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NVMe™ Project

OCP L.O.C.K.

1.1 (RC4)

Modular Base Specification
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VERSION HISTORY

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September 2025	1.0	Initial release
May 2026	1.1_RC1	Minor formatting and grammar fixes. Change and add missing KDF labels. Rotate HPKE keypairs on all resets. Modified the REPORT_HEK_METADATA command. Rename “Opal C_PIN” to “TCG C_PIN”. Remove REPORT_EPOCH_KEY_STATE. Illustrate usage of the internal DRBG for drive-firmware-specific use-cases. Deprecate the “preconditioned key extract” construct, and instead combine keys using SP 800-108 KDFs. Update HPKE references and diagrams. Update REWRAP_MPK command language. Fix INITIALIZE_MEK_SECRET mailbox code Rename ENDORSE_HPKE_PUB_KEY to GET_HPKE_PUB_KEY and remove endorsement from KMB. Endorsement is now performed by MCU using DPE. Make KMB mailbox fault handling generic and reference caliptra-sw. HEK seed lifecycle requirement changes. Remove salt from Wrapped Key AAD. Add padding and kem_ciphertext upper bound to SealedAccessKey. Add upper bound to Wrapped Key metadata and info len. Add upper bound to public key in GET_HPKE_PUB_KEY. Allow Write-only AUX and Metadata registers for the encryption engine. Removed “MPK secrets” entry from CSP table. This was a duplicate of “MEK secrets”. Removed Compliance entry 7. This shall now be enforced by KMB. Update EKP notice.
May 2026	1.1_RC2	Add KMB AES-XTS Equality check and Encryption Engine self-test.
May 2026	1.1_RC3	Remove KMB firmware notice.
June 2026	1.1_RC4	Address feedback: grammar and table formatting fixes. Mark LOAD_KAT_MEK as optional.

Current Template Version:

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2 Acknowledgements

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3 Compliance with OCP Tenets

3.1 Openness

OCP L.O.C.K. source for RTL and firmware will be licensed using the Apache 2.0 license. The specific mechanics and hosting of the code are work in progress due to CHIPS alliance timelines. Future versions of this spec will point to the relevant resources.

3.2 Efficiency

OCP L.O.C.K. is used to generate and load keys for use of encrypting user data prior to storing data at rest and decrypting stored user data at rest when read. So, it cannot yield a measurable impact on system efficiency.

3.3 Impact

OCP L.O.C.K. enables consistency and transparency to a foundational area of security of media encryption keys such that no drive firmware in the device ever has access to a media encryption key. Furthermore, no decrypted media encryption key exists in the device when power is removed from the device.

3.4 Scale

OCP L.O.C.K. is a committed intercept for storage products for Google and Microsoft. This scale covers both a significant portion of the hyperscale and enterprise markets.

3.5 Sustainability

The goal of OCP L.O.C.K. is to eliminate the need for cloud providers to destroy storage devices (e.g., SSDs) by providing a mechanism that increases the confidence that a media encryption key within the device is deleted during cryptographic erase. This enables repurposing the device and or components on the device at end of use or end of life. Given the size of the market serving cloud providers, this provides a significant reduction of e-waste.

4 Base specification

4.1 Introduction

OCP L.O.C.K. (Layered Open-source Cryptographic Key management) provides secure key management for Data-At-Rest protection in self-encrypting storage devices.

OCP L.O.C.K. was originally created as part of the Open Compute Project (OCP). The major revisions of the OCP L.O.C.K. specifications are published as part of Caliptra at OCP, as OCP L.O.C.K. is an extension to Caliptra. The evolving source code and documentation for Caliptra are in the repository within the CHIPS Alliance Project, a Series of LF Projects, LLC.

OCP L.O.C.K. may be integrated within a variety of self-encrypting storage devices, and is not restricted exclusively to NVMe™. OCP L.O.C.K. is designed for compatibility with the TCG Storage Architecture [1], including support for TCG Opal[1] [2], Enterprise [3], and Key Per I/O [4] specifications.

4.2 Background

In the life of a storage device in a datacenter, the device leaves the supplier, a customer writes user data to the device, and then the device is decommissioned. Customer data is not allowed to leave the data center. The cloud provider needs high confidence that the storage device leaving the datacenter is secure. The current default cloud provider policy to ensure this level of security is to destroy the drive. Other policies may exist that leverage drive capabilities (e.g., cryptographic erase), but are not generally deemed inherently trustworthy by these cloud providers [5]. This produces significant e-waste and inhibits any re-use/recycling.

Self-encrypting drives (SEDs) store data encrypted at rest using media encryption keys (MEKs). SEDs include the following building blocks:

- The storage media that holds data at rest.
- An encryption engine which performs line-rate encryption and decryption of data as it enters and exits the drive.
- A drive controller which exposes host-side APIs for managing the lifecycle of MEKs.

MEKs may be bound to user credentials, which the host must provide to the drive in order for the associated data to be readable. A given MEK may be bound to one or more credentials. This model is captured in the TCG Opal and Enterprise specifications.

MEKs may be erased, to cryptographically erase all data which was encrypted to the MEK. To erase an MEK, it is sufficient for the drive to erase all copies of it, or all copies of a key with which it was protected.

4.3 Threat model

The protected asset is the user data stored at rest on the drive. The adversary profile extends up to nation-states in terms of capabilities.

Adversary capabilities include:

- Interception of a storage device in the supply chain.

[1] Opal in the context of this document includes the Opal Family of SSCs: Opal SSC, Opalite SSC, Ruby SSC. Pyrite is excluded as Pyrite SSDs are non-SED.

- Theft of a storage device from a data center.
- Destructively inspecting a stolen device.
- Running arbitrary firmware on a stolen device.
  - This includes attacks where vendor firmware signing keys have been compromised.
- Attempting to glitch execution of code running on general-purpose cores.
- Stealing debug core dumps or UART/serial logs from a device while it is operating in a data center, and later stealing the device.
- Gaining access to any class secrets, global secrets, or symmetric secrets shared between the device and an external entity.
- Executing code within a virtual machine on a multi-tenant host offered by the cloud provider which manages an attached storage device.
- Accessing all device design documents, code, and RTL.

Given this adversary profile, the following are a list of vulnerabilities that OCP L.O.C.K. is designed to mitigate.

- MEKs managed by storage drive firmware are compromised due to implementation bugs or side-channels.
- MEKs erased by storage drive firmware are recoverable via invasive techniques.
- MEKs are not fully bound to user credentials due to implementation bugs.
- MEKs are bound to user credentials which are compromised by a vulnerable host.
- Cryptographic erase was not performed properly due to a buggy host.

4.4 OCP L.O.C.K. goals

OCP L.O.C.K. is being defined to improve drive security. In an SED that integrates Caliptra with OCP L.O.C.K. features enabled, Caliptra will act as a Key Management Block (KMB). The KMB will be the only entity that can read MEKs and program them into the SED's encryption engine. The KMB will expose services to drive firmware which will allow the drive to transparently manage each MEK's lifecycle, without being able to access the raw MEK itself.

The OCP L.O.C.K. KMB satisfies the following properties:

- Prevents leakage of media keys via firmware vulnerabilities or side-channels, by isolating MEKs to a trusted component.
- Binds MEKs to a given set of externally-supplied access keys, provisioned with replay-resistant transport security such that they can be injected without trusting the host.
- Uses epoch keys for attestable epoch-based cryptographic erase.

4.4.1 Non-goals

The following areas are out of scope for this project.

- Compliance with IEEE 1619^{TM}-2025 [6] requirements around key scope, i.e. restricting a given MEK to only encrypt a maximum of 2^{44} 128-bit blocks. Drive firmware will be responsible for enforcing this.
- Compliance with Common Criteria requirement FCS_CKM.1.1(c) [7] when supporting derived MEKs. Key Per I/O calls for DEKs to be injected into the device. To support OCP L.O.C.K.'s goals around enabling cryptographic erase, before the injected DEK is used to encrypt user data, the DEK is first conditioned with an on-device secret that can be

securely zeroized. FCS_CKM.1.1(c) currently does not allow injected keys to be thus conditioned and therefore does not allow for cryptographic erase under the Key Per I/O model. A storage device that integrates OCP L.O.C.K. and aims to be compliant with this Common Criteria requirement may not support Key Per I/O.

- Authorization for EPK/DPK/MPK rotation, or binding a given MEK to a particular locking range. Drive firmware is responsible for these.
- Mitigation against availability attacks carried out by attackers with physical presence.

4.5 Integrating OCP L.O.C.K.

OCP L.O.C.K. is a feature set conditionally compiled into Caliptra Subsystem 2.1+. It consists of functionality in Caliptra ROM and Runtime Firmware along with a hardware interface from Caliptra Core to a vendor-implemented encryption engine, which is the path by which Caliptra Core programs MEKs. This hardware interface leverages the AXI Manager which is only available in Caliptra Subsystem.

OCP L.O.C.K.'s KMB offers cryptographic services for drive firmware, which implements a host-facing storage interface, such as TCG Opal, Enterprise, or Key Per I/O. The host will interact with drive firmware to configure the storage device and actuate storage lifecycle events, such as MEK loading / unloading and cryptographic erase. Certain of these lifecycle events are handled by KMB on behalf of drive firmware.

In Caliptra Subsystem, drive firmware runs within the Manufacturer Control Unit (MCU) [8].

4.5.1 Integration verification

A product that integrates OCP L.O.C.K. will be expected to undergo an OCP S.A.F.E. review to ensure that L.O.C.K. is correctly integrated and that drive firmware correctly invokes L.O.C.K. services.

4.6 Architecture

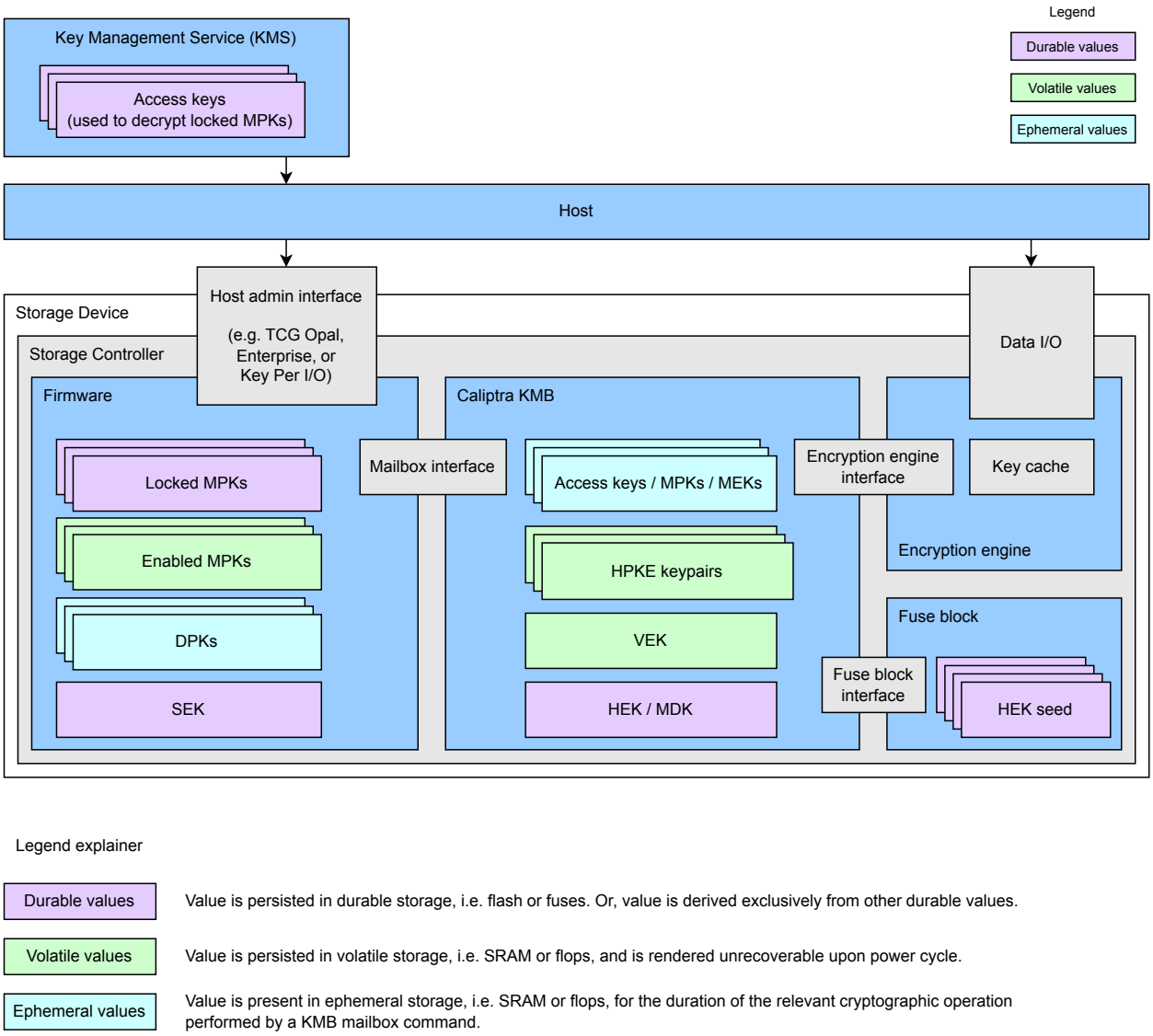

Figure 1: OCP L.O.C.K. high level blocks

To safeguard user data stored on the drive, KMB defines a set of “protection keys”, each of which must be available in order for an MEK to be accessible.

- The **data protection key (DPK)**, which is managed by the nominal owner of the data. A given MEK is bound to a single DPK.
  - In Opal or Enterprise, the DPK may be protected by the user’s C_PIN, while in Key Per I/O the DPK may be the DEK associated with a given key tag.
- A configurable number of **Multi-party Protection Keys (MPKs)**, which are each managed by an additional entity that must assent before user data is available. A given MEK may be bound to zero or more MPKs.

  - Each multi-party entity grants access to the data by providing an access key to the drive. Each MPK is protected by a distinct access key, which is never stored persistently within the drive. MPK access keys are protected in transit using HPKE [9]. This enables use-cases where the access key is served to the drive from a remote key management service, without revealing the access key to the drive's host.
  - Binding an MEK to zero MPKs allows for legacy Opal, Enterprise, or Key Per I/O support.

- A composite **epoch protection key (EPK)**, which is the output of a KDF of two "component epoch keys" held within the device: the **Soft Epoch Key (SEK)** and the **Hard Epoch Key (HEK)**. The EPK is managed by the storage device itself, and all MEKs in use by the device are bound to it.

  - All MEKs in use by the drive can be cryptographically erased by zeroizing either the SEK or HEK. New MEKs shall not be loadable until the zeroized epoch keys are regenerated.
  - KMB reports the zeroization state of the SEK and HEK, and therefore whether the drive is in a cryptographically erased state.
  - The SEK is managed by drive firmware and shall be held in rewritable storage, e.g. in flash memory.
  - The HEK is derived from a seed held in fuses and is only visible to KMB hardware. This provides assurance that an advanced adversary is unable to recover key material that had been in use by the drive prior to HEK seed zeroization.

The EPK, DPK, and set of configured MPKs are used together to derive an MEK secret, which protects a given MEK. The MEK protection is implemented as one of two methods:

- **MEK encryption** - the drive obtains a random MEK from KMB, encrypted by two keys: the MEK secret and the **MEK Deobfuscation Key (MDK)**, and is allowed to load that wrapped MEK into the encryption engine via KMB. This supports Opal or Enterprise use-cases.
- **MEK derivation** - the drive instructs KMB to derive an MEK from the MEK secret and load the MEK into the encryption engine. This may support either Opal, Enterprise, or Key Per I/O use-cases.

MEKs are never visible to drive firmware. Drive firmware instructs KMB to load MEKs into the key cache of the encryption engine, using standard interfaces described in Section 4.7. Each MEK has associated vendor-defined metadata, e.g. to identify the namespace and LBA range to be encrypted by the MEK.

KMB shall not cache MEKs in memory. The encryption engine shall remove all MEKs from the encryption engine on a power cycle or upon request from drive firmware.

All keys randomly generated by KMB are generated using a DRBG seeded by Caliptra's TRNG. The DRBG may be updated using entropy provided by the host.

4.6.1 Key hierarchy

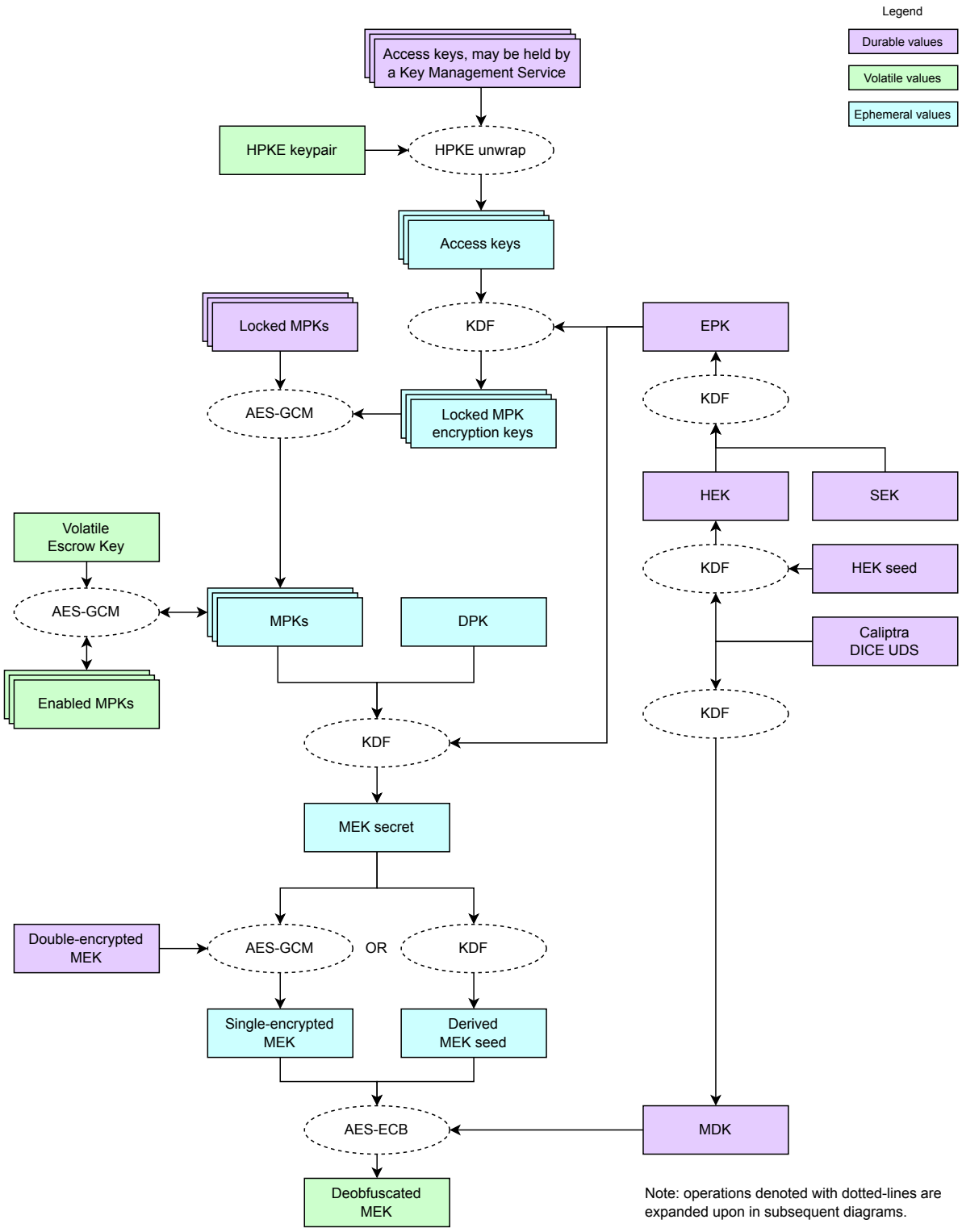

Figure 2: OCP L.O.C.K. key hierarchy

Table 1 enumerates the CSPs (Critical Security Parameters) used by KMB, along with where each CSP is held in the Key Vault (KV). KV slots 16-23 are reserved for OCP L.O.C.K.

Table 1: Critical Security Parameters

CSP	Usage	Lifecycle	KV slot number
UDS	Used to derive the DICE IDevID CDI, which in turn is used to derive the MDK and HEK. See Figures 20 and 17.	Held in the Key Vault during cold reset and zeroized after use. Rendered irrecoverable if zeroized from persistent storage.	0
MDK	Used to perform the inner encryption and decryption of each MEK. See Section 4.6.5.2.	Derived from the UDS during cold reset. Held in the Key Vault and lost on cold reset. Rendered irrecoverable if the DICE UDS is zeroized from persistent storage.	16
HEK seed	Contributes to the derivation of the HEK. See Section 4.6.4.1.	Randomly generated and stored in fuses. Drive firmware zeroizes the HEK seed from fuses on demand, according to the constraints given in Section 4.6.4.2.	N/A
HEK	Contributes to the derivation of the EPK. See Figure 11 for one of several flows where this is done.	Derived from the HEK seed and UDS during cold reset. Held in the Key Vault and lost on cold reset. Rendered irrecoverable if the HEK seed or the DICE UDS are zeroized from persistent storage.	22
SEK	Contributes to the derivation of the EPK. See Figure 11 for one of several flows where this is done.	Managed outside of Caliptra. Randomly generated by drive firmware and stored in flash. When held by Caliptra, the SEK is held in volatile memory and is zeroized after each use. Drive firmware zeroizes the SEK from flash on demand, according to the constraints given in Section 4.6.4.2.	N/A
EPK	Contributes to the derivation of each Locked MPK encryption key. See Figure 11 for one of several flows where this is done. Contributes to the derivation of each MEK secret. See Figure 18.	Derived from the HEK and SEK. Held in the Key Vault and zeroized after each use. Rendered irrecoverable if the SEK, HEK seed, or DICE UDS are zeroized from persistent storage.	17

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CSP	Usage	Lifecycle	KV slot number
Volatile Escrow Key (VEK)	Allows KMB firmware to escrow volatile secrets for future access by runtime KMB firmware. Encrypts/decrypts Enabled MPKs. See Figures 12 and 18.	Randomly generated when first needed at runtime. Held in the Key Vault and lost on cold reset.	18
HPKE private keys	Provides transport encryption for injected access keys. See Section 4.6.2.1.	Randomly generated on startup. Held in volatile memory, rotated on demand, and lost on cold reset.	N/A
Access keys	Contributes to the derivation of a Locked MPK encryption key. See Figure 11 for one of several flows where this is done.	Managed outside of Caliptra. Asymmetrically encrypted using the HPKE public key. When held by Caliptra, each access key is held in volatile memory and is zeroized after each use.	N/A
Locked MPK encryption keys	Encrypts/decrypts a Locked MPK. See Figure 11 for one of several flows where this is done.	Derived from the EPK and an injected access key. Held in the Key Vault and zeroized after each use. Rendered irrecoverable if the SEK, HEK seed, or DICE UDS are zeroized from persistent storage.	19
MPKs	Contributes to the derivation of an MEK secret. See Figure 18.	Randomly generated on demand. Encrypted with a Locked MPK encryption key or the VEK (depending on whether the MPK is locked or enabled). When decrypted, each MPK is held in volatile memory and is zeroized after each use. Rendered irrecoverable if the SEK, HEK seed, or DICE UDS are zeroized from persistent storage.	N/A
DPKs	Contributes to the derivation of an MEK secret. See Figure 18.	Managed outside of Caliptra. When held by Caliptra, the DPK is held in volatile memory and is zeroized after each use.	N/A
MEK secrets	Either encrypts/decrypts an MEK or is used to derive an MEK seed. See Sections 4.6.5.2 and 4.6.5.3.	Derived from the EPK, DPK, and zero or more decrypted MPKs. Held in the Key Vault and zeroized after each use. Rendered irrecoverable if the SEK, HEK seed, or DICE UDS are zeroized from persistent storage.	21

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CSP	Usage	Lifecycle	KV slot number
MEK seeds	Used to derive an MEK. See Section 4.6.5.3.	Derived from an MEK secret. Held by firmware and zeroized after each use. Rendered irrecoverable if the SEK, HEK seed, or DICE UDS are zeroized from persistent storage.	N/A
MEKs	Encrypts/decrypts user data written to the storage device. See Section 4.6.5.	Either randomly generated on demand and encrypted at rest with the MEK secret and MDK, or derived from the MEK secret. Held in the Key Vault and zeroized after programming to the Encryption Engine. Rendered irrecoverable if the SEK, HEK seed, or DICE UDS are zeroized from persistent storage.	23[1]

4.6.1.1 Key Vault

Some elements of the OCP L.O.C.K. key hierarchy are held in the Caliptra Key Vault. Such keys are wielded directly by hardware and cannot be read by firmware.

Other elements of the key hierarchy are not thus protected, and are held in KMB's memory instead. Table 2 describes why each such CSP is held outside of the Key Vault.

Table 2: CSPs visible to KMB firmware

Firmware-visible CSP	Reason for being visible to KMB firmware
SEK	Managed by drive firmware, passed in via mailbox command.
DPKs	Managed by drive firmware, passed in via mailbox command.
HPKE private keys	To mitigate side-channel attacks, the ECDH and ML-KEM engines mandate that any operation whose source includes a key from the Key Vault must place the result back in the Key Vault. If the HPKE private keys were held in the Key Vault, then the ECDH and ML-KEM Decaps results would be held in the Key Vault as well. Section 4.6.2.1.1 illustrates that these results are used to compute an HMAC message, a SHA3 digest, and an AES-GCM IV. Caliptra's Key vault hardware does not presently support these operations. Therefore, the ECDH and ML-KEM Decaps results cannot be held in the Key Vault; ergo, the HPKE private keys also cannot be held in the Key Vault.
Access keys	Each access key is encrypted using an HPKE private key. Since firmware manages the HPKE private keys, it is not meaningful to decrypt the access key into the Key Vault.

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[1] Randomly-generated MEKs are held in memory rather than the Key Vault when they are first generated. See Table 2 for more details.

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Firmware-visible CSP	Reason for being visible to KMB firmware
Decrypted MPKs	MPKs are encrypted at rest. The encryption key for a given MPK may be periodically rotated. To effectuate this, the MPK is decrypted using the old encryption key, and re-encrypted with the new encryption key. The AES engine does not presently support using keys in the Key Vault as messages to encrypt. Therefore, MPKs must be decrypted into memory when their encryption keys are rotated.
MEK seeds (only used for derived MEKs)	See Section 4.6.5.3 for rationale on why the MEK seed is readable by firmware.
Random MEKs (upon initial generation)	Caliptra does not presently support a data path between its DRBG and its AES engine. Therefore, when a random MEK is first generated, KMB firmware reads the random MEK from the DRBG, and then encrypts it with the MDK (inner layer) and MEK secret (outer layer). See Section 4.6.5.1.1 for additional details on the motivation for the inner layer of MDK encryption.

All keys held by KMB firmware are protected by Caliptra, and cannot be viewed by drive firmware.

4.6.1.2 Key Derivation

In this specification, several flows involve deriving keys via a key derivation function (KDF). This specification leverages the KDF in Counter Mode defined in NIST SP 800-108 [10] section 4.1, where the PRF is HMAC512. As each key produced by this KDF is no larger than 512 bits, a single invocation of the underlying PRF is needed. Therefore, each instance of `SP 800-108 KDF` in subsequent flows deconstructs to the following operation:

K_{OUT} = HMAC512(K_{IN}, 0x01 || Label [|| 0x00 || Context])

There is one exception to this in Section 4.6.5.3, where CMAC instead of HMAC is used as the PRF for a particular instance of KDF. See Section 4.6.5.3.1 for details.

4.6.1.3 Preconditioned AES

In this specification, several flows involve deriving a key for use in AES-GCM. In AES-GCM it is critical that IV collisions be avoided. To that end SP 800-38D [11] section 8.3 stipulates that AES-GCM-Encrypt may only be invoked at most 2^{32} times with a given AES key. One approach to address this constraint is to maintain counters to track the usage count of a given key. Such tracking would be difficult for Caliptra, which lacks direct access to rewritable storage which would be needed to maintain a counter that preserves its value across power cycles.

To elide the need for maintaining counters, this specification defines the “preconditioned AES-Encrypt” and “preconditioned AES-Decrypt” operations, illustrated in Figures 3 and 4. These operations are similar in principle to XAES-256-GCM [12].

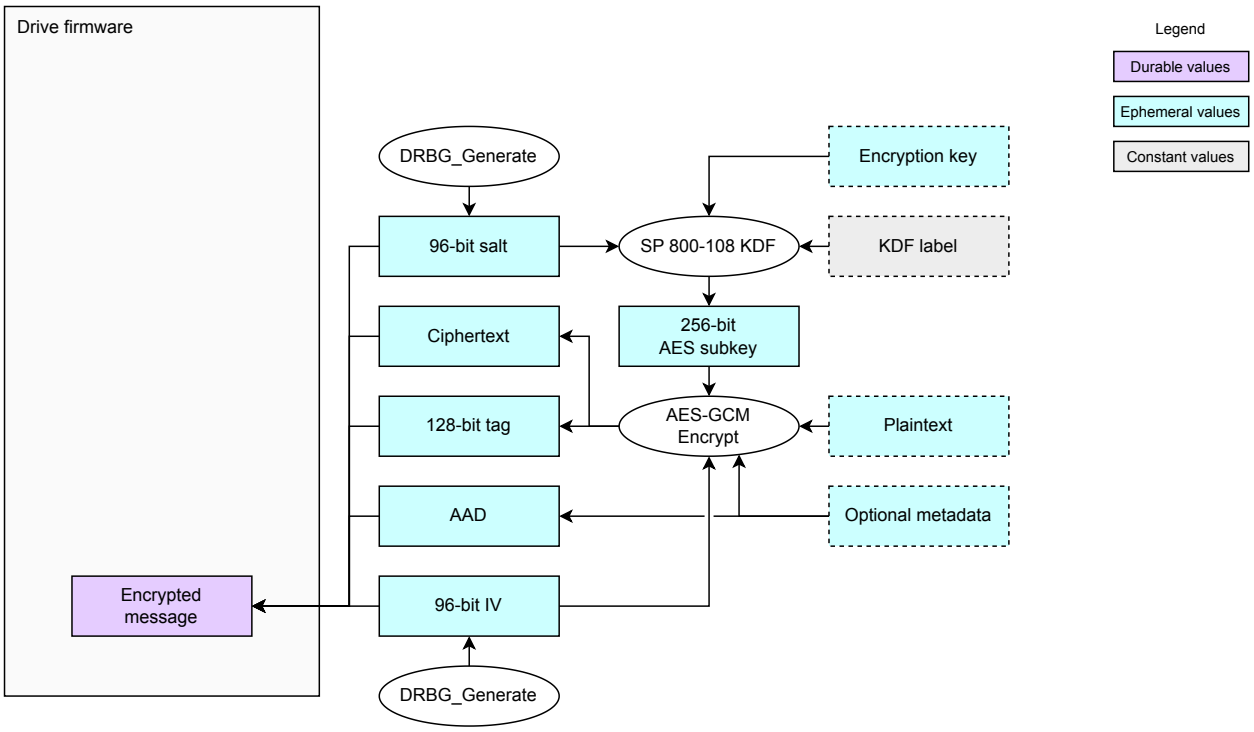

Figure 3: Preconditioned AES-Encrypt

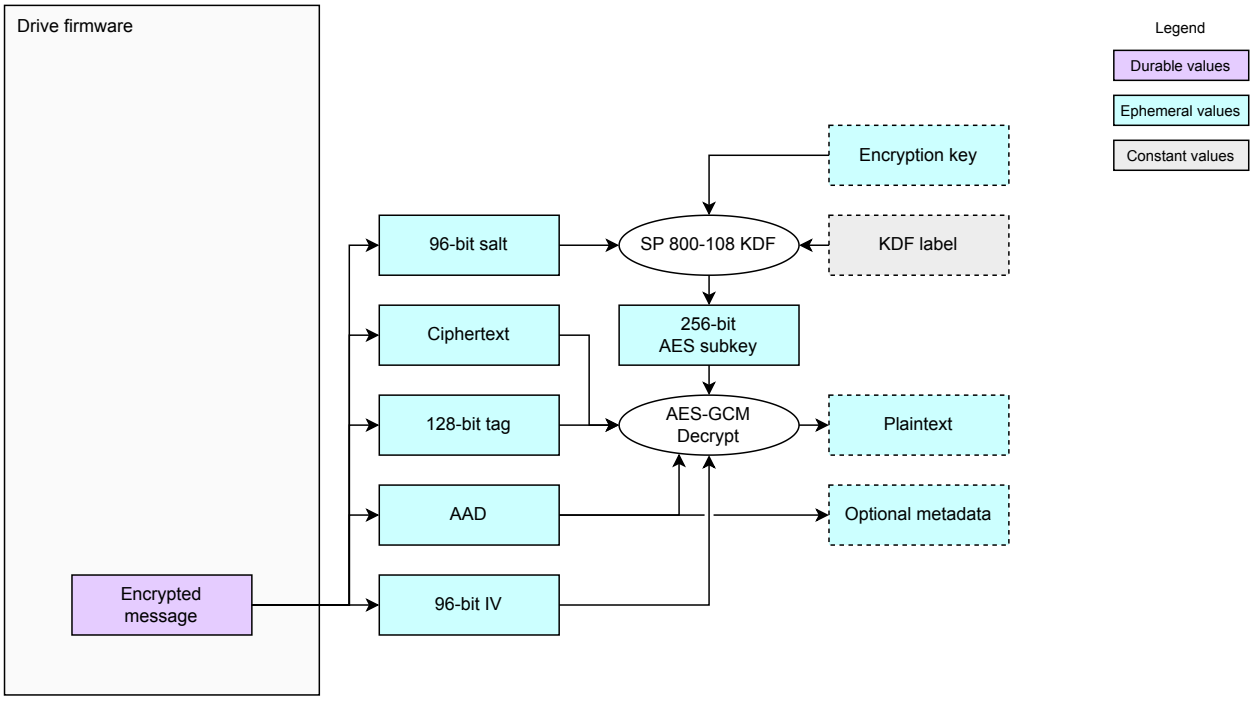

Figure 4: Preconditioned AES-Decrypt

Each encryption key is preconditioned using a randomly-generated 96-bit salt to compute a subkey, which is used with AES-GCM-Encrypt. This ensures that it is safe to use a given input encryption key in approximately 2^{80} preconditioned AES-Encrypt operations before an IV collision is expected to occur with probability greater than 2^{-32}. The 2^{80} limit is large enough that a given storage device will experience hardware failure well before that limit is reached. Ergo, usage counters within the drive are not needed for these keys. See Appendix A for additional details on the calculations behind this figure.

In addition to a plaintext message, this operation supports optional metadata for the message, which is attached as AAD.

4.6.1.4 VEK

The Volatile Escrow Key (VEK) is held in the Key Vault and is used to protect volatile keys held outside of the Key Vault, specifically Enabled MPKs.

The VEK is lazily generated upon first use and is lost when the drive shuts down. Lazy generation allows injected host entropy to contribute to the key's generation.

The VEK is randomly generated and held in a Key Vault slot. There does not exist a hardware data path directly between Caliptra's DRBG and Key Vault. Therefore, KMB firmware will read random data from the DRBG and send it to the Key Vault. To prevent KMB firmware from seeing the actual VEK, the randomness obtained by firmware is permuted using the HEK, as illustrated in Figure 5.

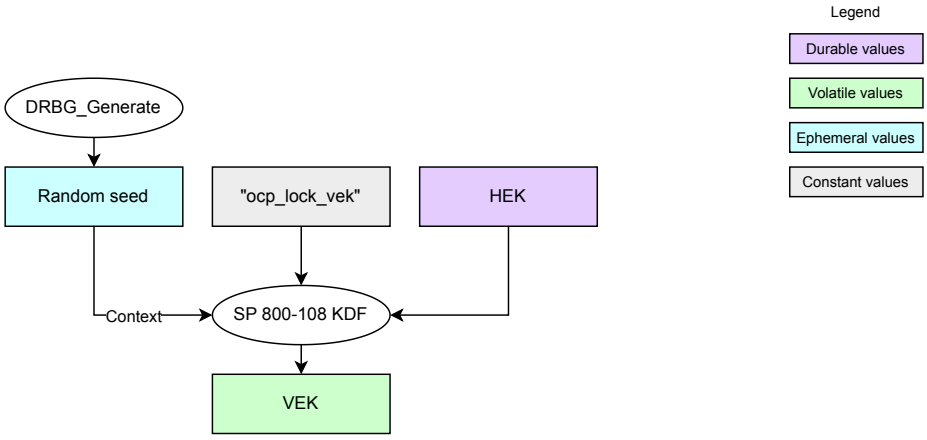

Figure 5: VEK Generation

4.6.2 MPKs

Multi-party Protection Keys (MPKs) are the mechanism by which KMB enforces multi-party authorization as a precondition to loading an MEK. MPKs exist in one of two states: locked or enabled. In both these states the MPK is encrypted to a secret known only to KMB.

- A Locked MPK's encryption key is derived from the HEK, SEK, and an externally-supplied access key to which the MPK is bound. The Locked MPK is held at rest by drive firmware.

- An Enabled MPK's encryption key is a common volatile secret held within KMB which is randomly generated and is lost when the drive shuts down. See Section 4.6.1.4 for details on how this key is generated. Enabled MPKs are held in drive firmware memory.

The externally-supplied access key is encrypted in transit using an HPKE public key held by KMB. The "enabled" state allows the HPKE keypair to be rotated after the access key has been provisioned to the storage device, without removing the ability for KMB to decrypt the MPK when later loading an MEK bound to that MPK.

For each MPK to which a given MEK is bound, the host is expected to supply the MPK's encrypted access key to drive firmware via a host-facing API. Upon receipt, drive firmware passes that encrypted access key to KMB, along with the Locked MPK, to produce the Enabled MPK which is cached in drive memory. This is performed once for each MPK to which the MEK is bound, prior to drive firmware instructing KMB to program the MEK. See Section 4.8 for details on how host-facing APIs map to KMB mailbox commands.

4.6.2.1 Transport encryption for MPK access keys

KMB maintains a set of HPKE keypairs, one per HPKE algorithm that KMB supports. HPKE keypairs are randomly generated on KMB startup, and mapped to unique handles. Keypairs may be periodically rotated. Drive firmware is responsible for enumerating the available HPKE public keys and exposing them to the user via a host interface. See Section 4.8 for how the public keys may be presented to the host.

When a user wishes to generate or enable an MPK (which is required prior to loading any MEKs bound to that MPK), the user performs the following steps:

1. Select the HPKE public key and obtain its certificate from the storage device.
2. Validate the HPKE certificate and attached DICE certificate chain.
3. Decode the HPKE capabilities of the storage device based on the HPKE certificate.
4. Seal their access key using the HPKE public key.
5. Transmit the sealed access key to the storage device.

Upon receipt, KMB will unwrap the access key and proceed to generate or enable the MPK.

Upon Caliptra cold reset or firmware-update reset, the HPKE keypairs are autonomously regenerated. See Section 4.6.8.

4.6.2.1.1 HPKE algorithm support

An HPKE variant relies on three types of algorithms: KEM, KDF, and AEAD. Table 3 describes the HPKE algorithms that KMB supports.

Table 3: HPKE algorithm support

Algorithm type	Algorithm	IANA code point	Reference document
KEM	ML-KEM-1024	0x0042	PQ and PQ/T Hybrid Algorithms for HPKE [13]
	ML-KEM-1024 + P-384	0x0051	
	P-384	0x0011	Hybrid Public Key Encryption [9]

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Algorithm type	Algorithm	IANA code point	Reference document
KDF	HKDF-SHA384	0x0002	Hybrid Public Key Encryption [9]
AEAD	AES-256-GCM	0x0002	Hybrid Public Key Encryption [9]

The definitions for the post-quantum KEMs are currently distributed across a number of documents. [14] contains generic constructions, [15] contains concrete parameterizations, and [13] contains HPKE IANA code-point assignments.[1]

Figures 6, 7, and 8 illustrate each KEM algorithm. The details of how the AES-GCM key and IV are derived are illustrated in Figure 9.

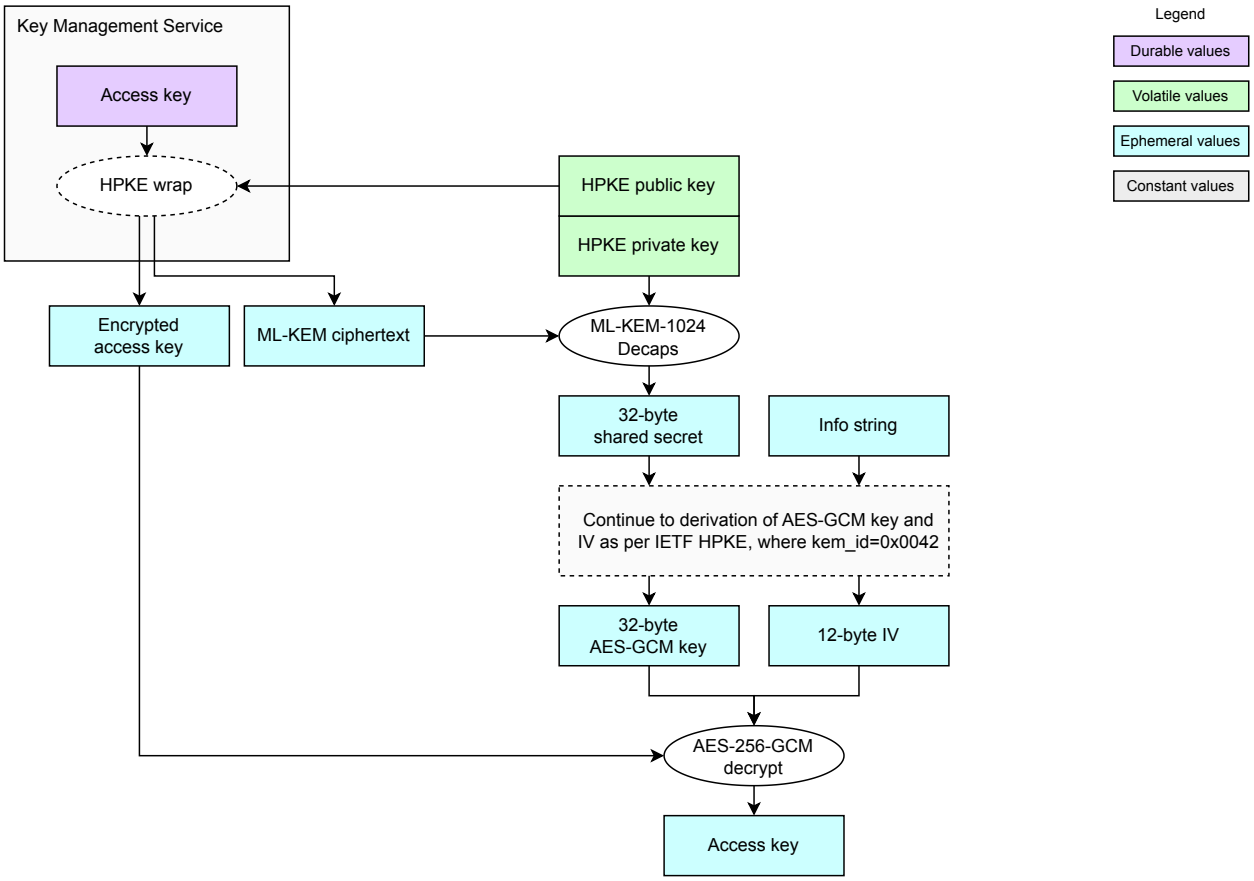


Figure 6: HPKE unwrap for access keys with ML-KEM-1024

[1] As of this specification's publication, post-quantum HPKE KEMs are not fully ratified in IETF. However, the draft authors are confident that the IANA code points and associated definitions will not change before the drafts are finalized.

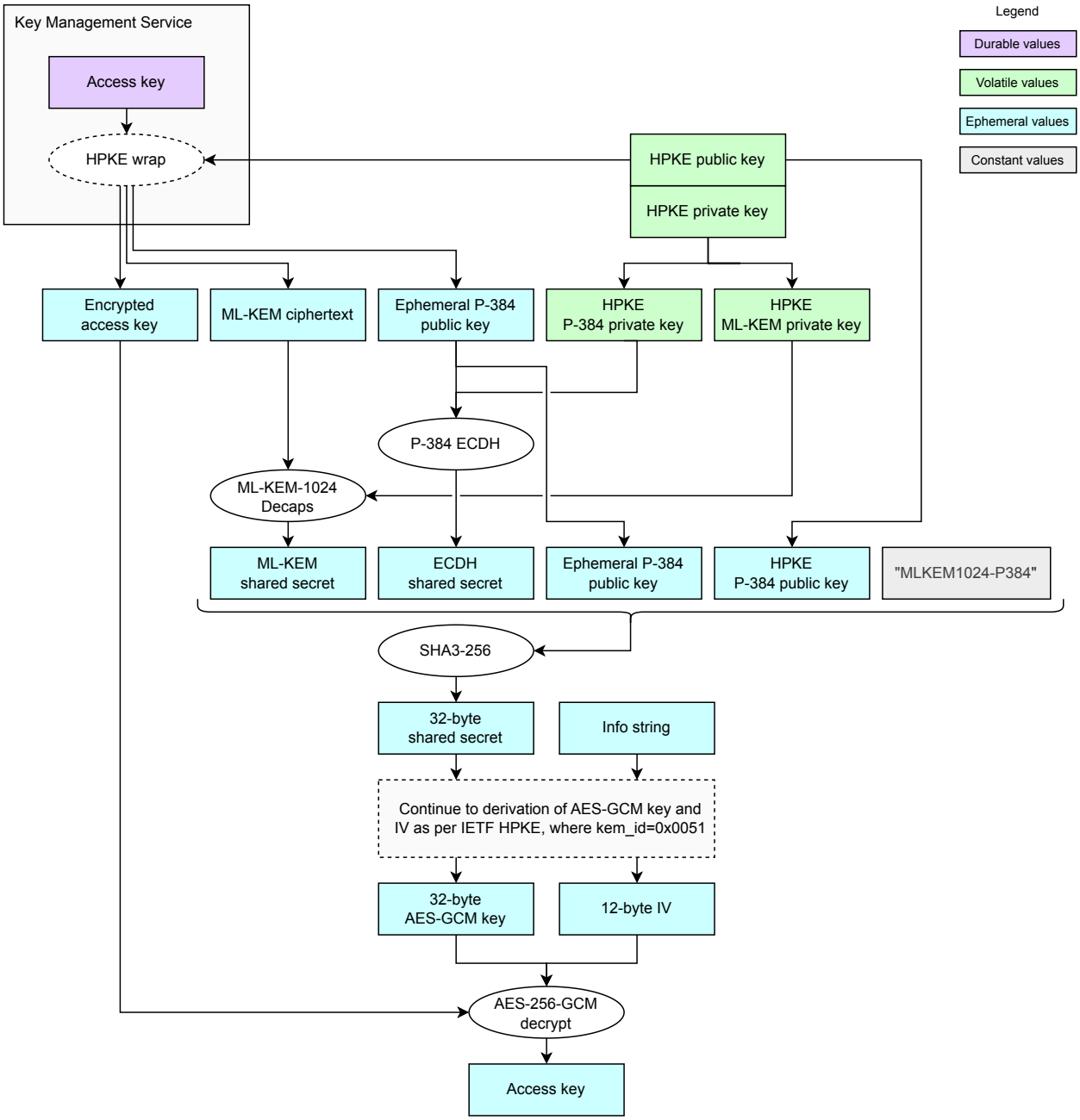


Figure 7: HPKE unwrap for access keys with hybrid ML-KEM-1024 + P-384 ECDH

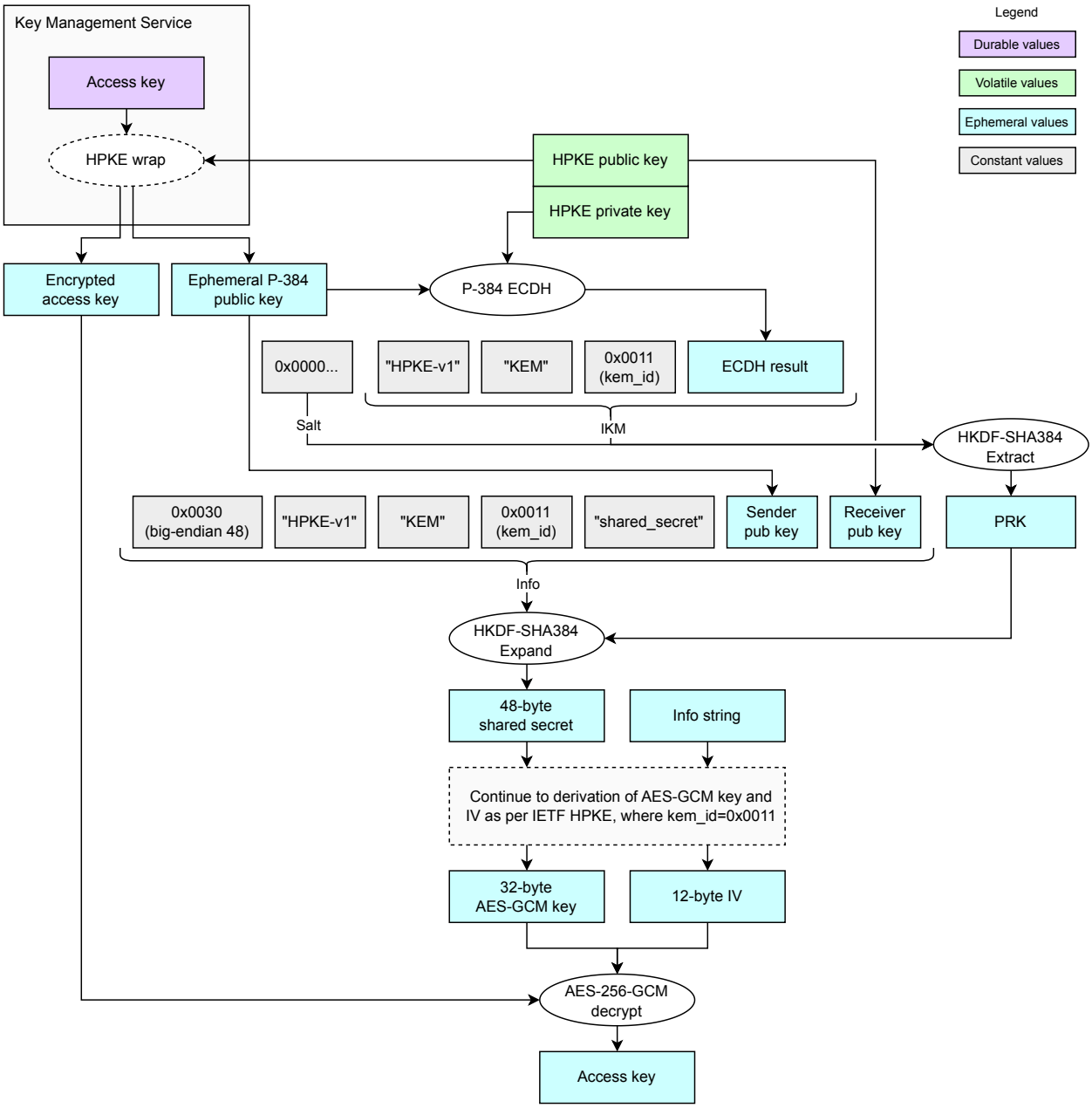


Figure 8: HPKE unwrap for access keys with P-384 ECDH

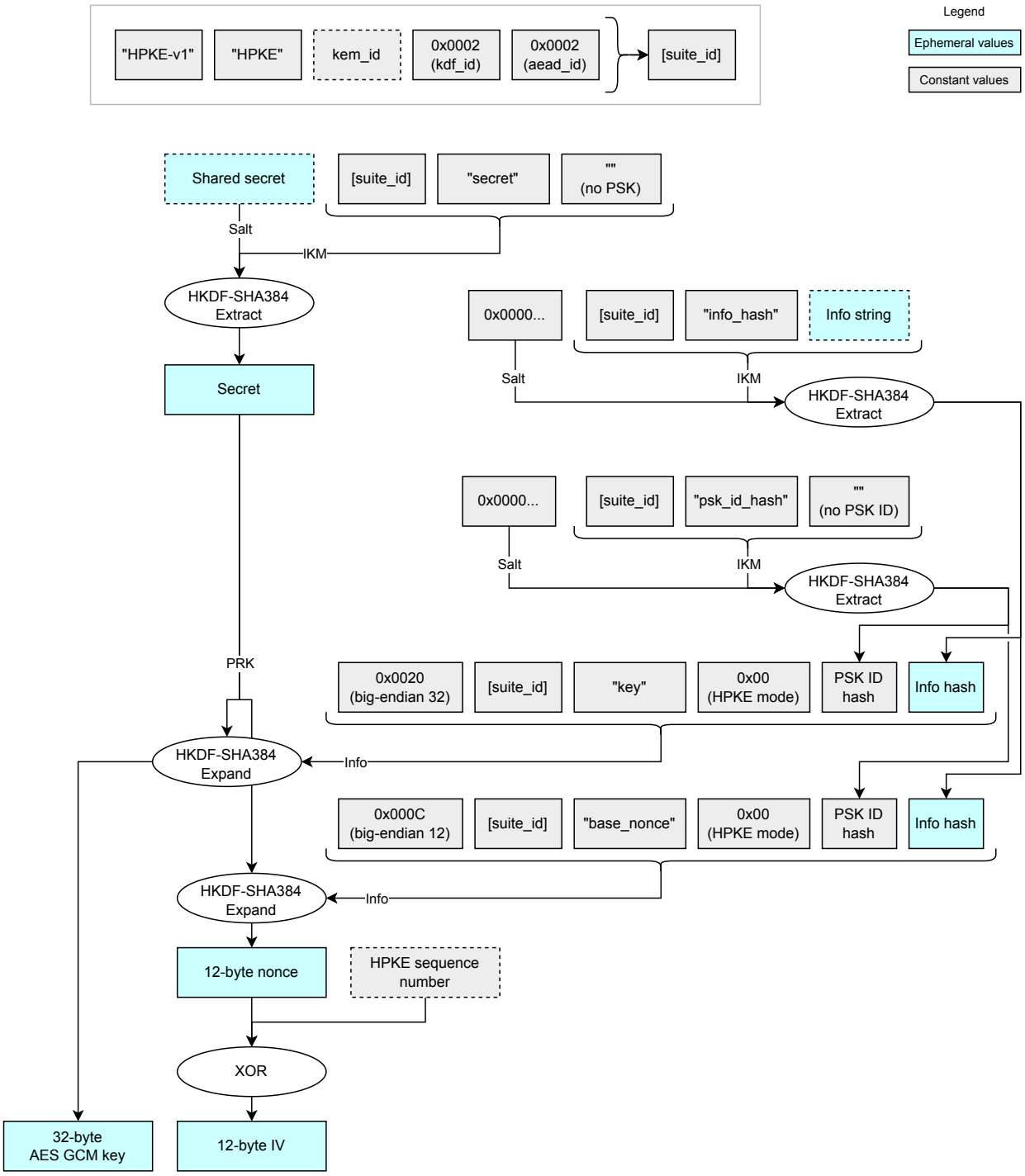


Figure 9: HPKE AES-GCM key and IV derivation

The HPKE sequence number is incremented for each decryption operation performed with keys derived from a given HPKE context. With the exception of MPK access key rotation as described in Section 4.6.2.2.3, all flows that accept HPKE payloads will perform a single decryption operation with the computed context. MPK access key rotation will perform two decryption

operations and will increment the sequence number between them.

4.6.2.1.2 HPKE public key retrieval

Upon request, KMB provides the public key for a given HPKE keypair. Drive firmware is then responsible for endorsing the public key.

4.6.2.1.3 HPKE public key endorsement

Drive firmware creates a certificate endorsing the HPKE public key retrieved from KMB. The certificate is signed by the MCU Firmware DPE context.

The endorsement includes the HPKEIdentifiers extension as defined in [16], with the `kem_id`, `kdf_id`, and `aead_id` identifiers populated based on the HPKE keypair's algorithms. See Table 3 for the algorithm identifiers supported by KMB.

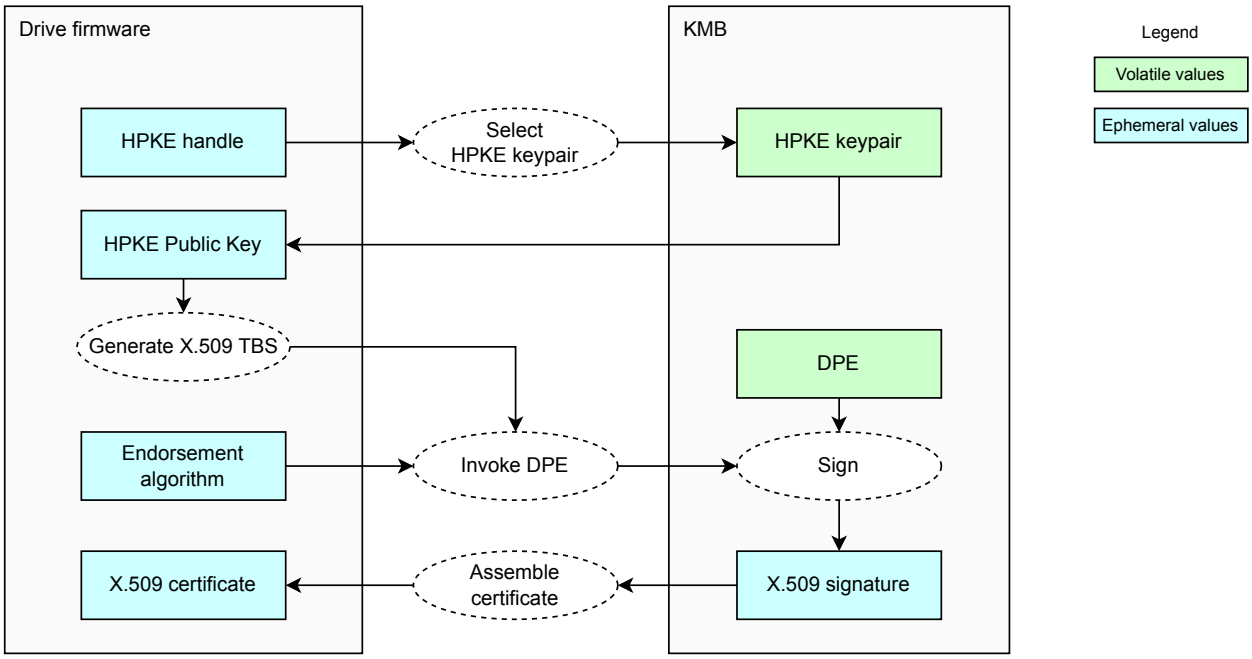


Figure 10: HPKE public key endorsement

4.6.2.2 MPK lifecycle

MPKs can be generated, enabled, and have their access keys rotated and tested.

4.6.2.2.1 MPK generation

Drive firmware may request that KMB generate an MPK, bound to a given access key.

To identify an MPK, at creation time drive firmware can provide "metadata" for the MPK, which is included in the generated Locked MPK and bound to the ciphertext as AAD. See Section 4.8 for guidance on how drive firmware should populate the metadata field for the MPK. Note that "metadata" in this context refers to metadata about the MPK, and bears no relation to metadata about an MEK.

KMB performs the following steps:

1. Unwrap the given MPK access key using the HPKE keypair held within KMB.
2. Randomly generate an MPK.
3. Derive an MPK encryption key from the HEK, SEK, and decrypted access key.
4. Encrypt the MPK to the MPK encryption key, attaching the given metadata as AAD.
5. Return the encrypted MPK to drive firmware.

Drive firmware may then store the encrypted MPK in persistent storage.

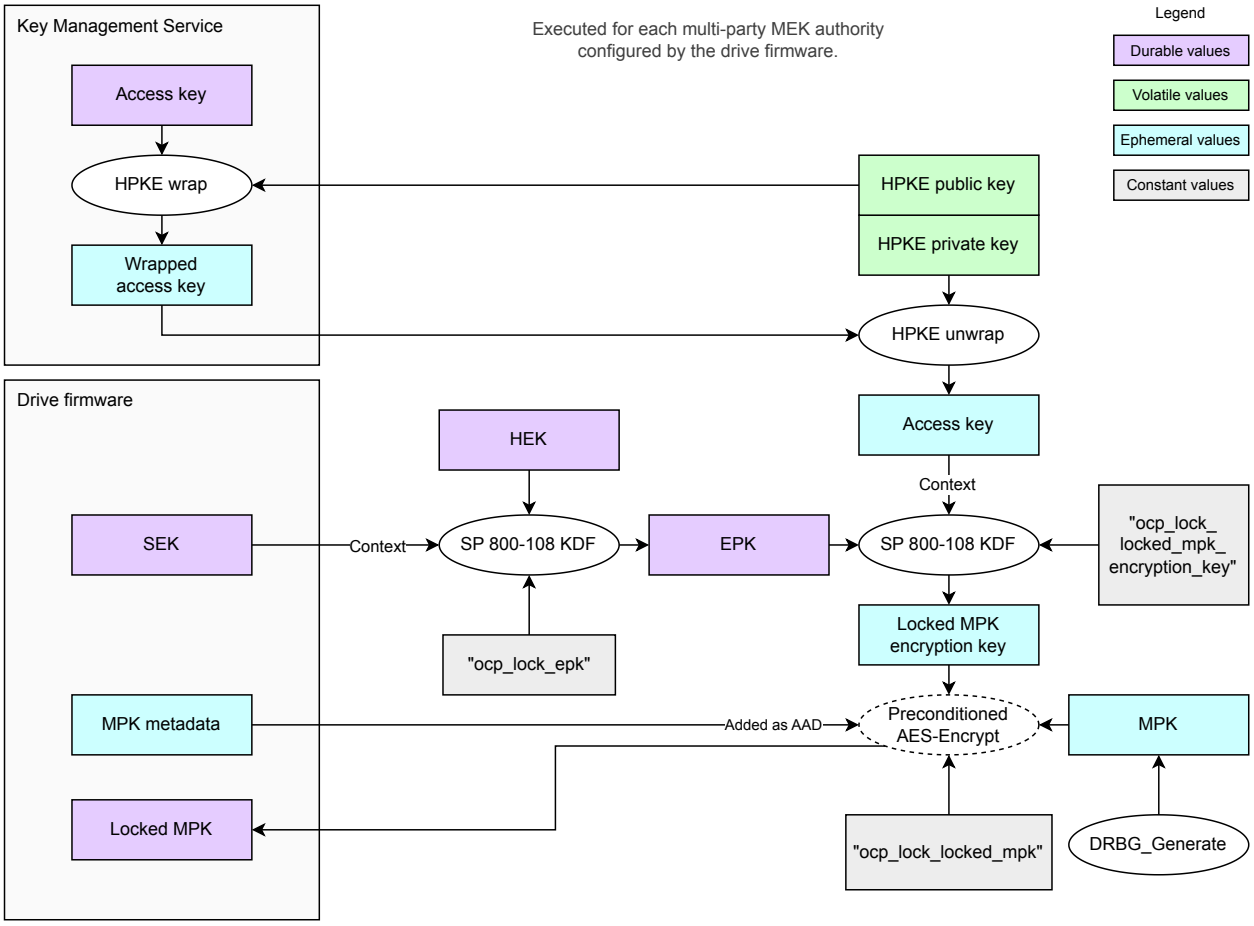


Figure 11: MPK generation

4.6.2.2.2 MPK enabling

Encrypted MPKs stored at rest in persistent storage are considered “locked”, and must be enabled before they can be used to load an MEK. Enabled MPKs are encrypted to the VEK when handled by drive firmware. Enabled MPKs are invalidated when the VEK is rotated, which occurs on Caliptra cold reset. See Section 4.6.8.

To enable an MPK, KMB performs the following steps:

1. Unwrap the given MPK access key using the HPKE keypair held within KMB.

2. Derive the MPK encryption key from the HEK, SEK, and decrypted access key.
3. Decrypt the MPK using the MPK encryption key.
4. Encrypt the MPK using the VEK, preserving the MPK metadata.
5. Return the re-encrypted “enabled” MPK to drive firmware.

Drive firmware may then stash the encrypted Enabled MPK in volatile storage, and later provide it to KMB when loading an MEK, as described in Section 4.6.5.

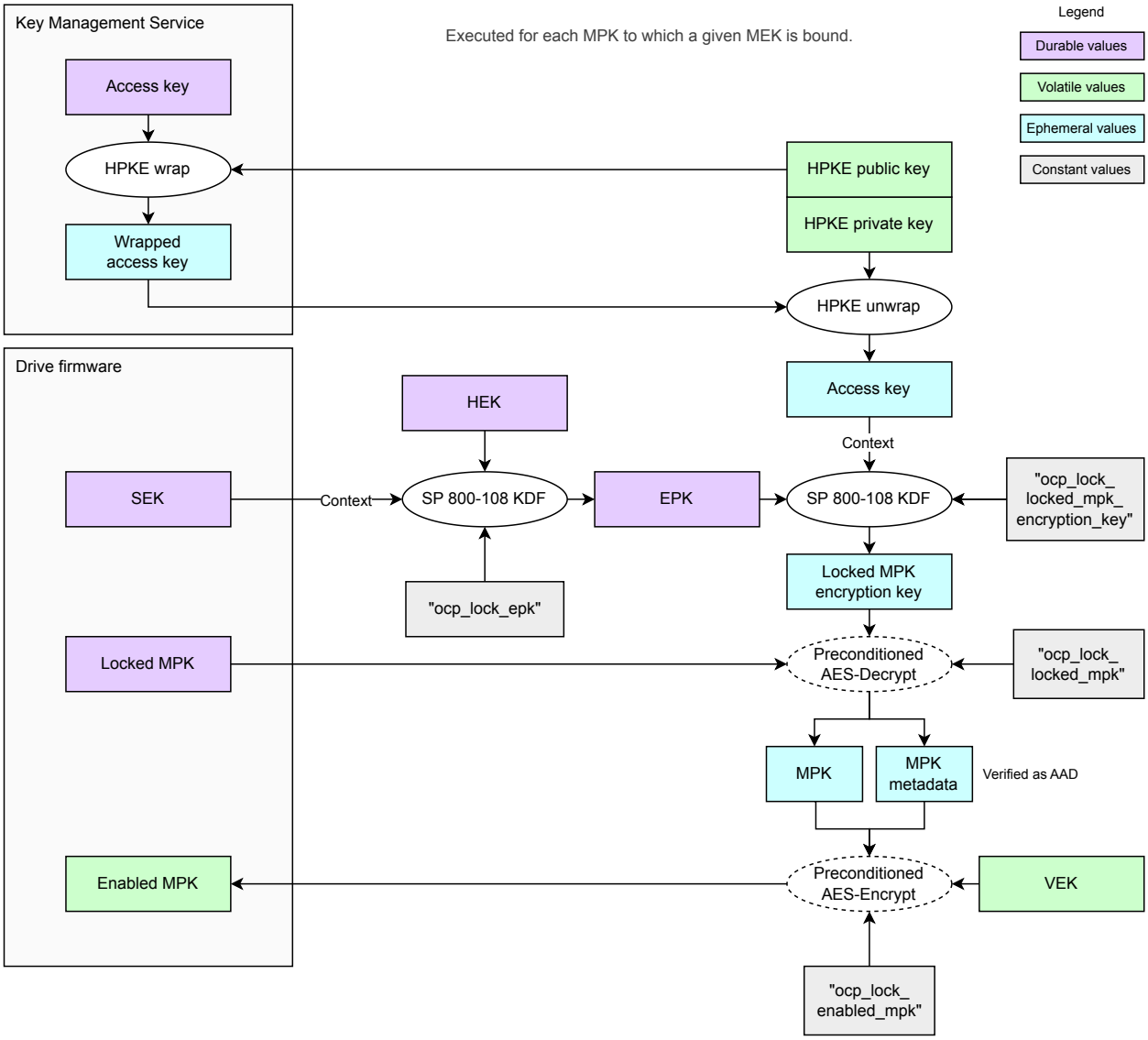


Figure 12: MPK enabling

4.6.2.2.3 MPK access key rotation

The access key to which an MPK is bound may be rotated. The user must prove that they have knowledge of both the current and new access key before a rotation is allowed. This is

accomplished by the user wrapping both their current and new access key in the same HPKE payload. KMB performs the following steps:

1. Unwrap the given current access key and new access key using the HPKE keypair held within KMB, incrementing the HPKE sequence number between each decryption operation. Note that the sequence number increment is a side-effect of the `ContextR.Open()` HPKE operation.
2. Derive the current MPK encryption key from the HEK, SEK, and decrypted current access key.
3. Derive the new MPK encryption key from the HEK, SEK, and decrypted new access key.
4. Decrypt the MPK using the current MPK encryption key.
5. Encrypt the MPK using the new MPK encryption key, preserving the MPK metadata.
6. Return the re-encrypted MPK to drive firmware.

Drive firmware then zeroizes the old encrypted MPK and stores the new encrypted MPK in persistent storage.

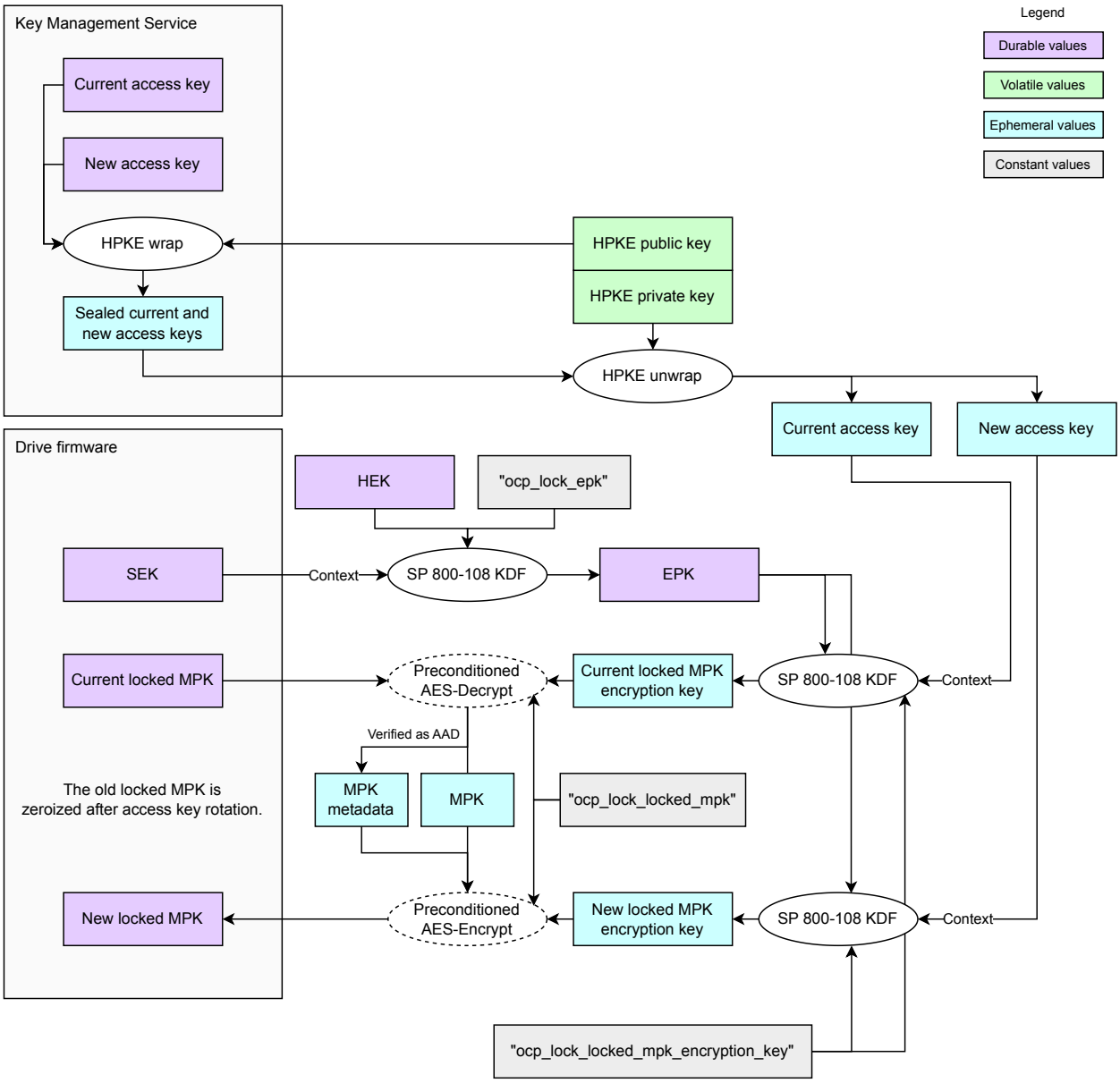


Figure 13: MPK access key rotation

4.6.2.2.4 MPK access key testing

A user that has bound an access key to an MPK may wish to confirm that their access key is in fact bound to the MPK. This can be useful after an access key rotation, to ensure that the rotation executed successfully on the storage device.

To test an MPK, KMB receives a wrapped MPK, wrapped MPK access key, and freshness nonce. KMB then performs the following steps:

1. Unwrap the given MPK access key using the HPKE keypair held within KMB.
2. Derive the MPK encryption key from the HEK, SEK, and decrypted access key.

3. Verify the integrity of the MPK ciphertext and AAD using the MPK encryption key, discarding the decrypted MPK in the process.
4. Calculate and return the digest SHA2-384(MPK metadata || access key || nonce).

The user can then verify that the returned digest matches their expectation.

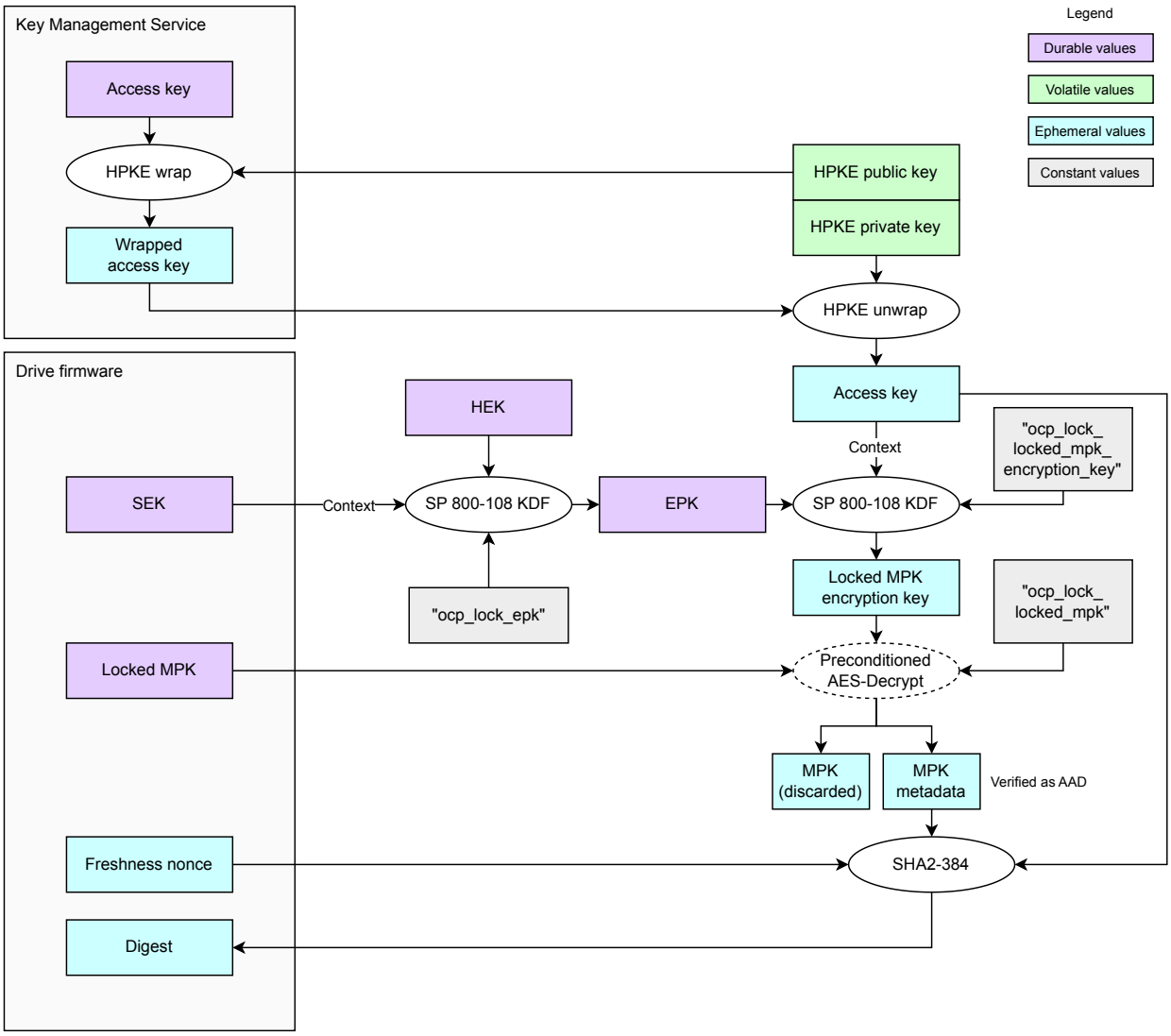


Figure 14: MPK access key testing

4.6.3 DPKs

Drive firmware provides a Data Protection Key (DPK) to KMB when generating, loading, or deriving an MEK. The DPK is used in a KDF, along with the HEK, SEK, and MPKs, to derive the MEK secret, as illustrated in Section 4.6.5.

4.6.3.1 Example flow when generating or loading an MEK

In this flow, the DPK may be encrypted by a user's C_PIN. Drive firmware logic which decrypts MEKs can be repurposed to produce the DPK. This flow may be used to support TCG Opal or Enterprise.

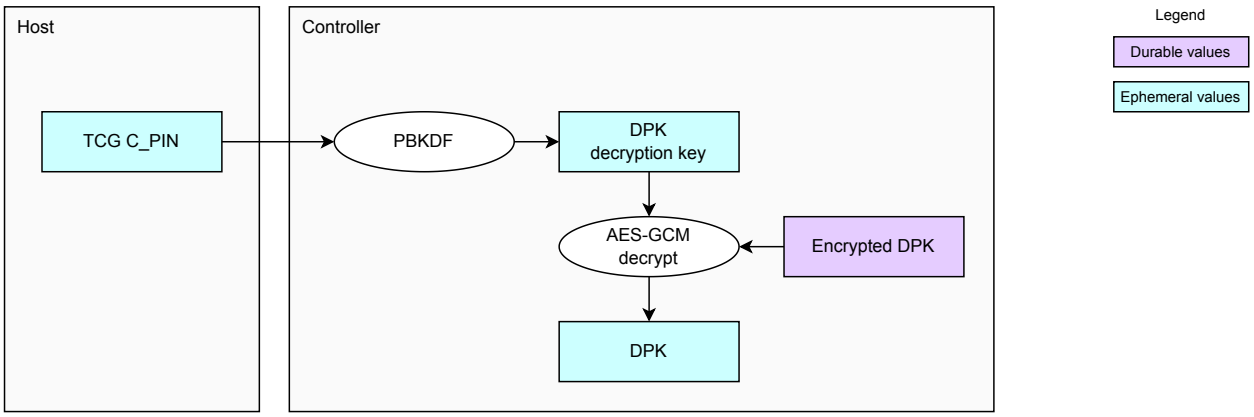


Figure 15: Example drive flow to decrypt a DPK based on a host-provided C_PIN

4.6.3.2 Example flow when deriving an MEK

In this flow, the DPK may be the imported key associated with a Key Per I/O key tag.

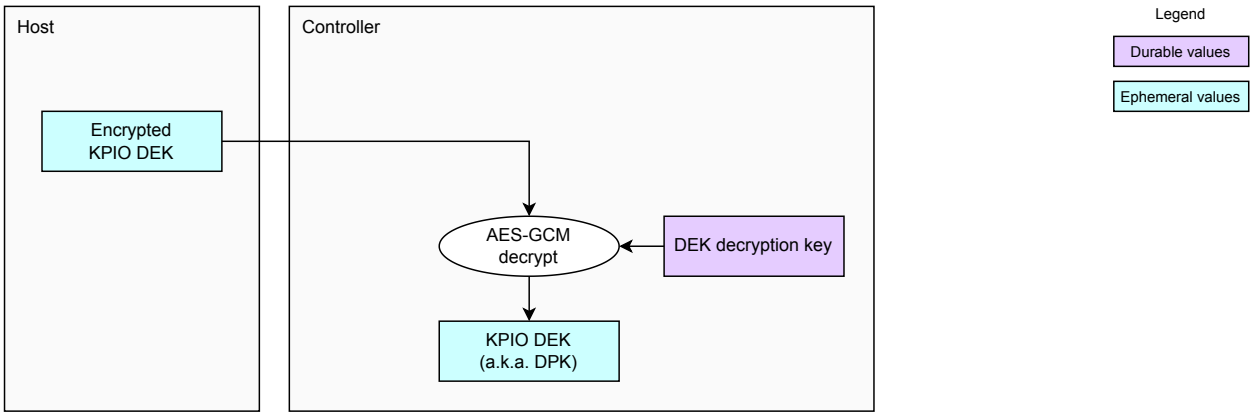


Figure 16: Example drive flow to accept an injected DPK

4.6.4 HEKs and SEKs

KMB supports a pair of epoch keys: the Hard Epoch Key (HEK) and Soft Epoch Key (SEK). Both must be available, i.e. non-zeroized, in order for MEKs to be loaded.

- The **HEK** is derived from seeds held in Caliptra's fuse block, and is never visible outside of Caliptra. If the HEK is zeroized, KMB does not allow MEKs to be loaded, with edge cases detailed in Section 4.6.4.1.

- The **SEK** is managed by drive firmware, and may be stored in flash. If the SEK is not randomized, drive firmware is responsible for enforcing that MEKs are not loaded.

Zeroizing either the HEK or SEK is equivalent to performing a cryptographic erase. HEK zeroization is effectively a “hard” cryptographic erase, as it is highly difficult to recover secrets from a zeroized fuse bank.

The drive must only provide HEK seeds or SEKs to KMB that are cryptographically-strong random values, because otherwise it is not possible to cryptographically erase data through zeroization of those values. Note: as depicted in Figure 17, MCU ROM may provide an all-zeroes HEK seed to KMB, provided that it correctly indicates to KMB that the HEK seed is not randomized.

4.6.4.1 HEK lifecycle

Caliptra with L.O.C.K. features a series of n 256-bit HEK slots present in a fuse bank, dubbed HEK_0..HEK_{n-1}, where $4 \leq n \leq 16$. The vendor is responsible for determining the number of HEK slots available in fuses. These HEK slots are programmed and read by MCU, via the Caliptra fuse controller. MCU is responsible for transitioning each HEK slot individually from blank → randomized → zeroized. MCU shall zeroize a HEK slot by blowing every bit.

Each HEK slot contains a HEK seed. MCU ROM reads the currently-randomized HEK slot from fuses during cold reset, and passes its contents to Caliptra Core via a fuse register.

There are two edge cases where the HEK is available even if there is no randomized seed available in the HEK fuse bank. In both cases, the HEK is derived from an all-zeroes HEK seed.

- To enable pre-production testing, if Caliptra is in the Unprovisioned or Manufacturing lifecycle state, the HEK is available.
- To enable lengthening the useful lifespan of the storage device, once all HEK slots have been zeroized, the device can be permanently transitioned into a mode where the HEK is available. A field-programmable “permanent-HEK” logical fuse bit is allocated to determine whether this mode is active.

In addition to the HEK seed, the HEK is derived from Caliptra’s DICE UDS. The mechanism used to compute the HEK is described in Figure 17. This flow is performed across MCU ROM and Caliptra ROM upon KMB startup.

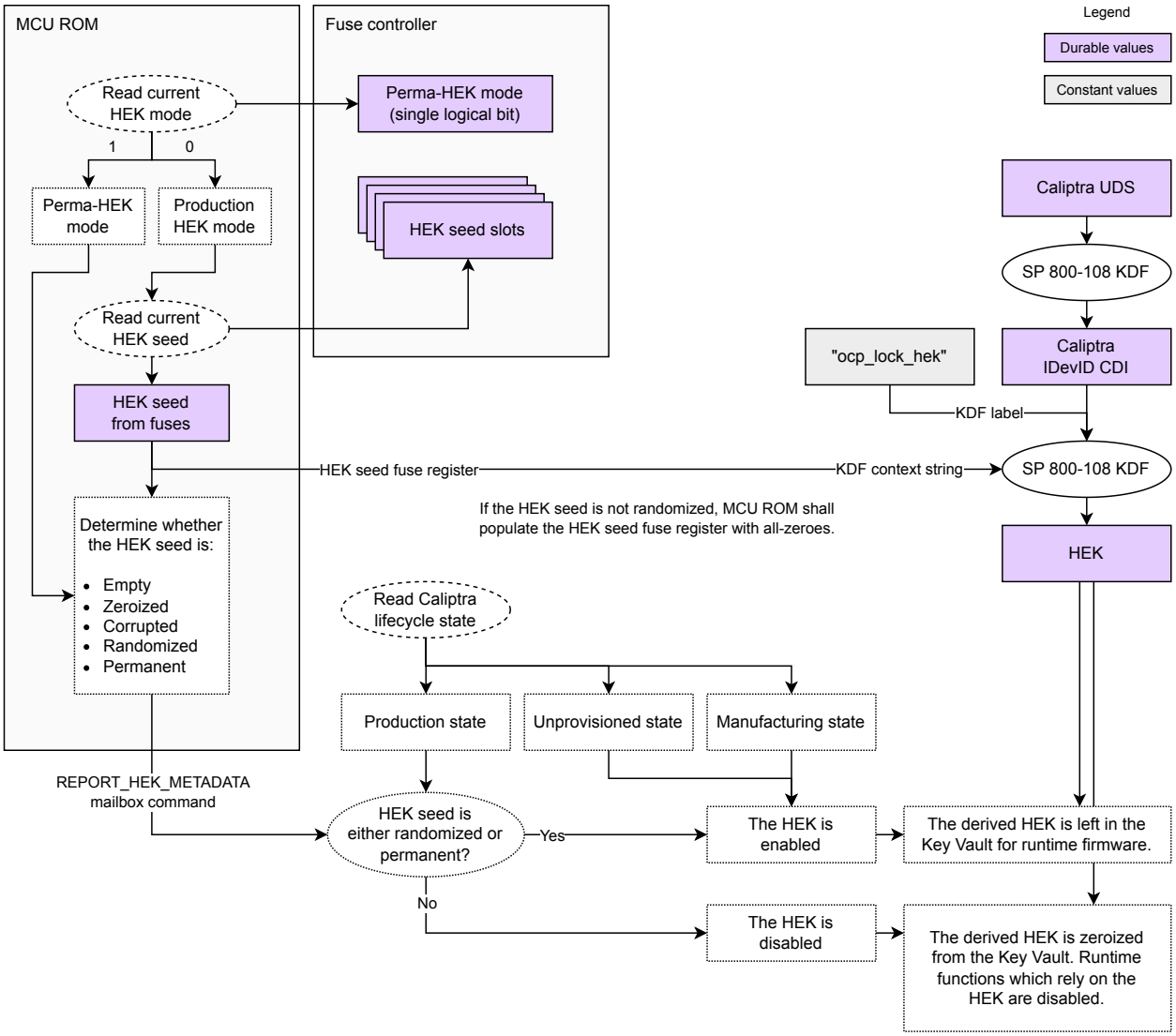


Figure 17: HEK derivation

MCU ROM is responsible for invoking the REPORT_HEK_METADATA command exactly once, after cold reset and before Caliptra FMC/runtime firmware is first loaded. If REPORT_HEK_METADATA is not invoked, KMB will zeroize the HEK and runtime functions which rely on it will be disabled.

By deriving the HEK in ROM based on secrets that are not available to runtime firmware, KMB ensures that compromised runtime firmware cannot derive the HEK using replayed HEK seed values.

Note: the HEK is derived before REPORT_HEK_METADATA is invoked due to IDevID having been zeroized from the Key Vault by the time Caliptra ROM is ready to handle mailbox commands.

4.6.4.2 HEK and SEK lifecycle

Drive firmware is responsible for managing the HEK and SEK lifecycle, including programming and zeroizing HEK seeds and entering perma-HEK mode.

A device out of manufacturing must be in the production lifecycle state and have a randomized HEK.

Drive firmware is responsible for enforcing the following:

- The SEK shall only be programmed once the HEK is available.
- The HEK seed shall only be zeroized once the SEK is zeroized.
- The HEK seed shall only be zeroized after it has been randomized or corrupted.
- Perma-HEK mode shall only be enabled once all HEK seeds have been zeroized.

Drive firmware is responsible for zeroizing the encryption engine's key cache when the SEK transitions from randomized to zeroized. HEK transitions involve power cycles and, as a result, the key cache is implicitly zeroized across such transitions.

4.6.5 MEKs

KMB can encrypt randomly-generated MEKs, or compute derived MEKs.

Figure 18 provides details on how the SEK, HEK, DPK, and MPKs are used to produce the MEK secret, which then either encrypts/decrypts a random MEK or is used to compute a derived MEK.

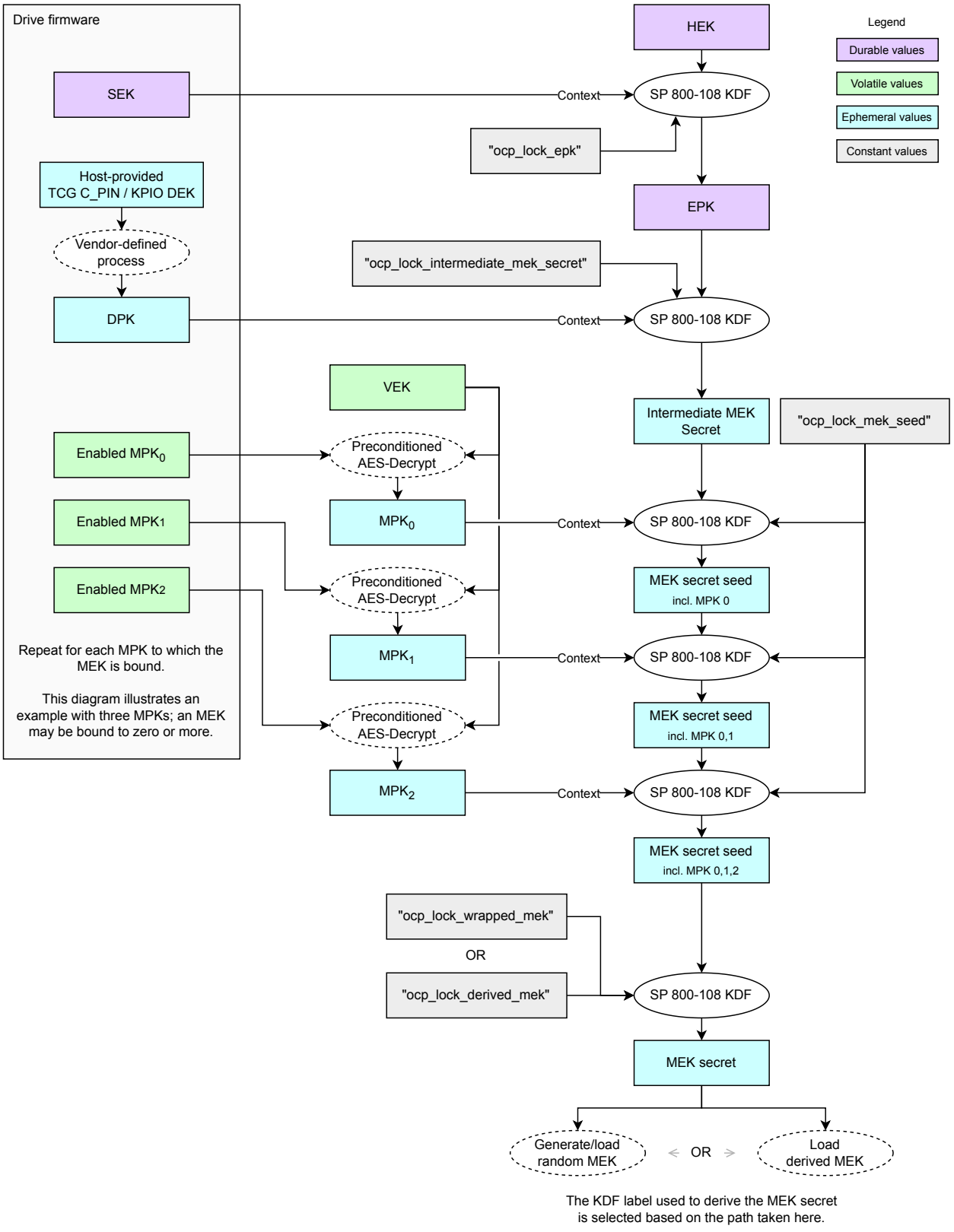


Figure 18: MEK secret derivation

Note: it is drive firmware's responsibility to ensure that MPKs are mixed in the correct order for a given MEK.

See Section 4.6.5.2 for how the MEK secret is used to generate and load random MEKs. See Section 4.6.5.3 for how the MEK secret is used to derive deterministic MEKs.

4.6.5.1 Support for non-MPA storage API flows

KMB allows an MEK to be bound to zero MPKs, which supports TCG flows that do not interact with the TCG MEK-MPA specification. The process for establishing such an MEK is illustrated in Figure 19.

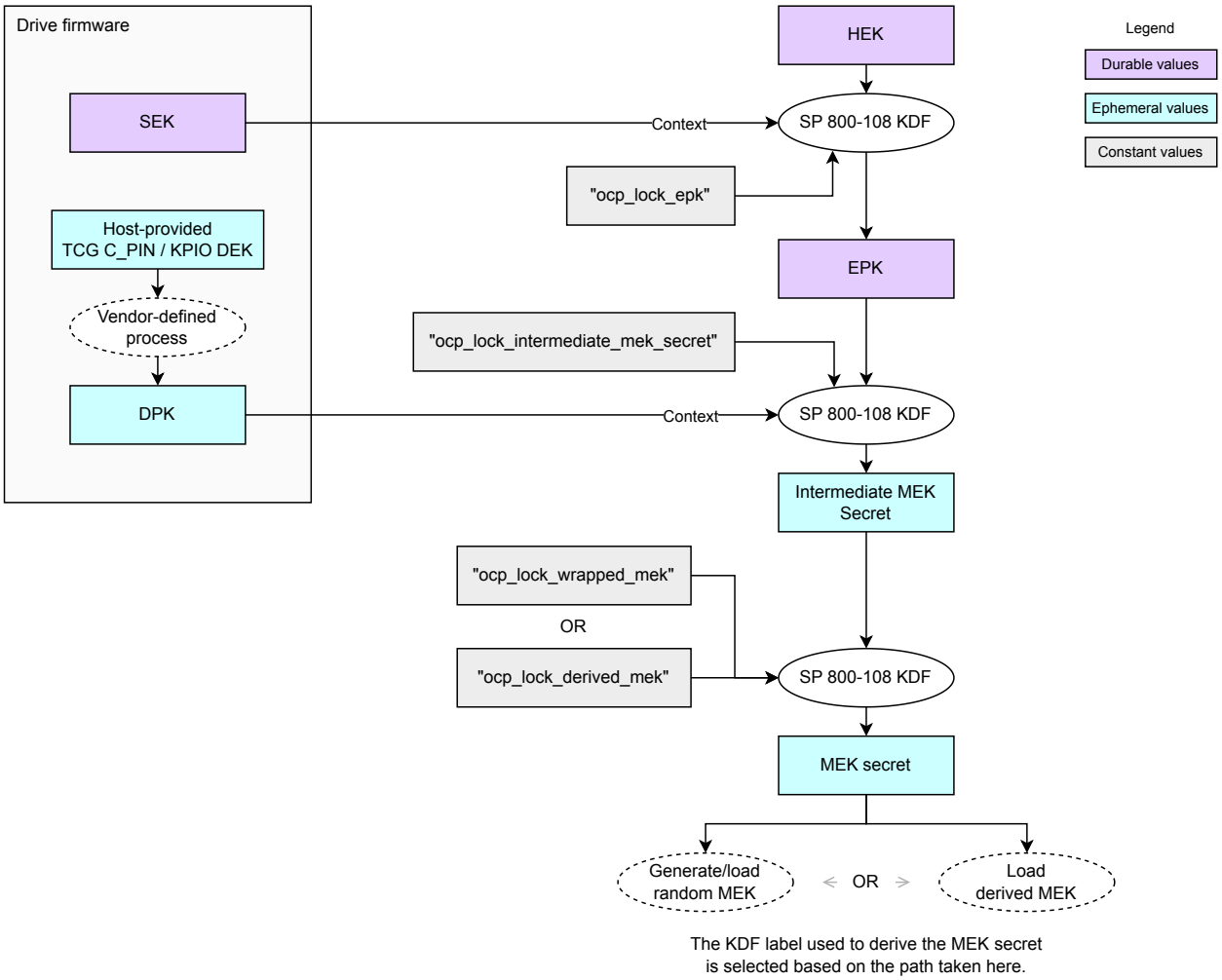


Figure 19: Establishing an MEK bound to zero MPKs

4.6.5.1.1 Protecting MEKs with the MDK

Randomly-generated MEKs are encrypted at rest with AES-GCM, as illustrated in Section 4.6.5.2. During initial MEK encryption, Caliptra's AES engine accepts the MEK plaintext from KMB firmware and returns the ciphertext back to KMB firmware. Later, during MEK

decryption, Caliptra's AES engine accepts the MEK ciphertext from KMB firmware and writes the decrypted plaintext to the Key Vault. From Caliptra hardware's perspective, AES-GCM encryption and decryption are the same operation. Therefore, if the MEK were protected with only a single layer of AES-GCM encryption, compromised KMB firmware could instruct Caliptra's AES engine to treat decryption like encryption and return the decrypted plaintext to KMB firmware, trivially disclosing the MEK.

To mitigate this, Caliptra hardware enforces that before an MEK can be loaded into the Key Vault, it must first pass through an AES-ECB decryption operation keyed using the MEK Deobfuscation Key (MDK). The MDK is derived in ROM upon cold reset, as described in Section 4.6.8 and illustrated in Figure 20.

Unlike with AES-GCM, Caliptra's AES engine can differentiate between encryption and decryption in AES-ECB mode. Hardware enforces that for any AES-ECB decryption operation using the Key Vault slot that holds the MDK, the result is always routed to the Key Vault. The MDK encryption layer therefore ensures that the plaintext MEK is never visible to KMB firmware once the MEK has been decrypted.

By deriving the MDK in ROM based on secrets that are not available to runtime firmware, KMB ensures that compromised runtime firmware cannot re-derive the MDK into a separate Key Vault slot, which could have looser protections for whether firmware can see the results of an AES-ECB decryption operation.

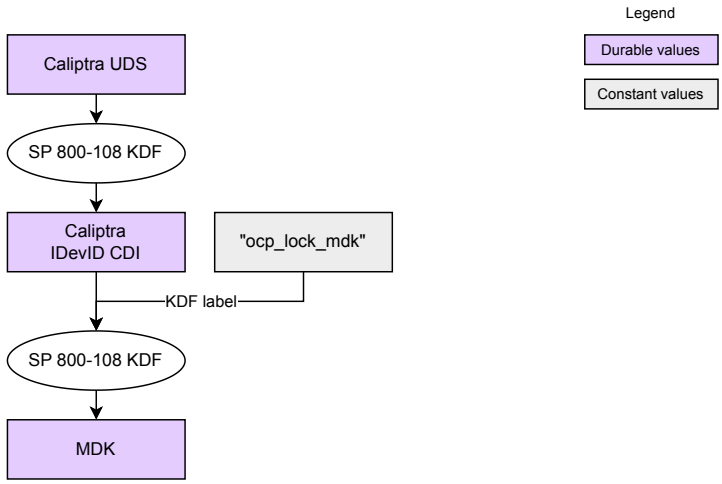


Figure 20: Deriving the MDK

4.6.5.2 Generating and loading a random MEK

Figures 21 and 22 elide the process of deriving the MEK secret, as those details are captured in Figure 18. When an MEK is generated or loaded, the inputs given in Figure 18 are provided by drive firmware so that KMB may derive the MEK secret.

Randomly-generated MEKs are given two layers of at-rest encryption: an inner AES-ECB layer using the MDK, and an outer AES-GCM layer using the MEK secret. The wrapped MEK's integrity tag is associated with the outer layer. The inner AES-ECB layer does not have its own

MAC. Therefore, the extra layer of encryption does not modify the size of the wrapped MEK. See Section 4.7.2.22.2 for details on the format and layout of the wrapped MEK.

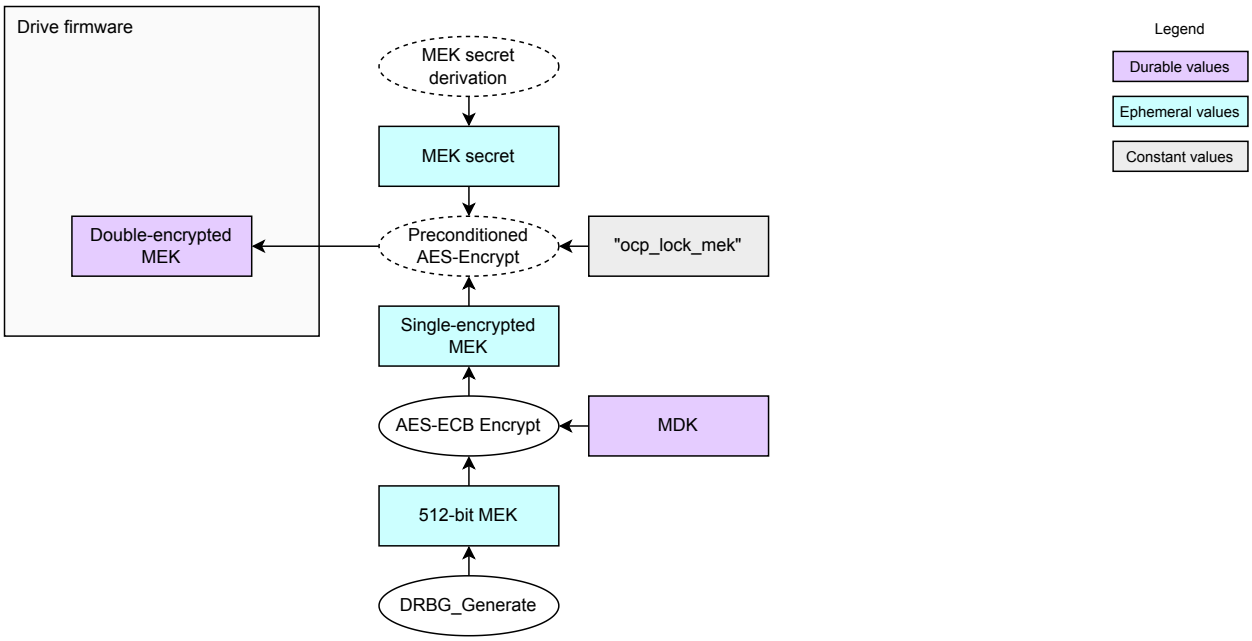


Figure 21: Generating an MEK

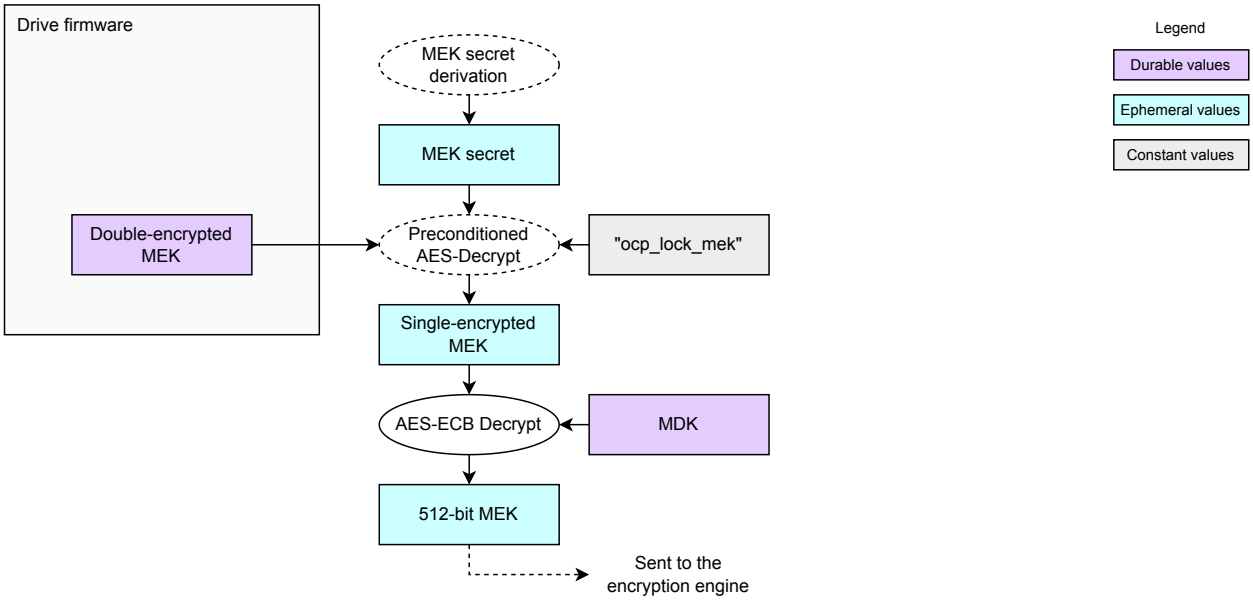


Figure 22: Loading an MEK

4.6.5.3 Deriving an MEK

Figure 23 elides the process of deriving the MEK secret, as those details are captured in Figure 18. When an MEK is derived, the inputs given in Figure 18 are provided by drive firmware so that KMB may derive the MEK secret.

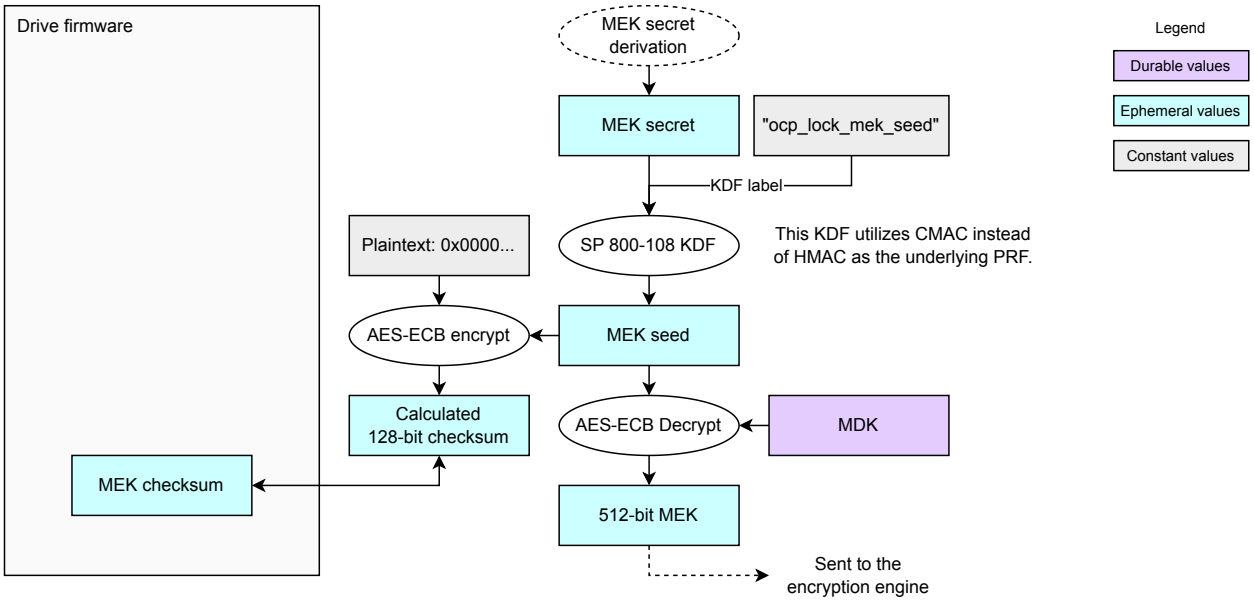


Figure 23: Deriving an MEK

4.6.5.3.1 Deobfuscating MEK seeds with the MDK

The MEK seed is calculated via CMAC instead of HMAC, and then “decrypted” via the MDK, for the following reasons:

- As described in Section 4.6.5.1.1, the only way to populate the Key Vault slot that holds the MEK is via the AES engine operating in ECB-decrypt mode (where the key is taken from the Key Vault slot that holds the MDK).
- The AES engine does not allow messages to be read from the Key Vault. Therefore, KMB must derive a key from the MEK secret that is readable by firmware, so firmware can pass it as an AES message to compute the MEK.
- Since the MEK secret is in the Key Vault, the result of any HMAC operations would be required to go back to the Key Vault, and not be available to firmware.
- The CMAC operation, by contrast, utilizes the AES engine in a manner that allows the results to be readable by firmware. Therefore, CMAC is used to compute the MEK seed from the MEK secret.
- The resulting MEK seed is then passed as an AES message to the AES engine, which uses it in a decryption operation to produce the derived MEK.

4.6.5.3.2 Derived MEK checksums

When deriving an MEK, drive firmware provides an MEK checksum to KMB. See Figure 23 for details on how the checksum is derived. If the provided checksum is non-zero, it is compared

with the calculated checksum. The operation fails (and the derived MEK is not sent to the encryption engine) if the provided checksum does not match the calculated checksum. This check is skipped if the provided checksum is all-zeroes.

Upon success, the calculated checksum is returned to drive firmware. Drive firmware may choose to store the checksum persistently and use it for future derivations, or may discard the returned checksum. The checksum allows drive firmware to ensure that an MEK derived in the future matches a given MEK derived previously. This check would be a precaution against mistakes or bit flips that would result in an incorrect MEK being programmed to the encryption engine, which could lead to data loss. This specification does not define how drive firmware should react to a checksum mismatch.

The checksum is not derived from the MEK directly, because Caliptra hardware restricts what operations can be done with the Key Vault slot that holds the MEK.

An example flow where the MEK checksum would be useful is as follows:

1. Drive firmware is instructed to establish a new MEK.
2. Drive firmware instructs KMB to produce the new MEK via DERIVE_MEK, as part of the sequence specified in Section 4.6.5.4.
3. Upon success, drive firmware is given the derived-MEK's checksum, which it stores in non-volatile memory.
4. On a subsequent boot, drive firmware reads the SEK into volatile memory, and is later asked to re-establish the MEK it derived in step 2.
5. The copy of the SEK held in volatile memory has suffered corruption since it was last read from persistent storage, and a bit has flipped.
6. Drive firmware invokes DERIVE_MEK. As part of this command, drive firmware provides the derived-MEK checksum it saved in non-volatile storage.
7. KMB detects the checksum mismatch and refuses to program the derived MEK. Drive firmware surfaces this failure to the host.

In this example, if the user had proceeded to write data to the disk using the MEK derived in step 6, that data would not be recoverable on subsequent boots unless the SEK experienced the exact same bit flip pattern as in step 5. The derived-MEK checksum allows the drive to detect this scenario and alert the user. Note that there are other possible mechanisms for mitigating this risk. The use of derived-MEK checksums is optional.

Note: a checksum is not produced for wrapped MEKs. For wrapped MEKs, any change in the inputs which produce the MEK secret would result in an error during AES-GCM decryption of the provided MEK.

4.6.5.4 MEK command sequence

KMB exposes the following mailbox commands for establishing an MEK:

- INITIALIZE_MEK_SECRET
- MIX_MPK
- GENERATE_MEK
- LOAD_MEK
- DERIVE_MEK

Figure 24 illustrates how these commands are used in sequence.

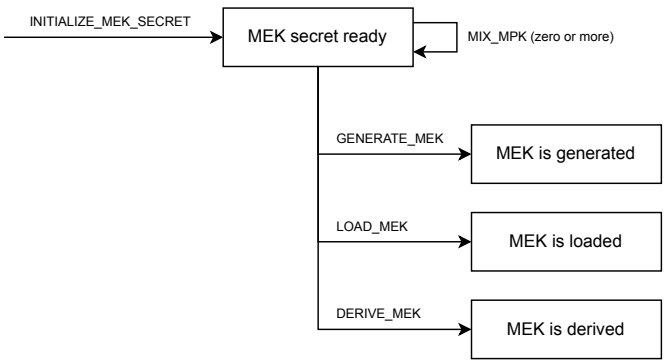


Figure 24: MEK command sequence

Integrators may elect to utilize either MEK generation or MEK derivation when establishing an MEK.

4.6.5.5 AES-XTS considerations

The MEK sent to the encryption engine may be used as an AES-XTS key. FIPS 140-3 IG [17] section C.I states that in AES-XTS, the key is "parsed as the concatenation of two AES keys, denoted by Key_1 and Key_2, that are 128 [or 256] bits long… Key_1 and Key_2 shall be generated and/or established independently according to the rules for component symmetric keys from NIST **SP 800-133rev2**, Sec. 6.3. The module **shall** check explicitly that $Key_1 \neq Key_2$, regardless of how Key_1 and Key_2 are obtained."

SP 800-133 [18] section 6.3 states: "The independent generation/establishment of the component keys K_1, …, K_n is interpreted in a computational and a statistical sense; that is, the computation of any particular K_i value does not depend on any one or more of the other K_i values, and it is not feasible to use knowledge of any proper subset of the K_i values to obtain any information about the remaining K_i values."

SP 800-108 [10] section 4 states that "the output of a key-derivation function is called the derived keying material and may subsequently be segmented into multiple keys. Any disjoint segments of the derived keying material (with the required lengths) can be used as cryptographic keys for the intended algorithms."

As the MEK sent to the encryption engine is either randomly or pseudorandomly generated, it satisfies the above constraints. Disjoint segments of derived keying material computed from a pseudorandom function are statistically and computationally independent.

KMB explicitly checks the inequality between Key_1 and Key_2 at specific steps in the following commands: - GENERATE_MEK: after generating a plain MEK (on `512-bit MEK` in Figure 21), - LOAD_MEK: before AES-ECB decryption (on `Single-encrypted MEK` in Figure 22), - DERIVE_MEK: before AES-ECB decryption (on `MEK seed` in Figure 23).

Since AES-ECB decryption (`Dec(key, data)`) with a fixed key is a 128-bit-wise permutation, `Dec(K, A) = Dec(K, B)` holds if and only if `A = B` holds for any AES key `K` and any 128-bit data `A` and `B`. Therefore, KMB can verify inequality of the resulting `512-bit MEK` by checking with the data before AES-ECB decryption: `Single-encrypted MEK` and `MEK seed`.

When DERIVE_MEK fails the inequality check, KMB regenerates `MEK seed` by applying additional KDFs using the same label, `"ocp_lock_mek_seed"`, until the check passes. Similarly, GENERATE_MEK repeatedly samples a randomness until the generated key satisfies the inequality. Instead of repeating infinitely, KMB only repeats *26 times* and returns an error if all attempts were failed. Under the (pseudo-)randomness assumption of underlying PRNG and KDF, this will give high enough probability to generate/derive a key passing the inequality check. With 26 repetitions, The probability to get an error is roughly one out of 10^{1000}.

In order to support both 256-bit and 512-bit AES-XTS keys, KMB checks both 128-bit-wise inequality and 256-bit-wise inequality. Thus, any MEK generated/loaded by KMB complies with AES-XTS key requirements. Vendors may elect to additionally implement an inequality check mechanism within their own encryption engines.

4.6.6 Random key generation via DRBG

KMB generates multiple kinds of random keys. KMB does this by using randomness obtained from a DRBG, which is seeded from a TRNG and which may be updated with entropy from the host.

Caliptra hardware [19] supports either an integrated or external DRBG. Caliptra Subsystem requires leveraging the integrated DRBG. This construction is illustrated in Figure 25.

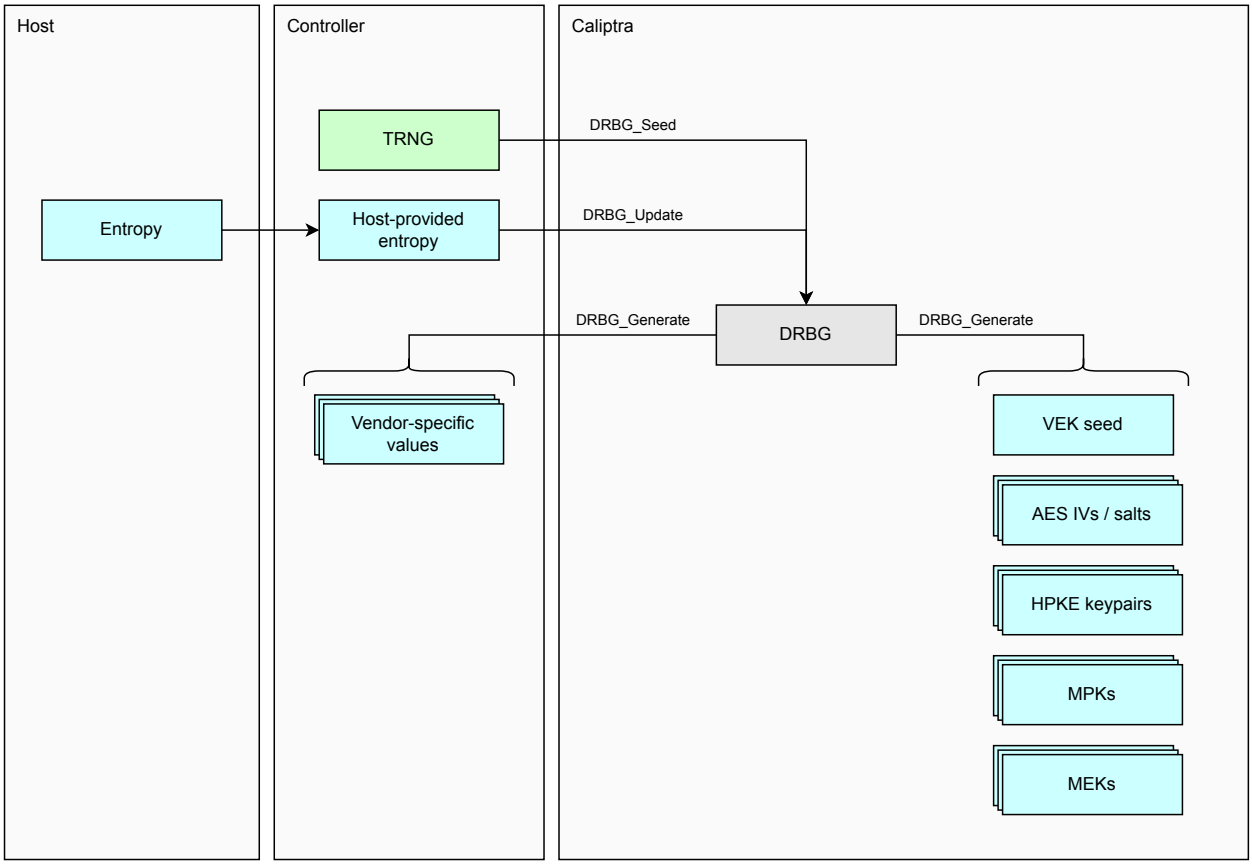


Figure 25: Integrated DRBG

Host-provided entropy can be mixed into the DRBG state via the CM_RANDOM_STIR Caliptra mailbox command.

Drive firmware can obtain randomness from Caliptra's DRBG via the CM_RANDOM_GENERATE Caliptra mailbox command.

4.6.7 Authorization

KMB exposes commands that allows drive firmware to manage the lifecycle of MPKs, HEKs, and MEKs. These lifecycle events have the potential to (and are in many cases designed to) trigger user data loss. The host interface that allows the host to trigger these lifecycle events must therefore implement authorization controls to ensure user data is not improperly destroyed. Drive firmware is responsible for implementing this authorization layer, the details of which are outside the scope of this specification.

4.6.8 Reset behavior

This section defines expected behavior for KMB across each Caliptra reset type, as defined in [20].

Table 4: Behavior on Caliptra reset types

Caliptra reset type	Behavior
Cold boot / cold reset	Caliptra ROM derives the HEK and MDK, then sets the LOCK_IN_PROGRESS bit in the SS_OCP_LOCK_CTRL register. Next, Caliptra runtime firmware performs the following steps: • Determines whether a HEK is available, based on the fuse configuration. If a HEK is unavailable, KMB enters a mode where MEKs are not allowed to be loaded. • Initializes random HPKE keypairs for each supported algorithm, and assigns handles to them, reported via ENUMERATE_HPKE_HANDLES. The VEK is not initialized upon cold reset, as it is generated lazily upon first use. See Section 4.6.1.4 for details.
Warm reset / firmware update reset	The HEK, MDK, and VEK are undisturbed. HPKE keypairs are discarded prior to reset and are regenerated after reset.

Caliptra cold boot / cold reset shall only be triggered by an NVMe subsystem reset [21] caused by main power being applied to the subsystem.

A given integration may trigger a Caliptra warm reset in response to other reset events.

4.7 Interfaces

OCP L.O.C.K. defines two interfaces:

- The encryption engine interface is exposed from the vendor-implemented encryption engine to KMB, and defines a standard mechanism for programming MEKs and control messages.
- The mailbox interface is exposed from KMB to storage drive firmware, and enables the drive to manage MEKs and associated keys.

4.7.1 Encryption engine interface

This section defines the interface between KMB and an encryption engine. An encryption engine is used to encrypt/decrypt user data. Its design and implementation are vendor specific. MEKs are generated or derived within KMB and used by the encryption engine to encrypt and decrypt user data. The interface defined in this section is used to load MEKs from KMB to the encryption engine or to cause the encryption engine to unload (i.e., remove) loaded MEKs. MEKs shall not be accessible to drive firmware as they are being transferred between KMB and the encryption engine.

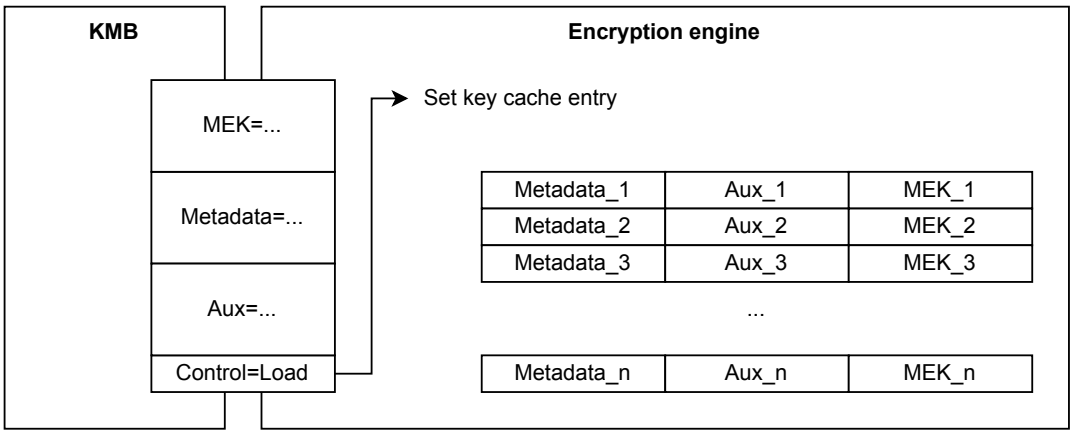
4.7.1.1 Overview

The encryption engine uses an MEK stored in volatile memory to encrypt and decrypt user data. For the purposes of this specification, the entity within the encryption engine used to store the MEKs is called the key cache. Each encryption and decryption of user data is coupled to a specific MEK which is stored in the key cache bound to a unique identifier, called metadata. Each (metadata, MEK) pair is also associated with additional information, called aux, which is used neither as MEK nor an identifier, but has some additional information about the pair. Therefore, the key cache as an entity which stores (metadata, aux, MEK) tuples.

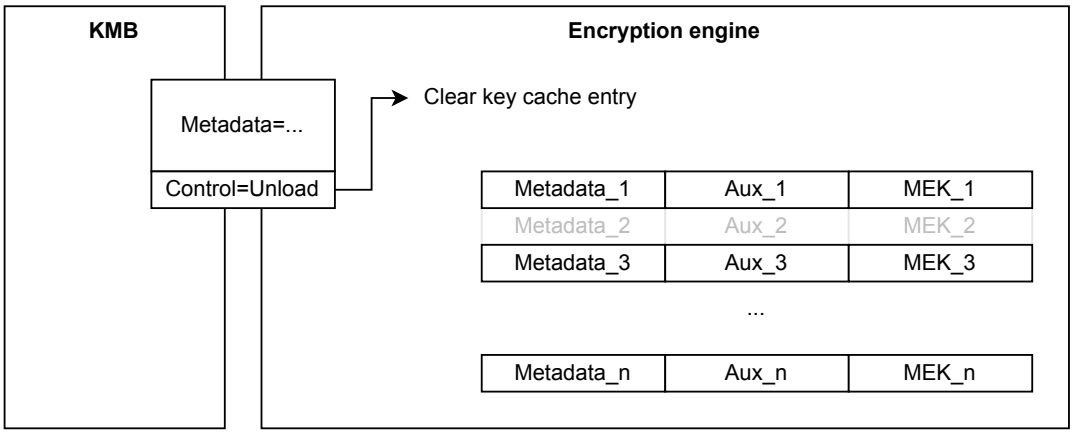
To ensure that MEKs are only ever visible to KMB and the encryption engine, KMB is the only entity which can load and unload (metadata, aux, MEK) tuples. Drive firmware arbitrates all operations in the KMB → encryption engine interface, and is therefore responsible for managing which MEK is loaded in the key cache. Drive firmware has full control on metadata and optional aux. Figure 26 is an illustration of the KMB → encryption engine interface which shows:

- The tuple for loading an MEK.
- The metadata for unloading an MEK.
- An example of a key cache configuration within the encryption engine.

Populate MEK into encryption engine



Remove MEK from encryption engine



Sanitize encryption engine

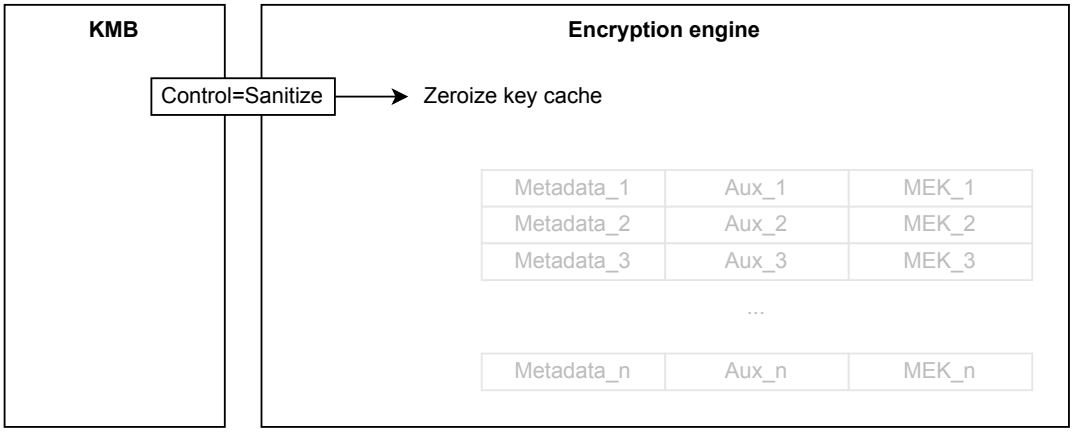


Figure 26: KMB to encryption engine SFR interface

The behavior of I/O through the encryption engine during the execution of an SFR command is vendor-defined.

4.7.1.2 Special Function Registers

KMB uses Special Function Registers (SFRs) to communicate with the encryption engine as shown in Table 5 and each of the following subsections which describe the registers.

The OCP_LOCK_MEK_ADDRESS register represents the combined registers SS_KEY_RELEASE_BASE_ADDR_L and SS_KEY_RELEASE_BASE_ADDR_H and shall contain the fixed base address of the MEK register.

The SS_KEY_RELEASE_SIZE register shall contain the size of the MEK, in bytes. This shall be set to 40h by the MCU ROM.

MCU ROM is responsible for configuring SS_KEY_RELEASE_BASE_ADDR_L, SS_KEY_RELEASE_BASE_ADDR_H and SS_KEY_RELEASE_SIZE, prior to setting CPTRA_FUSE_WR_DONE to prevent further modifications.

Table 5: KMB to encryption engine SFRs

Register	Address	Byte Size	Description
Media Encryption Key (MEK)	OCP_LOCK_MEK_ADDRESS	40h	Register to provide MEK.
Metadata (METD)	OCP_LOCK_MEK_ADDRESS + 40h	14h	Register to provide metadata
Auxiliary Data (AUX)	OCP_LOCK_MEK_ADDRESS + 60h	20h	Register to provide auxiliary values
Control	OCP_LOCK_MEK_ADDRESS + 80h	4h	Register to handle commands

OCP_LOCK_MEK_ADDRESS contains the base address for the SFRs shown in Table 5. The vendor is responsible for ensuring that KMB can access these SFRs through these addresses.

For alignment, offsets OCP_LOCK_MEK_ADDRESS + OCP_LOCK_MEK_LENGTH + 14h..20h (inclusive) are intentionally unallocated.

In the register definitions that follow, the “Type” column indicates whether KMB may read from or write to the given register.

4.7.1.2.1 Media Encryption Key register

Table 6: OCP_LOCK_MEK_ADDRESS: MEK – Media Encryption Key

Bytes	Type	Reset	Description
63:00	WO	0h	**Media encryption key:** This field specifies a 512-bit encryption key.

The encryption engine is free to interpret the provided key in a vendor-defined manner. One sample interpretation for AES-XTS-256 is presented in Figure 27.

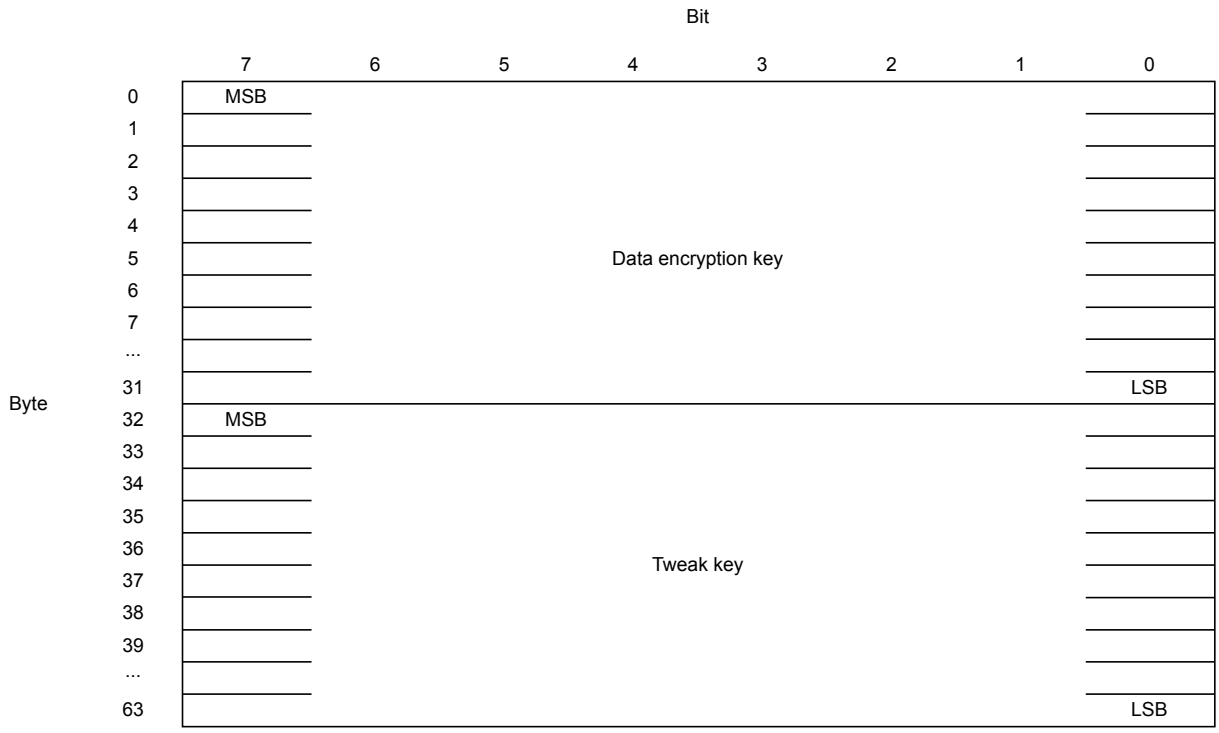


Figure 27: MEK format example for AES-XTS-256

If an algorithm used by the encryption engine does not require 512 bits of key material, the encryption engine is free to disregard unused bits.

Within KMB, loaded MEKs are only ever present in the Key Vault, so that they can be protected against firmware-level attacks. KMB will write MEKs into the encryption engine's key cache using the DMA engine. The DMA engine will copy the key value stored in Key Vault slot 23 to the destination address, specified by OCP_LOCK_MEK_ADDRESS.

4.7.1.2.2 Metadata register

Table 7 defines the Metadata register used to pass additional data related to the MEK.

Table 7: Offset OCP_LOCK_MEK_ADDRESS + 40h: METD – Metadata

Bytes	Type	Reset	Description
19:00	RW/WO[1]	0h	**Metadata (METD):** This field specifies metadata that is vendor specific and specifies the entry in the encryption engine for the MEK.

KMB and the encryption engine must be the only components which have access to MEKs. Each MEK is associated with non-secret metadata, in order for the MEK to be used for any key-related operations including data I/O. The **METD** field is used to convey this metadata.

[1] Register shall be either read write or write only.

When loading or deriving an MEK, KMB takes an **METD** value as input from drive firmware and writes it to the **METD** register without any modification. This allows the vendor full control of the MEK indexing algorithm.

Two examples of how a storage device might leverage the **METD** field are provided: Logical Block Addressing (LBA) range-based metadata, and key-tag based metadata.

When an SSD stores data with address-based encryption, an MEK can be uniquely identified by an (LBA range, Namespace ID) pair. Then, the (LBA range, Namespace ID) pair can be leveraged into **METD** as illustrated in Figure 28.

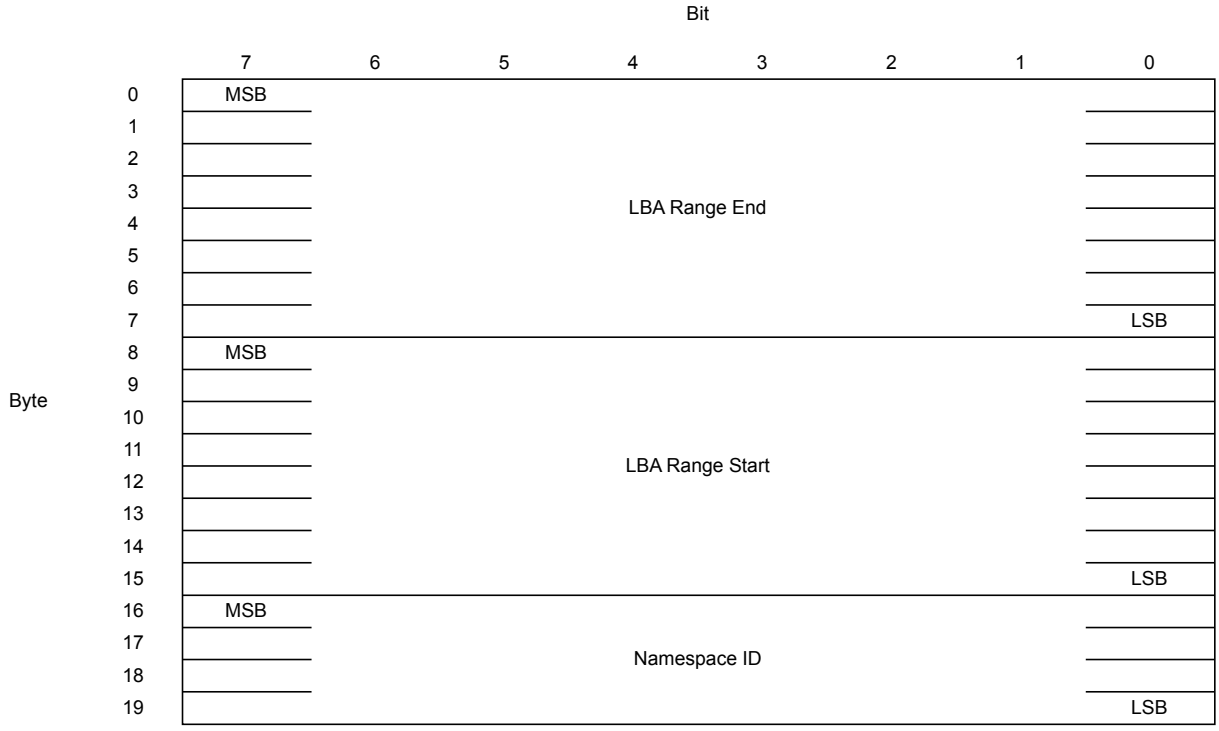


Figure 28: LBA range based metadata format

Address-based encryption is not the only encryption mechanism in SSDs. For example, in TCG Key Per I/O, an MEK is selected by a key tag, which does not map to an address. Figure 29 shows an example of **METD** in such cases.

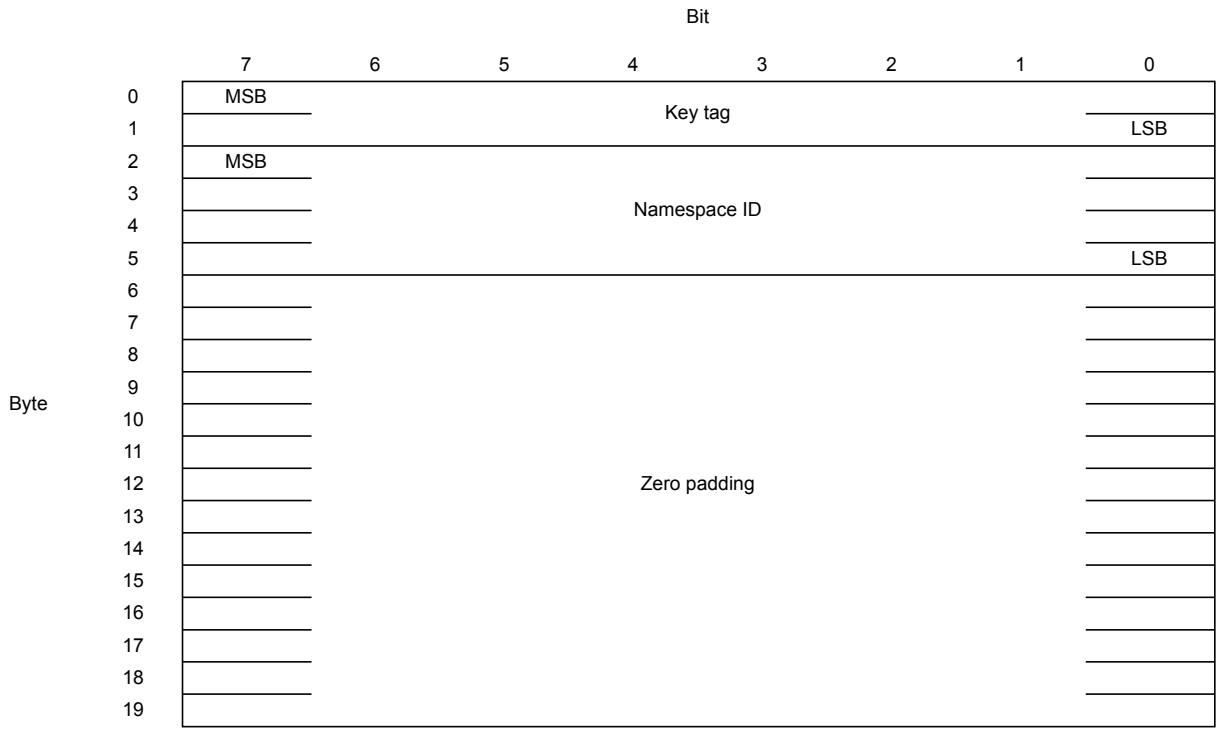


Figure 29: Key tag based metadata format

The above examples are not the only possible values of **METD**. Vendors may design and use their own **METD** if it is more suitable for their system.

4.7.1.2.3 Auxiliary Data register

Table 8 defines the Auxiliary Data register used to pass additional vendor-specific data related to the MEK.

Table 8: OCP_LOCK_MEK_ADDRESS + 60h: AUX – Auxiliary Data

Bytes	Type	Reset	Description
31:00	RW/WO	0h	**Auxiliary Data (AUX):** This field specifies auxiliary data associated to the MEK.

The **AUX** field supports vendor-specific features on MEKs. KMB itself only supports fundamental functionalities in order to minimize attack surfaces on MEKs. Moreover, vendors are free to design and implement their own MEK-related functionality within the encryption engine, as long as that functionality cannot be used to exfiltrate MEKs. In order to support these functionalities, some data may be associated and stored with an MEK, and the **AUX** field facilitates this association.

When drive firmware instructs KMB to load an MEK, drive firmware is expected to provide an **AUX** value. Similar to the **METD** field, KMB will write the **AUX** value into the Auxiliary Data register without any modification.

One simple use case of the **AUX** field is to store an offset of initialization vector or nonce. It can also be used in a more complicated use case. Here is an example. Suppose that there exists a vendor who wants to design a system which supports several modes of operation through the encryption engine while using KMB. Then, a structure of **AUX** value as on Figure 30 can be used.

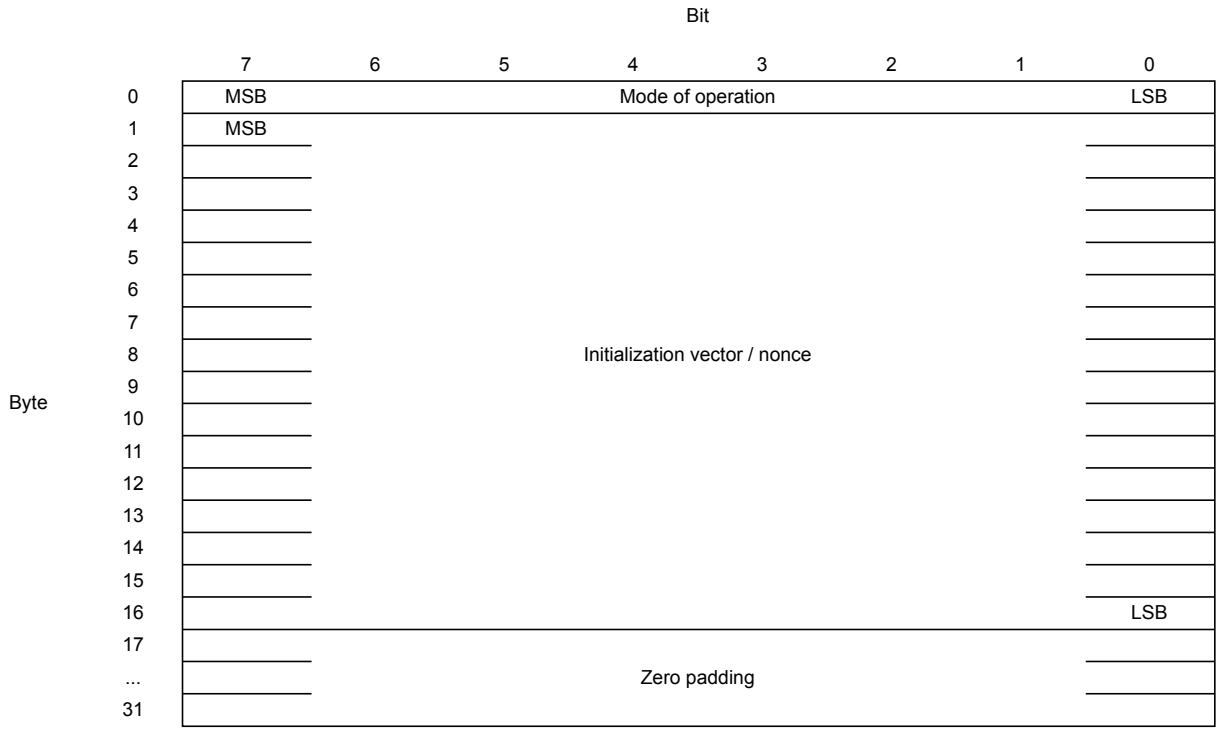


Figure 30: Auxiliary data format example

When drive firmware instructs KMB to load an MEK, drive firmware can use the **AUX** value to specify which mode of operation should be used and which value should be used as an initialization vector or a nonce with the generated MEK.

4.7.1.2.4 Control register

Table 9 defines the Control register used to sequence the execution of a command and obtain the status of that command.

Table 9: Offset OCP_LOCK_MEK_ADDRESS + 80h: CTRL – Control

Bits	Type	Reset	Description

(continued on next page)

(continued from previous page)

Bits	Type	Reset	Description
31	RO	0h	**Ready (RDY):** After any reset, the default value of this bit shall be 0b. Once the encryption engine is initialized and becomes ready to handle commands, the encryption engine shall set this bit from 0b to 1b. When a fatal error has occurred in the encryption engine, the encryption engine may set this bit from 1b to 0b. KMB checks that this bit is set to 1b before issuing any commands to the encryption engine.
30:20	RO	0h	Reserved
19:16	RO	0h	**Error (ERR):** When the encryption engine sets the DONE bit from 0b to 1b, the encryption engine sets this field to 0000b if the command specified by the CMD field succeeded, or a non-zero value if the command failed. See Table 10. Encryption engine error codes are surfaced back to drive firmware. If the DONE bit is set to 1b by KMB, then this field is set to 0000b.
15:6	RO	0h	Reserved
5:2	RW	0h	**Command (CMD):** This field specifies the command to execute or the command associated with the reported status. See Table 11.
1	RW	0b	**Done (DONE):** This bit indicates the completion of a command by the encryption engine. If this bit is set to 1b by the encryption engine, then the encryption engine has completed the command specified by the CMD field and the ERR field indicates the status of the execution of that command. A write by KMB of the value 1b to this bit shall cause the encryption engine to: • set the DONE bit to 0b, • set the EXE bit to 0b, • set the ERR field to 0000b, and • set the CMD bit to 0000b.
0	RW	0b	**Execute (EXE):** After any reset, the default value of this field shall be 0b. When this bit is set from 0b to 1b by KMB, the encryption engine shall execute the command specified in the CMD field. Once the execution is complete, the encryption engine shall simultaneously set this bit from 1b to 0b, set the DONE bit from 0b to 1b, and populate the ERR field. While the EXE bit is 1b, the encryption engine is busy.

Table 10: CTRL error codes

Value	Description
0h	Command successful
1h	Invalid command code
2h to 3h	Reserved
4h to Fh	Vendor Specific

Table 11: CTRL command codes

Value	Description
0h	Reserved
1h	**Load MEK:** Load the key specified by the AUX field and MEK register into the encryption engine as specified by the **METD** field.
2h	**Unload MEK:** Unload the MEK from the encryption engine as specified by the **METD** field.
3h	**Zeroize**: Unload all of the MEKs from the encryption engine (i.e., zeroize the encryption engine MEKs).

4h	**Load KAT MEK**: Load a fixed MEK, along with the auxiliary metadata specified by the **AUX** field, into the encryption engine as specified by the **METD** field. The fixed MEK is as follows in hex string:
	`0000 0000 0000 0000 0000 0000 0000 0000`
	`1111 1111 1111 1111 1111 1111 1111 1111`
	`2222 2222 2222 2222 2222 2222 2222 2222`
	`3333 3333 3333 3333 3333 3333 3333 3333`
	Note: this command is intended to support FIPS validation and is optional. If an encryption engine implementation does not support this command and wishes to be FIPS-compliant, the implementation is responsible for satisfying FIPS KAT requirements via a separate mechanism.

5h to Fh	Reserved

From KMB, the Control register is the register to write a command and receive its execution result. From its counterpart, the encryption engine, the Control register is used to receive a command and write its execution result.

The expected change flow of the Control register to handle a command is as follows:

1. If **RDY** is set to 1b, then KMB writes **CMD** and **EXE**
    1. **CMD:** either 1h, 2h or 3h
    2. **EXE:** 1b
2. The encryption engine writes **ERR** and **DONE**
    1. **ERR:** either 0b or a non-zero value depending on the execution result
    2. **DONE:** 1b
3. KMB writes **DONE**
    1. **DONE:** 1b
4. The encryption engine writes **CMD**, **ERR**, **DONE** and **EXE**
    1. **CMD:** 0h
    2. **ERR:** 0h
    3. **DONE:** 0b
    4. **EXE:** 0b

KMB therefore interacts with the Control register as follows in the normal circumstance:

1. KMB writes **CMD** and **EXE**
    1. **CMD:** either 1h, 2h or 3h
    2. **EXE:** 1b
2. KMB waits for **DONE** to be 1
3. KMB writes **DONE**
    1. **DONE:** 1b
4. KMB waits for **DONE** to be 0

Since the Control register is a part of the encryption engine whose implementation can be unique to each vendor, behaviors of the Control register with respect to unexpected flows are left for vendors. For example, a vendor who wants robustness might integrate a write-lock into the Control register in order to prevent two almost simultaneous writes on the EXE bit. Vendors shall ensure that any customizations remain compatible with the interface defined in this specification.

4.7.1.3 Control register state machine

Figure 31 illustrates the control register's state machine as it transitions from power-on to executing a command.

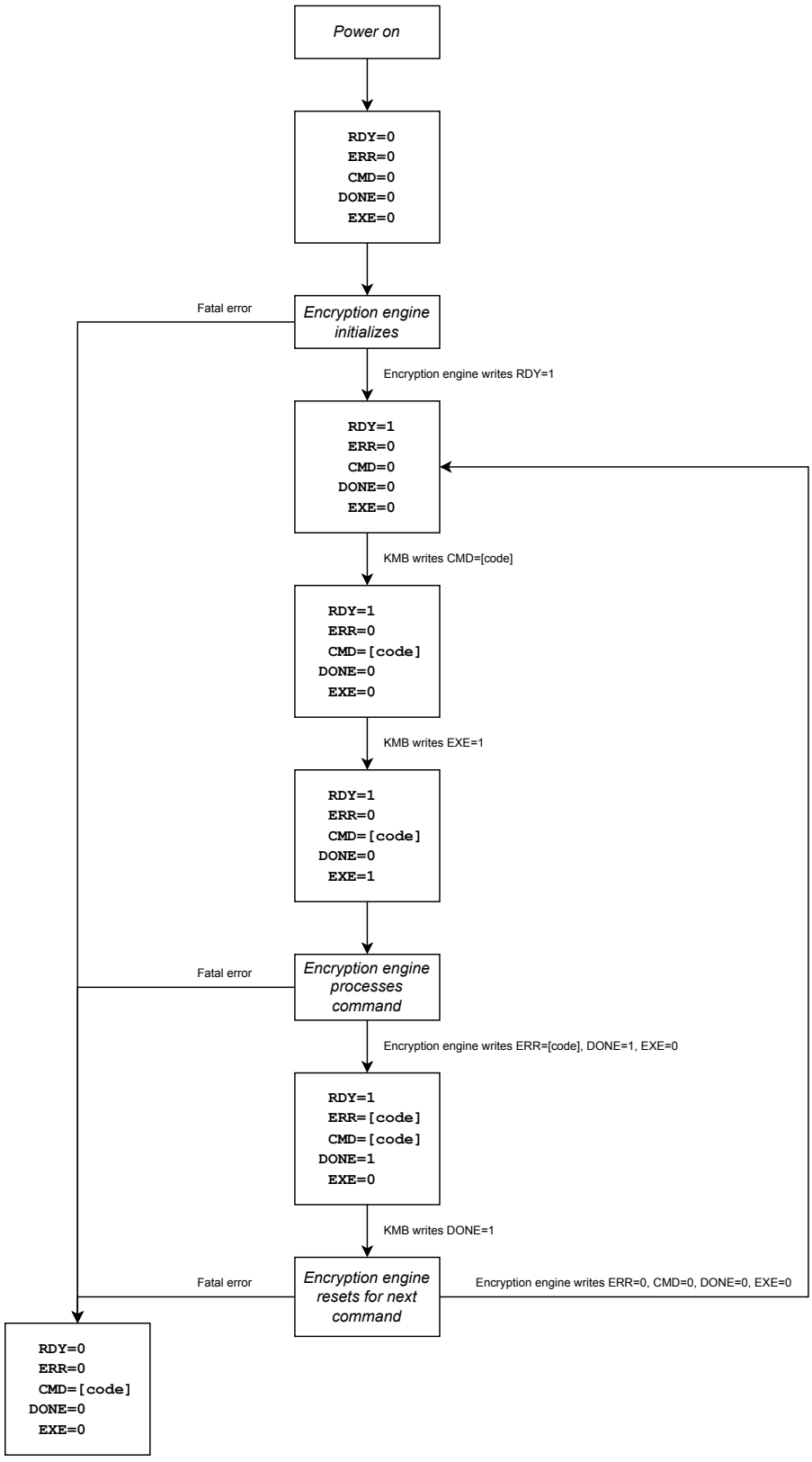


Figure 31: Control register state machine

4.7.1.4 KMB command sequence

Figure 32 shows a sample command execution. This is an expected sequence when drive firmware instructs KMB to load an MEK. This sequence would occur as part of the DERIVE_MEK or LOAD_MEK mailbox commands. The internal behavior of the encryption engine is one of several possible mechanisms, and can be different per vendor.

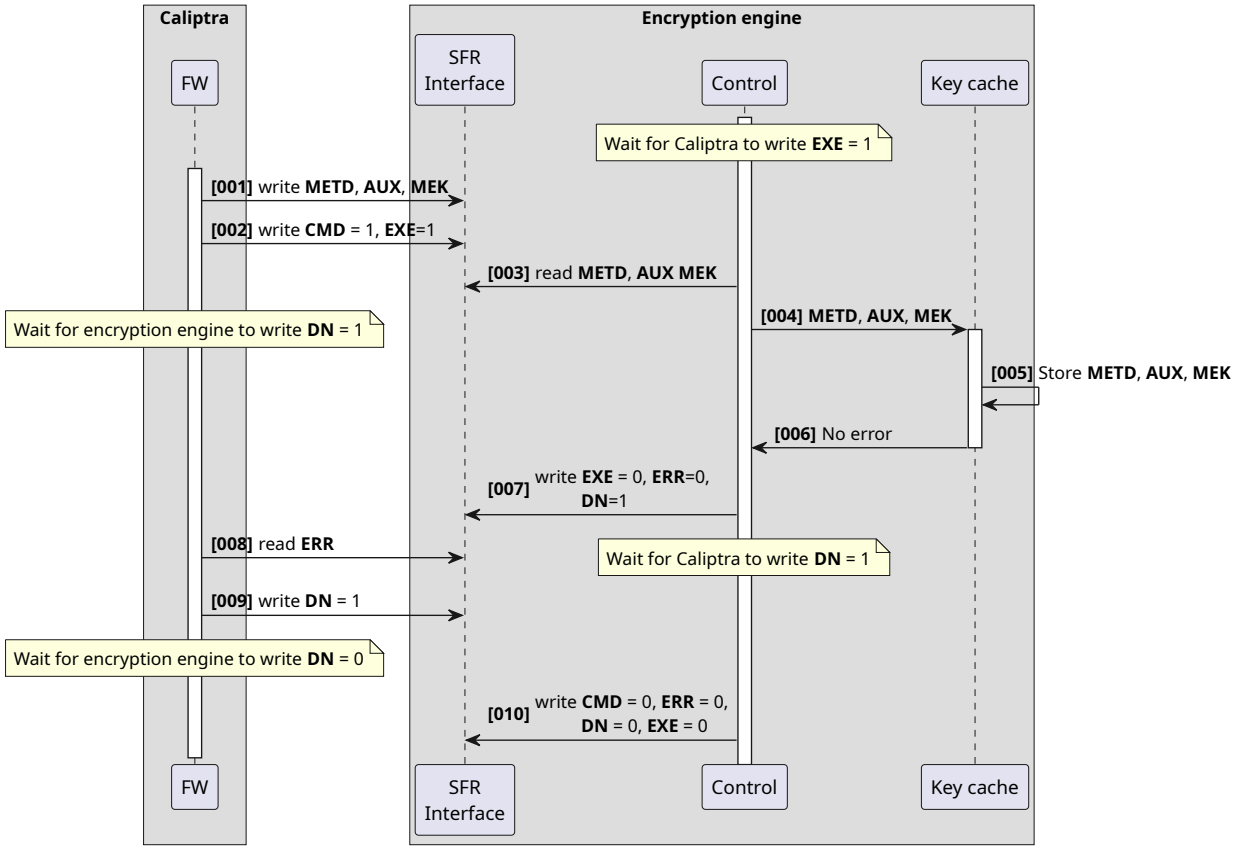


Figure 32: Command execution example for loading an MEK

4.7.2 Mailbox interface

This section provides the mailbox commands exposed by Caliptra as part of OCP L.O.C.K.

4.7.2.1 FIPS status indicator

Each mailbox command returns a `fips_status` field. This provides an indicator of whether KMB is operating in FIPS mode. Table 12 provides the possible values for this field.

Note: all multi-byte fields (i.e. `u16` and `u32`) that are not byte arrays are interpreted as little endian.

Table 12: Values for the FIPS status field

Value	Description
0h	FIPS mode enabled.
1h to FFFFh	Reserved.

4.7.2.2 Encryption engine timeout

Each mailbox command that causes a command to execute on the encryption engine includes a `cmd_timeout` value indicating the amount of time KMB firmware will wait until the command has completed. If this timeout is exceeded, KMB aborts the command and reports a `LOCK_ENGINE_TIMEOUT` result code.

For such commands, KMB firmware will return a `LOCK_EE_NOT_READY` error immediately if the encryption engine is not ready to execute a command.

4.7.2.3 Side-channel mitigations

Several mailbox commands invoke ECDH and/or ML-KEM Decaps. These operations involve deterministic data-dependent operations and are potentially susceptible to timing attacks and power analysis. To mitigate such attacks, Caliptra leverages masking in hardware, and introduces random jitter delays in firmware before handling mailbox commands.

4.7.2.4 REPORT_HEK_METADATA

This command is exposed by Caliptra ROM and allows MCU ROM to report metadata about the HEK. This command must be called exactly once after each cold reset and before loading Caliptra's FMC and runtime firmware.

By exposing this command in ROM, Caliptra de-privileges runtime compromise of drive firmware that might cause it to mis-report the HEK seed state, which could lead to incorrect device state attestations.

Command Code: 0x5248_4D54 ("RHMT")

Table 13: REPORT_HEK_METADATA input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.
total_slots	u16	Total number of HEK seed slots.
active_slot	u16	Currently-active HEK seed slot. Zero-indexed.
seed_state	u16	HEK seed state: • 1h: HEK_PROGRAMMED • 4h: HEK_PROGRAMMED_EMPTY • all others: HEK_UNAVAILABLE

padding	u16	Reserved.

The `HEK_AVAILABLE` flag in the response (Table 15) indicates whether Caliptra has successfully derived the HEK. Caliptra determines HEK availability based on its current lifecycle state and the `seed_state` reported by MCU ROM:

- If Caliptra is in the `Unprovisioned` or `Manufacturing` lifecycle state, the HEK is always available.
- If Caliptra is in the `Production` lifecycle state, the HEK is available if:
  - `seed_state` is `HEK_PROGRAMMED` AND the HEK seed fuse is not empty (not all 0s and not all 1s).
  - OR `seed_state` is `HEK_PROGRAMMED_EMPTY`.

Table 14: REPORT_HEK_METADATA output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
flags	u32	Additional information for the caller. See Table 15.
reserved	u32[3]	Reserved.

Table 15: REPORT_HEK_METADATA output flags

Name	Offset	Description
HEK_AVAILABLE	Byte 0 bit 31	When set indicates HEK is available.

4.7.2.5 GET_STATUS

Allows drive firmware to determine if the encryption engine is ready to process commands as well as vendor-defined drive encryption engine status data.

Command Code: 0x4753_5441 (“GSTA”)

Table 16: GET_STATUS input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.

Table 17: GET_STATUS output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32[4]	Reserved.
ctrl_register	u32	Value of the CTRL register from the SFR interface.

4.7.2.6 GET_ALGORITHMS

Allows drive firmware to determine the types of algorithms supported by KMB for KEM, MPK, and access key generation.

Command Code: 0x4741_4C47 (“GALG”)

Table 18: GET_ALGORITHMS input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.

Table 19: GET_ALGORITHMS output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32[4]	Reserved.
hpke_algorithms	u32	Identifies the supported HPKE algorithms: {kem/aead/kdf}_id • Byte 0 bit 0: 0x0011, 0x0002, 0x0002 [9] • Byte 0 bit 1: 0x0042, 0x0002, 0x0002 [13] • Byte 0 bit 2: 0x0051, 0x0002, 0x0002 [13] See Table 3 for definitions of each HPKE algorithm identifier.
access_key_sizes	u32	Indicates the length of plaintext access keys: • Byte 0 bit 0: 256 bits

Each of the `hpke_algorithms` and `access_key_sizes` fields shall be reported as a non-zero value.

4.7.2.7 CLEAR_KEY_CACHE

This command unloads all MEKs in the encryption engine.

Command Code: 0x434C_4B43 (“CLKC”)

Table 20: CLEAR_KEY_CACHE input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.
cmd_timeout	u32	Timeout in ms for command to encryption engine to complete.

Table 21: CLEAR_KEY_CACHE output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32	Reserved.

4.7.2.8 ENUMERATE_HPKE_HANDLES

This command returns a list of all currently-active HPKE handles for resources held by KMB.

Command Code: 0x4548_444C (“EHDL”)

Table 22: ENUMERATE_HPKE_HANDLES input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.

Table 23: ENUMERATE_HPKE_HANDLES output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32	Reserved.
hpke_handle_count	u32	Number of HPKE handles (N).
hpke_handles	HpkeHandle[N]	List of (HPKE handle value, HPKE algorithm) tuples.

Table 24: HpkeHandle contents

Name	Type	Description
handle	u32	Handle for HPKE keypair held in KMB memory.

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Name	Type	Description
hpke_algorithm	u32	HPKE algorithm. Shall be a bit value indicated as supported in Table 19.

4.7.2.9 GET_HPKE_PUB_KEY

This command returns the specified HPKE public key.

Command Code: 0x4748_504B (“GHPK”)

Table 25: GET_HPKE_PUB_KEY input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.
hpke_handle	u32	Handle for HPKE keypair held in KMB memory.

Table 26: GET_HPKE_PUB_KEY output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32	Reserved.
pub_key_len	u32	Length of HPKE public key (`Npk` in [9]).
pub_key	u8[1665]	HPKE public key. Size returned in `pub_key_len`.

4.7.2.10 ROTATE_HPKE_KEY

This command rotates the HPKE keypair indicated by the specified handle and stores the new HPKE keypair in volatile memory within KMB.

Command Code: 0x5248_504B (“RHPK”)

Table 27: ROTATE_HPKE_KEY input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.
hpke_handle	u32	Handle for old HPKE keypair held in KMB memory.

Table 28: ROTATE_HPKE_KEY output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32	Reserved.
hpke_handle	u32	Handle for new HPKE keypair held in KMB memory.

4.7.2.11 GENERATE_MPK

This command unwraps the specified access key, generates a random MPK, then encrypts the MPK with a Locked MPK encryption key. The Locked MPK is returned for the drive to persistently store. The given `metadata` is placed in the `metadata` field of the returned MPK to cryptographically tie them together.

Command Code: 0x474D_504B (“GMPK”)

Table 29: GENERATE_MPK input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.
sek	u8[32]	Soft Epoch Key.
metadata_len	u32	Length of the metadata field.
metadata	u8[32]	Metadata associated with the wrapped key. Size returned in `metadata_len`.
sealed_access_key	SealedAccessKey	HPKE-sealed access key.

Table 30: GENERATE_MPK output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32	Reserved.
encrypted_mpk	LockedMpk	MPK encrypted to access_key.

4.7.2.12 REWRAP_MPK

This command follows the Access Key rotation flow.

The drive stores the returned Locked MPK and zeroizes the old Locked MPK.

Command Code: 0x5245_5750 (“REWP”)

Table 31: REWRAP_MPK input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.
sek	u8[32]	Soft Epoch Key.
current_locked_mpk	LockedMpk	Current MPK to be rewrapped.
sealed_access_key	SealedAccessKey	HPKE-sealed current access key.
new_ak_ciphertext	u8[access_key_len+Nt]	New access key ciphertext and authentication tag. `access_key_len` is provided by the SealedAccessKey. `Nt` is the HPKE value associated with the `aead_id` identifier from the SealedAccessKey's `hpke_algorithm`. See Section 4.7.2.22.1 for details.

Table 32: REWRAP_MPK output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32	Reserved.
new_locked_mpk	LockedMpk	MPK encrypted to new_access_key.

4.7.2.13 ENABLE_MPK

This command decrypts `sealed_access_key`, then uses it to derive a Locked MPK encryption key, which is used to decrypt `locked_mpk`. The MPK is then re-encrypted with the VEK. The Enabled MPK is returned.

Command Code: 0x524D_504B ("RMPK")

Table 33: ENABLE_MPK input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.
sek	u8[32]	Soft Epoch Key.
sealed_access_key	SealedAccessKey	HPKE-sealed access key.

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Name	Type	Description
locked_mpk	LockedMpk	MPK encrypted to the HEK and access key.

Table 34: ENABLE_MPK output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32	Reserved.
enabled_mpk	EnabledMpk	MPK encrypted to the VEK.

4.7.2.14 INITIALIZE_MEK_SECRET

This command shall initialize the MEK secret seed as described in Figure 18.

Command Code: 0X494D_4B53 (“IMKS”)

Table 35: INITIALIZE_MEK_SECRET input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.
sek	u8[32]	Soft Epoch Key.
dpk	u8[32]	Data Protection Key.

Table 36: INITIALIZE_MEK_SECRET output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32	Reserved.

4.7.2.15 MIX_MPK

This command decrypts the specified MPK with the VEK, and then updates the MEK secret seed in KMB by performing a KDF with the MEK secret seed and the decrypted MPK.

When generating an MEK, one or more MIX_MPK commands are processed to modify the MEK secret seed.

The MEK secret seed must already be initialized by INITIALIZE_MEK_SECRET or this command shall return an error.

Command Code: 0x4D4D_504B (“MMPK”)

Table 37: MIX_MPK input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.
enabled_mpk	EnabledMpk	MPK encrypted to the VEK.

Table 38: MIX_MPK output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32	Reserved.

4.7.2.16 TEST_ACCESS_KEY

This command is used by the host to check the input access key is associated with the given MPK. The `nonce` is a random value to be included in the digest calculation to prevent response replay attacks. The output is calculated as SHA2-384(metadata || decrypted access key || nonce). The metadata is taken from the provided MPK’s `metadata` field.

Command Code: 0x5441_434B (“TACK”)

Table 39: TEST_ACCESS_KEY input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.
sek	u8[32]	Soft Epoch Key.
nonce	u8[32]	Host-provided random value.
locked_mpk	LockedMpk	Locked MPK associated with the access key.
sealed_access_key	SealedAccessKey	HPKE-sealed access key.

Table 40: TEST_ACCESS_KEY output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.

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Name	Type	Description
digest	u8[48]	SHA-384 hash of the MPK's metadata, decrypted access key, and nonce.

4.7.2.17 GENERATE_MEK

This command generates a random 512-bit MEK and encrypts it using the MEK secret.

INITIALIZE_MEK_SECRET must be invoked prior to this command or an error shall be returned.

Command Code: 0x474D_454B ("GMEK")

Table 41: GENERATE_MEK input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.

Table 42: GENERATE_MEK output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32	Reserved.
wrapped_mek	WrappedMek	MEK encrypted to the derived MEK secret.

4.7.2.18 LOAD_MEK

This command decrypts the given encrypted 512-bit MEK using the MEK secret.

The decrypted MEK, specified metadata, and aux_metadata are loaded into the encryption engine key cache. The metadata format is vendor-defined and specifies the information to the encryption engine on where within the key cache the MEK is loaded.

INITIALIZE_MEK_SECRET must be invoked prior to this command or an error shall be returned.

Command Code: 0x4C4D_454B ("LMEK")

Table 43: LOAD_MEK input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.

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Name	Type	Description
metadata	u8[20]	Metadata for MEK to load into the drive encryption engine (i.e. NSID + LBA range).
aux_metadata	u8[32]	Auxiliary metadata for the MEK (optional; i.e. operation mode).
wrapped_mek	WrappedMek	MEK encrypted to the derived MEK secret.
cmd_timeout	u32	Timeout in ms for command to encryption engine to complete.

Table 44: LOAD_MEK output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32	Reserved.

4.7.2.19 DERIVE_MEK

This command derives an MEK using the MEK secret.

The derived MEK, specified metadata, and aux_metadata are loaded into the encryption engine key cache. The metadata format is vendor-defined and specifies the information to the encryption engine on where within the key cache the MEK is loaded.

INITIALIZE_MEK_SECRET must be invoked prior to this command or an error shall be returned.

Command Code: 0x444D_454B (“DMEK”)

Table 45: DERIVE_MEK input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.
mek_checksum	u8[16]	Checksum used to validate the derived MEK. May be all-zeroes, in which case no check is performed.
metadata	u8[20]	Metadata for MEK to load into the drive encryption engine (i.e. NSID + LBA range).
aux_metadata	u8[32]	Auxiliary metadata for the MEK (optional; i.e. operation mode).
cmd_timeout	u32	Timeout in ms for command to encryption engine to complete.

Table 46: DERIVE_MEK output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32	Reserved.
mek_checksum	u8[16]	Checksum calculated for the derived MEK.

4.7.2.20 UNLOAD_MEK

This command causes the MEK associated to the specified metadata to be unloaded for the key cache of the encryption engine. The metadata format is vendor-defined and specifies the information to the encryption engine on where within the key cache, the MEK is loaded.

Command Code: 0x554D_454B (“UMEK”)

Table 47: UNLOAD_MEK input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.
metadata	u8[20]	Metadata for MEK to unload from the drive encryption engine (i.e. NSID + LBA range).
cmd_timeout	u32	Timeout in ms for command to encryption engine to complete.

Table 48: UNLOAD_MEK output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32	Reserved.

4.7.2.21 LOAD_KAT_MEK

This command loads a fixed MEK into the encryption engine. The following hex value will be used as the MEK:

```
0000 0000 0000 0000 0000 0000 0000 0000
1111 1111 1111 1111 1111 1111 1111 1111
2222 2222 2222 2222 2222 2222 2222 2222
3333 3333 3333 3333 3333 3333 3333 3333
```

This value is intentionally selected to avoid potential endianness issues and to comply with FIPS 140-3 requirements for the key used in AES-XTS (AES-XTS considerations). AES-XTS uses a 256-bit (resp. 512-bit) key, and its first 128-bit (resp. 256-bit) half and second 128-bit

(resp. 256-bit) half shall not be identical. With the selected MEK, any 256-bit or 512-bit substring satisfies this condition.

The command loads the fixed MEK, specified metadata, and aux_metadata into the encryption engine. The formats of metadata and aux_metadata are vendor-defined and will act as an identifier and additional information for the loaded MEK.

The MEK loaded with this command is intended only for Known Answer Test (KAT) purposes of the underlying block cipher in the encryption engine. The loaded MEK should be immediately unloaded by using UNLOAD_MEK or CLEAR_KEY_CACHE once the KAT is complete. Using this MEK for user data encryption will compromise all data protection mechanism integrated within a storage device.

This command's implementation triggers the **Load KAT MEK** command as defined in Table 11. As noted, encryption engine implementations are not required to support this command. In such cases, the LOAD_KAT_MEK mailbox command will return an error.

Command Code: 0x4C4B_4154 ("LKAT")

Table 49: LOAD_KAT_MEK input arguments

Name	Type	Description
chksum	u32	Checksum over other input arguments, computed by the caller.
reserved	u32	Reserved.
metadata	u8[20]	Metadata for MEK to load into the drive encryption engine (i.e. NSID + LBA range).
aux_metadata	u8[32]	Auxiliary metadata for the MEK (optional; i.e. operation mode).
cmd_timeout	u32	Timeout in ms for command to encryption engine to complete.

Table 50: LOAD_KAT_MEK output arguments

Name	Type	Description
chksum	u32	Checksum over other output arguments, computed by Caliptra.
fips_status	u32	Indicates if the command is FIPS approved or an error.
reserved	u32	Reserved.

4.7.2.22 Common mailbox types

This section defines common types used to interface between drive firmware and KMB. These types are common patterns found in both requests and responses.

4.7.2.22.1 SealedAccessKey type

This type holds an HPKE-wrapped access key.

Table 51: SealedAccessKey contents

Name	Type	Description
hpke_handle	u32	Handle for HPKE keypair held in KMB memory.
hpke_algorithm	u32	HPKE algorithm. Must be a bit value indicated as supported in Table 19.
access_key_len	u32	Access key length in bytes. Must be the scalar value associated with a bit value indicated as supported in Table 19.
info_len	u32	Length of the info field.
info	u8[256]	Info to use with HPKE unwrap. Size returned in `info_len`.
kem_ciphertext	u8[1665]	HPKE encapsulated key. Cipher text size is defined by the KEM algorithm.
padding	u8[3]	Reserved.
ak_ciphertext	u8[access_key_len+Nt]	Access key ciphertext and authentication tag.

`Nenc` and `Nt` are HPKE values associated with the `kem_id` and `aead_id` identifiers from the given `hpke_algorithm`. For example, if byte 0 bit 0 of `hpke_algorithm` is set (indicating `kem_id` 0x0011 and `aead_id` 0x0002), then according to [9], `Nenc` and `Nt` would be 97 and 16, respectively.

4.7.2.22.2 WrappedKey type

AES-256-GCM is used for all wrapping and unwrapping.

Table 52: WrappedKey contents

Name	Type	Description
key_type	u16	Type of the wrapped key. • 0h: Reserved • 1h: LOCKED_MPK (ciphertext held at rest) • 2h: ENABLED_MPK (ciphertext held in RAM) • 3h: WRAPPED_MEK • 4h to FFFFh: Reserved
reserved	u16	Reserved.
salt	u8[12]	Random salt for the given wrapped key.
metadata_len	u32	Length of the metadata field.
key_len	u32	Length of the encrypted key.
iv	u8[12]	Initialization vector for AES operation.
metadata	u8[32]	Metadata associated with the wrapped key. Size returned in `metadata_len`.
ciphertext	u8[key_len+16]	Key ciphertext and authentication tag.

The AAD for the encrypted message is constructed as `key_type` || `metadata_len` || `metadata`.

Variants of WrappedKey will be used to reduce duplicating information in commands. The following names will be used for WrappedKeys of a specific `key_type` and `key_len`:

Table 53: WrappedKey variants

Name	key_type	key_len
LockedMpk	LOCKED_MPK	32
EnabledMpk	ENABLED_MPK	32
WrappedMek	WRAPPED_MEK	64

4.7.2.23 Fault handling

KMB mailbox command failures are surfaced by the `cptra_fw_error_fatal` and `cptra_fw_error_non_fatal` registers. For a comprehensive list of error codes and their definitions, integrators should refer to the Caliptra software reference implementation and specifications.

- Runtime error codes and mailbox status codes are documented in the Caliptra Runtime Specification [22].
- ROM error codes are documented in the Caliptra ROM Specification [23].
- The complete set of error code constants is defined in the Caliptra Error library [24].

In general, KMB mailbox errors should be surfaced to the host. Errors may be caused by ill-formed commands, timeouts, or errors reported by the encryption engine. When an encryption engine error occurs, the error code surfaced by Caliptra includes the state of the encryption engine's CTRL register.

4.8 Host APIs

In addition to supporting TCG Opal, Enterprise, and Key Per I/O, OCP L.O.C.K. provides underlying support for the Media Encryption Key Multiparty Authorization (MEK-MPA) Opal feature-set [16]. These bindings are described in Table 54.

Table 54: Mapping between KMB mailbox commands and host-facing storage APIs

KMB mailbox command	Related host-facing API	Description
ENUMERATE_HPKE_HANDLES	TCG MEK-MPA	The HPKE public keys reported in the Certificate table are enumerated internally by this command.
GET_HPKE_PUB_KEY	TCG MEK-MPA	The HPKE public keys produced by this command are endorsed by the MCU using the DPE context.
ROTATE_HPKE_KEY	TCG MEK-MPA	When GenKey is invoked on an HPKE Certificate table entry, the key is rotated via this command.

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KMB mailbox command	Related host-facing API	Description
GENERATE_MPK	TCG MEK-MPA	When an AccessCondition is initialized, via InitializeAccessCondition, its key material is produced by this command. The MPK's metadata must be set to the AccessCondition's UID. The SealedAccessKey's `info` must be set to the concatenation of the hex value of the InitializeAccessCondition method UID and the hex value of the target AccessCondition object UID.
REWRAP_MPK	TCG MEK-MPA	When an AccessCondition's access key is changed via ChangeAccessKey, the rotation is accomplished via this command. The SealedAccessKey's `info` must be set to the concatenation of the hex value of the ChangeAccessKey method UID and the hex value of the target AccessCondition object UID.
ENABLE_MPK	TCG MEK-MPA	When an AccessCondition is enabled via EnableAccess, that action is performed by this command. The SealedAccessKey's `info` must be set to the concatenation of the hex value of the EnableAccess method UID and the hex value of the target AccessCondition object UID.
TEST_ACCESS_KEY	TCG MEK-MPA	When an AccessCondition's access key is tested via TestAccessKey, that action is performed by this command. The SealedAccessKey's `info` must be set to the concatenation of the hex value of the TestAccessKey method UID and the hex value of the target AccessCondition object UID.

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KMB mailbox command	Related host-facing API	Description
MIX_MPK	TCG MEK-MPA	When a K_AES_* entry is created or unlocked, and that entry is bound to an AccessCondition, the K_AES_* entry is bound to the AccessCondition via this command.
GENERATE_MEK	TCG Opal or Enterprise	When a K_AES_* entry is created, that action may be performed by this command.
LOAD_MEK	TCG Opal or Enterprise	When a K_AES_* entry is unlocked, that action may be performed by this command.
DERIVE_MEK	TCG Opal or Enterprise	When a K_AES_* entry is unlocked, that action may be performed by this command.
DERIVE_MEK	TCG Key Per I/O	When a key tag with an associated DEK is injected, the MEK is derived via this command.

Rotation of the HEK and SEK and injection of host entropy require additional host APIs beyond those available in TCG Opal, Enterprise, or Key Per I/O. Such APIs are beyond the scope of the present document.

4.9 Terminology

Table 55: Acronyms and abbreviations used throughout this document

Abbreviation	Description
AES	Advanced Encryption Standard
CSP	Critical Security Parameter
DPK	Data Protection Key
DICE	Device Identifier Composition Engine
DRBG	Deterministic Random Bit Generator
ECDH	Elliptic-curve Diffie–Hellman
ECDSA	Elliptic Curve Digital Signature Algorithm
EPK	Epoch Protection Key
HEK	Hard Epoch Key
HMAC	Hash-Based Message Authentication Code
HPKE	Hybrid Public Key Encryption
IETF EAT	IETF Entity Attestation Token
KDF	Key Derivation Function

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Abbreviation	Description
KEM	Key Encapsulation Mechanism
KMB	Key Management Block
L.O.C.K.	Layered Open-Source Cryptographic Key-management
MDK	MEK Deobfuscation Key
MEK	Media Encryption Key
ML-DSA	Module-Lattice-Based Digital Signature Algorithm
ML-KEM	Module-Lattice-Based Key-Encapsulation Mechanism
MPK	Multi-party Protection Key
NIST	National Institute of Standards and Technology
OCP	Open Compute Project
RTL	Register Transfer Level
SED	Self-encrypting drive
SEK	Soft Epoch Key
SSD	Solid-state drive
TCG	Trusted Computing Group
TRNG	True Random Number Generator
UART	Universal asynchronous receiver-transmitter
VEK	Volatile Escrow Key
XTS	XEX-based tweaked-codebook mode with ciphertext stealing

4.10 Compliance

This section enumerates requirements for devices that integrate OCP L.O.C.K.

Table 56: Compliance requirements

Item	Requirement	Mandatory
1	The device shall integrate Caliptra.	Yes
2	OCP L.O.C.K. shall be enabled by setting the input strap `ss_ocp_lock_en` in Caliptra Core or `cptra_ss_strap_ocp_lock_en_i` in Caliptra Subsystem.	Yes
3	When a storage device is in a production lifecycle state, MEKs shall only be programmable to the encryption engine via Caliptra. See Section 4.6.	Yes
4	The encryption engine shall remove all MEKs from the encryption engine on a power cycle or during zeroization of the storage device. See Section 4.6.	Yes
5	When the device is shipped it must be in the production lifecycle state and have a randomized HEK. See Section 4.6.4.2.	Yes
6	MCU ROM shall populate the HEK seed fuse register and invoke REPORT_HEK_METADATA upon cold reset. See Sections 4.6.4.1 and 4.7.2.4.	Yes

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Item	Requirement	Mandatory
7	The drive shall only provide HEK seeds or SEKs that are cryptographically-strong random values. See Section 4.6.4.	Yes
8	Drive firmware shall implement authorization controls to gate lifecycle events that have the potential to trigger data loss. See Section 4.6.7.	Yes
9	KMB shall have access to the SFRs defined in Table 5 through the address defined by OCP_LOCK_MEK_ADDRESS. See Section 4.7.1.2.	Yes
10	MCU ROM shall configure registers SS_KEY_RELEASE_BASE_ADDR_L, SS_KEY_RELEASE_BASE_ADDR_H and SS_KEY_RELEASE_SIZE, then setting CPTRA_FUSE_WR_DONE to prevent further modifications. Additionally, OCP_LOCK_MEK_LENGTH must be set to 40h. See Section 4.7.1.2.	Yes
11	Upon KMB cold reset or firmware update reset, drive firmware shall enumerate HPKE keypairs supported by KMB and advertise them to the host, if drive firmware supports a host-facing API for doing so. See Section 4.6.2.1.	Yes
12	Integrations shall invoke Caliptra resets according to the directives given in Section 4.6.8.	Yes
13	The encryption engine shall not allow user data to be encrypted with the MEK loaded by LOAD_KAT_MEK command.	Yes

4.11 Repository location

See https://github.com/chipsalliance/Caliptra/tree/main/doc/ocp_lock.

Appendix A: Preconditioned AES-Encrypt calculations

This appendix expands on Section 4.6.1.3 and provides additional details behind the claim that approximately 2^{80} preconditioned AES-Encrypt operations for a given encryption key are needed before an IV collision is expected to occur with probability greater than 2^{-32}.

To satisfy FIPS, it is sufficient to demonstrate that no single AES-GCM key will be used more than 2^{32} times. With a 96-bit salt, a given encryption key can be expanded to up to 2^{96} possible subkeys. This can be put in terms of the “Balls into bins” problem [25], where we are looking for the number of balls (m) required for the maximum load across 2^{96} bins (n) to be 2^{32}. An approximation for the maximum load where $m > n$ is given as $m/n + \sqrt{m \cdot log(n)/n}$. Rearranging to solve for m via the quadratic formula yields $m \approx 2^{128}$. Therefore, a given encryption key may be used in at most 2^{128} preconditioned AES-Encrypt operations before any subkey derived from that key is used in more than 2^{32} AES-GCM-Encrypt operations.

However, the 2^{32} encryption limit is a means to an end, namely ensuring a low probability of IV collisions. The Birthday paradox [26] implies that the probability of a collision between n generated IVs where d is the number of possible IVs is approximately $n^2/(2d)$. The chances of a 96-bit IV collision across 2^{32} IVs is therefore approximately $2^{2 \cdot 32}/2^{96+1} = 2^{-33}$ for a given subkey. If each of the 2^{96} derived subkeys might be used up to 2^{32} times, the expected number of derived subkeys that experience a collision is approximately $2^{96} \cdot 2^{-33} = 2^{63}$. Clearly a limit of 2^{128} encryption operations for a given encryption key, while meeting the letter of the FIPS requirements, is too large for safety.

We can calculate the safe margin by simply considering the 96-bit salt concatenated to the 96-bit IV. What we are really after is the maximum number of preconditioned AES-Encrypt invocations with a given encryption key such that the likelihood of experiencing a collision of the 192-bit (salt || IV) pair is at most 2^{-32}. Leveraging the Birthday paradox equation where $p(n, d) \approx n^2/(2d)$, $n \approx \sqrt{2d \cdot p} = \sqrt{2^{192+1} \cdot 2^{-32}} = 2^{80.5}$.

Therefore, a given encryption key may safely be used in at most $2^{80.5}$ preconditioned AES-Encrypt operations before an IV collision is expected to occur with probability greater than 2^{-32} across all of the AES-GCM subkeys derived from the encryption key.

Appendix B: EAT format for attesting to the epoch key state

This format is currently under public review within TCG Storage as part of the Epoch Key Purge feature set[1].

[1] https://trustedcomputinggroup.org/wp-content/uploads/TCG_Storage_Epoch_Key_Purge_Feature_v1_00_r0_32_30032026-RC1.pdf

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