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Satellites International Limited

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Hambridge Road
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under contract to

The European Space Agency

ESTEC Purchase Order No. 102282

TMS320C25 RADIATION TESTING

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Table of Contents

1 INTRODUCTION

1.1 Scope

This document presents the results of radiation testing performed by Satellites International Limited (SIL) under ESTEC Purchase Order No.102282. This involved recommissioning the Meteosat P2 board and ESA Standard Dosimeter EGSE; and suitably modifying it for the purpose of radiation testing. The EGSE was interfaced to a PC to enable the test results to be monitored and logged. Total Dose and Single Event Upset (SEU) testing was then performed at AEA Technology, Harwell in association with ESTEC, SAGEM and Texas Instruments, France. Test reports issued by Texas Instruments and AEA Technology are appended to this document.

1.2 Background

Future space applications will require ever increasing processing power. Before a high performance device can be submitted to a design it is necessary to gain a degree of confidence as to its flight worthiness. The Texas Instruments TMS320C25 has been identified as a possible candidate and this report provides an initial evaluation of its radiation performance.

The experiment is designed to provide data on two different types of radiation effects.

Total Dose: this is the long-term cumulative effect of ionising radiation which results in increased power consumption and changes in the input and output levels of a CMOS chip until eventually it becomes inoperative.

Single Event Upset: caused by a high energy particle which results in a bit flip of a memory cell, where a '1' becomes a '0' or vice - versa. These events are non-destructive to the chip, but clearly corrupt the stored data.

Satellites International Limited (SIL), in collaboration with SAGEM and Texas Instruments (TI), France, designed and implemented an experimental board using the TMS320C25 for the Meteosat P2 spacecraft. The experiment is operating successfully in orbit and SIL is actively involved in processing and evaluating the flight data on a routine basis. The engineering model of the board flown on Meteosat P2 has been used as the basis of the test hardware.

2 TEST SETUP

The test hardware is based on the engineering model of the Meteosat P2 flight hardware. It is controlled by an adapted version of the Electrical Ground Support Equipment (EGSE) that was used to commission the original flight hardware. The relevant data monitored by the EGSE is logged and analysed by a PC. A block diagram of the hardware is shown in Fig 2.1

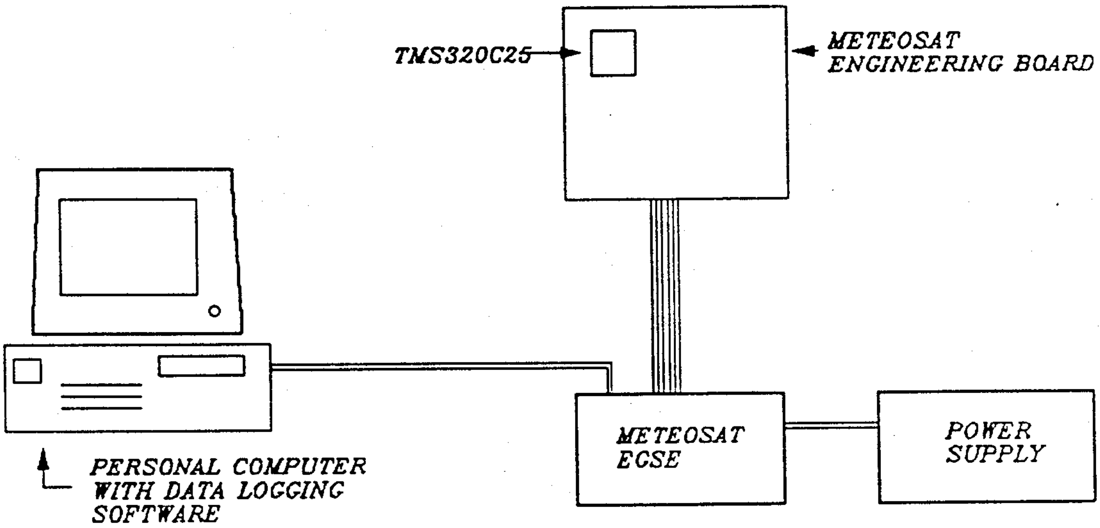


Figure 2.1 TMS Test Hardware

2.1 Test Description

Initially the TMS320 is in standby mode. The test cycle is initiated by the EGSE as an active low pulse on the SAMPLE TM input. After 426ms the TMS320 comes out of standby mode and performs a self test lasting 26ms. During this active time window the EGSE monitors the TMS supply current.

Approximately 1.76 seconds after SAMPLE TM the TMS320 performs a test of one of the 32 k x 8 static RAMs, and approximately 1.57 seconds later it tests the other SRAM. The RAM tests last approximately 0.6 secs and between the tests it returns to standby mode. During the SRAM tests the EGSE monitors the respective SRAM supply currents.

Approximately 6 seconds after issuing a SAMPLE TM pulse, another SAMPLE TM pulse is sent by the EGSE. The TMS320 responds by returning a status word on SDO reporting the results of its test. A further 6 seconds later the EGSE sends another SAMPLE TM. During this period the TMS320 is essentially in standby mode. It responds to the SAMPLE TM by returning a zoom status word which gives information to elaborate on the information contained in the previous status word. This SAMPLE TM also restarts the sequence. The complete process is shown graphically in figure 2.2

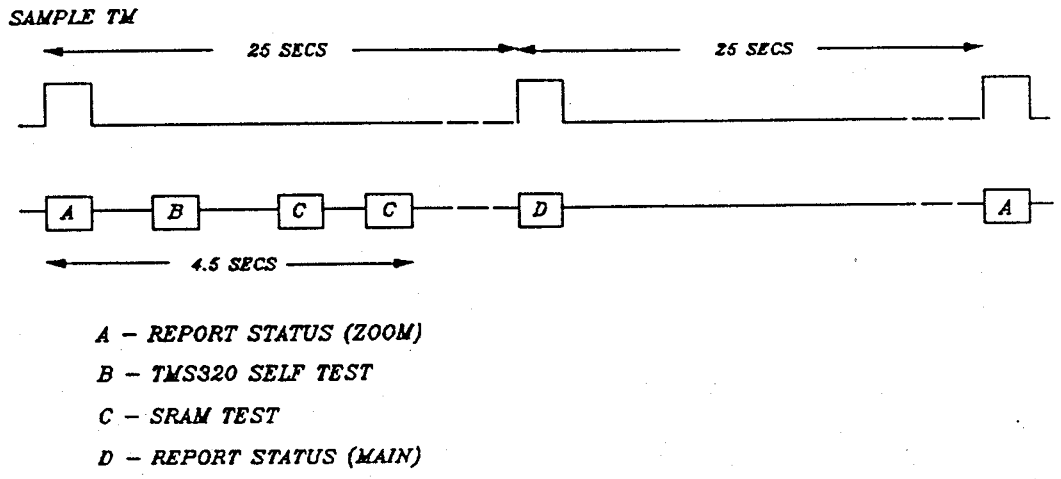


Figure 2.2 TMS320 Test Cycle

2.2 Test Hardware

As already mentioned the test hardware is based on the Meteosat engineering model and EGSE. However, to perform the tests certain modifications were necessary. The TMS320 latch up protection on the Meteosat engineering model was disabled to avoid triggering due to an increase in supply current during irradiation. Also to enable the TMS320 to be irradiated without affecting the ancilliary electronics, a flying lead containing the chip and its clock circuitry was manufactured so that it could be operated external from the Meteosat board.

The EGSE required modification to reduce the period between SAMPLE TM pulses from 25 seconds (necessary to commission the flight board) to 6 seconds. This was chosen to give a more practical data acquisition rate, and is essentially the minimum necessary for the TMS320 to complete its tests. An interface was also added to the EGSE to communicate with the PC.

2.3 Test Software

This was written in Turbo Pascal and was responsible for logging the time, TMS320 status and TMS320 supply current. It also monitored the SRAM supply current, although this was not essential. All data was displayed on the screen numerically, and, for the supply currents, graphically. The software also decoded the status in order to count the number of upsets in the different areas in the TMS320 and signalled the presence of latchup and failure both on the screen and audibly. The devices were deemed to have failed when the normal operational sequence of serial data of B0-40-B0-40 changed to a constant stream of 00-00-00-00.

3 TEST FACILITIES

Both total dose and SEU testing were performed at AEA Technology, Harwell. The test facilities are described in the following subsections:

3.1 Total Dose Testing

Total Dose evaluation was performed using a Cobalt - 60 source at the radiation facility at AEA Harwell. The irradiation facility is illustrated in figure 3.1. The EGSE and data acquisition system was installed outside the chamber and controlled the Meteosat board via a 15 meter cable. The device was operated external to the board using the special test lead so that the board could be shielded with lead.

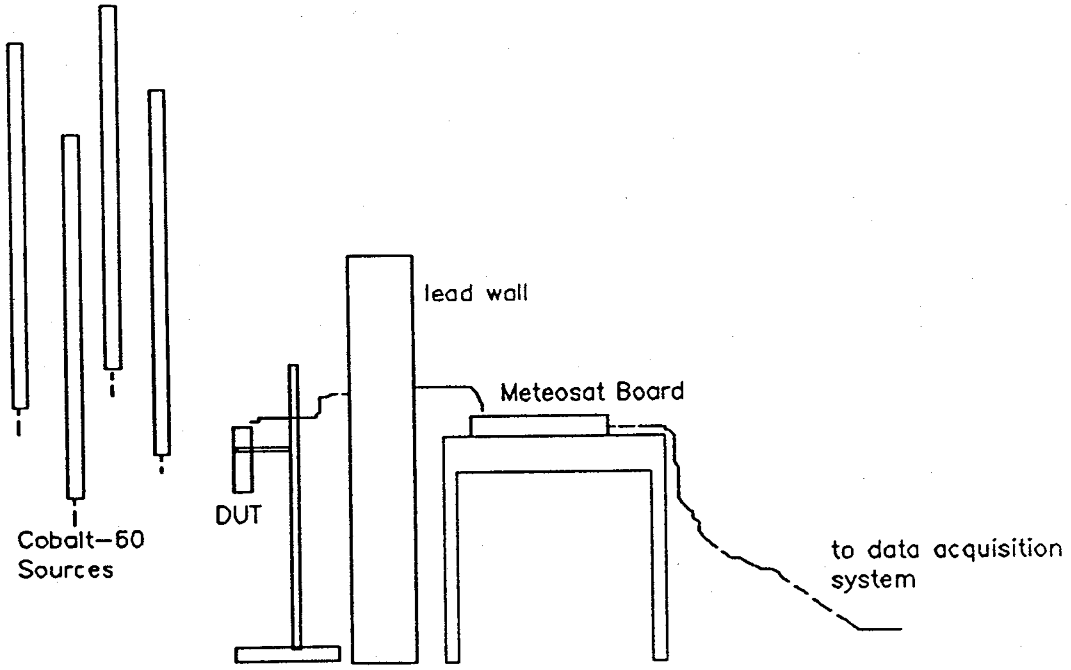


Figure 3.1 Cobalt - 60 Irradiation System

3.2 SEU Testing

SEU tests were performed using two facilities at AEA Harwell. An upper limit on SEU cross section was found using Californium-252. The system used is shown in figure 3.2. The Meteosat board was placed in the bell jar and connected to the EGSE and data acquisition system via a special airtight connector. To enable the device to be placed directly under the source it was operated external to the board using the special test lead.

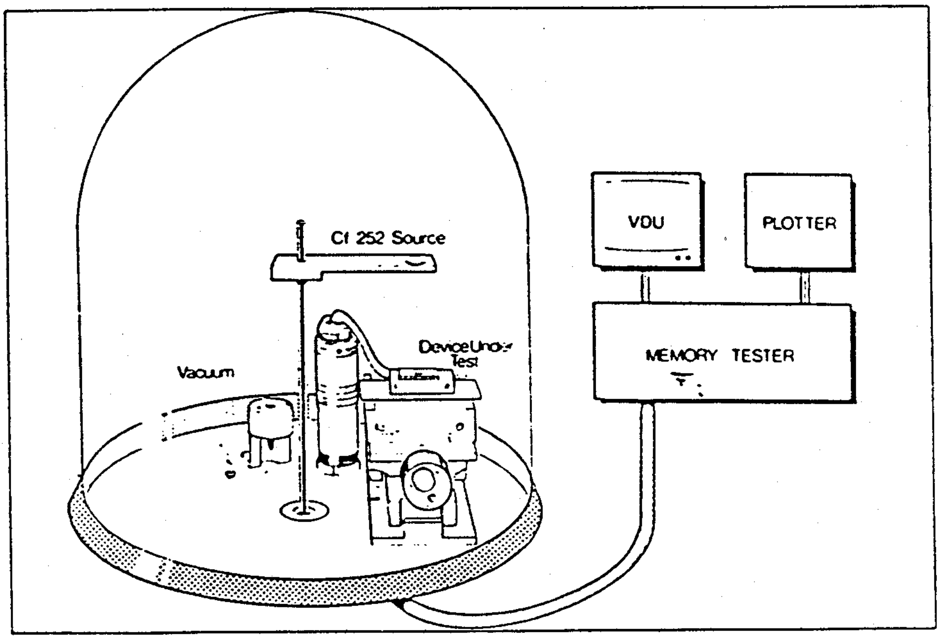


Figure 3.2 Californium - 252 Irradiation System

Lower LET ions were obtained using a tandem Van de Graaf accelerator. The irradiation system is illustrated in figure 3.3. The Meteosat board was placed in the chamber behind the DUT socket. The device was mounted on the DUT socket and connected to the board using the special test lead. The Meteosat board was connected to the EGSE and data acquisition system via an airtight connector.

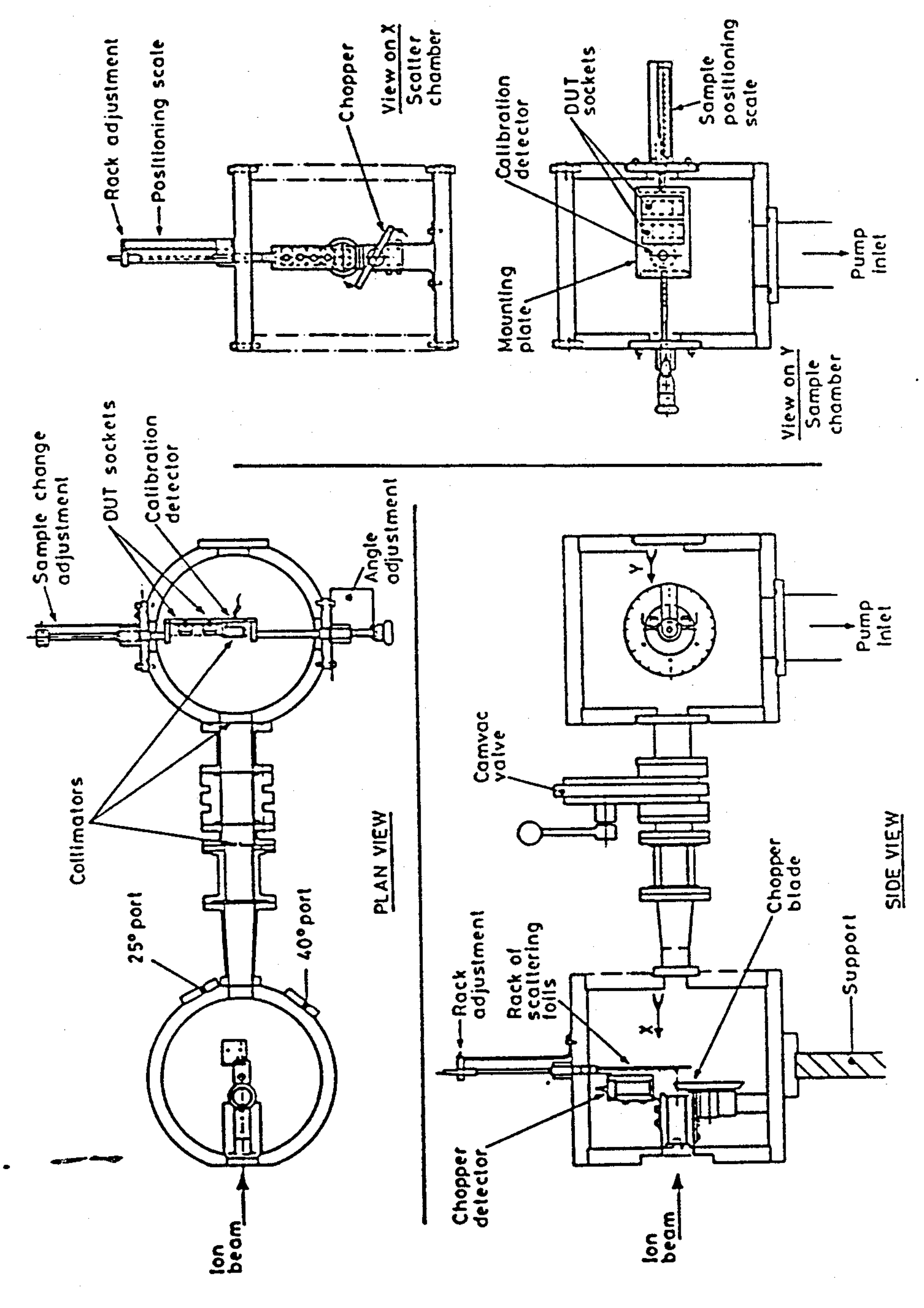


Figure 3.3 Van de Graff Irradiation System

The ion species and energies used are shown in Table 3.1

Species	Incident Energy (Mev)	Scattering Energy (Mev)	Scattering Angle (deg)	LET in Si (Mev/mg/sqcm)	Range in Si (um)
Cf-252	-	-	-	43	15
Chlorine	45	41.4	40	18.5	11.5
Oxygen	35	33.7	40	5.4	22.8

Table 3.1 Ion Species

4 TEST PROGRAMME

Total Dose testing was performed on the 40 MHz devices during the week beginning 27 July 1990. The devices were monitored using the modified Meteosat board, EGSE and data acquisition equipment. Three devices were irradiated to functional failure. One device was then irradiated to 70% of the failure dose and one to 30% of the failure dose.

Once removed from the chamber, the operational status of the devices was checked in a Texas Instruments supplied Evaluation Board.

Single Event Upset testing was performed during the two weeks commencing 10 September 1990. Again, the devices were monitored using the modified Meteosat board, EGSE and data acquisition equipment. Ten devices were irradiated: five of the 40 MHz version and five of the 50 MHz version.

Total dose testing of the 50 MHz device was performed on 9 October 1990.

5 RESULTS

5.1 Total Dose Testing

Two versions of the TMS320C25 were tested : a 40MHz version and a 50MHz version

5.1.1 Total Dose: 40MHz Device

For the 40MHz version the dose rate was approximately 14 kRad/hr.
3 devices were tested to functional failure. The device numbers and failure doses are shown in Table 5.1

Device Number	Failure Dose
6	6.7 kRad
7	6.4 kRad
8	6.5 kRad

Table 5.1 40 MHz TMS320 Failure Dose

Device Number 2 was then irradiated to 30% of the failure dose, and device Number 3 to 70% of the failure dose.

Following irradiation, the failed devices were tested in a Texas Instruments (T.I.) supplied Evaluation Board and were found to be still functional. Hence 3 further devices, numbers 10, 12 and 13, were irradiated to doses of 8 kRad, 10 kRad and 12 kRad respectively. At these doses, all showed failure in both the TI evaluation board and the SIL test hardware.

All the devices were then sent to T.I. for Mega-one testing. The results are summarised in Table 5.2

Device Number	Total Dose (kRad)	SIL Test Hardware	TI Test Hardware	Mega-one Test Hardware	Mega-one Test one week later	Mega-one Test 2 weeks later
2	1.95	OK	OK	OK	OK	OK
3	4.55	OK	OK	FAIL	FAIL	FAIL
6	6.70	FAIL	OK	FAIL	FAIL	FAIL
7	6.40	FAIL	OK	FAIL	FAIL	OK *
8	6.50	FAIL	OK	FAIL	FAIL	OK *
10	8.00	FAIL	FAIL	FAIL	FAIL	OK *
12	10.00	FAIL	FAIL	FAIL	FAIL	FAIL
13	12.00	FAIL	FAIL	FAIL	FAIL	OK *

* 24 hr anneal at 150°C applied to these units.

Table 5.2 40MHz TMS320 Test Results

The results confirm that the devices have failed by approximately 6.5 kRads. The T.I. evaluation board shows functionality at 6.5 kRad because it does not perform sufficiently comprehensive testing. The Mega-one tester showed failure of device 3 at 4.55 kRad for low frequency tests (6.7kHz) but it was fully functional when tested at high frequency (40MHz).

The variation in supply current with total dose for the TMS320 is shown in Figure 5.1

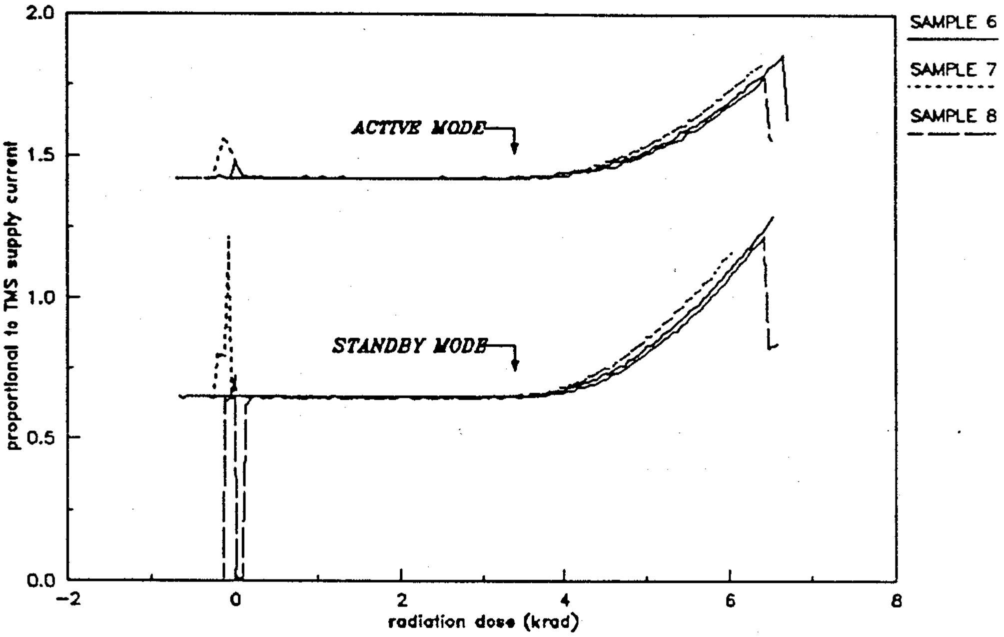


Figure 5.1 TMS Supply Current vs Radiation Dose

The two curves depict the variation in the supply current during the main status phase when the device is active, and the zoom status phase when it is in standby mode. It can be seen that the supply current begins to increase at a dose of 4 kRad. The correlation between devices is excellent.

5.1.2 Total Dose : 50MHz

For the 50MHz version the dose rate was approximately 13 kRad/hr. Three devices were tested to functional failure . The device numbers and failure doses are shown in Table 5.3

Device Number	Failure Dose
2	5.53 kRad
3	5.53 kRad
4	5.53 kRad

Table 5.3 50 MHz TMS320 Failure Dose

Device number 5 was then irradiated to 70% of the failure dose.
They were all then sent to T.I. for further testing. The results from these tests have not been received.

5.2 SEU Testing

SEU testing was performed using Californium 252 and then various ion species in the Tandem Accelerator. The results for each source are summarised in tables 5.4 to 5.6 below. All upsets are seen in the TMS320 internal RAM.

Source : Californium - 252
Effective : LET : 43 MeV/mg/cm^2
Range : 15 um.

Device Number	Device Type	Upsets	Effective cross section (cm^2)
14	40MHz	158	5.97×10^{-3}
15	40MHz	120	6.09×10^{-3}
16	40MHz	115	6.38×10^{-3}
17	40MHz	127	5.93×10^{-3}
18	40MHz	122	5.90×10^{-3}
6	50MHz	125	5.81×10^{-3}
7	50MHz	147	5.19×10^{-3}
8	50MHz	118	5.38×10^{-3}
9	50MHz	121	5.12×10^{-3}
10	50MHz	116	5.29×10^{-3}

Table 5.4 SEU Test Results at an Effective LET of 43 Mev/mg/cm^2

Oxygen Beam
Effective LET : 5.4 MeV/mg/cm^2
Range : 22.8 um

Device No	Device Type	Events	Cross Section cm^2
16	40MHz	16	2.0×10^{-3}
8	50MHz	11	2.4×10^{-3}

Table 5.5 SEU Test Results at an Effective LET of 5.4 MeV/mg/cm^2

Chlorine Beam
Effective LET : 18.6 MeV/mg/cm^2
Range : 11.5 um

Device No	Device Type	Faraday		Chopper		Events	Cross Section (cm^2)
		Counts	Fluence	Counts	Fluence		
15	40MHz	437.6		723	2.55×10^{4}	88	3.46×10^{-3}
16	40MHz	468.2		529	1.86×10^{4}	83	4.46×10^{-3}
7	50MHz	404.8		746	2.63×10^{4}	63	2.40×10^{-3}
8	50MHz	430.4		761	2.68×10^{4}	74	2.76×10^{-3}
9	50MHz	610.8		2391	8.42×10^{4}	249	2.96×10^{-3}

Table 5.6 SEU Test Results at an Effective LET of 18.6 MeV/mg/cm^2

6 CONCLUSION

The Engineering Model of the TMS-300 experiment has been successfully recommissioned and it and the EGSE suitably modified to enable radiation tests to be performed. In association with ESTEC, SAGEM, Texas Instruments and the AEA Harwell, radiation testing has been performed.

The total dose hardness results for the TMS320C25 are in the range of 6.5 kRad for the 40 MHz version and 5.5 kRad for the 50MHz version. Annealing at room temperature does not return functionality. However, after a period of 24 hours at 150°C full functionality is restored.

The TMP version of the TMS320C25 was reported to have a tolerance in the region of 25 kRads. Texas Instruments made significant technology changes in progressing from TMP to TMS versions and further changes were made in progressing from 40MHz to 50MHz version. These have resulted in a device which has a total dose tolerance which will unfortunately be too low for many space applications.

Single Event upsets were only seen in the internal RAM. The TMS320 on the flight board, has suffered upsets in all the functional areas, although the majority have been seen in the internal RAM. For the internal RAM the SEU cross sections show good correlation between devices. The effective cross section for various LET values is shown in tables 6.1 and 6.2

LET (MeV/mg/cm^2)	Effective cross section (cm^2)
43	6×10^{-3}
18.6	4×10^{-3}
5.4	2×10^{-3}

Table 6.1 Effective Cross Section vs LET for the 40 Mhz Device

LET (MeV/mg/cm^2)	Effective cross section (cm^2)
43	5.3×10^{-3}
18.6	2.7×10^{-3}
5.4	2.4×10^{-3}

Table 6.2 Effective Cross Section vs LET for the 50 Mhz Device

Appendix A Report Supplied by Texas Instruments

esa / estec contract

aop/wk/301487

Purchase Order 102284 dated 14/06/1990

Radiation testing of 320C25 from TEXAS INSTRUMENTS

REPORT CONTENT

- POST RADIATION MEGAONE CHARACTERISATION REPORT
- LIST OF PARTS DELIVERED
- ICC VERSUS FRQUENCY AND VCC
- ORIGINAL CONTRACT COPY

TEXAS
INSTRUMENTS
FRANCE

This is the final report of the characterization work done on 320C25 samples submitted to total dose exposure , and anneal.
This report include total dose tests made on both 320C25 versions (50 Mhrz and 40 Mhz)

1) Total dose results on 40 Mhz version

Following the irradiation steps made in AEA HARWELL, we did Megaone test on 07/27 , then on 08/03 and on 08/09, 150 dc anneal was made 08/09 for 24h on 4 units, new measurements were then made on 10/18 and then on 01/15/91.

A surprise was found at first tests (07/27)when we measured unit #3 irradiated at 5 Krads and good at SIL and TI test board :
Some specific patterns in the test program were failing in particular test conditions (Low frequency). The use of very low frequency in the test program explained the miscorrelation between the application board and megaone test. (see page 4)

If anneal seems to happen at room temperature ,but after long time period . Units irradiated to failure started to recover functionnality after 3 monthes room temperature anneal.
The high temperature anneal (150 DC 24 hrs) recover 100% functionnality of the device even when irradiated up to 12 Krads.

At the end , I think we can consider the 320c25 as a 5Krad device when used in standard conditions (VCC = 5v Frequency over 10 Mhz)
Degradation mechanism can be explained by leakages in the circuit resulting in increase of ICC's currents and loose of functionnality due to the dynamic logic (sensitivity found first at low frequency high VCC).
We may note also the extreme reproductibility of the results from units to units (even when we go to detailed ICC values under irradiation)
Anneal occur quickly at high temperature and slowly at room temperature
This can be encouraging in finding better total dose tolerance using lower dose rates.

You will find following the data collected and some associated graphs.

IRRADIATION HARDWARE SUMMARY DESCRIPTION

	Frequency	*Test content and conditions*
SIL Hardware :	*20 Mhz*	*ExhaustiVe self test of 320C25* *Standard levels/timings*
TI test board :	*40 Mhz*	*Standard set of instruction execution* *Standard levels/timings*
Mega one tester : *Test program*	*6.7 Mhz Fmin* *40 Mhz Fmax*	*All parametrics measurements check* *All functionnal patterns* *Timming : Spec / loose* *Clock Duty cycle : Min / Max* *Levels : Spec / loose* *VCC : 4.5v / 5.5v*

FUNCTIONNAL TEST RESULTS

Unit #	Total Dose krads	H/W SIL	TI	07/26 M1	08/03 M1	08/09 M1	18/10 M1	01/15 M1
2	1.95	ok	ok	Good	Good	Good	Good	Good
3	4.55	ok	ok	Good HF Fail LF See note 1	Good HF Fail LF See note 1	Good HF Fail LF See note 1	Good	Good
6	6.70	F	ok	Fail HF Fail LF See note 2	Fail HF Fail LF See note 2	Fail HF Fail LF See note 2	Good HF Fail HF	Good
7	6.40	F	ok	Good HFLV Fail HFHV Fail LF See note 3	Fail HF Fail LF See note 3	Good	Good	Good
8	6.50	F	ok	Good HFLV Fail HFHV Fail LF See Note 3	Good HF Fail LF	Good	Good	Good
10	8.00	F	F	Fail HF Fail LF See note 2	Fail HF Fail LF See note 2	Good	Good	Good
12	10.00	F	F	Fail HF Fail LF See Note 4	Fail HF Fail LF See note 4	Fail HF Fail LF See note 4	Good HFLV Fail HFHV Fail LF	Good HF Fail LF
13	12.000	F	F	Fail HF Fail LF	Fail HF Fail LF	Good	-	Good

Note : LF low frequency
HF High frequency
HFLV High frequency low VCC (4.5V)
HFHV High frequency high VCC (5.5V)

Note 1 : Low frequency failed only on the restricted pattern list.
2 : High frequency failed only on the restricted pattern list.
3 : High frequency failed only at high VCC (5.5V) on the restricted pattern list
Unit is Good at low VCC (4.5V) high frequency
4 : Some patterns works at low Vcc high frequency
5 : Start to work at low frequency

** 24 hrs anneal at 150 dc applied to units 7,8,10 and 13
** between 08/03 and 08/09 measurements.

FUNCTIONNAL FAILURE MECHANISM

When irradiated, the first failure mechanism to occur is at low frequency , then high frequency fail.
On VCC side the most critical VCC is VCC max (5.5V) then VCC min (4.5V) .

Miscorrelation experienced between SIL hardware and TI test board (at 6.5 krad dose) is probably due to the frequency difference between SIL hardware (20 Mhz) and TI test board (40 Mhz).

Miscorrelation between SIL/TI boards and Megaone test experienced on unit #3 is due to the use of worst case timming and levels always used on a test program. With standard timing/levels as in SIL/TI application boards, units still work. This is confirmed by the failure on only a restricted pattern list and only at low frequency experienced on this unit on Megaone test.

Recovery (anneal) happen in the reverse mode than degradation Anneal happens very slowly. (Low recovery after 2 weeks at room temperature, but functionnality recovers after 3 monthes.

First functionnal failure is almost always on the same patterns (See restricted pattern list) . showing that most of the circuit is not dead at the same dose level.

Functionnal anneal occurs slowly at room temperature, (Unit #6 recover full functionnality after 6 monthes.)
With high temperature anneal (150 Dc) all units recovered full specification functionnality immediatly (24 Hrs)

CONCLUSION : *We can consider that critical functionnal failure happen in the range of 5 Krad, while dramatic fails happen in the 5-10 krads range.*
Functionnal failure anneal happen at room temperature showing that 320C25 may be more radiation tolerant in low dose rate environment.

ICC power and ICC standy by
Results and calculations

To report ICC power and ICC standby values on the same graph or to compare behaviour during irradiation and anneal, some calculation are needed, because test conditions were not the same in SIL hardware/software and Megaone test program :

SIL Hardware : VCC = 5 v Freq = 20 Mhz

Megaone : VCC = 5.5 V Freq = 40 Mhz (Worst case)

Characterisation data showed the impact of those 2 tests conditions on the value. (see graph attached)

What was done in folowing data report, was :

1) Calculation of real value

Time for given dose calculated from dose rate
Value of ICC ICC STBY collected
Values divides by 17.2 (Sil input) -> Result in Amp.

2) Calculation of degradation factor from initial SIL value to value at a given dose :

$$\frac{I\ (x\ krad) - I\ (initial)}{I\ (initial)}$$

3) Claculation of a correlated value

*(1+ degradation factor) * I (initial on Megaone)*

Note : Initial value of SIL hardware and Megaone test explained by Frequency/Vcc test conditions (See Graph)

ICC power and ICC standy by
Data collected

	Unit #							
	2	3	6	7	8	10	12	13
* Initial measurement M1								
ICC STBY	70	68	68	68	70	70	68	70
ICC	137	137	137	137	137	137	137	138

	Unit #							
	2	3	6	7	8	10	12	13
* Initial measurement SIL								
SIL ICC STBY	38	38	38	38	38	37	38	38
SIL ICC	82	82	82	82	83	83	82	82
ICC STBY degradation factor	0	0	0	0	0	0	0	0
ICC degradation factor	0	0	0	0	0	0	0	0
ICC STBY correlated value	70	68	68	68	70	70	68	70
ICC correlated value	137	137	137	137	137	137	137	137

	Unit #							
	2	3	6	7	8	10	12	13
* After 2 Krad								
SIL ICC STBY	38	38	38	38	38	37	38	38
SIL ICC	82	82	82	82	83	83	82	82
ICC STBY degradation factor	0	0	0	0	0	0	0	0
ICC degradation factor	0	0	0	0	0	0	0	0
ICC STBY correlated value	70	68	68	68	70	70	68	70
ICC correlated value	137	137	137	137	137	137	137	137

	Unit #							
	2	3	6	7	8	10	12	13
* After 3 Krad								
SIL ICC STBY		38	38	38	38	37	38	38
SIL ICC		82	82	82	83	83	82	82
ICC STBY degradation factor		0	0	0	0	0	0	0
ICC degradation factor		0	0	0	0	0	0	0
ICC STBY correlated value		68	68	68	70	70	68	70
ICC correlated value		137	137	137	137	137	137	137

	Unit #							
	2	3	6	7	8	10	12	13
* After 4 Krad								
SIL ICC STBY		38	38	38	38	37	38	38
SIL ICC		82	82	82	83	83	82	82
ICC STBY degradation factor		0	0	0	0	0	0	0
ICC degradation factor		0	0	0	0	0	0	0
ICC STBY correlated value		68	68	68	70	70	68	70
ICC correlated value		137	137	137	137	137	137	137

ICC power and ICC standy by
Data collected CNTD

	Unit #							
	2	3	6	7	8	10	12	13
* After 5 Krad								
SIL ICC STBY		47	45	42	45	45	43	44
SIL ICC		87	87	85	87	87	85	87
ICC STBY degradation factor		.237	.184	.125	.184	.216	.132	.158
ICC degradation factor		.048	.048	.037	.061	.048	.037	.061
ICC STBY correlated value		84	81	77	83	85	77	81
ICC correlated value		144	144	142	145	144	142	146

	Unit #							
	2	3	6	7	8	10	12	13
* After 6 Krad								
SIL ICC STBY			59	56	59	59	57	62
SIL ICC			95	94	95	95	94	98
ICC STBY degradation factor			.552	.474	.500	.595	.500	.632
ICC degradation factor			.145	.146	.158	.145	.146	.195
ICC STBY correlated value			105	100	105	112	102	114
ICC correlated value			157	157	159	157	157	165

	Unit #							
	2	3	6	7	8	10	12	13
* After 6.5 Krad								
SIL ICC STBY			68	70	71	66	-	-
SIL ICC			102	104	101	99	-	-
ICC STBY degradation factor			.789	.842	.868	.783	-	-
ICC degradation factor			.232	.268	.232	.192	-	-
ICC STBY correlated value			122	125	131	125	-	-
ICC correlated value			169	174	169	163	-	-

	Unit #							
	2	3	6	7	8	10	12	13
* After 7 Krad								
SIL ICC STBY						74	nv	81
SIL ICC						105	102	nv
ICC STBY degradation factor						1.00	nv	1.13
ICC degradation factor						.265	.243	nv
ICC STBY correlated value						140	nv	149
ICC correlated value						173	170	nv

ICC power and ICC standy by
Data collected CNTD

				Unit #				
	2	3	6	7	8	10	12	13
* After 8 Krad								
SIL ICC STBY						nv	nv	nv
SIL ICC						nv	nv	147
ICC STBY degradation factor						nv	nv	nv
ICC degradation factor						nv	nv	.793
ICC STBY correlated value						nv	nv	nv
ICC correlated value						nv	nv	247

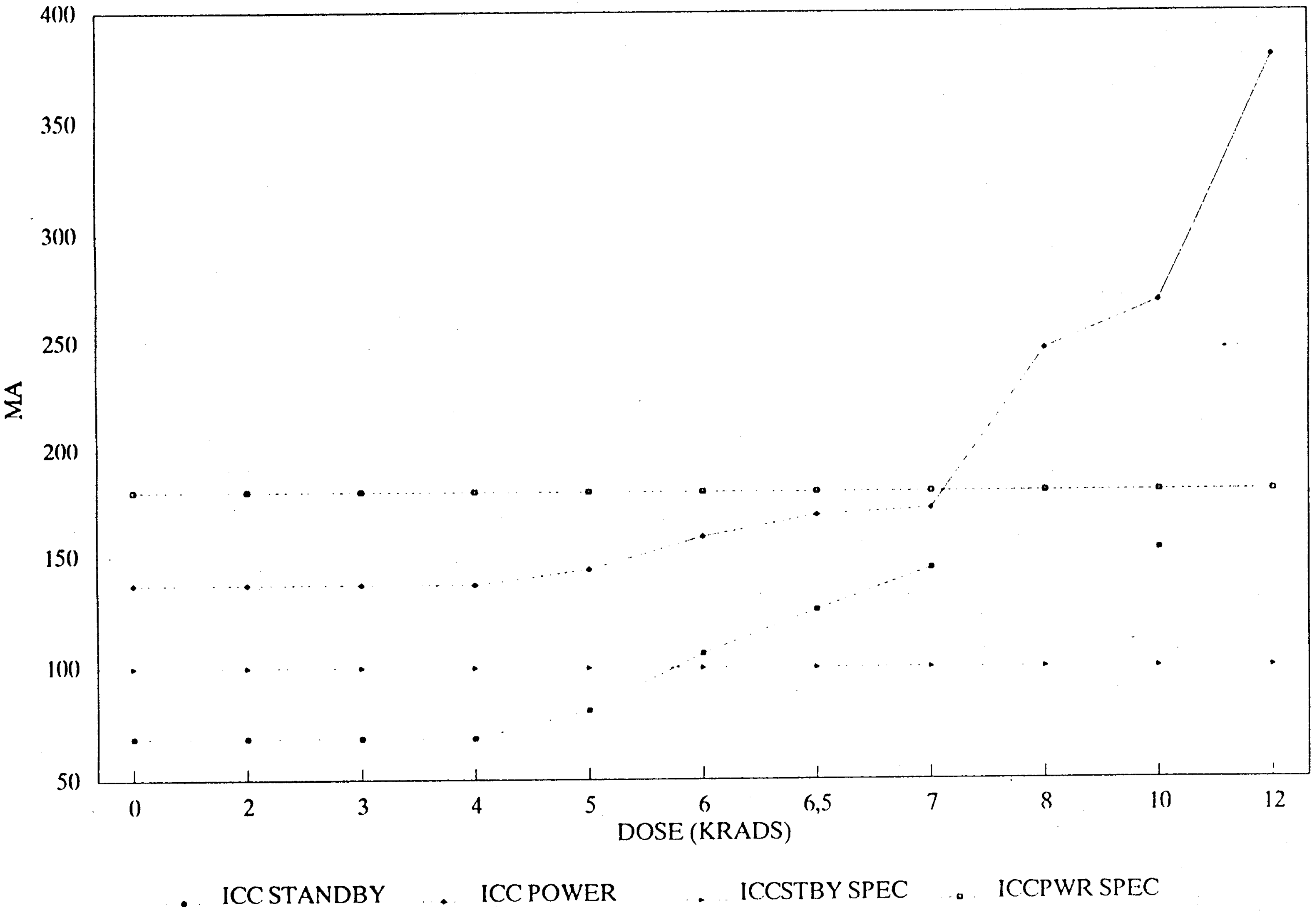
				Unit #				
	2	3	6	7	8	10	12	13
* After 10 Krad								
SIL ICC STBY							86	nv
SIL ICC							122	198
ICC STBY degradation factor							1.26	nv
ICC degradation factor							0.488	.793
ICC STBY correlated value							153	nv
ICC correlated value							204	333

				Unit #				
	2	3	6	7	8	10	12	13
* After 12 Krad								
SIL ICC STBY								nv
SIL ICC								226
ICC STBY degradation factor								nv
ICC degradation factor								1.76
ICC STBY correlated value								nv
ICC correlated value								380

Note : Blank values when irradiation was stopped
- when no data considered
nv when the data is not valid (not in STBY mode for example)
All values are in mA

320C25 TOTAL DOSE TESTS

CURRENTS UNDER IRRADIATION



ICC power and ICC standy by
Data collected (ANNEAL)

	Unit #							
	2	3	6	7	8	10	12	13
* LAST CORRELATED VALUES READ UNDER IRRADIATION								
DOSE (Krads)	2	5	6.5	6.5	6.5	8	10	12
ICC STBY	70	84	122	125	131	nv	153	nv
ICC	137	144	169	174	169	nv	204	226

	Unit #							
	2	3	6	7	8	10	12	13
* MEGAONE MEASUREMENT 07/26								
ICC STBY	67	74	92	99	87	93	nv	nv
ICC	132	137	160	166	155	161	nv	nv

	Unit #							
	2	3	6	7	8	10	12	13
* MEGAONE MEASUREMENT 08/03								
ICC STBY	68	73	90	97	84	89	101	nv
ICC	133	137	158	164	150	158	168	nv

	Unit #			
	2	3	6	12
* MEGAONE MEASUREMENT 08/09				
ICC STBY	68	73	90	98
ICC	132	136	158	165

	Unit #			
	7	8	10	13
* MEGAONE MEASUREMENT 08/09 (Units with 24 hrs at 150 dc)				
ICC STBY	66	66	66	66
ICC	131	130	129	131

	Unit #							
	2	3	6	7	8	10	12	13
* MEGAONE MEASUREMENT 10/18								
ICC STBY	58	63	77	57	57	56	83	
ICC	127	132	145	126	126	126	151	

ICC power and ICC standy by
Data collected (ANNEAL) Cntd

	Unit #							
	2	3	6	7	8	10	12	13
* MEGAONE MEASUREMENT 01/15								
ICC STBY	56	59	69	58	56	55	55	
ICC	126	128	135	124	125	125	124	

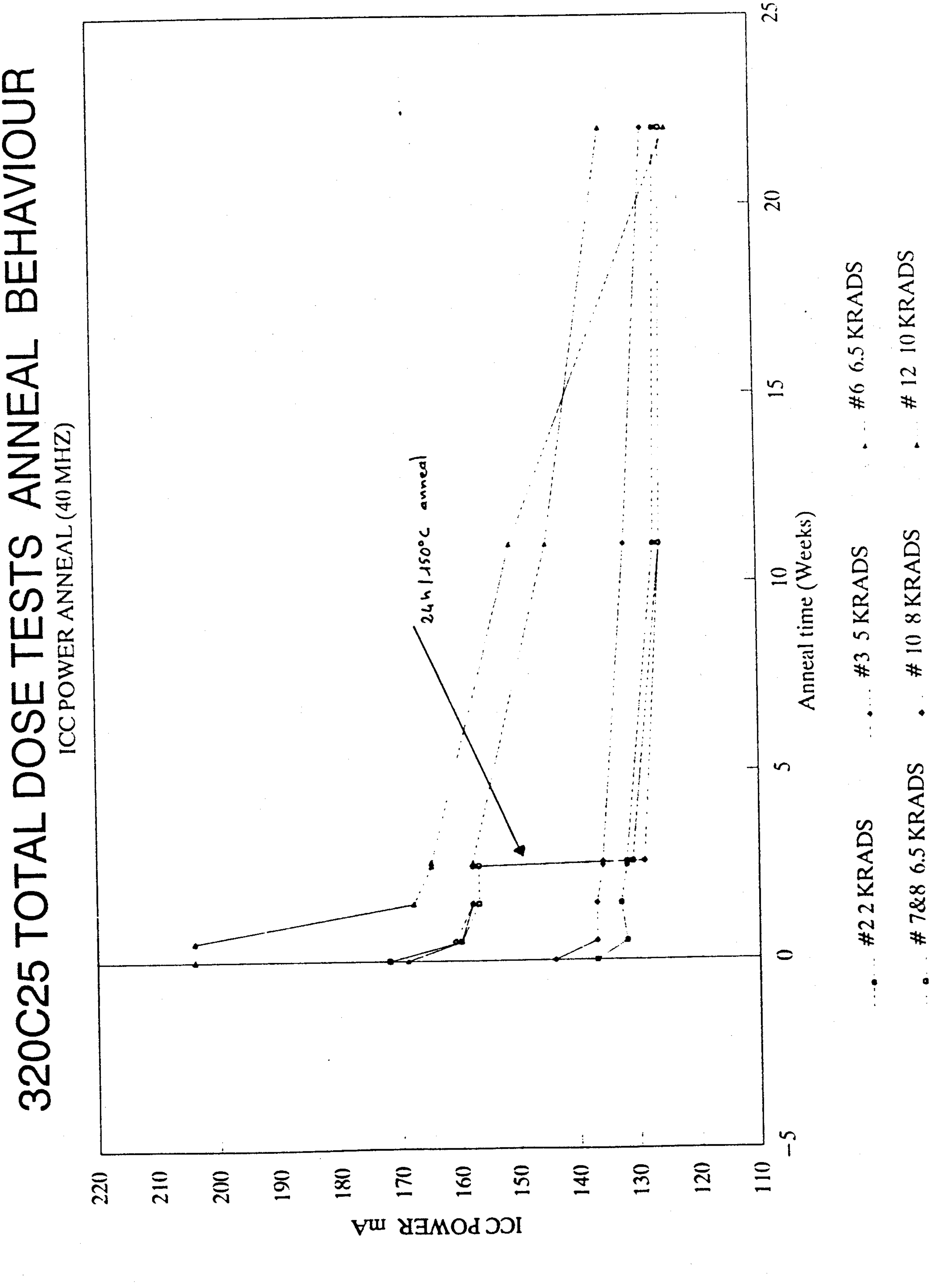
Note : Blank values when irradiation was stopped
- when no data considered
nv when the data is not valid (not in STBY mode for example)
All values are in mA

ICC DEGRADATION MECHANISM

ICC Degradation start to happen at around 5 Krad , with ICC STBY going out of specification at 7.5 Krad after 30 % degradation, For Power ICC same behaviour is found at same dose levels.

ICC recovery happen (All valid data within specification at first anneal reading).

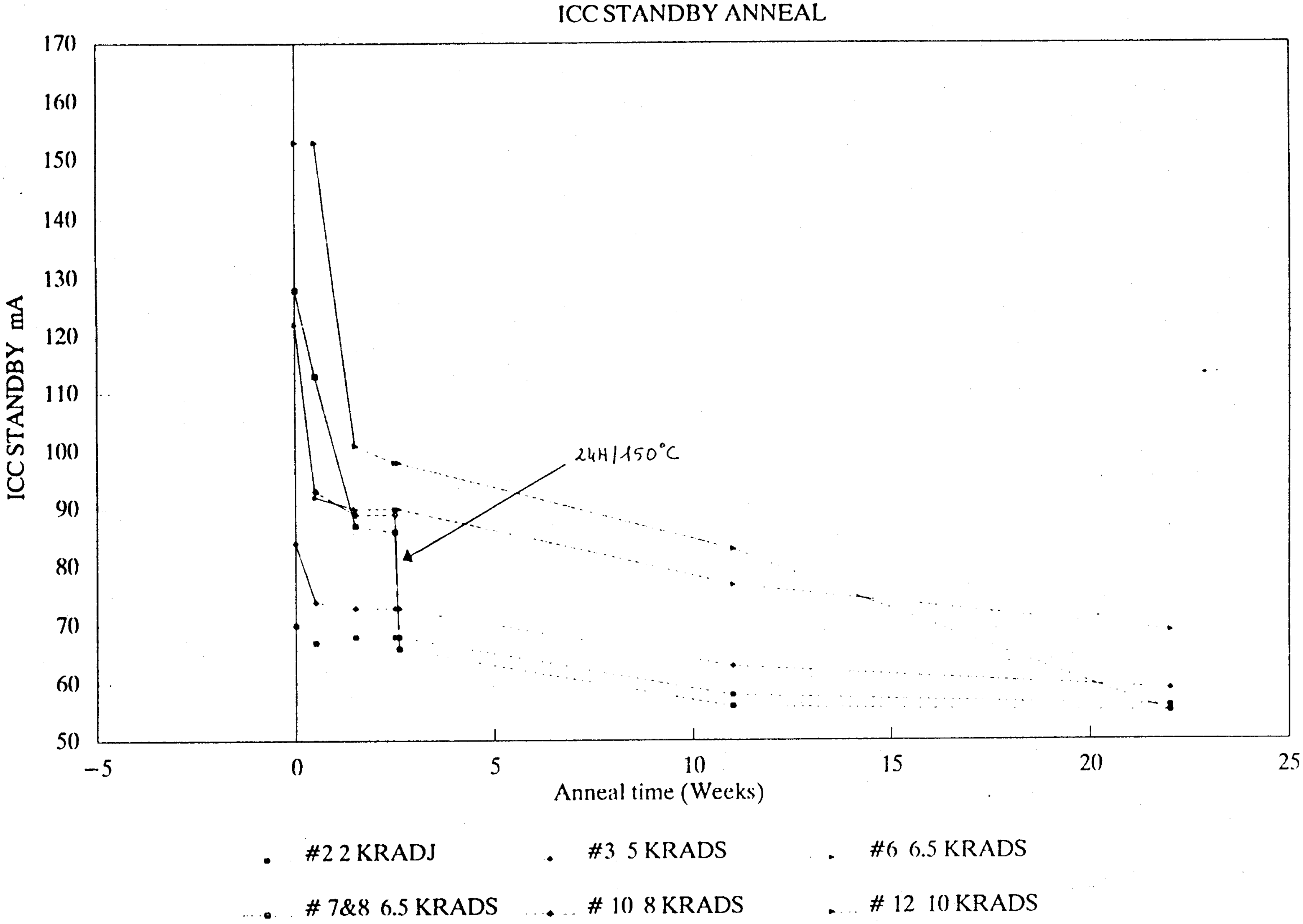
After 24hrs at 150 Dc all units (even irradiated up to 12 Krads) recovered their initial values.



320C25 TOTAL DOSE TESTS ANNEAL BEHAVIOUR

ICC POWER ANNEAL (40 MHZ)

320C25 TOTAL DOSE TESTS ANNEAL BEHAVIOUR



LIST OF FUNCTIONNAL PATTERNS NAMES USED FOR 320C25 TEST
58 TEST PATTERNS

```
ALUPattern,
SHVALU1Pattern,
SHVALU2Pattern,
SHVALU3Pattern,
HIMALU4Pattern,          *
ARPattern,
SHVARPattern,
BRPattern,               *
SHVBRPattern,
GREGPattern,
SHVGREGPattern,
HOLDPattern,
HOLDIDLEPattern,
HOLDRAMPattern,
HOLDRDYPattern,
SHVRDYPattern,
INTLPattern,
SHVINTLPattern,
SHVINTL2Pattern,
IOPattern,
SHVIOPattern,
MULTPattern,
SHVMULT1Pattern,
SHVMULT2Pattern,
NEWINSTPattern,          *
PCPFPattern,
SHVPCSTKPattern,
RALUPattern,
RAMBNDPattern,
RAMCHKPattern,
RAM0Pattern,
RAM1Pattern,
SHVRAM2Pattern,
ROMPattern,
PLAPattern,
RPTPattern,
STPattern,
SHVSTPattern,
TIMPattern,
SHVINTSPattern,
INTSPattern,             *
SPMINPattern,
SPXLONGPattern,
SPRLONGPattern,
SPXMITIPattern,
SPXMITOPattern,
SPRECVPattern);
```

(*) PATTERNS FAILING WHEN ONLY RESTRICTED LIST

2) Total dose results on 50 Mhz version

A new set of radiation tests (total dose) was conducted in AEA HARWELL in october to adress the 50 Mhz version.

Samples were provided from a commercial flow , still in PGA 68 pin packages, date code : 9007.

3 units were irradiated to failure and 1 unit to 70 % as the failure mode level.
No data were supplied with the samples back to TIF so we cannot characterize the current behaviour under irradiation. We wiil concentrate of post radiation characterization data and anneal effects.

Here also unit #5 irradiated at 70 % of the failing level is found not 100 % good even if ok on SIL hardware. Same miscorrelation explanation as for the 40 Mhz version.

First ICC reading on Megaone show very marginal ICChold almos within the product specification, showing that the ICC recovery happen in the first days. (It would be interesting to compare immediate post irradiation ICC data from SIL hardware and first reading in TIF).

Then room temperature anneal occur as for the 40 Mhz version either for currents values and functionnality.
No high temperature anneal was done .

As a first comment, we can consider that the 50 Mhz version tested is slightly worse than the 40 Mhz , with a total dose tolerance in the range of 4 krads instead of 5 krads.
Here also, note the extreme reproductibility of the results from units to units (even when we go to detailed ICC values under irradiation)
Anneal occur even at room temperature .This can be encouraging in finding better total dose tolerance using lower dose rates.

You will find following the data collected and some associated graphs.

IRRADIATION HARDWARE SUMMARY DESCRIPTION

as per 40 Mhz version

FUNCTIONNAL TEST RESULTS

Unit #	*Total Dose krads*	*H/W SIL*	*TI*	*10/18 M1*	*01/15 M1*
5	*3.9*	*ok*	*-*	*Good HFLV* *Good LFLV* *Good HFHV* *Fail LFHV*	*Good HFLV* *Good LFLV* *Good HFHV* *Fail LFHV(Only a restricted pattern list)*
2	*5.53*	*F*	*-*	*Fail HF* *Fail LF*	*Good HFLV* *Fail HFHV* *Fail LF*
3	*5.53*	*F*	*-*	*Fail HF* *Fail LF*	*Good HFLV* *Fail HFHV* *Fail LF*
4	*5.53*	*F*	*-*	*Fail HF* *Fail LF*	*Good HFLV* *Fail HFHV* *Fail LF*

Note : LF low frequency
HF High frequency
HFLV High frequency low VCC (4.5V)
HFHV High frequency high VCC (5.5V)
LFLV Low frequency low VCC (4.5V)
LFHV Low frequency high VCC (5.5V)

FUNCTIONNAL FAILURE MECHANISM

When irradiated, the first failure mechanism to occur is at low frequency , then high frequency fail.
On VCC side the most critical VCC is VCC max (5.5V) then VCC min (4.5V) .

Miscorrelation between SIL/TI boards and Megaone test experienced on unit #5 is due to the use of worst case timming and levels always used on a test program. With standard timing/levels as in SIL/TI application boards, units still work. This is confirmed by the failure on only a restricted pattern list and only at low frequency high VCC condition as experienced in Megaone test program.

Functionnal anneal occurs at room temperature, in the reverse mode as the degradation experienced under irradiation.

CONCLUSION : *We can consider that critical functionnal failure happen in the range of 4 Krad, while dramatic fails happen in the 5 krads range.*
Functionnal failure anneal happen at room temperature showing that 320C25 may be more radiation tolerant in low dose rate environment.
Functionnal degradation and behaviour is similar in 40 Mhz and 50 Mhz versions of the 320C25.

ICC power and ICC standy by
Data collected

Not available

ICC power and ICC standy by
Data collected (ANNEAL)

		Unit #				
		5	2	3	4	
* LAST CORRELATED VALUES READ UNDER IRRADIATION						
	DOSE (Krads)	3.9	5.5	5.5	5.5	SIL
	ICC STBY	-	-	-	-	Not available
	ICC	-	-	-	-	

		Unit #			
		5	2	3	4
* MEGAONE MEASUREMENT 10/18					
	ICC STBY	58	102	104	103
	ICC	118	160	162	162

		Unit #			
		5	2	3	4
* MEGAONE MEASUREMENT 01/15					
	ICC STBY	56	99	102	101
	ICC	118	158	159	157

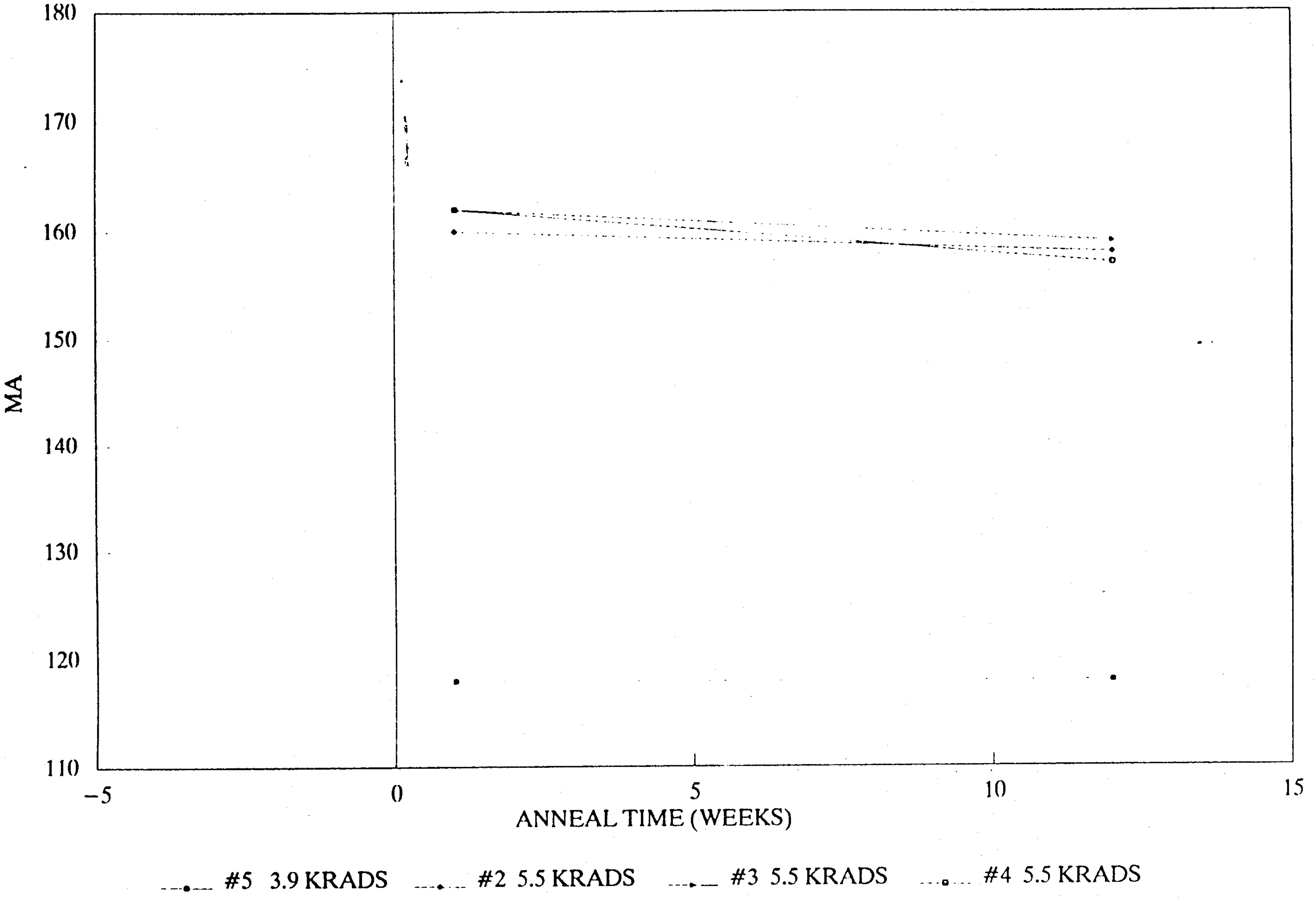
ICC DEGRADATION MECHANISM

Here also ICC stby go out of the specification when critical functionnal failures start to occur at 5.5 krads level.

ICC recovery happen as for the 40 Mhz version, but as first reading was done after one week - and based on the 40 Mhrz , the anneal happen in the very first days- we need to compare end of irradiation measurements at SIL and first read on megaone to really draw the final conclusion. Probably, as irradiation was not continued after first fail, i.e the ICC degradation was not severe enough, all the recovery already happen at first Megaone readings.

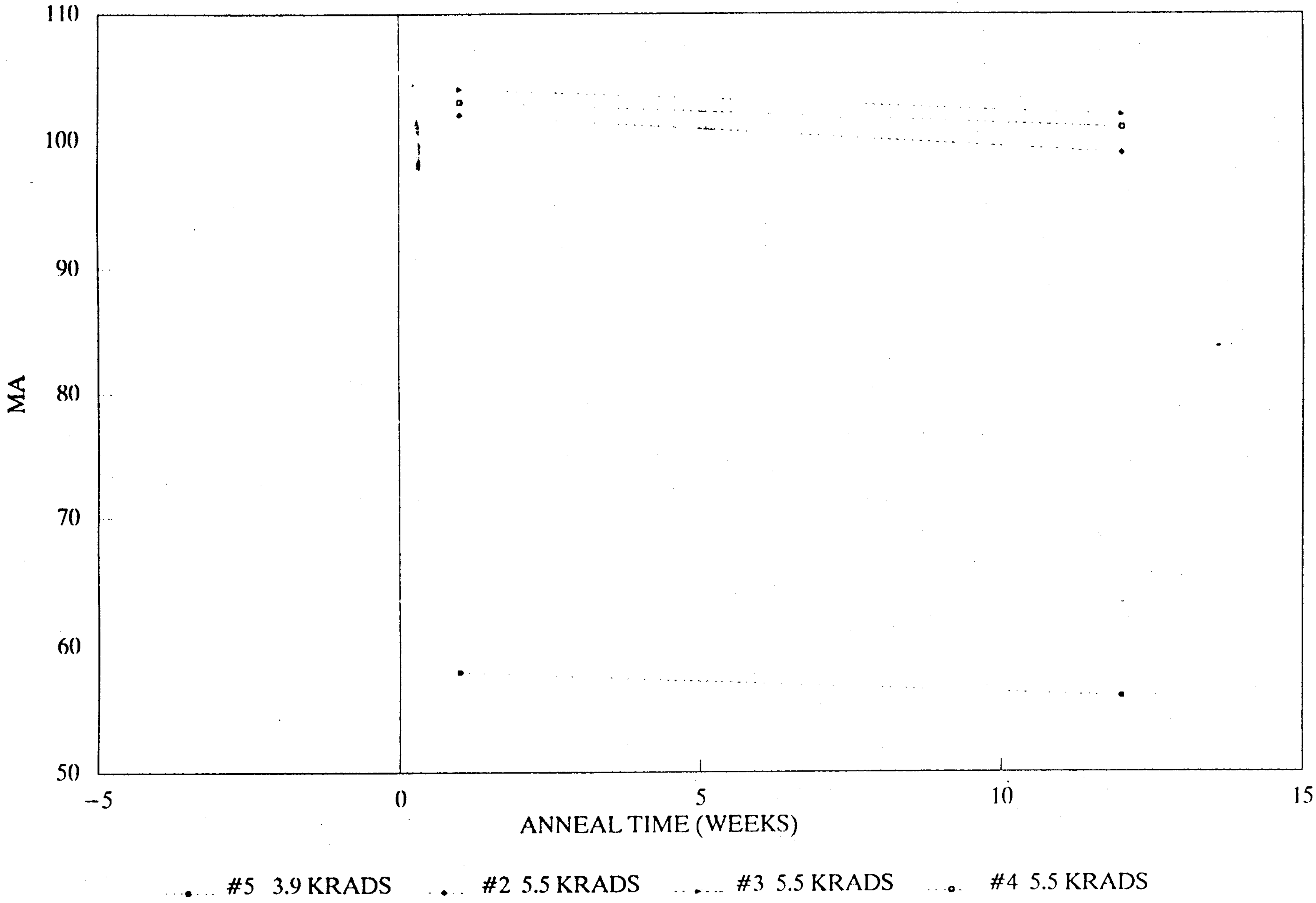
320C25 TOTAL DOSE TESTS ANNEAL BEHAVIOUR

ICC POWER ANNEAL (50 MHRZ)



320C25 TOTAL DOSE TESTS ANNEAL BEHAVIOUR

ICC STANDBY ANNEAL (50 MHRZ)



3) General conclusion :

During this total dose characterization of 320C25 , we find that the device show functionnal failures in the range of 5 Krads. Parametrics readings are going out of the product specification at equivalent level.

2 versions of 320C25 were tested (40 Mhz and 50 Mhz) and were found very similar (1 krad worse for the 50 Mhz version). At that stage, we cannot conclude if the difference is due to the version or to the natural spread of diffusion lots. Future production tests will give more details on lot to lot spread (If any).

The stability and reproductibility of results is very good within the same unit batch, either for degradation or recovery mechanism. The radiation tolerance spread is very uniform within a batch. This can be used to reduce radiation tests sample size on this product and then decrease test costs.

Anneal at room temperature always happen and this may indicate a lower sensitivity of 320C25 to total dose when used in lower dose rate environment.

February 1991

Jean Michel MAUREL

UNITS DELIVERED

10 UNITS DELIVERED IN JULLY 1990

COMMING FROM TI ESA/SCC LEVEL
B FLOW EVALUATION
BAR REV AS (40 MHZ)

5 UNITS DELIVERED IN AUGUST 1990

COMMING FROM TI ESA/SCC LEVEL
B FLOW EVALUATION
BAR REV AS (40 MHZ)

10 UNITS OF COMMERCIAL TMS320C25

BAR REV BU (50 MHZ)
DATE CODE 9007

TES:

ALL ICC DATA WAS TAKEN FROM THE 320C25 SPLIT LOT (#71037) CHARACTERIZATION PERFORMED 7/88.

ALL ICC DATA IS MEAN (NOMINAL) DATA.

LV = VCCmin = 4.75v
HV = VCCmax = 5.25v
HF = 10.5mhz (CLKOUT PERIOD = 95ns)

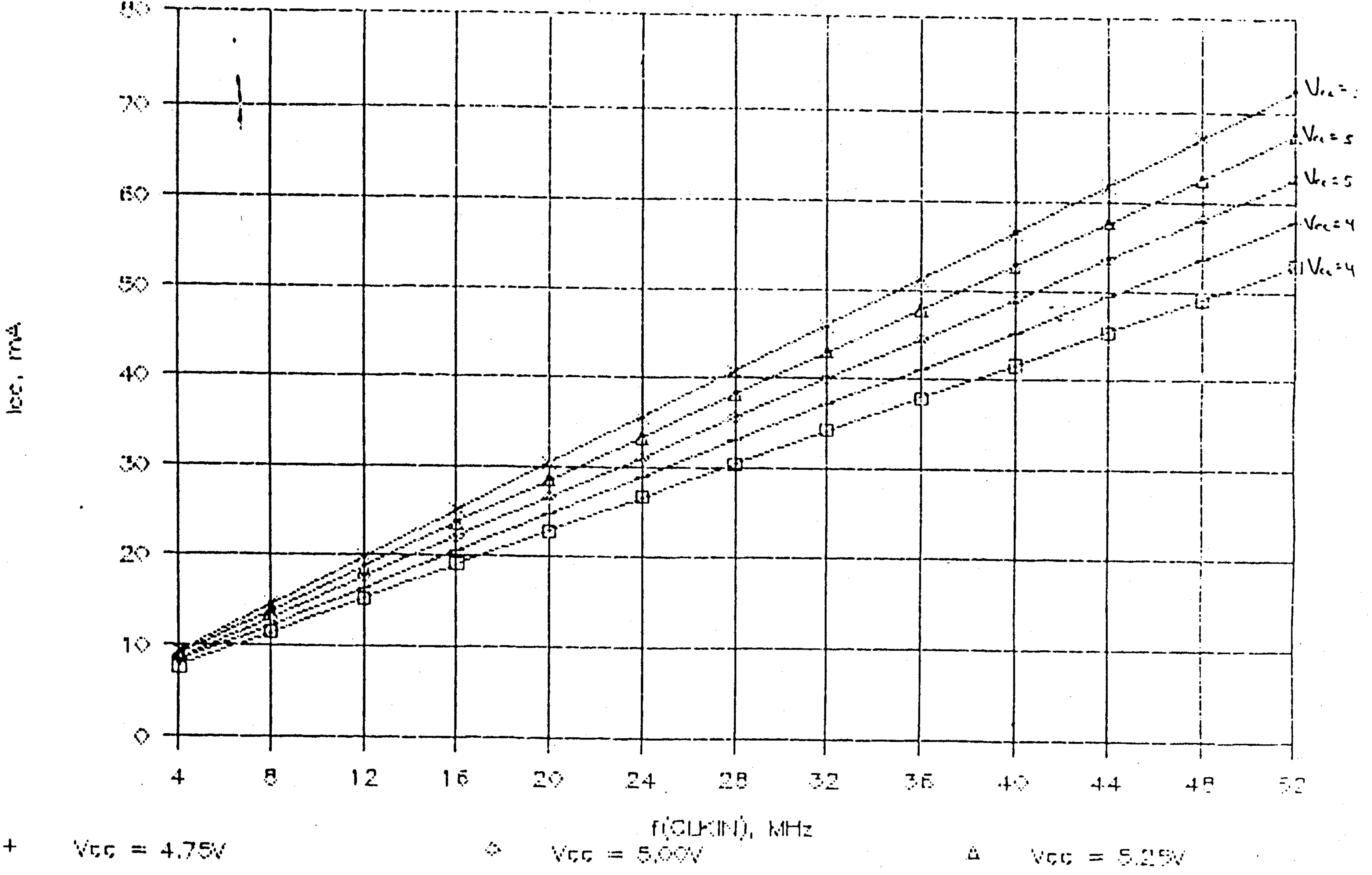
NORMAL-MODE ICC

CASE TEMP	(LV/HF) NORM ICC	(HV/HF) NORM ICC
-40C	111.38ma	127.68ma
0C	110.98ma	127.01ma
25C	111.26ma	127.33ma
105C	111.77ma	127.88ma
120C	112.38ma	128.55ma

11/8/88

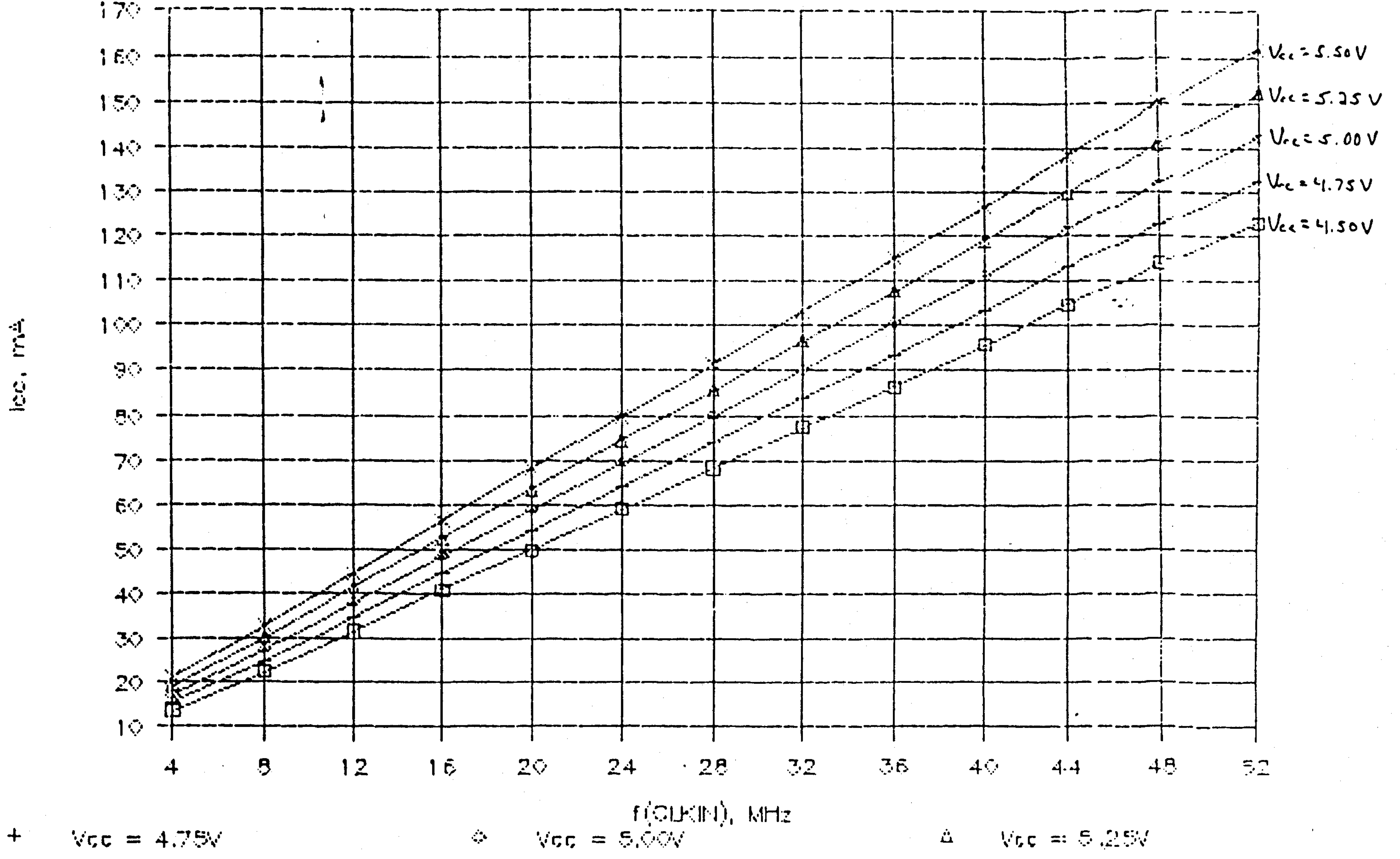
Icc vs. f(CLKIN) and Vcc

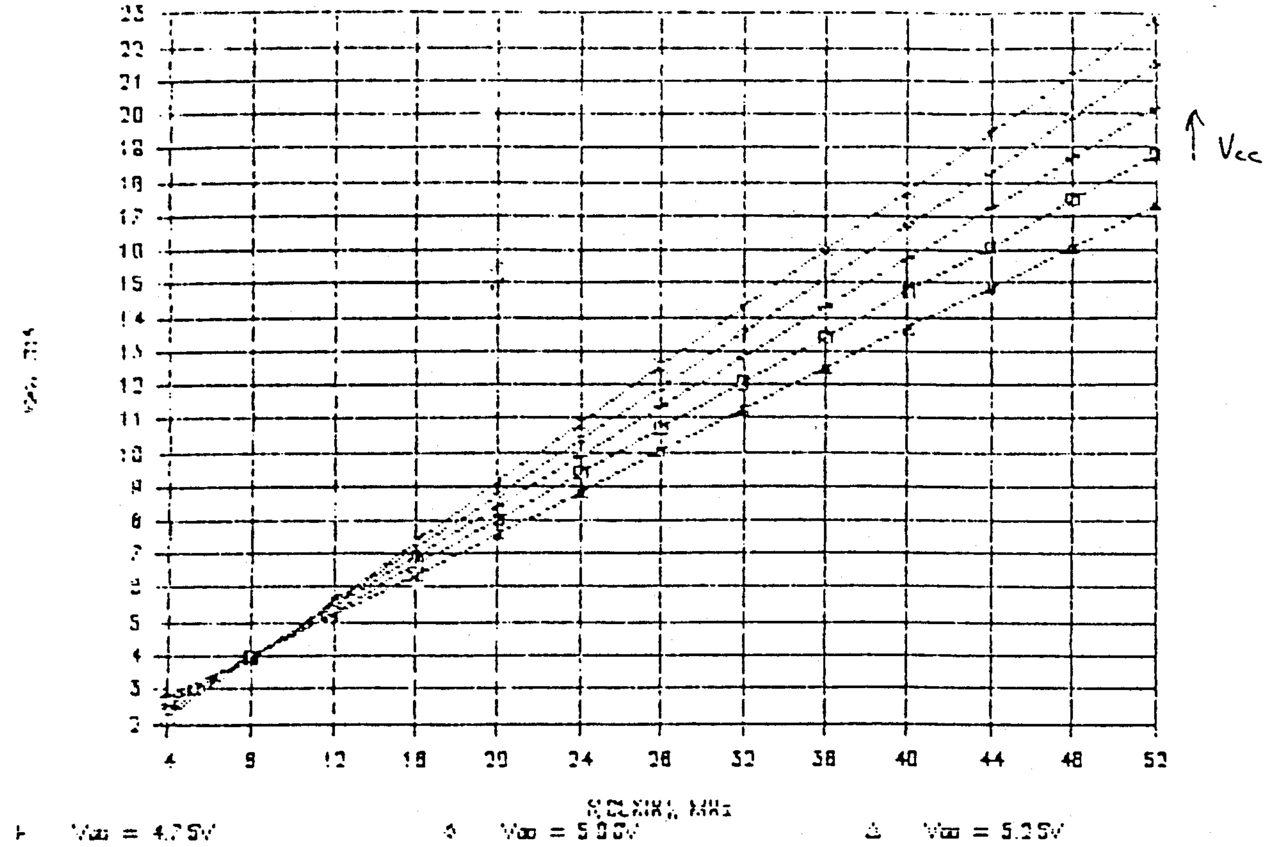
Powerdown Mode



Icc vs. f(CLKIN) and Vcc

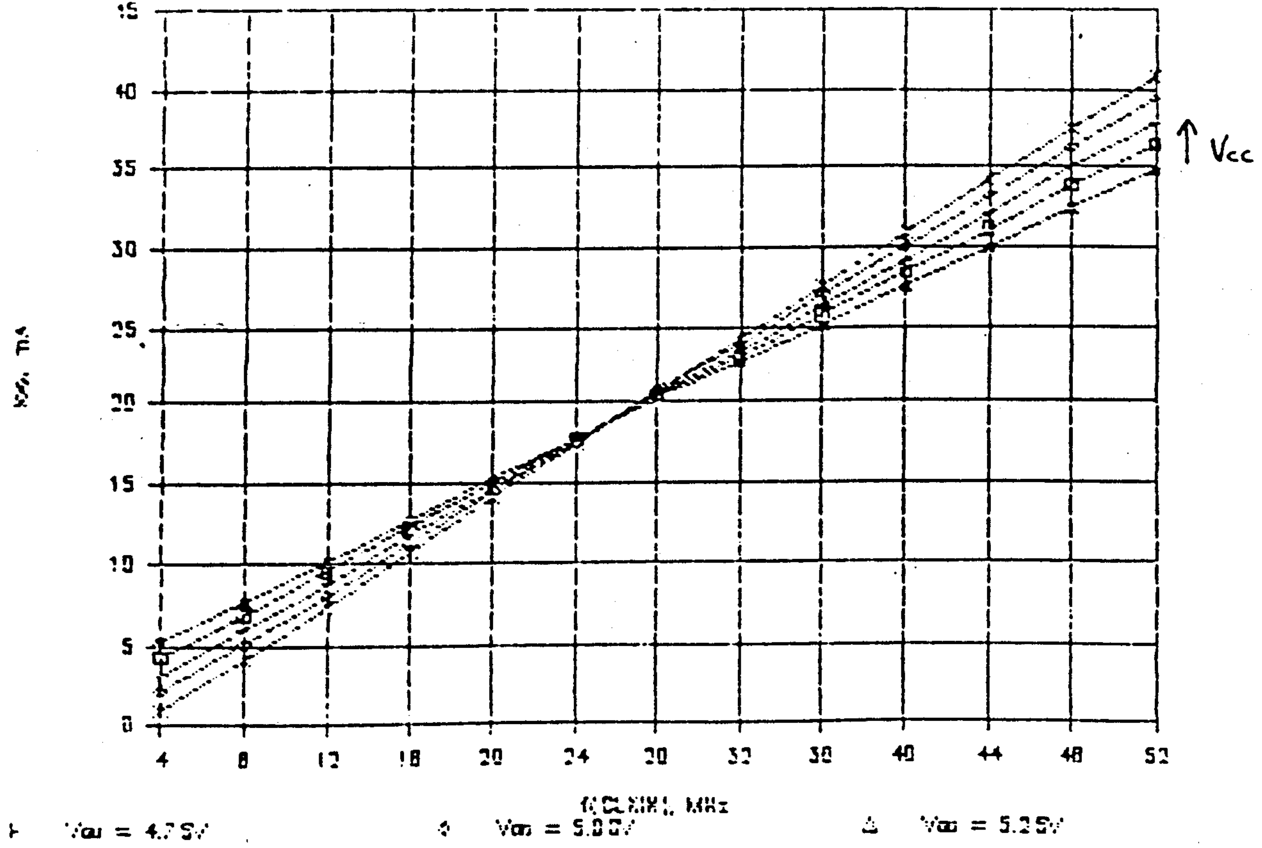
Normal Operating Mode





Icc Reduction (PGA/PLCC)

Powerdown Mode



Icc Reduction (PGA/PLCC)

Normal Operating Mode

Appendix B Report Supplied by AEA Technology Harwell

SEU and Total Dose Characterisation of the TMS320C25

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February 1991

TKS/IB/TMS320C25-TKSOCT89

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5 February 1991

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Order No. 194593

SEU and Total Dose Characterisation of the TMS 320 C 25

Introduction

The Texas Instruments' TMS320C25 is an advanced digital signal processor, currently flown in the ESA Meteosat SEU experiment under the TDP programme and under consideration for various scientific payloads in the future. The device was tested for total dose sensitivity using a ^{60}Co radiactive cell and for heavy ion induced single event upset (SEU) using a ^{252}Cf fission particle source and the Harwell Tandem Generator.

Samples of both the 40 MHz (13) and the new 50 MHz (9) variants were provided by Texas Instruments (France). The samples were marked as follows:

(a) TMS 320C25 GB EVAL SCCB (date code 8910)

(b) TMS 320C25 GBL (date code WBU 9007)

All the samples were supplied in 68 pin ceramic pin grid array packages and those included for SEU evaluation were unsealed with lids merely taped on. In addition, one sample of the preliminary TMP320C25 together with various samples of 256k SRAMS manufactured by EDI and Fujitsu was supplied by ESTEC for accelerator testing only, as flown in the Meteosat experiment.

Experimental

The devices were electrically tested for SEU/SEL and functionally during the total dose tests using the engineering model of the Meteosat experiment running at 20MHz. This was designed by SAGEM (France) and supplied by Satellites International under ESA contract. A detailed description of the system has been provided to ESTEC by SAGEM/SIL. Essentially, the system was designed to load the on board RAM and various registers of the device with a checkerboard bit pattern and read the data bank after a suitable interval. The iteration cycle lasted approximately six seconds. Unfortunately, only one upset in the whole device could be correctly identified during each cycle. Upsets could be identified as occuring in the on board RAM, ALU, multiplier or elsewhere. In addition, the supply current of the device was monitored in order to detect latch-up, in which event the supply would be interrupted and the system reset. During a test, the status of the device, numbers of upsets and operating supply currents were logged by a PC computer. These data files were passed to SIL for interpretation.

In addition to the above test system, the devices were fully characterised before and after irradiation by TI (Nice), using a "Mega One" LSI test system running at up to 40MHz. TI also participated in the total dose testing of the 40MHz samples (a), providing a test board running at 40MHz in a PC computer.

First the 40MHz samples were tested for total dose sensitivity using a ^{60}Co source at 14 krad(Si) hr^{-1}. The device under test was irradiated whilst operated by the Meteosat EGSE system, extended off the board by ~15cm of ribbon cable. Three devices were irradiated to failure, to determine the dose required for failure as indicated by the Meteosat experiment. Two further samples were irradiated to 30% and 70% of this dose respectively, in order to provide degraded but operating samples for TI to evaluate. All five of the above samples remained functional when tested in the TI 40MHz board. A further three samples were then irradiated to 8, 10 and 12 krad(Si) respectively, in order to provide a wider spread of the sample doses (see Results and Discussions later). All the samples were then taken by TI to Nice for evaluation.

Secondly, three samples of the 50MHz version were irradiated using the ^{60}Co source at a dose rate of 13 krad (Si) hr^{-1} until failure. A further sample was then irradiated to 70% of the failure dose, as above. The samples were then sent by SIL to TI for evaluation. All of above the irradiations and electrical tests were performed at room temperature (25 ± 5 °C).

The heavy ion irradiations were performed using a ^{252}Cf source as described elsewhere (1). The de-lidded samples were placed in a vacuum chamber together with the ^{252}Cf source. The die was then irradiated with the fission particles, whose mean LET is greater than the charged particles likely to be found in space, at a flux of 106 fission particles cm^{-2} min^{-1}.

The samples were then irradiated with lower LET ions beams, using the dedicated single event test facility on the Harwell Tandem Generator. This facility and its mode of operation has been described in a separate report (2). The tests were commenced by irradiations with 45 MeV ^{35}Cl^{8+} ions, which had an LET of 18.5 MeV mg^{-1}cm^{2} (Si). Further irradiations were made using 35 MeV ^{16}O^{6+} ions and 35 MeV ^{12}C^{5+} ions, which had LET's of 5.4 and 2.9 MeV mg^{-1} cm^{2} (Si), respectively. Unfortunately, the data for 35 MeV oxygen was rather limited due to the failure of the test system during the original run, which resulted in restricted tests being performed during a later programme.

Results and Discussion

The dose to failure was determined to be 6.5 ± 0.1 krad(Si) for the 40MHz samples and 5.5 ± 0.1 krad(Si) for the 50MHz samples. Detailed evaluations by TI indicated that 40 MHz devices irradiated to 4.6 krad show functional failure when tested at low speed (6.7 MHz) but not at high speed. It was also found that failure was observed earlier when tested at higher supply voltage (5.5 volts compared with 4.5 volts). These results have been discussed at greater length in the report from TI to ESTEC.

Particular problems were experienced in the SEU testing due to the inability to cope with anything other than low event rates and the fragility of the hardware/software. This resulted in the need to observe the system closely at all times, (preventing overnight testing) and irradiate at low fluxes. Some of the accelerator test time was eventually lost due to the total failure of the system. Throughout the testing no upsets were observed other than in the internal RAM and no latch-up was observed. The numbers of upsets in the RAM were used to calculate the device cross section in cm^2 by:

$$\sigma_u = \frac{\text{Number of events}}{\text{Fluence}}$$

The numbers of upsets and the corresponding cross sections are given for each sample in Tables 1 to 8.

It can be seen that the three circuits of the TMS320C25 were broadly similar in SEU behaviour, but with detailed differences as follows. The saturation cross section for the 40MHz devices appeared to be rather larger than that for the 50MHz. devices, which is probably due to a mask geometry shrink being implemented in the 50MHz device in order to assist the high speed performance. During the 45 MeV chlorine irradiations, the TMP variant showed similar behaviour to the standard 40MHz devices. However, the ^{252}Cf data and the 35 MeV carbon data show the TMP as being more sensitive than either the standard 40MHz or 50MHz devices. The LET threshold for the device type appears to be of the order of 3 MeV mg^{-1} cm^2 (Si), but is highest for the 40 MHz variants and lowest for the TMP. A slightly lower LET threshold for a smaller geometry device is entirely to be expected, but the difference between the 40MHz and TMP devices was rather surprising. For information, the die sizes of the TMP and 40MHz devices were measured as 7.8 x 8.8mm, whilst the 50MHz device was 6.9 and 7.6 mm.

No detailed evaluation will be made of the results for the static RAMs, because the presence of passivation layers on some of the samples prevented adequate measurements of the saturation cross sections with ^{252}Cf and the chlorine ion beam. Since ESTEC has possession of the samples, it is possible that they may make suitable measurements on some of the samples at other facilities which have more penetrating ion beams. However, the results obtained indicate that the EDI devices have an LET threshold of about 2 MeV mg^{-1} cm^2 (Si), the Fujitsu devices are approximately 3 MeV mg^{-1} cm^2 (Si), and the Matra Harris devices have a threshold significantly below 3 MeV mg^{-1} cm^2 (Si).

Conclusions

Various versions of the TMS320C25 digital signed processor manufactured by Texas Instruments, have been evaluated for sensitivity to total ionizing dose and single event upset. The LET threshold for SEU appears to be similar to those for commercial microprocessors typically available. However, the total dose response is rather disappointing. Further work is to be performed, to evaluate the total dose degradation at low dose rates (< 100 rad(Si) hr^{-1}).

A significant amount of data has also been produced on the SEU sensitivity of three brands of 256K CMOS static RAM to low LET ion beams. Within two brands, distinct differences were observed between devices of differing geometries and manufacturing process. However, the LET threshold for SEU appears to be not much lower than those observed for some 64K SRAMs.

References

1. The use of ^{252}Cf for cosmic ray simulation.
   T. K. Sanderson
   AEA Industrial Technology Report No. AERE R 12578, July 1987.

2. The single event upset (SEU) test facility on the Harwell Tandem Generator for cosmic ray simulation.
   T. K. Sanderson, D. Mapper, J. H. Stephen and J. Farren.
   AEA Industrial Technology Report No. AERE R 12896, November 1987.

TABLE 1

^{252}Cf Test Results for 40MHz TMS320C25

S/N	Fluence (p cm^{-2})	No of Events	Cross Section (cm^{-2})
TMP	2.96 x 10^{4}	245	8.28 x 10^{-3}
14	2.63 x 10^{4}	157	5.97 x 10^{-3}
15	1.97 x 10^{4}	120	6.09 x 10^{-3}
16	1.81 x 10^{4}	115	6.38 x 10^{-3}
17	2.14 x 10^{4}	127	5.92 x 10^{-3}
18	2.07 x 10^{4}	122	5.90 x 10^{-3}
Mean:			6.05 x 10^{-3} ± 0.20 x 10^{-3} (3.2%)

Mean LET = 43.0 MeV mg^{-1}cm^{2}(Si).

TABLE 2

^{252}Cf Test Results for 50MHz TMS320C25

S/N	Fluence (p cm^{-2})	No of Events	Cross Section (cm^{-2})
(6*	1.97 x 10^{4}	120	6.09 x 10^{-3})
7	2.83 x 10^{4}	147	5.19 x 10^{-3}
8	2.19 x 10^{4}	118	5.38 x 10^{-3}
9	2.36 x 10^{4}	121	5.12 x 10^{-3}
10	2.19 x 10^{4}	116	5.29 x 10^{-3}
Mean:			5.25 x 10^{-3} ± 0.11 x 10^{-3} (2.2%)

* Result suspect as device showed erratic behaviour, omitted from mean calculation.

Mean LET = 43.0 MeV mg^{-1}cm^{2}(Si).

TABLE 3

45 MeV ^{35}Cl Test Results for TMS320C25

Type	S/N	Fluence (p cm^{-2})	No of Events	Cross Section (cm^{-2})
TMP (EXPT)	-	1.69×10^4	63	3.72×10^{-3}
" "	-	2.62×10^4	83	3.17×10^{-3}
			mean	3.45×10^{-3}
40 MHz	14	4.21×10^4	93	2.21×10^{-3}
	14	1.35×10^4	52	3.86×10^{-3}
	15	2.55×10^4	88	3.46×10^{-3}
	16	1.86×10^4	83	4.46×10^{-3}
			mean	3.50×10^{-3}
50 MHz	7	2.63×10^4	63	2.40×10^{-3}
	8	2.68×10^4	74	2.76×10^{-3}
	9	8.42×10^4	249	2.96×10^{-3}
			mean	2.71×10^{-3}

LET = 18.5 MeV mg^{-1} cm^2 (Si).

TABLE 4

35 MeV ^{16}O Test Results for TMS320C25

Type	S/N	Fluence ($p\ cm^{-2}$)	No of Events	Cross Section (cm^{-2})
40 MHz	14	7.91×10^3	16	2.02×10^{-3}
50 MHz	8	4.46×10^3	11	2.37×10^{-3}

LET = 5.4 MeV $mg^{-1}\ cm^2$ (Si).

TABLE 5

35 MeV ^{12}C Test Results for TMS320C25

Type	S/N	Fluence	No of Events	Cross Section (cm^{2})
TMP (EXPT)	-	7.89×10^{5}	10	1.27×10^{-5}
40 MHz	14	9.98×10^{5}	0	$\leq 1.00 \times 10^{-6}$
	15	1.08×10^{6}	0	$\leq 9.30 \times 10^{-7}$
	17	1.06×10^{6}	0	$\leq 9.41 \times 10^{-7}$
			mean	$\leq 1.0 \times 10^{-6}$
50 MHz	7	1.02×10^{6}	3	2.95×10^{-6}
	8	9.34×10^{5}	4	4.28×10^{-6}
	9	9.45×10^{5}	4	4.24×10^{-6}
	10	6.04×10^{5}	4	6.62×10^{-6}
			mean	4.52×10^{-6}

LET = 2.9 MeV mg^{-1} cm^{2} (Si).

TABLE 6

Tandem Results for EDI 256K SRAMs

Ion	Angle of Tilt (degrees)	Effective LET (MeV mg^{-1} cm^2(Si))	Device Type	No of Events	Fluence ($p\ cm^{-2}$)	Cross Section (cm^{-2})
O	60	10.8	A	158	1.08×19^4	1.46×10^{-2}
O	48	8.1	A	199 330	9.80×10^3 1.52×10^4	2.03×10^{-2} 2.14×10^{-2}
				mean		2.09×10^{-2}
O	0	5.4	A	330 540	2.17×10^4 3.83×10^4	1.52×10^{-2} 1.41×10^{-2}
				mean		1.47×10^{-2}
			B			1.09×10^{-2}
C	60	5.8	C	253 204	2.55×10^4 1.99×10^4	0.99×10^{-2} 1.02×10^{-2}
				mean		1.01×10^{-2}
C	50	4.5	A	526	7.25×10^4	7.26×10^{-3}
			B	501	1.09×10^5	4.60×10^{-3}
C	30	3.4	C	319 253	3.45×10^5 2.53×10^5	0.93×10^{-3} 1.00×10^{-3}
				mean		0.97×10^{-3}
C	0	2.9	A	812 727	3.19×10^5 2.62×10^5	2.54×10^{-3} 2.78×10^{-3}
				mean		2.66×10^{-3}
			B	433 359	6.96×10^5 6.33×10^5	6.22×10^{-4} 5.67×10^{-4}
				mean		5.95×10^{-4}
			C	175 189	6.28×10^5 6.47×10^5	2.79×10^{-4} 2.92×10^{-4}
				mean		2.86×10^{-4}
Li	70	2.8	A	42 126	5.41×10^4 1.22×10^5	3.1×10^{-3} 4.1×10^{-3}
				mean		3.6×10^{-3}
Li	60	1.9	A	8	1.16×10^6	2.8×10^{-5}

TABLE 7

Tandem Results for Fujitsu 256K SRAMs

Ion	Angle of Tilt (degrees)	Effective LET (MeV mg^{-1} cm^{2}(Si))	S/N	No of Events	Fluence (p cm^{-2})	Cross Section (cm^{-2})
Cl	0	18.5	5	131	2.64×10^{3}	4.96×10^{-2}
			5	139	2.53×10^{3}	5.49×10^{-2}
				339	4.93×10^{3}	6.88×10^{-2}
				mean		5.78×10^{-2}
			22	503	1.97×10^{4}	2.56×10^{-2}
				363	1.58×10^{4}	2.29×10^{-2}
				126	4.82×10^{3}	2.61×10^{-2}
				mean		2.49×10^{-2}
O	0	5.4	5	661	4.43×10^{4}	1.49×10^{-2}
				698	4.72×10^{4}	1.48×10^{-2}
				mean		1.49×10^{-2}
			22	632	6.96×10^{4}	9.09×10^{-3}
				858	9.98×10^{4}	8.60×10^{-3}
				mean		8.85×10^{-3}
C	50	4.5	5	539	1.43×10^{5}	3.77×10^{-3}
				569	1.55×10^{5}	3.67×10^{-3}
				mean		3.72×10^{-3}
			22	528	1.89×10^{5}	2.79×10^{-3}
				567	1.93×10^{5}	2.94×10^{-3}
				mean		2.87×10^{-3}
C	0	2.9	5	82	4.05×10^{5}	2.02×10^{-4}
				71	3.19×10^{5}	2.23×10^{-4}
				mean		2.13×10^{-4}
			22	230	9.72×10^{5}	2.37×10^{-4}
				249	1.00×10^{6}	2.49×10^{-4}
				mean		2.43×10^{-4}
Li	70	2.8	22	5	1.06×10^{6}	4.7×10^{-6}
Li	60	1.9	22	1	1.21×10^{6}	$\leq 3.3 \times 10^{-6}$

TABLE 8

Tandem Results for Matra Harris 256K SRAM

Ion	Angle of Tilt (degrees)	Effective LET (MeV mg^{-1} cm^2(Si))	No of Events	Fluence (p cm^{-2})	Cross Section (cm^{-2})
CL	60	5.8	402 334	1.42×10^4 1.18×10^4	2.83×10^{-2} 2.83×10^{-2}
			mean		2.83×10^{-2}
C	0	2.9	681 726	2.44×10^4 2.59×10^4	1.44×10^{-2} 1.47×10^{-2}
			mean		1.46×10^{-2}