PRE-PROGRAMMED FLASH MEMORY
RECOMMENDED BEST PRACTICES, X-RAY AND POST OVEN REFLOW

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Dave Rohona, Data I/O Corporation
Data I/O’s programming systems are used by the world’s leading manufacturers, programming centers, and contract manufacturers, to securely program integrated circuits and bring their devices to life.
The term **eMMC** is short for "**embedded Multi-Media Controller**" and refers to a package consisting of both flash memory and a flash memory controller integrated on the same silicon die.

The term **UFS** is short for **“Universal Flash Storage”**. UFS offers read and write speeds that are significantly faster than eMMC while retaining the same power consumption figures.

**eMMC** and **UFS** Flash Memory are available in 3 grades:
- Consumer
- Industrial
- Automotive (is most robust)
• **NAND flash memory** is a type of nonvolatile storage technology that does not require power to retain data.

• **3D NAND Replaces 2D NAND**
  – 2D planar fades out, except for niche applications
  – 3D NAND stacks transistor vertically, solves speed and cost issues

• **Triple-level-cell (TLC) NAND Flash will Dominate**
  – TLC Flash stores 3 bits of data per cell
  – Lower price per gigabyte compared to SLC/MLC NAND
By 2025, On-board Storage Will Exceed 1TB

NVM Storage in Infotainment

- Infotainment / Navigation: 64 – 512 GB
- Digital Cluster: 4 – 32 GB
- Rear-Seat Entertainment: 16 – 64 GB
- Connectivity: 4 – 16 GB
- ADAS / Autonomous Driving: 8 – 16 GB
- HD-Maps: 8 – 512 GB
- Accident recording: 8 – 64 GB

In 2025 on board storage > 1TB
## Memory Structure Trend in Automotive Systems

<table>
<thead>
<tr>
<th>Application</th>
<th>Level 1 Driver Assistance</th>
<th>Level 2 Partial Driving Automation</th>
<th>Level 3 Conditional Driving Automation</th>
<th>Level 4-5 High/Full Driving Automation</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>~2015</td>
<td>NOW</td>
<td>2020</td>
<td>2025</td>
</tr>
<tr>
<td>ADAS</td>
<td></td>
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<tr>
<td>Recognition</td>
<td>NOR</td>
<td>e-MMC</td>
<td>e-MMC</td>
<td>UFS</td>
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<tr>
<td>Decision</td>
<td></td>
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<td>UFS</td>
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<tr>
<td>Event Data Recorder</td>
<td></td>
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<tr>
<td>Wireless</td>
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<tr>
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<td>V2X</td>
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<td>Telematics</td>
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<tr>
<td>Information</td>
<td></td>
<td></td>
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<tr>
<td>IVI</td>
<td>SD card</td>
<td>e-MMC</td>
<td>UFS</td>
<td></td>
</tr>
<tr>
<td>Cluster</td>
<td>NOR</td>
<td>e-MMC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Total Density:**
- ~64GB
- ~96GB
- ~1.5TB
- ~3TB

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*Estimation by Toshiba Memory Corporation.*
X-ray Inspection of Radiation Sensitive Devices
Recommended Best Practices for Preprogrammed Managed NAND

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  ▪ Email: vineeth.bastin@nordsondage.com
Problem Statement

Managed-NAND integrates NAND flash memory and an embedded controller chip in a single package to perform error correction (ECC), wear-leveling and bad-block management internally

- Managed-NAND ships in commercial, industrial and automotive grades, with automotive grade being the most robust
- Preprogramming is the preferred method for programming large files, gigabytes (GB) of data into Managed-NAND Flash
- Low Energy Radiation is a source of stress for pre-programmed managed NAND devices
  - At X-ray, low energy photons have a >95% probability of being absorbed by the device which may result in subtle bit flips, an unintentional state switch from logic 0 to 1 or vice versa of a programmed bit
Test Purposes

- **Education**
  - Understand how an operator sets up an X-ray machine
  - Understand the impact of X-ray machine settings on image quality

- **Criteria**
  - Sample test using automotive grade Managed-NAND
  - Source parts from multiple flash memory suppliers
  - Test parts of different lithographies, 15nm and 20nm

- **Goals**
  - Find the breaking points, unsafe X-ray setup parameters
  - Establish safe X-ray setup parameters that provide a quality image
  - Publish a set of recommended best practices
Equipment Used

The following test equipment was used for our X-ray test study

- Tests were performed using an offline X-ray machine, with and without optional filtering tray
- Data verification was performed using a desktop device programmer
- Two vendors of automotive grade eMMC devices were chosen, Vendor A at 15nm and Vendor B at 20nm
- 10 samples of each eMMC test device were preprogrammed with an X/OR data pattern prior to X-ray
X-ray Test and Data Validation Process

1. Insert preprogrammed test device onto tray
   - Aluminum Tray and Filtering Tray (150 Micron Zinc)
2. Input X-ray machine settings
3. Verify image quality
4. Begin X-ray inspection for targeted time
5. Remove device from X-ray
6. Insert device into Programmer socket
7. Run Verify Test to confirm data integrity (Pass/Fail)
   - If Fail, stop test and discard device, record findings
   - If Pass, reinsert device back into X-ray machine
   - Go to Step #4
Vendor A – Test #1
15nm eMMC, Managed NAND

Initial Setup Parameters (Max Settings)

- Filtering Tray: No
- Tube Voltage: 120KV
- Tube Wattage: 5W
- Distance to Target: 1.5mm
- Exposure Time: 10 min.
- Image Clarity/Quality: Excellent

Test Results

- 1st pass, data verify: Fail
- Estimated RADS: 20,000
Vendor A – Test #2
15nm eMMC, Managed NAND

Setup Parameter Changes
- Tube Voltage from 120KV to: 100KV
- Distance to Target, 1.5mm to: 12.4mm
- Exposure Time, 10 minutes to: 5.5 min.
- Image Clarity/Quality: Excellent

Test Results
- 1st pass, data verify: Fail
- Device marked as: Bad
Vendor A – Test #3
15nm eMMC, Managed NAND

Setup Parameter Changes
■ Tube Voltage from 100KV to: 80KV
■ Tube Wattage from 5W to: 3W
■ Exposure time, 5.5min. to: 5.0 min.
■ Image Clarity/Quality: Excellent

Test Results
■ 1st pass, data verify: Pass
■ Repeat X-ray test: Same device
■ 2nd pass, data verify: Fail
■ Device marked as: Bad
Vendor A – Test #4
15nm eMMC, Managed NAND

Setup Changes
- Filtering Tray (150 micron zinc): Yes
- Image Clarity/Quality: Excellent

Test Results
- 6 consecutive times through X-ray: Pass
- Post 7th X-ray inspection, data verify: Fail
- Device marked as: Bad
- Cumulative exposure time before fail: 30 min.
Summary: Vendor A (15nm Managed NAND)

- Zinc Filtering (150 micron) had the biggest impact
  - X-ray setup parameters of 80KV, 3W, 12.5mm distance are typical
  - 5 minutes of exposure time is excessive, not typical for inline X-ray, we chose worst case

- The zinc filter layer absorbs the low energy photons, preventing them from reaching the silicon device, but leaving higher energy photons for inspection purposes
  - This reduces the silicon dose typically by a factor of 5x
Vendor B – Test #1
20nm Managed NAND

Initial Setup Parameters
- Same as Vendor A, Test #4

Expectations
- 20nm lithography should be more robust
- We expect >6 consecutive passes through X-ray

Results
- 1\textsuperscript{st} pass, data verify: Pass
- 2\textsuperscript{nd} pass data verify: Fail
- Device marked as bad (this was shocking)
- We repeated the test with a fresh device
- Same Results
Vendor B – Test #2
20nm Managed NAND

Setup Parameter Changes
- Filtering tray: No
- Tube Voltage from 80KV to: 60KV
- Tube Wattage from 3W to: 2W
- Image clarity/quality: Excellent

Test Results
- 1st pass, data verify: Pass
- Repeat X-ray test: Same device
- 2nd pass, data verify: Fail
- Device marked as: Bad
Vendor B – Test #3
20nm Managed NAND

Setup Parameter Changes

- Filtering tray: Yes
- Tube Wattage from 2W to: 3W
- Verified image clarity/quality

Test Results

- 3 consecutive times through X-ray: Pass
- Post 4th X-ray inspection, data verify: Fail
Vendor B – Test #4
20nm Managed NAND

Setup Parameter Changes
- Tube Voltage from 60KV to: 80KV
- Tube Wattage from 3W to: 2W
- Verified image clarity/quality

Test Results
- 3 consecutive times through X-ray: Pass
- Post 4th X-ray inspection, data verify: Fail
Vendor B – Test #5
20nm Managed NAND

Setup Parameter Changes
- Tube Voltage from 80KV to: 60KV
- Verified image clarity/quality

Test Results
- 5 consecutive times through X-ray: Pass
- Post 6th X-ray inspection, data verify: Fail
Summary: Vendor B (20nm Managed NAND)

- Again, Zinc Filtering (150 micron) had the biggest impact
  - *X-ray setup parameters of 60KV, 2W, 12.5mm distance provided a quality image*

- Higher lithography doesn’t always equate to being more robust through X-ray
X-ray Test Summary

- All target based X-ray sources produce a spectrum of high and low energy photons, which enable imaging of devices
  - However, for radiation sensitive silicon components, low energy photons <12kV can cause problems
  - This is because they have a >95% probability of being absorbed by the device. This near complete absorption means they play almost no part in the image formation

- Processing preprogrammed Managed-NAND Flash Memories through X-ray is safe when following recommended best practices
  - Zinc Filtering is the single most important requirement
  - While it’s not possible to apply one X-ray machine’s setup parameters to all machine vendors and models, our study should help provide some basic guidelines to follow

- For today’s X-ray machine operator
  - There are needs for risk awareness, education and recommended best practices
  - View our X-ray findings and recommended best practices at www.dataio.com/xray
Vendor A, Oven Reflow and X-ray
15nm eMMC, Managed NAND

Test Results

- Preprogramming on-board, reflow, X-ray
- With filtering tray
- Exposure Time: 5 min.
- 6 consecutive cycles through X-ray: Pass
- Cumulative exposure time before fail: 30 min.

Qty. 10 Vendor A Devices (All Pass)
- Preprogrammed on LumenX Programmer
- Processed 1x through reflow
- Processed 6x through X-ray
- Using Data I/O recommended best practices, X-ray
Vendor B, Oven Reflow and X-ray
15nm eMMC, Managed NAND

Test Results

- Preprogramming on-board, reflow, X-ray
- With filtering tray
- Exposure Time: 5 min.
- 6 consecutive cycles through X-ray: Pass
- Cumulative exposure time before fail: 30 min.

Qty. 10 Vendor B Devices (All Pass)
- Preprogrammed on LumenX Programmer
- Processed 1x through reflow
- Process 6x through X-ray
- Using Data I/O recommended best practices, X-ray
Our Goal: Data Retention Awareness
Pre-programmed Memory, Managed NAND, eMMC

Data Retention Risk
Without X-ray Filtering

Minimize Data Retention Risk
With X-ray Filtering

Bit flip

Before X-ray

After X-ray

Pre-programmed Memory

Loader Printer SPI Chip Mouter Ic Mouter Reflow X-ray Unloader

Offline Pre-programming

Tape Input Reel of Pre-programmed Parts
Data I/O partnered with Nordson DAGE for a joint study

Processing Preprogrammed Managed NAND Flash Through X-ray is Safe When Following Recommended Best Practices
Filtering is critical

Follow published best practices
- Refer to Data I/O's X-Ray White Paper or contact Dave Rohona
DATA RETENTION CONCERNS AT OVEN REFLOW FOR AUTOMOTIVE GRADE 3D UFS

- Data Retention Study with Toshiba (Now Kioxia)
- Data I/O Recommended Best Practices
Memory vendor messaging to automotive accounts has creating concerns and uncertainty that preprogramming may no longer be safe moving forward.

**Key Concerns:**
- MLC on UFS may no longer be supported and replaced with TLC
- Preprogramming 3D UFS, TLC through reflow at >150°C may lower the cell lifetime*

*Automotive has a significant installed base of Data I/O eMMC programming equipment that can easily be upgraded to UFS; but the process must be reliable
Data I/O and a leading UFS memory vendor have collaborated to better understand the impact of oven reflow (temperature) on data retention for Automotive Grade 3D UFS, TLC devices.

**Experiment shows:**

- Reflow slows down read performance, but does not cause reliability failures (bit flip). More reflows cause more read performance slow down, but do not cause loss of data.
  - Up to 3 reflows possible
  - Forced Refresh after reflow fixes read performance issues completely

From our joint study, we have concluded that preprogramming is safe and full performance is maintained with a post reflow refresh.

With this study complete, supplier decided to release a 100% pre programming capable part to the market. Others are following.
## PREPROGRAMMING TEST PLAN – AUTOMOTIVE 3D UFS

### 7 EVALUATIONS, 20PCS OF 128GB, 50PCS OF 256GB (2 FIRMWARE VERSIONS)

### Evaluation Process
1. Preprogram (100%), without PSA
2. Reflow at standard profile
3. Read data, check error rate (%)
4. Measure read performance (MB/s)
5. **Selective Refresh**, measure time
6. **Force Refresh**, measure time
7. Erase user data
8. **Repeat for next reflow cycle**

<table>
<thead>
<tr>
<th>Evaluation Number</th>
<th>Evaluation Details</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaluation-1 (128GB)</td>
<td>10pcs</td>
<td>10pcs</td>
</tr>
<tr>
<td>• Evaluation of reflow 1x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Evaluation of reflow 2x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluation-2 (128GB)</td>
<td>10pcs</td>
<td>10pcs</td>
</tr>
<tr>
<td>• Evaluation of reflow 1x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Evaluation of reflow 3x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluation-3 (256GB)</td>
<td>9pcs</td>
<td>9pcs</td>
</tr>
<tr>
<td>• Evaluation of reflow 3x</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Evaluation-4 (256GB)</td>
<td>20pcs</td>
<td>20pcs</td>
</tr>
<tr>
<td>• Evaluation of reflow 1x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Evaluation of reflow 2x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluation-5 (256GB)</td>
<td>21pcs</td>
<td>21pcs</td>
</tr>
<tr>
<td>• Evaluation of reflow 1x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Evaluation of reflow 3x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**Data iO**
Data I/O - MFG Reflow Profile
Recommended by EMS Partner, Approved by Semi-Partner

Semi-Vendor - JEDEC Max Reflow Profile
Used by Semi-Partner

<table>
<thead>
<tr>
<th>IR Condition</th>
<th>T_peak=251degC, t_peak=30sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>STANDAR</td>
<td>TC1</td>
</tr>
<tr>
<td>Liquid Time</td>
<td>86</td>
</tr>
<tr>
<td>Peak Temperature</td>
<td>247</td>
</tr>
</tbody>
</table>

Profile Name: LEADFREE2 5-13-2019
Process Name: ProcessNameHere
Recipe Name: LEADFREE2
Product Name: DATA/I0
User Name: CHI HOI TAING
Conveyor Speed: 25
Number of Samples: 424
Maximum Distance: 176
Liquid Temperature: 217
DATA RETENTION RESULTS

- **Evaluations 1, 2 (128GB)**
  - 20pcs
  - Evaluation after reflow (1x and 2x), (1x and 3x)
  - *No data errors found*

- **Evaluations 4, 5 (256GB)**
  - 41pcs
  - Evaluation after reflow (1x and 2x), (1x and 3x)
  - *No data errors found*

- **Evaluation-3 (256GB)**
  - 9pcs
  - Evaluation after reflow (3x)
  - Shipped to Memory Vendor for analysis, *no data errors found*
ADDITIONAL CONCERNS

• Data integrity is not an issue
  – No data errors in any test

• Read performance degrades after reflow

• Memory vendors are recommending a Refresh
  – Forced refresh recovers read performance
  – Also ensures long-term data retention
    – Should be done within 20 months of reflow for best reliability
  – Restores TLC NAND cells to optimal condition
✓ Using Manual-Force Refresh, Read performance is **completely** recovered after refresh

✓ Data I/O recommends to **use Manual-Force Refresh after reflow**
  - from both “read performance” and “data retention” points of view

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**Read Performance**
*After Manual-Force Refresh, 256GB UFS*

<table>
<thead>
<tr>
<th>IR Condition</th>
<th>Before IR</th>
<th>IRx1</th>
<th>IRx2</th>
<th>IRx3</th>
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</thead>
<tbody>
<tr>
<td>JEDEC (J-STD-020E)</td>
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<tr>
<td>T_peak=260degC, t_peak=30sec</td>
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<td></td>
</tr>
</tbody>
</table>
- Data sourced from a combination of Data I/O measurements and Memory Vendor-provided information
- Refresh times may vary between memory vendors

<table>
<thead>
<tr>
<th>Utilization</th>
<th>32 GB Density</th>
<th>64 GB Density</th>
<th>128 GB Density</th>
<th>256 GB Density</th>
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</thead>
<tbody>
<tr>
<td>100%</td>
<td>16 minutes</td>
<td>17 minutes</td>
<td>20 minutes</td>
<td>40 minutes</td>
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<tr>
<td>75%</td>
<td>12 minutes</td>
<td>13 minutes</td>
<td>15 minutes</td>
<td>30 minutes</td>
</tr>
<tr>
<td>50%</td>
<td>8 minutes</td>
<td>9 minutes</td>
<td>10 minutes</td>
<td>20 minutes</td>
</tr>
</tbody>
</table>
Preprogramming Automotive Grade 3D UFS, TLC is safe when performing a Manual Force Refresh after oven reflow

- Zero data loss, all tests
- Performance is recovered after manual force refresh cycle
- Refresh times are near constant for both Standard MFG Reflow temperature at 251degC, and JEDEC Peak Reflow temperature at 260degC

After the study, the memory supplier decided to support 100% preprogramming
### Memory Vendor Positions

**Preprogramming Automotive Grade 3D UFS, TLC**

<table>
<thead>
<tr>
<th>Automotive 3D UFS, TLC</th>
<th>Toshiba</th>
<th>Western Digital</th>
<th>Micron</th>
<th>Samsung</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preprogramming Support</strong> (x% of device density)</td>
<td>100%</td>
<td>100%</td>
<td>30% (SLC Mode)</td>
<td>10%</td>
</tr>
<tr>
<td><strong>Manual Force Refresh</strong> (Recommended after oven reflow, at test)</td>
<td>Yes</td>
<td>Yes</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td><strong>Future preprogramming Support, Full-Capacity (100%)</strong></td>
<td></td>
<td></td>
<td></td>
<td>Under Consideration</td>
</tr>
<tr>
<td>Later generations of current/future designs</td>
<td></td>
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</tr>
</tbody>
</table>
TO ENSURE DATA RETENTION FOR AUTOMOTIVE GRADE 3D UFS, TLC
PERFORMING A MANUAL FORCE REFRESH IS THE MOST IMPORTANT REQUIREMENT

Pre Programming

Solder Reflow

Manual Force Refresh

Offline Automated Programming

Thermal Profiles
✓ JEDEC guidelines
✓ Reflow Profile Temp
✓ Number of Cycles

Data I/O Recommended
Best Practices
✓ LumenX Programmer
✓ Production State Awareness (PSA)
✓ Annual Device Support Contract (DSC)

End Product
✓ Boot
✓ Manual Force Refresh

TLC NAND
as Good as New

TLC NAND as Good as New
DATA RETENTION AND READ PERFORMANCE AWARENESS
PRE-PROGRAMMED 3D NAND, AUTOMOTIVE GRADE UFS

Thermal Impact on Read Performance (MB/s)

Read Performance Restored Data Refresh at Test

OFFLINE PRE-PROGRAMMING
TAPE INPUT REEL OF PRE-PROGRAMMED PARTS

Before X-ray
Pre-programmed Memory
KEY TAKEAWAYS

1. Data I/O conducted a joint study with Toshiba to study the impact of reflow on TLC NAND.

2. Study revealed no data retention errors after 3x reflow.

3. Perform a refresh after reflow and TLC NAND is as good as new.
Thank You!
**WHAT CAUSES A BIT-FLIP?**

- As more threshold voltage levels are stored on the floating gate, SLC to MLC to TLC
  - the more constrained the distributions become in order to separate any two voltage thresholds for a pair of adjacent logic states

- Erase/Program cycles cause distribution to flatten and widen (shift-right)

- A cell reading “10” might now read “00”. This is what causes bit-flips

- X-ray and reflow may cause reference voltage threshold to (shift-left)