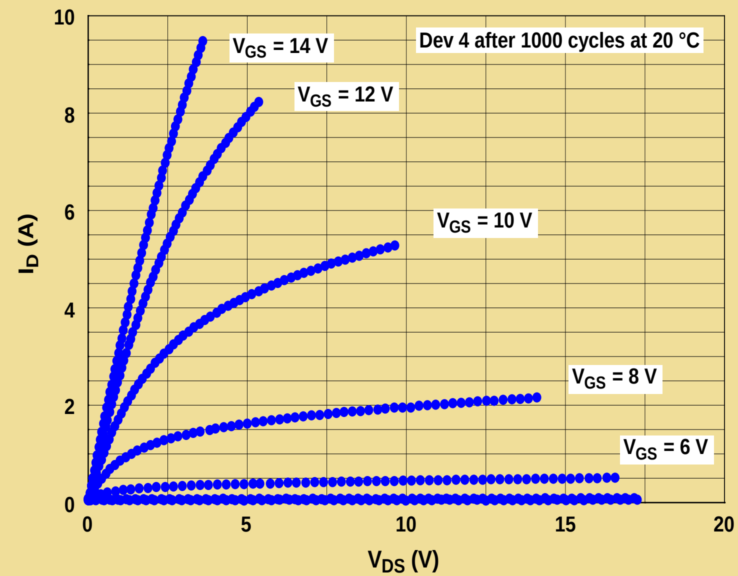
Pre-cycling



After 750 cycles

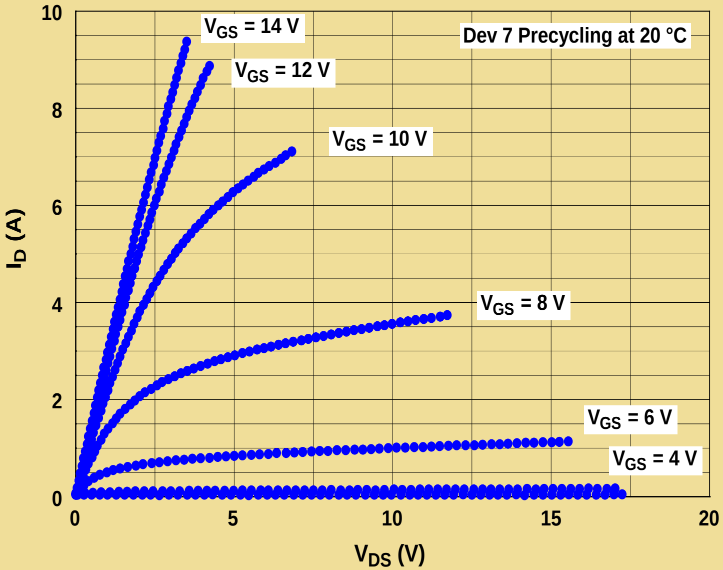


After 500 cycles

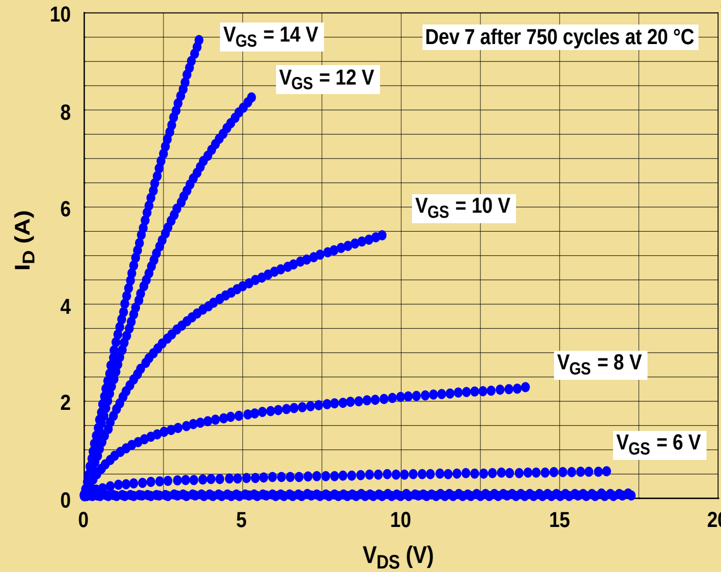


After 1000 cycles

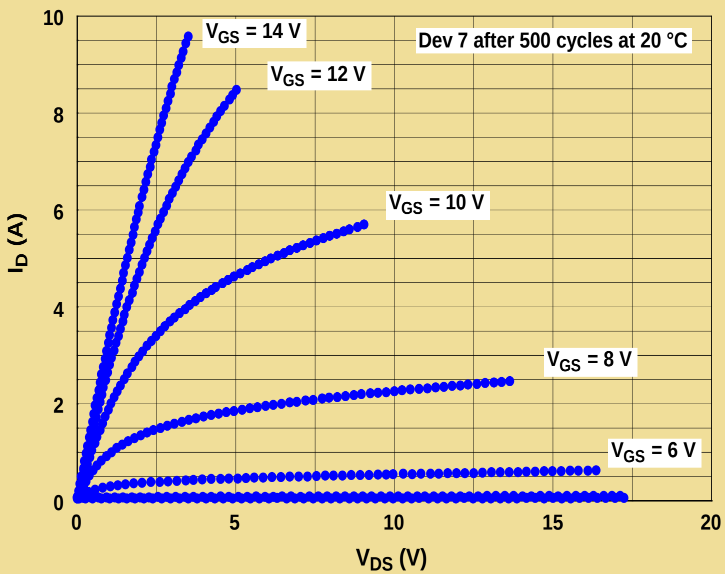
I/V Curves (SiC Dev 7 Biased OFF, irradiated)



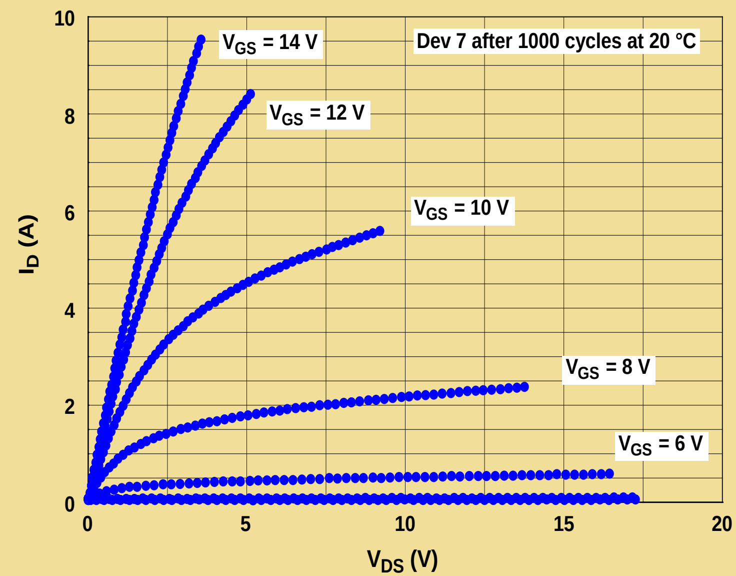
Pre-cycling



After 750 cycles

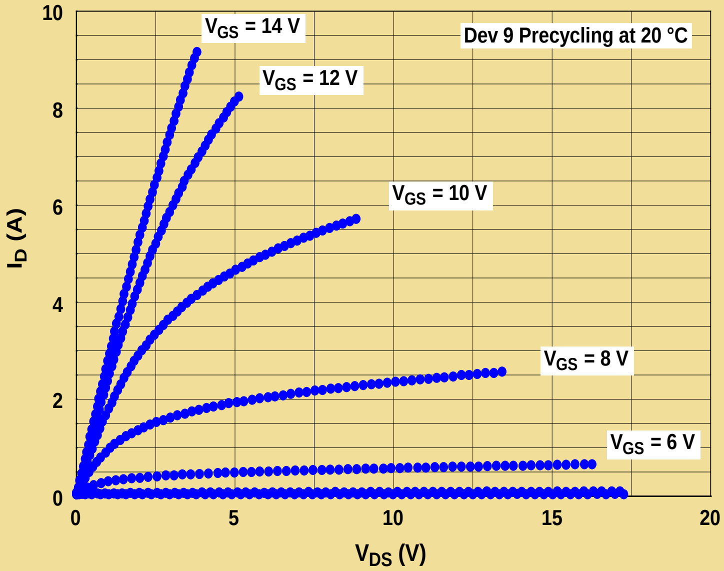


After 500 cycles

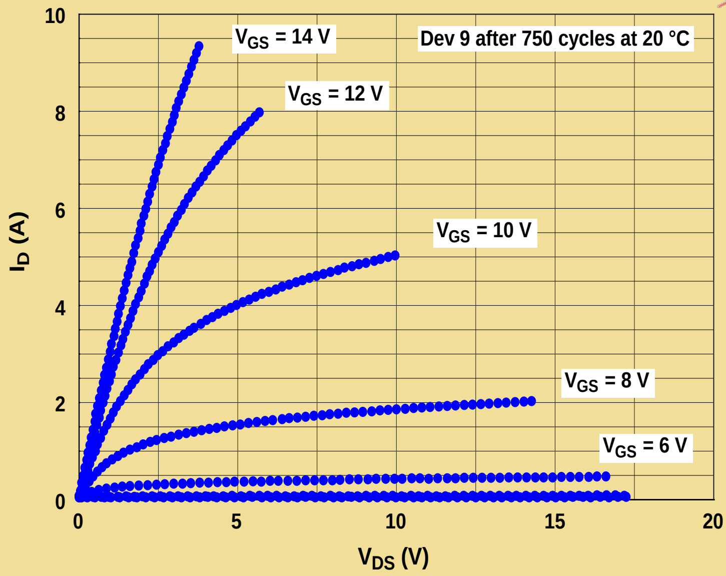


After 1000 cycles

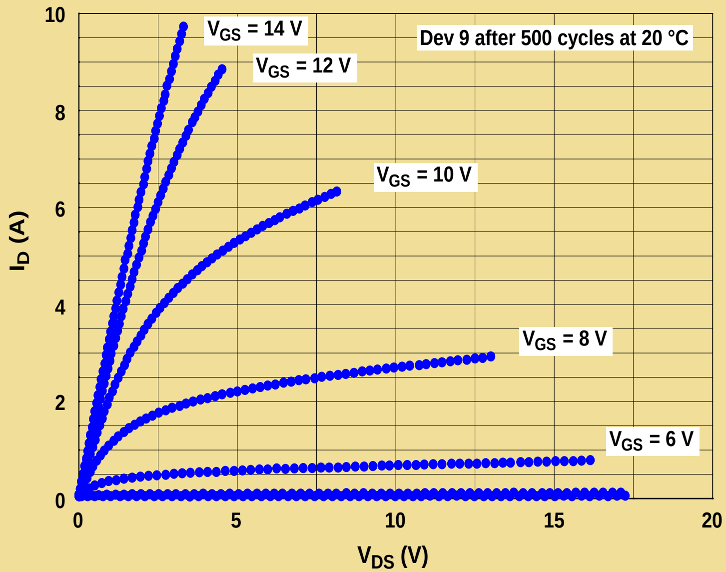
I/V Curves (SiC Dev 9 GRND, irradiated



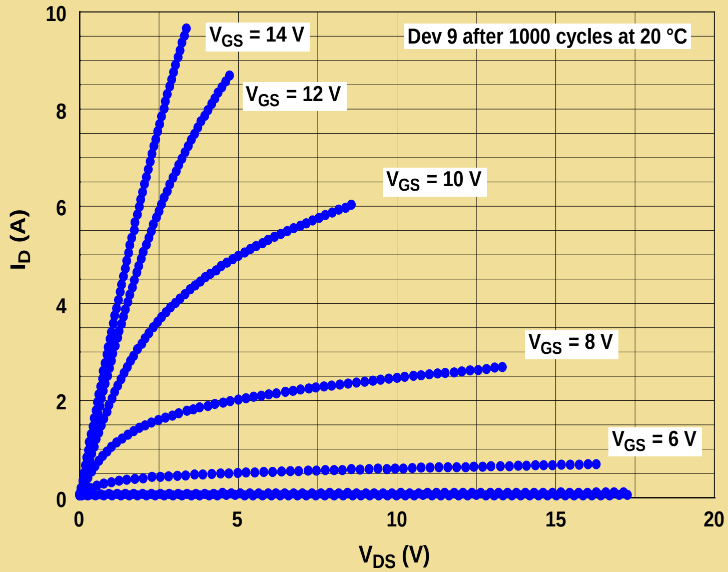
Pre-cycling



After 750 cycles



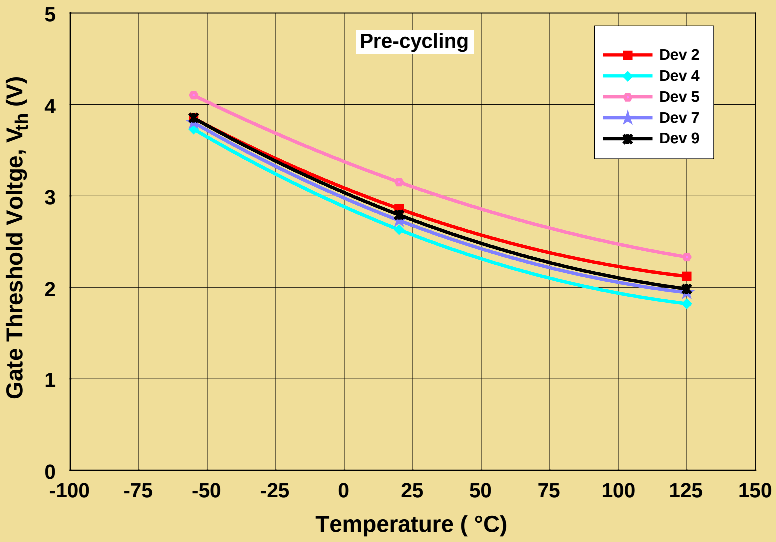
After 500 cycles



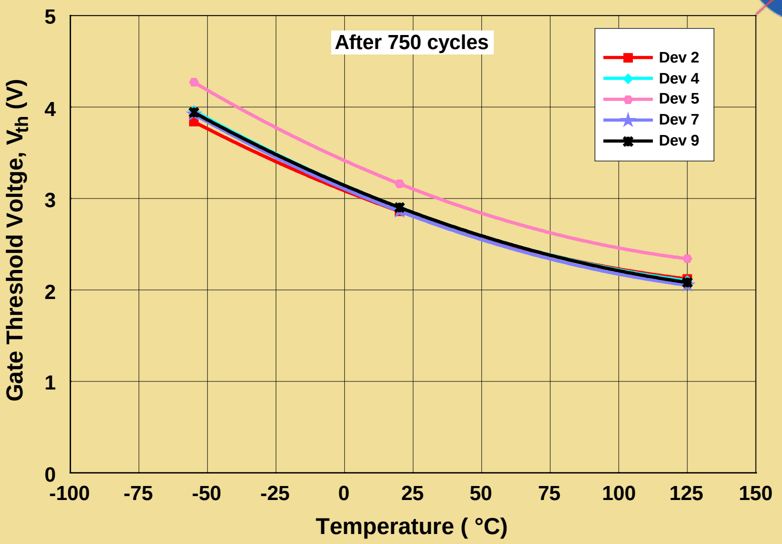
After 1000 cycles

Threshold Voltage

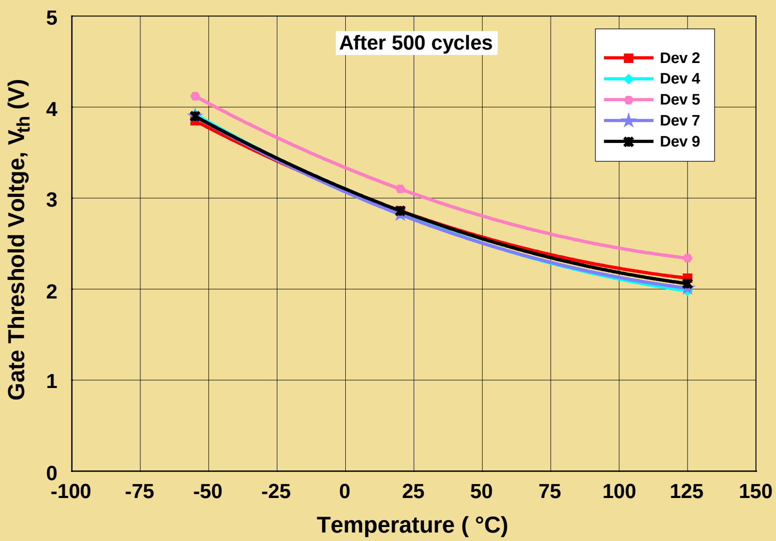
CMF20120D SiC MOSFETs



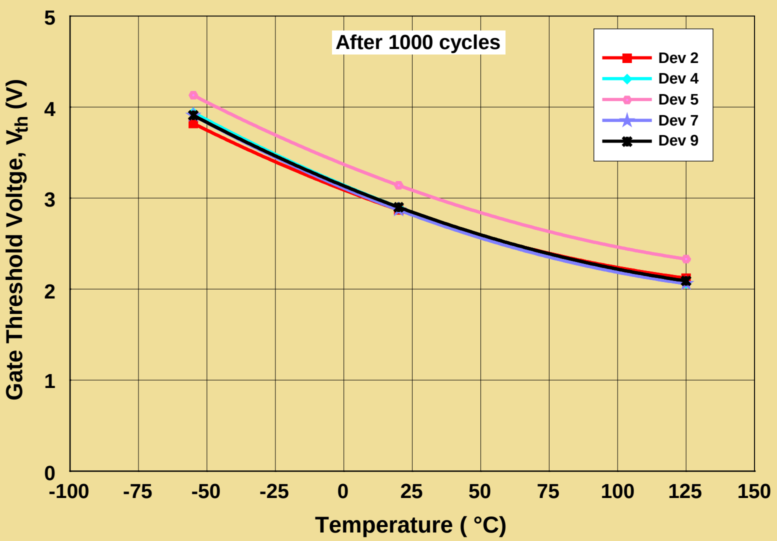
Pre-cycling



After 750 cycles



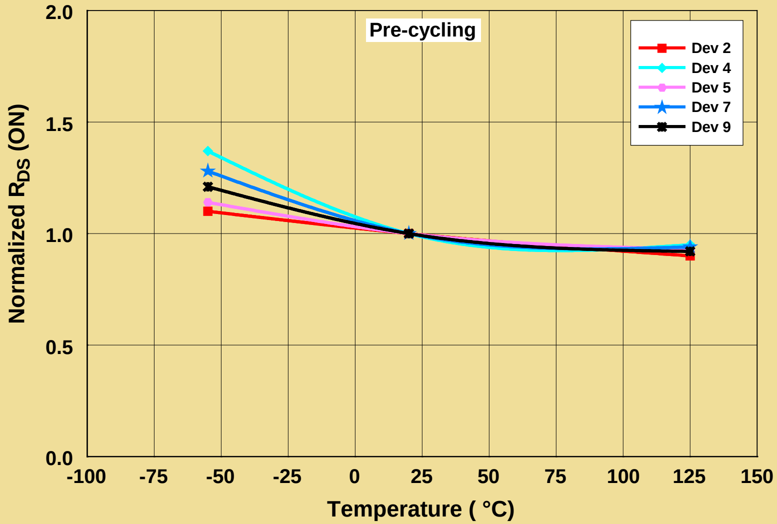
After 500 cycles



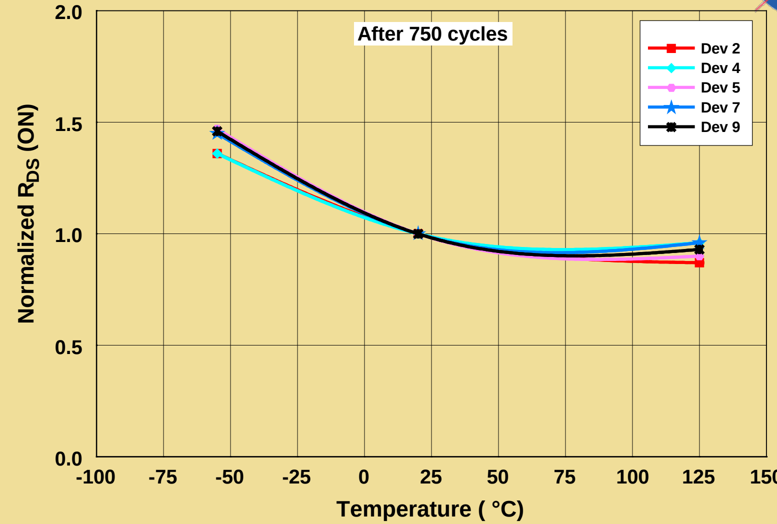
After 1000 cycles

On-State Resistance

CMF20120D SiC MOSFETs

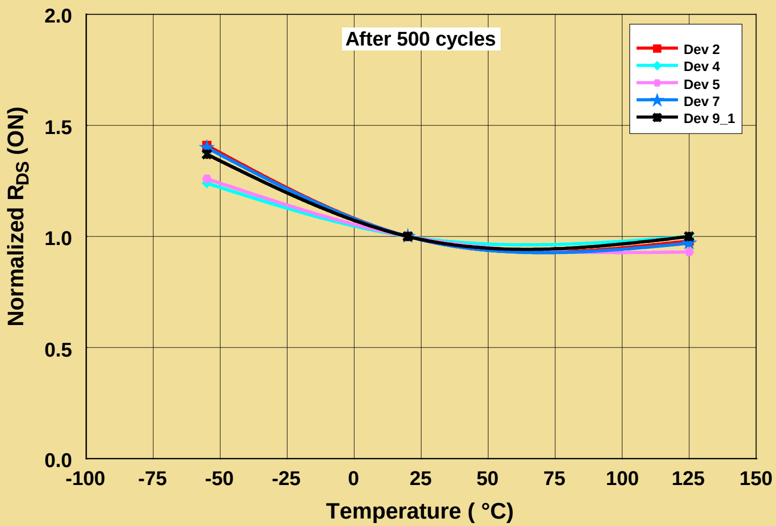


Pre-cycling



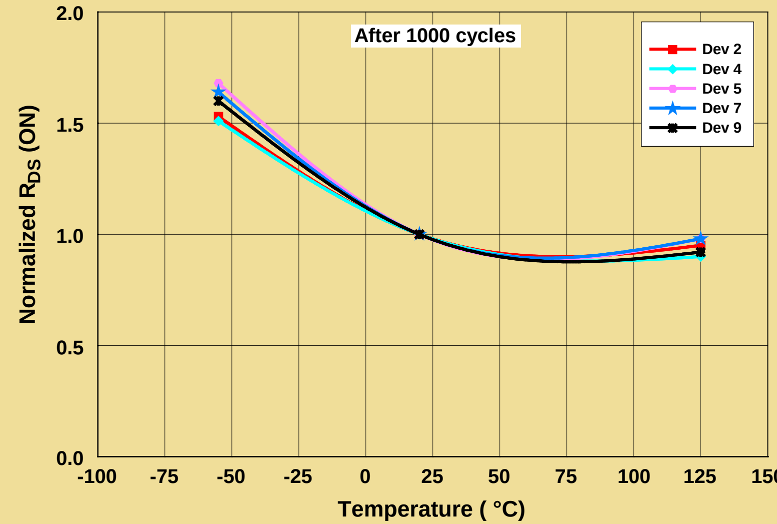
After 750 cycles

Continued Increase at -50 ºC



After 500 cycles

Increase at -50 ºC



After 1000 cycles

Continued Increase at -50 ºC

OBSERVATIONS

CMF20120D SiC MOSFETs

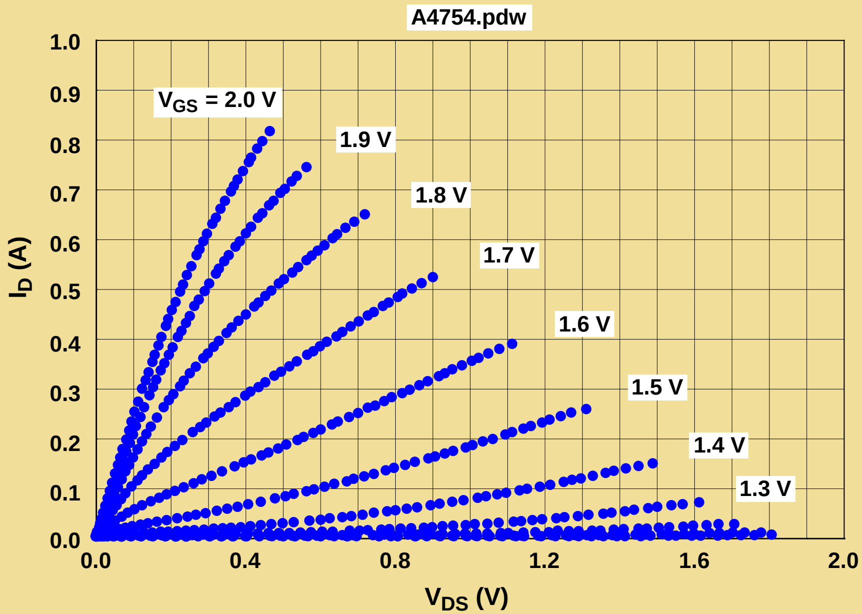
- *Radiation*
  - All parameters, except breakdown voltage, stayed within "specifications" to 600 krad
  - There is a time-dependent dose effect (evident between 250 and 300 krad steps)
  - Small sample size and large part-to-part variability

- *Thermal Cycling*
  - All devices maintained functionality after 1000 cycles
  - No effect on gate threshold voltage
  - On-state resistance increased with cycling, notably at low temperatures. Trend was same for control and irradiated parts
  - No alteration in device packaging or terminations

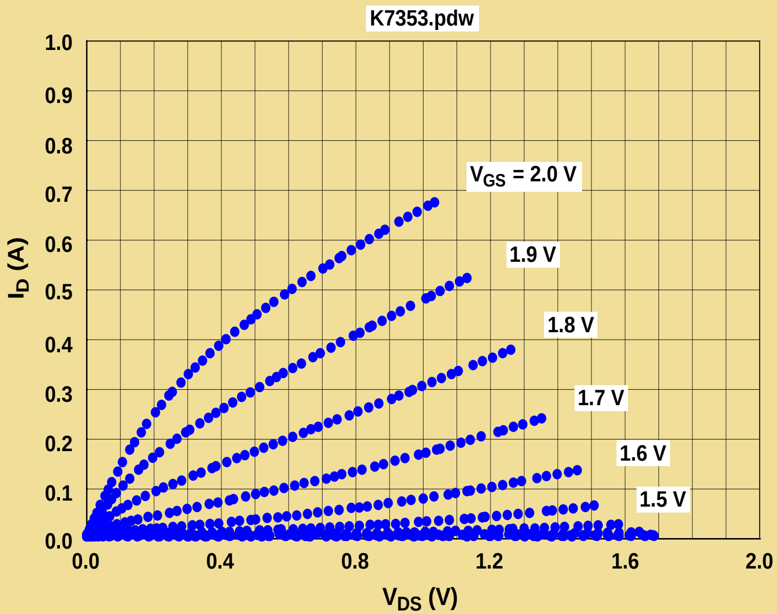
Second Generation GaN FETs

Irradiated by JPL at TAMU

EPC 2012 GaN FET (Rated 200V, 3A, 100mΩ), Precycling @ 20 ºC



Control (un-irradiated)



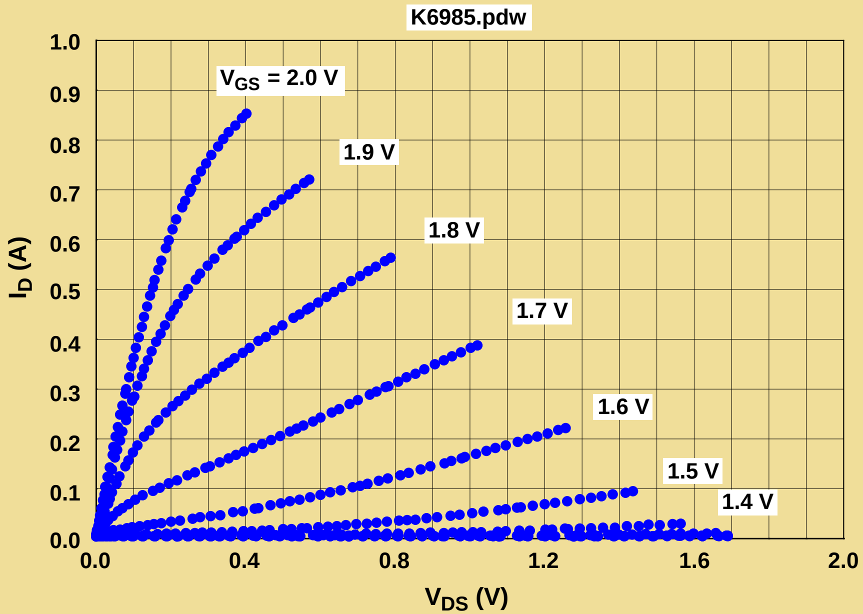
Irradiated

Decrease in Transconductance

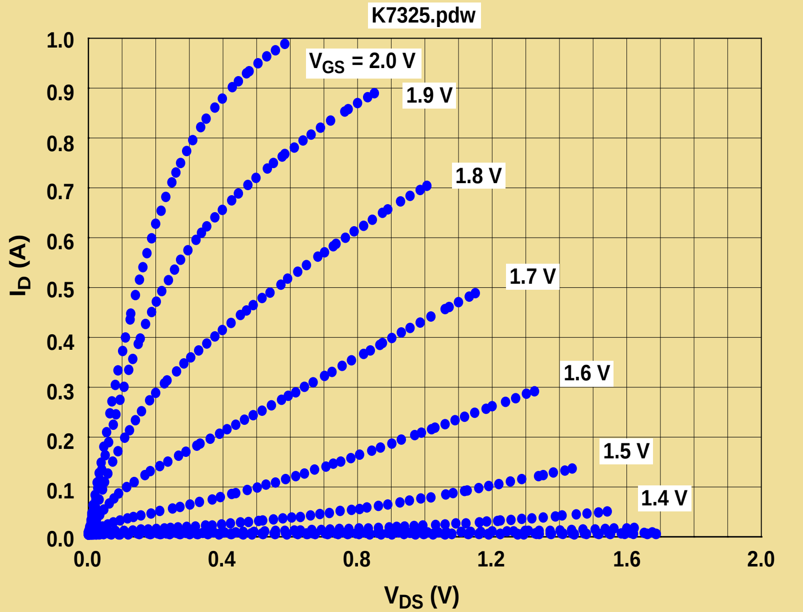
Second Generation GaN FETs

Irradiated by JPL at JPL

EPC 2014 GaN FET (Rated 40V, 10A, 16mΩ), Precycling @ 20 ºC



Control (un-irradiated)

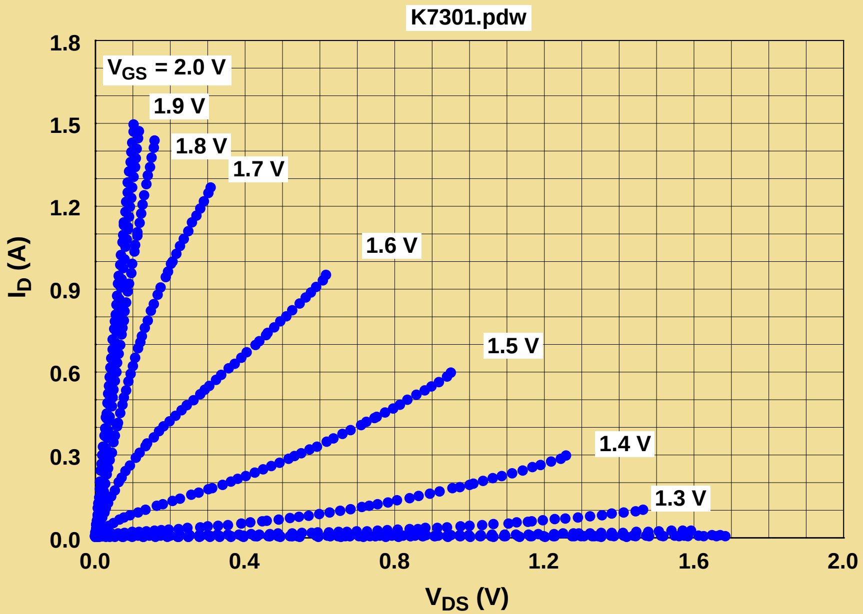


Irradiated
Slight Increase in Transconductance

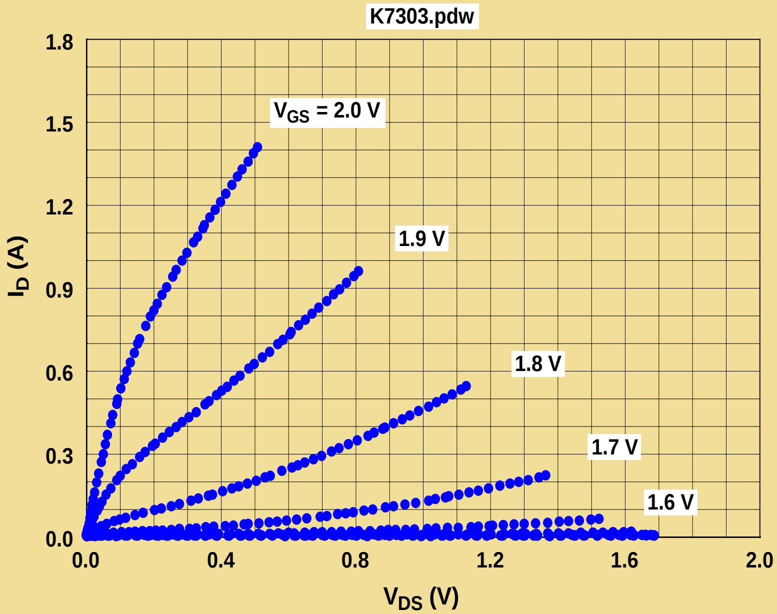
Second Generation GaN FETs

Irradiated by JPL at TAMU

EPC 2015 GaN FET (Rated 40V, 33A, 4mΩ), Precycling @ 20 ºC



Control (un-irradiated)



Irradiated

Decrease in Transconductance

Planned Work

- Conduct multi-stress tests (electrical/thermal) on these control and irradiated GaN & SiC power devices
- Perform overstress tests to determine failure mechanisms
- Repeat work on newly-developed GaN and SiC COTS power devices in support of NEPP Program

ACKNOWLEDGMENT

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