MAKING (→) NAND HEALTH ACTIONABLE

A Structured Approach to UFS Flash Monitoring

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A Structured Approach to UFS Flash Monitoring

1. Introduction

Modern embedded systems increasingly depend on NAND flash not only as storage, but as a managed, adaptive subsystems whose behavior directly impacts performance, reliability, and system lifetime. Yet many failures, degradations, and premature end-of-life events arise not from the memory itself, but from a lack of visibility into how workload, firmware behavior, platform conditions, and health monitoring interact over time. This white paper introduces a structured, bottom-up model for UFS NAND flash health registers that mirrors real device operation—from raw workload and physical effects to firmware control and actionable health indicators. By clearly separating measurement from interpretation, internal behavior from external stress, and reversible effects from irreversible wear, the model provides a consistent and practical framework for understanding, monitoring, and managing NAND behavior in real systems.

To keep NAND health information actionable and scalable, the topics are defined along clear functional boundaries that reflect how storage is used, managed, and evaluated in real products. Each topic isolates a specific dimension—usage, measured behavior, interpreted health, firmware control, and platform influence—so that system stakeholders can quickly understand what is happening, why it is happening, and where action is required. This structure turns complex device telemetry into clear executive insight without requiring deep NAND expertise.

In safety-critical systems, reliable decision-making depends on clearly separating cause, observed behavior, and interpreted condition. The topics are therefore defined to isolate externally applied workload, measured internal effects, irreversible physical wear, firmware reaction mechanisms, and platform-induced stress. This deterministic structure supports traceability, fault attribution, and compliance with functional safety requirements by ensuring that health indicators are grounded in measurable facts, that irreversible degradation is explicitly visible, and that system-level risks are not mistakenly attributed to the memory device itself.

1.1 Workload

This topic describes **how the host system actually uses the NAND storage** over time. It tracks how much data is read and written, how often fast buffers like SLC or pSLC are used. Together, these metrics explain real-world usage intensity and access patterns, helping relate device wear, performance, and lifetime behavior to the actual workload applied by the SoC.

1.2 Health / Statistics

This topic provides **detailed, quantitative insight into device reliability and aging.** It measures erase cycles, error correction events, bit flips, reclaim operations, failures, resets, and feature usage counters. These statistics are essential for detecting abnormal behavior, accelerated wear, or emerging data-integrity risks long before the device reaches end-of-life.

1.3 Health / Status

This topic summarizes the device's condition in **easy-to-interpret health indicators.** It includes bad block counts, remaining spare capacity, pre-end-of-life warnings, and normalized health percentages for different memory regions. The focus is not raw detail, but **decision guidance,** helping the system know when the device is healthy, degrading, or close to needing protective actions such as workload reduction and at most extreme action read-only operation.

1.4 FW-OS / Admin

This topic covers **firmware identity, configuration, and control state.** It reports firmware versions, update history, power and performance states, thermal throttling status, administrative features, and internal modes. These fields help ensure traceability and support system integration, debugging, and maintenance by clearly showing **what firmware is running and how the device is currently managed.**

1.5 SoC / Platform

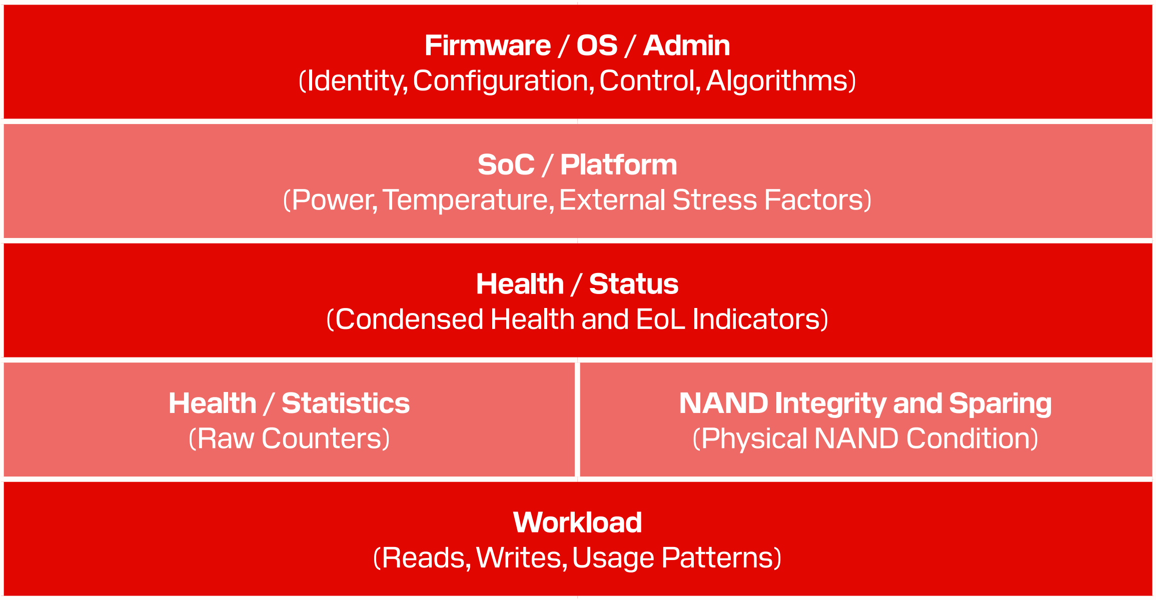
This topic reflects the **quality and stability of the operating environment** provided by the SoC and system hardware. It tracks ungraceful shutdowns, voltage drops, resets, write aborts, thermal events, and power-management changes. These metrics help distinguish whether issues come from NAND wear or from **platform-level problems such as unstable power, heat, or system behavior.**

1.6 FW-OS / Algorithm

This topic exposes **internal firmware protection and optimization mechanisms.** It monitors how often advanced algorithms—such as reclaim, purge, data-path protection, write boosting, and feature-based optimizations—are activated and used. The goal is to help ensure that the NAND controller is actively **protecting data, optimizing endurance, and recovering performance as designed** under real operating conditions.

2. Layer Structure

The figure below illustrates these topics: It mirrors how NAND devices actually operate in real systems: physical memory responds to workload, firmware manages that response, the platform imposes constraints, and health information is progressively distilled into actionable signals.



2.1 Bottom-Up: From Cause to Effect

The model starts with Workload at the bottom because workload is the root cause of almost all NAND behavior. Reads, writes, access patterns, and feature usage directly determine how often memory cells are programmed, erased, and stressed. Without knowing how the device is used, all higher-level health or status indicators lack context.

From workload, the model moves upward to Health / Statistics, which records the effects of that usage. These counters represent what the device has actually experienced as a result of workload and time. They are not interpretations, but factual observations.

2.2 Separation of Measurement and Interpretation

A key design principle of the model is the strict separation between:

- Measured data (Health / Statistics), and
- Interpreted condition (Health / Status)

Raw counters alone are difficult to use directly at system level, especially for non-experts. Therefore, Health / Status is placed above Health / Statistics as an abstraction layer that converts complex internal behavior into simple indicators such as health levels or warnings. This avoids pushing decision logic into the host system and keeps interpretation consistent.

2.3 Explicit Isolation of Irreversible Physical Wear

NAND Integrity & Sparing is intentionally positioned alongside Health / Statistics but conceptually distinct. While many counters can fluctuate or stabilize, physical NAND wear—such as consumed spare blocks—is irreversible. By separating this layer, the model makes it clear which aspects of device aging can be managed algorithmically and which represent hard physical limits.

This separation is critical for lifetime prediction and long-term reliability planning.

2.4 External vs. Internal Responsibility

The SoC / Platform layer exists above device-internal layers to explicitly separate external stress from internal behavior. Power instability, thermal conditions, and platform power management are outside the NAND's control but strongly influence reliability metrics.

Placing this layer above health and integrity emphasizes that not all degradation originates inside the memory and helps avoid incorrectly attributing system issues to the NAND device itself.

2.5 Control Plane at the Top

The model places Firmware / OS / Admin at the top because firmware defines how the device reacts to everything beneath it. Firmware algorithms determine wear leveling behavior, error recovery strategy, throttling thresholds, and reporting formats. Administrative data such as firmware version and update history provides the context needed to compare telemetry across time or across systems.

Positioning firmware at the top reflects its role as the control and interpretation plane, not as a source of physical behavior.

This structure helps that:

- Root causes are not confused with symptoms
- Measurements are not confused with decisions
- Device behavior is not confused with platform behavior
- Firmware effects are visible and traceable

This layer model mirrors how NAND devices actually operate in real systems: physical memory responds to workload, firmware manages that response, the platform imposes constraints, and health information is progressively distilled into actionable signals.

3. Summary

UFS NAND flash reliability depends on the interaction of workload, firmware behavior, and platform conditions. The layered health model clarifies these interactions by separating causes from symptoms, measurements from interpretation, and device behavior from system stress.

System architects and Testing & Quality experts should use health data during normal operation, not only after failures. Align workload profiles with lifetime expectations, monitor detailed health metrics for early wear detection, and use high-level indicators for automated system actions. Maintain firmware traceability, correlate NAND health with power and thermal events, and verify that firmware protection mechanisms function correctly in real workloads.

On SANDISK® NAND flash UFS devices, the required information is obtained via a single read command that returns an approximately 500-byte data block, enabling subsequent analysis.

Applying this approach enables predictive reliability management, improving robustness, helping extend product lifetime, and increasing storage transparency across the product lifecycle.

Acronym	Full Name	**Explanation** (Plain Language)
NAND	NAND Flash Memory	A type of non-volatile memory used to store data in solid-state storage devices.
SLC	Single-Level Cell	NAND memory that stores 1 bit per cell; very fast and highly durable but low capacity.
pSLC	Pseudo-Single-Level Cell	A portion of multi-level NAND operated like SLC to improve speed and durability.
TLC	Triple-Level Cell	NAND memory that stores 3 bits per cell; higher capacity but slower and less durable than SLC.
SoC	System on Chip	The main processor that controls and communicates with the storage device.
FW	Firmware	Embedded software inside the storage device that manages NAND behavior.
OS	Operating System	System software that interacts with the storage device via the host platform.
FW-OS	Firmware / Operating System	Refers collectively to firmware-level and OS-level device management functions.
Admin	Administrative	Configuration, management, and reporting functions of the storage device.
Platform	System Platform	The combined hardware and power environment in which the device operates.
ECC	Error Correction Code	Technique used to detect and correct bit errors in NAND data.
End-of-Life (EoL)	End of Device Lifetime	The stage at which NAND wear limits are reached and reliability can no longer be guaranteed.
Pre-End-of-Life	Pre-EoL	Early warning that NAND wear is approaching critical limits.
FW Update	Firmware Update	Process of installing new firmware to fix issues or add features.
Read-Only (RO)	Read-Only Mode	Protective mode where data can be read but no longer written to prevent data loss.
Data Path Protection	DPP	Mechanisms that help protect data while it moves inside the storage device.

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