Network Working Group
Internet-Draft
Intended status: Standards Track
Expires: 3 September 2026

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2 March 2026

# SAFE: Sealed, Algorithm-Flexible Envelope
draft-sullivan-safe-00

## Abstract

SAFE defines an encryption envelope that encrypts a payload once for multiple recipients. Decryption can require multiple credentials in sequence (public keys, passphrases, or other registered methods), so no single factor suffices. The format is designed for large, writable files: it supports streaming decryption, random-access reads at block granularity, and selective re-encryption of modified blocks without re-keying. Recipient privacy modes allow locks to omit identifying metadata. SAFE accommodates post-quantum key encapsulation without format changes, provides algorithm agility through IANA registries, and defines a mandatory-to-implement profile for interoperability.

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## 1. Introduction

SAFE is an encryption format for files and objects. A SAFE-encoded file contains an encrypted payload and one or more LOCK blocks. Each LOCK wraps a content encryption key (CEK) for one recipient; multiple LOCKs allow multiple recipients to decrypt the same payload without duplicating ciphertext. A LOCK can require several credentials in sequence (a passphrase AND a private key, for example), so neither factor alone suffices.

The payload is split into fixed-size blocks, each encrypted with AEAD [RFC5116] and a per-block random nonce. Blocks can be decrypted individually or streamed sequentially. An aligned binary layout (Section 6.4.2) places each ciphertext block at a predictable offset, enabling O(1) random reads. Per-block random nonces (Section 5.7.4) allow individual blocks to be re-encrypted without re-wrapping the CEK or touching other blocks.

Existing formats address subsets of these capabilities; Section 2 surveys the differences. SAFE provides algorithm agility through IANA registries (Section 9) and accommodates post-quantum key encapsulation mechanisms without format changes. Recipient privacy modes (Section 8.6) allow HPKE steps to omit key identifiers, preventing passive observers from linking files to recipients. A mandatory-to-implement profile ensures interoperability.

For example, a deployment might require that documents be decryptable only with both a passphrase AND a recipient private key. The LOCK block for such a recipient would contain two Step lines:

```
Step: pass(kdf=argon2id, salt=...)
Step: hpke(kem=p-256, id=..., kemct=...)
```

Both steps are evaluated with the known passphrase and private key to derive the key that wraps the CEK. Neither factor alone suffices. See Section 5.7.1.1 for the cryptographic details.

## 2. Comparison with Related Formats

The following table compares SAFE with existing encryption formats on the capabilities most relevant to encrypted file storage. X indicates native support, P indicates that the capability is achievable but is not a design goal of the format, and - indicates no support.

| Capability | SAFE | JWE | CMS | S/MIME | SFrame | Age | TLS | MLS | Chunked OHTTP |
|---|---|---|---|---|---|---|---|---|---|
| Large-file framing | X | P | P | P | - | X | - | - | X |
| Streaming decrypt | X | P | X | X | X | X | X | - | P |
| Random-access reads | X | - | - | - | P | - | - | - | - |
| Random-access writes | X | - | - | - | P | - | - | - | - |
| Multi-recipient (single ciphertext) | X | X | X | X | - | X | - | X | - |
| Multi-factor per recipient | X | P | P | P | - | - | - | - | - |
| Algorithm agility | X | X | X | X | X | - | X | X | P |
| Restricts insecure configurations | X | P | P | P | P | X | X | X | - |

Table 1

JWE ([RFC7516]) encrypts the entire plaintext as a single AEAD operation; its JSON Serialization wraps the content encryption key per recipient but defines no block structure for streaming or random access.

CMS ([RFC5652]) and OpenPGP ([RFC9580]) wrap a content-encryption key per recipient and support streaming, but neither defines fixed-size blocks for random access or selective rewrite. Both provide recipient-level composition (multiple recipients, each with one key), not per-recipient multi-factor.

SFrame ([RFC9605]) targets real-time media: low-latency per-frame AEAD for conferencing, not stored-object encryption.

Age [AGE] streams fixed-size chunks with counter-derived nonces and wraps keys per recipient but deliberately avoids algorithm agility (single cipher suite, no registries). Counter-based nonces prevent selective editing; modifying any block requires re-encrypting the entire payload.

TLS [RFC8446] provides streaming authenticated encryption of point-to-point channels with strong algorithm agility and mandatory cipher suites, but operates on sequential records with no random access, multi-recipient, or stored-object semantics.

MLS [RFC9420] provides group key agreement and per-message encryption for multiple recipients. Messages are individually encrypted, not stored as a single encrypted object with block-level access.

Chunked OHTTP [I-D.ietf-ohai-chunked-ohttp] splits HTTP message bodies into individually encrypted chunks for incremental processing through an oblivious relay. It targets live HTTP streaming, not stored-object encryption, and provides no random access or multi-recipient support.

SAFE's block construction builds on the STREAM [STREAM] streaming AEAD pattern (truncation detection via a last-block indicator in Section 5.7.6) and extends it with per-block random nonces (Section 5.7.4) so that individual blocks can be re-encrypted without re-wrapping the CEK.

## 3. Protocol Overview

This section summarizes the encryption and decryption procedures. Normative details appear in the referenced sections.

Given a plaintext and a set of recipients (each defined by one or more credentials), an encryptor produces a SAFE object:

1. Select AEAD, Block-Size, and Hash (or use defaults).
2. Generate a random 32-octet CEK using SafeRandom (Appendix C).
3. For each recipient, build a LOCK: generate step artifacts (salts, KEM ciphertexts), derive a KEK, and wrap the CEK.
4. Derive payload_key from CEK (Section 5.7.3).
5. Split plaintext into blocks; encrypt each with a per-block nonce.
6. Write the file: optional CONFIG, LOCK blocks, and payload.

Given a SAFE object and the appropriate credentials (private keys, passphrases, or other step inputs), a decryptor recovers the plaintext:

1. Parse CONFIG, LOCK, and DATA blocks.

2. Try each LOCK until one succeeds: evaluate its steps with the recipient's credentials to derive a KEK, then unwrap the CEK.

3. Verify the commitment prefix.

4. Derive payload_key from CEK (Section 5.7.3).

5. Decrypt requested blocks.

The CEK enables multi-recipient encryption (wrap once per recipient). The KEK binds each recipient's credentials to the CEK. The payload_key is derived from the CEK and the encryption_parameters (the AEAD, Block-Size, and Hash; Section 5.5), providing domain separation: the same CEK with different configurations produces different ciphertext.

## 4. Conventions and Notation

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

Header text is UTF-8. Base64 means [RFC4648] with padding equals signs and no line wrapping in the source value. When Base64 values appear in SAFE blocks, Encryptors SHOULD wrap lines at 64 characters; Decryptors MUST accept any line length and MUST ignore line breaks within Base64 values. Integers serialized in binary are unsigned and in network byte order. LF denotes the newline U+000A; Encryptors MUST use LF, Decryptors MUST accept LF and MAY accept CRLF.

String constants used in Encode AAD labels are ASCII and begin with SAFE- (e.g., SAFE-DATA, SAFE-STEP). LabeledDerive labels are ASCII (e.g., commit, kek); the protocol prefix SAFE-v1 is added automatically.

ABNF follows [RFC5234].

### 4.1. Notation

This document uses the following notation:

| Symbol | Meaning |
|---|---|
| \|\| | Byte string concatenation |
| XOR | Bitwise exclusive-or of equal-length octet strings |
| len(x) | Length of x in octets |
| x[i:j] | Slice of x from octet i (inclusive) to j (exclusive), zero-indexed |
| uint8(n) | 8-bit unsigned integer n (single octet) |
| I2OSP(n, w) | w-octet big-endian encoding of non-negative integer n |
| lp16(x) | I2OSP(len(x), 2) \|\| x — 2-byte length-prefixed encoding |
| Encode(x1, ..., xn) | lp16(x1) \|\| ... \|\| lp16(xn) — multi-value length-prefixed encoding |
| uint64(n) | 64-bit unsigned integer n in network byte order (big-endian) |
| floor(x) | Largest integer less than or equal to x |
| ceil(x) | Smallest integer greater than or equal to x |

Table 2

All integers serialized in binary are unsigned and use network byte order (big-endian). Multi-byte integer fields are serialized most-significant byte first.

### 4.2. Text Encoding

SAFE header lines (fence markers, field names, field values) MUST contain only ASCII printable characters (0x20-0x7E) plus LF (0x0A). Derive info strings and AEAD AAD prefixes use ASCII. Decryptors MUST reject malformed UTF-8 in text fields.

SAFE uses standard Base64 per [RFC4648] Section 4. Padding is REQUIRED. Base64 values in headers MAY wrap across lines; continuation lines MUST begin with whitespace. Decryptors MUST strip leading whitespace from continuation lines before decoding. In armored encoding, the DATA block's Base64 MAY contain line breaks; Decryptors MUST ignore them.

Encryptors MUST use LF (0x0A) line terminators. Decryptors MUST accept LF and MAY accept CRLF. Decryptors MUST strip trailing whitespace from header lines.

Case sensitivity: All field names, identifiers, and fence markers are case-sensitive.

All multi-octet integers in binary (block index, nonce construction) use network byte order (big-endian).

### 4.3. Terminology

CEK (Content-Encryption Key): A randomly generated 32-octet key used to derive the payload encryption key. The CEK is wrapped independently for each recipient.

KEK (Key-Encryption Key): A 32-octet key derived from a LOCK's step sequence. Used to wrap or unwrap the CEK.

MTI (Mandatory To Implement): In algorithm tables, "Yes" means implementations MUST support the algorithm; "No" means support is OPTIONAL.

## 5. Algorithms

### 5.1. Default Parameters

The following defaults apply whenever a CONFIG block is absent or when a field is omitted from the CONFIG block:

| Field | Default Value |
|---|---|
| AEAD | aes-256-gcm |
| Block-Size | 65536 |
| Hash | sha-256 |
| Lock-Encoding | armored |
| Data-Encoding | armored |

Table 3

Implementations MUST use these values for any omitted fields. CONFIG need only include fields that differ from the defaults; see Section 6.1.

## 5.2. Algorithm Summary Tables

This section provides a quick reference of all cryptographic algorithms and identifiers used in SAFE. Detailed specifications appear in later sections.

### 5.2.1. AEAD Algorithms

| Algorithm | Identifier | Nk | Nn | NMR | MTI |
|---|---|---|---|---|---|
| AES-256-GCM | aes-256-gcm | 32 | 12 | No | Yes |
| ChaCha20-Poly1305 | chacha20-poly1305 | 32 | 12 | No | No |
| AES-256-GCM-SIV | aes-256-gcm-siv | 32 | 12 | Yes | No |
| AEGIS-256 | aegis-256 | 32 | 32 | No | No |
| AEGIS-256X2 | aegis-256x2 | 32 | 32 | No | No |

Table 4

Nk/Nn are key/nonce sizes in octets. "NMR" indicates nonce-misuse resistance (see Section 8.9). AEADs without NMR permit plaintext recovery under nonce reuse; encryptors SHOULD select an NMR AEAD when nonce reuse cannot be ruled out. All AEADs provide [RFC5116]

semantics with 16-octet tags. All SAFE DATA payloads begin with a 32-octet commitment prefix LabeledDerive("commit", CEK, encryption_parameters, 32) that binds the ciphertext to the CEK and the negotiated algorithm parameters (see Section 8.12).

### 5.2.2. Key Encapsulation Mechanisms

| KEM | Identifier | HPKE KEM ID | Encap Size | Auth | MTI |
|---|---|---|---|---|---|
| X25519 | x25519 | 0x0020 | 32 octets | Yes | Yes |
| P-256 | p-256 | 0x0010 | 65 octets | Yes | No |
| ML-KEM-768 | ml-kem-768 | 0x0041 | 1088 octets | No | No |

Table 5

HPKE KEM IDs are defined in [RFC9180] Section 7.1 and the IANA HPKE KEM Identifiers registry.

Conforming implementations MUST support X25519. All other KEMs are OPTIONAL. ML-KEM-768 enables hybrid post-quantum constructions via multi-step step sequences (see Section 5.6.3.2).

All KEMs use HPKE [RFC9180] in export-only mode (AEAD ID 0xFFFF). The encryptor calls SetupBaseS (or SetupAuthS when sid or shint is present) to produce a KEM ciphertext and an HPKE context, then calls Export on the context to derive the step secret (Section 5.6.3.4). When a sender parameter is present, HPKE Auth mode is used (see Section 5.6.3.1). The KEM identifier appears in hpke(...) step tokens (Section 5.6.3). SAFE maintains a registry mapping string identifiers to HPKE KEM IDs (Section 9.2).

### 5.2.3. Step Types

| Step Type | Token Format | Parameters | Secret |
|---|---|---|---|
| Passphrase | pass(kdf=..., salt=...) | kdf, salt | 32 octets |
| HPKE | hpke(kem=X, kemct=..., ...) | kem, kemct, id/ hint, sid/shint | 32 octets |

Table 6

Step types are composed via multiple Step lines within a LOCK block, with AND semantics: all steps are required to derive the KEK. Each step conforms to the interface defined in Section 5.6 and produces a 32-octet secret that contributes to KEK derivation (Section 5.7.1). Additional step types MAY be registered per Section 9.4.

## 5.3. Algorithm Requirements

MTI algorithms and defaults are listed in the summary tables above. AEADs used with SAFE MUST provide [RFC5116] semantics with a 16-octet authentication tag. KEMs MUST use HPKE export-only mode (AEAD ID 0xFFFF) as specified in Section 5.6.3. When sid or shint is present, HPKE Auth mode is used (Section 5.6.3.1).

## 5.4. Hash Function and KDF

SAFE piggybacks on the HPKE KDF interface. HPKE [RFC9180] and [I-D.ietf-hpke-pq] define two KDF classes:

Two-stage KDFs (e.g., HKDF-SHA256, KDF ID 0x0001):

* KDF.Nh: output size of Extract (32 for HKDF-SHA256)

* KDF.Extract(salt, ikm) -> prk (Nh octets)

* KDF.Expand(prk, info, L) -> okm (L octets)

Single-stage KDFs (e.g., TurboSHAKE256, [I-D.ietf-hpke-pq]):

* KDF.Derive(ikm, L) -> okm (L octets). For TurboSHAKE256: TurboSHAKE256(M=ikm, D=0x1F, L).

The Hash config parameter selects both the KDF and its class. Any KDF registered for SAFE MUST be registered in the HPKE KDF Identifiers registry [RFC9180] and MUST implement either the two-stage (Extract/Expand/Nh) or single-stage (Derive) interface.

### 5.4.1. LabeledDerive

LabeledDerive binds every derivation to the protocol version and a call-site label. The ikm and info parameters accept a single octet string or a list; list elements are individually lp16-encoded by Encode().

Callers that require suite binding include encryption_parameters in the info argument. Config-independent derivations such as key identifiers (Section 5.6.3.3) omit it.

```
Two-stage (HKDF):

LabeledDerive(label, ikm, info, L):
    prk = Extract(
        "SAFE-v1",
        Encode("SAFE-v1", label, ...ikm))
    return Expand(prk,
        Encode("SAFE-v1", label, ...info,
               I2OSP(L, 2)), L)

Single-stage (XOF):

LabeledDerive(label, ikm, info, L):
    return Derive(
        Encode("SAFE-v1", label, ...ikm,
               I2OSP(L, 2), ...info), L)
```

### 5.5. Encryption Parameters

The encryption_parameters is an ordered list of the effective parameters (defaults augmented by any config overrides):

```
encryption_parameters = [aead_id, block_size, hash_id]
```

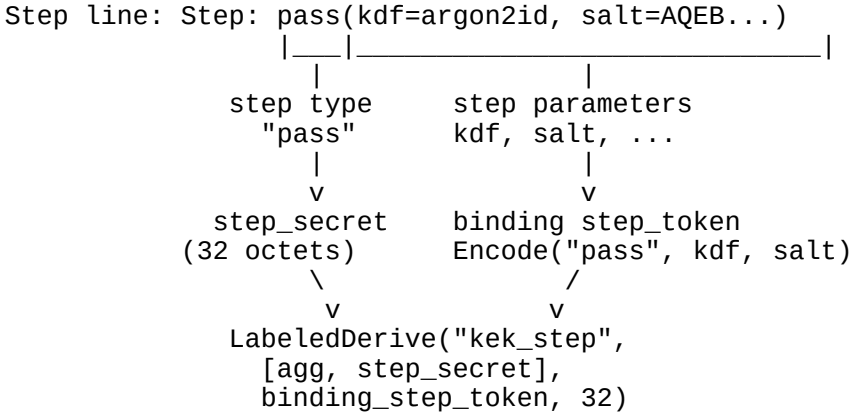
aead_id, block_size, and hash_id are the ASCII string forms of the AEAD, Block-Size, and Hash parameters respectively. LabeledDerive splices this list via ...encryption_parameters and applies lp16 framing to each element (Section 5.4.1).

AEAD identifiers MUST be lowercase ASCII and match exactly the registered values in Section 9.1. Block-Size MUST be rendered as a decimal string with no leading zeros (except for the value 0 itself). Hash identifiers MUST be lowercase ASCII and match exactly the registered values in Section 9.3.

LabeledDerive binds encryption_parameters throughout the key schedule: the KEK aggregator initialization and final derivation (Section 5.7.1), and each payload schedule call (Section 5.7.3). See Appendix I for a worked example.

### 5.6. Steps

Step terminology at a glance:




#### 5.6.1. Step Interface

A step is a registered cryptographic operation that produces a 32-octet step secret from user-supplied credentials or cryptographic material. Each step type MUST define:

Step name: A unique ASCII identifier used in step tokens (e.g., "pass", "hpke").

Parameters: An ABNF grammar for step-specific parameters appearing in the token (e.g., kem=x25519, id=...).

Derivation: A deterministic algorithm that produces exactly 32 octets. The algorithm MUST be reproducible given the same inputs. The step definition MUST specify all required inputs for both encryption and decryption.

KEK schedule integration: The step secret and binding step_token feed into the KEK schedule (Section 5.7.1) via LabeledDerive("kek_step", [agg, step_secret], step_token, 32). The step secret (ikm) enters Extract; the step token (info) enters Expand. The on-wire step token appears verbatim in the LOCK block. Each step type defines an Encode form: the canonical binary encoding of its cryptographically relevant fields via Encode() (Section 4.1). The Encode form serves as the binding step_token in the KEK schedule. Display-only fields (label, hint, shint) are excluded. The binding forms for the built-in step types are:

| Step | Binding step_token |
|---|---|
| pass | Encode("pass", kdf, salt) |
| hpke | Encode("hpke", kem, kemct, id) |
| hpke (auth) | Encode("hpke", kem, kemct, id, "auth", sid) |

Table 7

String values (kdf, kem) are UTF-8; binary values (salt, kemct, id, sid) are raw decoded octets, not Base64.

Fields computed for binding (hpke id, hpke sid, webauthn-prf rpid) may be omitted on-wire for privacy but are deterministically reconstructed during decryption and always appear in the binding form. For hpke, id is always present in the binding step_token even when omitted from the on-wire token; it is computed during trial decryption. Similarly, sid is optional on-wire but always present in auth-mode binding; when omitted, it is computed from the candidate sender public key.

Registration: New step types are registered via the IANA SAFE Step Names registry (Section 9.4) with Specification Required policy. The registration MUST include: step name, parameters grammar, inputs, derivation algorithm, Encode binding form, and any step-specific parameter definitions. See Appendix K for an example.

label (OPTIONAL, any step): A human-readable display name intended to help users identify which passphrase, credential, or key to use during decryption (e.g., "Work laptop", "Recovery key"). The label is always excluded from the binding step_token and has no cryptographic effect. Encryptors MAY include a label in any step token; Decryptors MUST ignore it for binding purposes. The label value MUST match the grammar 1*(ALPHA / DIGIT / "-").

Steps are registered in the IANA SAFE Step Names registry (Section 9.4). The following subsections define the initial registered steps.

### 5.6.2. Passphrase step

The passphrase step derives a 32-octet step secret from a user passphrase using a password-based KDF. The kdf parameter selects the algorithm:

| KDF | Algorithm | Parameters | MTI |
|---|---|---|---|
| argon2id | Argon2id [RFC9106] | m=65536 KiB, t=2, p=1 | Yes |
| pbkdf2 | PBKDF2-HMAC-SHA-256 [RFC8018] | iter=600000 | No |

Table 8

The step token format is:

```
pass(kdf=<kdf>,salt=<Base64>)
pass(kdf=<kdf>,salt=<Base64>,label=<text>)
```

The kdf parameter is REQUIRED. The label parameter is OPTIONAL and is for display only; it is not included in the binding step_token (Section 5.6). Encryptors MUST generate a fresh 16-octet salt using SafeRandom(16, "SAFE-PASS-SALT") for each pass(...) step in a LOCK. Decryptors MUST reject pass(...) steps whose salt value does not decode to exactly 16 octets.

Grammar:

```
pass-step   = "pass(" pass-params ")"
pass-params = "kdf=" kdf-name "," "salt=" salt
              [ "," "label=" label-value ]
kdf-name    = "argon2id" / "pbkdf2"
salt        = 1*BASE64CHAR
label-value = 1*( ALPHA / DIGIT / "-" )
```

Encode form:

```
Encode("pass", kdf, salt)
```

Binding step_token: Encode("pass", kdf, salt).

The step secret is computed as follows:

For kdf=argon2id: Argon2id(passphrase, salt, m=65536, t=2, p=1, T=32) per [RFC9106] Section 3.1.

For kdf=pbkdf2: PBKDF2(PRF=HMAC-SHA-256, Password=passphrase, Salt=salt, c=600000, dkLen=32).

In both cases, salt is the decoded value of the salt parameter.

Implementations SHOULD prefer argon2id for its memory-hardness properties. Implementations MAY support pbkdf2 for environments where Argon2id is not permitted by policy.

#### 5.6.3. HPKE step

The HPKE step token has three forms:

```
hpke(kem=x25519, kemct=<Base64>, id=<Base64>)    ; Identified mode
hpke(kem=x25519, kemct=<Base64>, hint=<digits>)  ; Hinted mode
hpke(kem=x25519, kemct=<Base64>)                 ; Anonymous mode
```

The parameters are:

kem (REQUIRED): The KEM algorithm. Supported values: x25519, p-256, ml-kem-768.

kemct (REQUIRED): The Base64-encoded HPKE KEM encapsulated key material (the KEM ciphertext). This value MUST decode to the encapsulated key length for the selected KEM (see Section 5.2.2).

id (OPTIONAL): The key identifier computed as LabeledDerive("SAFE-SPKI-v1", spki_der, "", 32) using the configured Hash (default: sha-256). When present, Decryptors match this value against their local keys. When omitted, Decryptors perform trial decryption. See Section 5.6.3.3 and Section 8.6.

hint (OPTIONAL): A 4-digit decimal value (0000-9999) assigned by the recipient out-of-band; not solely dependent on the public key. When present, Decryptors filter candidate keys to those associated with this hint in their local key storage. Mutually exclusive with id.

Encryptors MUST include exactly one of: id, hint, or neither (but not both id and hint).

##### 5.6.3.1. HPKE Auth Mode

In Base mode, any party who knows a recipient’s public key can create a valid SAFE object for that recipient. Auth mode [RFC9180] uses SetupAuthS/SetupAuthR, which bind the HPKE context to the sender’s private key so that the decryptor can verify who produced the object. This is useful for offline encrypted file exchange where the recipient needs assurance of origin (for example, encrypted firmware images, signed-then-encrypted document workflows, or air-gapped key escrow) without requiring a separate signature layer.

The presence of sid or shint selects HPKE Auth mode (mode_auth) instead of Base mode. Auth mode MUST only be used with DHKEM-based KEMs (x25519, p-256). Encryptors MUST NOT include sid or shint with ml-kem-768 or other non-DHKEM KEMs, because these KEMs do not define AuthEncap/AuthDecap.

sid (OPTIONAL): The sender's key identifier, computed as LabeledDerive("SAFE-SPKI-v1", spki_der, "", 32) using the same Hash as id. When present with a Base64 value, Decryptors match it against known sender public keys. The special value anon indicates anonymous sender auth mode: the sender's key is not identified, and Decryptors perform trial decryption across candidate sender keys. Mutually exclusive with shint.

shint (OPTIONAL): A 4-digit decimal value (0000-9999) assigned by the sender out-of-band; parallels hint for recipient keys. When present, Decryptors filter candidate sender keys to those associated with this value. Mutually exclusive with sid.

Encryptors MUST include exactly one of sid or shint (but not both) when using Auth mode.

Auth mode token forms extend the base forms:

```
hpke(kem=x25519, kemct=<B64>, id=<B64>, sid=<B64>)
hpke(kem=x25519, kemct=<B64>, sid=<B64>)
hpke(kem=x25519, kemct=<B64>, sid=anon)
hpke(kem=x25519, kemct=<B64>, shint=1234)
```

All combinations of recipient identification (id, hint, or anonymous) and sender identification (sid, shint, or sid=anon) are valid.

Each HPKE step uses HPKE [RFC9180] in export-only mode with ciphersuite (KEM_ID, KDF_ID, 0xFFFF) constructed from the KEM's registered identifiers (Section 5.6.3.2). AEAD ID 0xFFFF disables Seal/Open; only Export is used.

For Base mode (default):

```
;; Encryptor
(kemct, ctx) = SetupBaseS(pkR, info="")
step_secret  = ctx.Export(exporter_context, L=32)

;; Decryptor
ctx          = SetupBaseR(kemct, skR, info="")
step_secret  = ctx.Export(exporter_context, L=32)
```

For Auth mode (sid or shint present):

```
;; Encryptor
(kemct, ctx) = SetupAuthS(pkR, skS, info="")
step_secret  = ctx.Export(exporter_context, L=32)

;; Decryptor
ctx          = SetupAuthR(kemct, skR, pkS, info="")
step_secret  = ctx.Export(exporter_context, L=32)
```

The kemct value is the KEM ciphertext (enc in HPKE terminology). The exporter_context is defined in Section 5.6.3.4.

This design uses HPKE's standardized key schedule and export interface for KDF agility, while SAFE's own LabeledDerive function handles KEK aggregation, payload key derivation, and nonce constructions.

#### 5.6.3.2. Supported KEMs

The following table lists the KEMs defined in the IANA HPKE KEM Identifiers registry [RFC9180] that are recognized by SAFE:

| KEM | KEM ID | KDF ID | HPKE Ciphersuite | Key Encoding | MTI |
|---|---|---|---|---|---|
| x25519 | 0x0020 | 0x0001 | (0x0020, 0x0001, 0xFFFF) | [RFC8410] | Yes |
| p-256 | 0x0010 | 0x0001 | (0x0010, 0x0001, 0xFFFF) | [RFC5480] | No |
| ml-kem-768 | 0x0041 | (see below) | (0x0041, KDF_ID, 0xFFFF) | (see below) | No |

Table 9

The HPKE Ciphersuite column shows the (KEM_ID, KDF_ID, AEAD_ID) triple used with HPKE's Setup functions. AEAD ID 0xFFFF selects export-only mode per [RFC9180] Section 5.3.

* DHKEM-based KEMs (x25519, p-256) use HKDF-SHA256 (KDF ID 0x0001) per [RFC9180], regardless of SAFE's Hash parameter. Implementations using these KEMs require a SHA-256 implementation for HPKE operations.

* ML-KEM-768 uses the KDF selected by the Hash parameter per [I-D.ietf-hpke-pq]: HKDF-SHA256 (KDF ID 0x0001) when Hash=sha-256, TurboSHAKE256 (KDF ID 0x0013) when Hash=turboshake256. When Hash=turboshake256, the HPKE implementation MUST conform to the one-stage key schedule defined in [I-D.ietf-hpke-hpke].

ML-KEM-768 key encoding follows [I-D.ietf-lamps-kyber-certificates]. Auth mode requires AuthEncap/AuthDecap, which are defined only for DHKEM-based KEMs. ML-KEM-768 MUST NOT be used with Auth mode. Additional KEMs from the IANA HPKE KEM Identifiers registry MAY be supported following the process defined in Section 9.2.

#### 5.6.3.3. Key Identifier Computation

The id parameter in hpke(...) steps identifies the intended recipient public key. Key identifiers hash the SubjectPublicKeyInfo (SPKI) DER encoding rather than raw key bytes. This ensures key identifiers are consistent with certificate fingerprint practices and include the algorithm OID, preventing collisions between keys of different types.

```
spki_der = DER-encode SubjectPublicKeyInfo for pk
           per the KEM's registered SPKI Encoding ({{iana-kem}})
           DER encoding MUST be canonical.

id = Base64( LabeledDerive("SAFE-SPKI-v1",
    spki_der, "", 32) ) per {{RFC4648}}
```

The resulting Base64 string is the value of the id parameter (44 characters for the 32-octet output).

#### 5.6.3.4. HPKE Step Secret Derivation

When the step sequence includes one or more hpke(...) steps, the LOCK MUST include a corresponding kemct parameter value for each HPKE step, in the same order as they appear in the step sequence. Encryptors MUST generate a fresh encapsulation per LOCK; reusing a prior encapsulation is prohibited.

For Auth mode, the decryptor resolves the sender public key as follows:

* If sid is present: match against known sender public keys using the configured Hash.

* If shint is present: filter candidate sender keys by the hint value.

* If neither is present: try all locally known sender keys matching the kem type.

The step secret is derived via HPKE's Export interface:

```
exporter_context = LabeledDerive("SAFE-STEP",
    step_token, "", 32)

step_secret = ctx.Export(exporter_context, L=32)
```

where ctx is the HPKE context returned by SetupBaseS/R (or SetupAuthS/R for auth mode) as described in Section 5.6.3.2, and step_token is the binding form defined in Section 5.6.

When id or sid is omitted from the on-wire token, the decryptor reconstructs it during trial decryption per Section 5.6.

The KEM binds the shared secret to the recipient key (and for auth mode, the sender key). The exporter_context binds the step secret to the step token, preventing key-confusion attacks where an attacker substitutes one recipient's encapsulation for another's. Suite binding is not needed here because the final KEK derivation commits to encryption_parameters (Section 5.7.1).

Encode form:

```
Encode("hpke", kem, kemct, id)
Encode("hpke", kem, kemct, id,
       "auth", sid)                    ; auth
```

Binding step_token: Encode("hpke", kem, kemct, id) for base mode; Encode("hpke", kem, kemct, id, "auth", sid) for auth mode. Display-only fields (hint, shint) are not included. The id and sid fields are reconstructed per Section 5.6 when omitted on-wire.

## 5.7. Key Schedules

SAFE uses two applications of LabeledDerive (Section 5.4). The KEK derivation produces a LOCK-specific KEK from its ordered step secrets. The payload derivation produces the per-file payload key, commitment, and (for NMR AEADs) nonce base from the CEK and encryption parameters.

The following diagram shows the two independent chains:

```
   +-> KEK chain (per lock)
   |     agg = LabeledDerive("kek_init", "",
   |               encryption_parameters, 32)
   |     agg = LabeledDerive("kek_step",
   |               [agg, secret],
   |               step_token, 32)
   |     ...
   |     derived_kek = LabeledDerive("kek", agg,
   |               encryption_parameters, Nk)
   |     Encrypted-CEK = AEAD.Seal(derived_kek, nonce,
   |                               "", CEK)
   |
   +-> Payload chain (lock-independent)
         commitment  = LabeledDerive("commit",
                         CEK, encryption_parameters,
                         32)
         payload_key = LabeledDerive("payload_key",
                         CEK, encryption_parameters,
                         Nk)
         nonce_base  = LabeledDerive("nonce_base",
                         CEK, encryption_parameters,
                         Nn)
                       // only if NMR suite
```

Payload encryption is performed once under CEK and does not depend on lock structure. Locks are independent wrappers of the same CEK and can be added or removed without touching payload ciphertext.

#### 5.7.1. KEK schedule

The KEK schedule derives a KEK from an ordered sequence of step secrets using a running aggregator.

Algorithm:

```
agg = LabeledDerive("kek_init", "",
          encryption_parameters, 32)

for each (step_token_i, step_secret_i) in order:
    agg = LabeledDerive("kek_step",
              [agg, step_secret_i],
              step_token_i, 32)

derived_kek = LabeledDerive("kek", agg,
                  encryption_parameters, Nk)
```

Each step folds the aggregator and step secret into ikm (Extract) as an Encode-framed array. The step token is placed in info (Expand). Suite binding enters at kek_init and again at the final kek derivation, where encryption_parameters commits the aggregator to the negotiated AEAD, Block-Size, and Hash.

#### 5.7.1.1. Multi-Step Example

Consider a LOCK block with two steps requiring both a passphrase and a private key:

```
Step: pass(kdf=argon2id, salt=<Base64>)
Step: hpke(kem=p-256, id=<Base64>, kemct=<Base64>)
Encrypted-CEK: <Base64>
```

Evaluation proceeds per Section 5.7.1:

```
agg = LabeledDerive("kek_init", "",
          encryption_parameters, 32)

// Step 1: passphrase
step_secret_1  = Argon2id(passphrase, salt)
agg = LabeledDerive("kek_step",
          [agg, step_secret_1],
          step_token_1, 32)

// Step 2: HPKE (export-only mode)
ctx            = SetupBaseR(kemct, sk, info="")
step_secret_2  = ctx.Export(
    exporter_context =
        LabeledDerive("SAFE-STEP",
            step_token_2, "", 32),
    L = 32)
agg = LabeledDerive("kek_step",
          [agg, step_secret_2],
          step_token_2, 32)

derived_kek = LabeledDerive("kek", agg,
                  encryption_parameters, Nk)
```

The derived_kek depends on both factors. Each step is bound to its position via the aggregator chaining through ikm, preventing step reordering.

### 5.7.2. Sealing Encrypted-CEK

The per-step salt and kemct values MUST be unique per LOCK. Reusing these values with the same credentials produces the same step_secret, weakening KEK uniqueness.

With derived_kek computed per Section 5.7.1, the Encrypted-CEK field is:

```
Encrypted-CEK = lock_nonce || AEAD.Seal(
    key   = derived_kek,
    nonce = lock_nonce,
    aad   = "",
    pt    = CEK )
```

The derived_kek already depends on encryption_parameters (via kek_init and the final kek derivation) and all step_tokens (via kek_step chaining), so no additional AAD is needed.

Encryptors MUST generate lock_nonce using SafeRandom(Nn, "SAFE-LOCK-NONCE"); each LOCK requires a fresh value.

### 5.7.3. Payload schedule

The payload schedule derives the commitment, payload key, and (for NMR AEADs) nonce base from the CEK using LabeledDerive.

```
commitment  = LabeledDerive("commit", CEK,
                  encryption_parameters, 32)
payload_key = LabeledDerive("payload_key", CEK,
                  encryption_parameters, Nk)
```

For NMR AEADs (NMR=Yes in Section 5.2.1), the payload schedule also derives nonce_base:

```
nonce_base  = LabeledDerive("nonce_base", CEK,
                  encryption_parameters, Nn)
```

For non-NMR AEADs, nonce_base is not derived.

The commitment prefix is always 32 octets for all AEADs. Decryptors MUST verify the commitment before decrypting any block (see Section 8.12).

Each call independently derives from CEK with distinct labels. Using the wrong AEAD identifier or Block-Size when attempting decryption produces different LabeledDerive outputs, causing AEAD verification to fail on every block. This binding provides implicit integrity assurance that the decryptor is using the correct encryption parameters.

#### 5.7.4. Per-block Nonces

Each block is encrypted with a unique nonce. The nonce size Nn is determined by the AEAD algorithm (see Section 9.1). Encryptors MUST ensure nonce uniqueness within a CEK's lifetime.

The per-block encryption produces:

```
(ciphertext_i, tag_i) = AEAD.Seal(key   = payload_key,
                                  nonce = nonce_i,
                                  aad   = aad_i,
                                  pt    = plaintext_block_i)
```

For non-NMR AEADs, Encryptors MUST use one of the nonce constructions defined in Appendix D. Each block's nonce and tag are stored:

```
block_metadata_i = nonce_i || tag_i      (Nn + 16 octets)
```

Where nonce_i is Nn random octets and aad_i is defined below. In armored mode, blocks are stored as nonce_i || ciphertext_i || tag_i. In binary mode, the block metadata (nonce + tag) is stored separately from the ciphertext to enable single-seek block access.

For NMR AEADs, per-block nonces are derived deterministically from nonce_base (Section 5.7.3):

```
nonce_i = nonce_base XOR pad(uint64(i))
```

where pad() zero-extends uint64(i) to Nn octets (XOR applied to the last 8 octets of nonce_base). Nonces are not stored; only the authentication tag is kept:

```
block_metadata_i = tag_i                 (16 octets)
```

See Section 8.9 for security rationale.

This design enables re-encryption of the payload without re-wrapping the CEK for each recipient, and supports selective editing of individual blocks. For non-NMR AEADs, per-block random nonces allow CEK reuse across payload revisions while maintaining AEAD security.

### 5.7.5. Block Rewrite Rules

When re-encrypting a modified block, the procedure depends on the AEAD's nonce-misuse resistance property.

For non-NMR AEADs (stored nonce required):

```
Rewriting block i:
  nonce_i  = SafeRandom(Nn, "SAFE-NONCE")
  (ct, tag) = AEAD.Seal(payload_key, nonce_i,
                        data_aad(i, is_final),
                        new_plaintext)
  Update stored nonce_i and tag_i
```

For NMR AEADs (derived nonce):

```
Rewriting block i:
  nonce_i  = nonce_base XOR pad(uint64(i))
  (ct, tag) = AEAD.Seal(payload_key, nonce_i,
                        data_aad(i, is_final),
                        new_plaintext)
  Update stored tag_i only
```

NMR rewrites reuse the derived nonce for that block index. Because the AEAD is nonce-misuse resistant, this degrades to deterministic encryption: identical plaintext at the same index produces identical ciphertext, leaking equality but not content. See Section 8.9.1.

### 5.7.6. Block AAD

For block index i in the range 0 <= i < N, the associated data binds each block to its position and indicates whether it is the final block:

```
data_aad(i, is_final) = Encode("SAFE-DATA",
    I2OSP(i, 8), I2OSP(is_final, 1))
```

Where I2OSP(i, 8) is the block index in network byte order and is_final is 0x01 for the last block (index N-1) and 0x00 for all preceding blocks. Encode provides prefix-free framing via lp16 (Section 4.1). No KDF call is needed: payload_key already depends on encryption_parameters (Section 5.7.3), and the AEAD tag authenticates the AAD under that key.

The is_final flag provides truncation detection: if a decryptor decrypts block i with is_final=0 and no subsequent block exists, truncation has occurred. It also prevents extension attacks: appending blocks after a block marked is_final=1 will fail AEAD verification.

For streaming writes where the total block count is unknown, encryptors buffer the last block until more data arrives or the stream ends. All emitted blocks use is_final=0; only when the stream closes does the encryptor encrypt the final block with is_final=1.

Encryptors MUST ensure block indices remain below 2^64. Encryptors SHOULD limit i to at most 2^48 to avoid Base64 strings exceeding typical filesystem or object store limits; this is a practical recommendation, not a protocol limit. Decryptors MUST reject block indices i where i >= 2^64.

## 6. File Layout

A SAFE encoding is the concatenation of an optional config header (Section 6.1), one or more LOCK blocks (Section 6.2), and exactly one data block (Section 6.4). There is no version marker in the fences. Multiple LOCK blocks provide multi-recipient encryption; the data block is shared.

### 6.1. SAFE CONFIG

The config header may be omitted when all defaults apply. When present, it lists only non-default parameters. The config does not need to be parsed before attempting decryption if the decryptor already knows or can infer the default parameters.

The header is:

```
-----BEGIN SAFE CONFIG-----
AEAD: aes-256-gcm | chacha20-poly1305 | aegis-256 | aegis-256x2
Block-Size: 16384 | 65536
Hash: sha-256 | turboshake256
Lock-Encoding: armored | readable
Data-Encoding: armored | binary | binary-linear
-----END SAFE CONFIG-----
```

All CONFIG fields are optional. Omitted fields use default values (Section 5.1): AEAD defaults to aes-256-gcm, Block-Size to 65536, Hash to sha-256, Lock-Encoding to armored, and Data-Encoding to armored. Hash selects the hash function used throughout the protocol (Section 5.4); any identifier in the SAFE KDF Identifiers registry (Section 9.3) is valid. Lock-Encoding specifies the LOCK block

representation (Section 6.2). Data-Encoding specifies the payload format (Section 6.3): "armored" uses Base64 within DATA fence markers, "binary" uses block-aligned raw binary after the last LOCK, and "binary-linear" uses sequential raw binary after the last LOCK. The encoding fields are presentational choices that do not affect cryptographic operations. NMR AEADs (NMR=Yes in Section 5.2.1) implicitly use derived nonces: per-block nonces are computed from the key schedule and block index, and the format nonce length is 0 (nonces are not serialized). Non-NMR AEADs use stored random nonces. See Section 5.7.4 for details.

Implementations MUST support Lock-Encoding: armored and Data-Encoding: armored. Support for Lock-Encoding: readable and Data-Encoding: binary or binary-linear is OPTIONAL.

A conformant SAFE file MAY omit the SAFE CONFIG block entirely; parsers MUST treat this identically to a CONFIG block with all defaults. When CONFIG is present, it MAY contain any subset of fields. Implementations MUST construct encryption_parameters using defaults for any omitted fields.

Field names within the SAFE config are case-sensitive. Encryptors MUST NOT include duplicate field names; Decryptors MUST reject SAFE config blocks containing duplicate fields. Decryptors MUST reject SAFE config blocks containing unknown field names.

The order of fields within a CONFIG block is not significant. Encryptors MAY emit fields in any order; Decryptors MUST accept fields in any order.

All header lines MUST contain only ASCII characters (bytes 0x20-0x7E and LF). Encryptors MUST NOT include non-ASCII characters in field names or values. Decryptors MUST reject SAFE config blocks containing non-ASCII octets or malformed UTF-8 sequences.

Implementations SHOULD bound SAFE config size; Decryptors MAY reject SAFE CONFIG headers exceeding 64 KiB.

Field values MAY wrap across multiple lines using the same rules as LOCK blocks (Section 6.2.1.2): continuation lines MUST be indented with at least two spaces, and Decryptors MUST concatenate continuation lines (stripping leading whitespace) before processing.

#### 6.1.1. Block-Size Selection

SAFE defines two Block-Size values:

65536 (default): Larger chunks amortize per-chunk AEAD overhead and

reduce I/O syscalls, yielding higher throughput for sequential encrypt and decrypt. This value is appropriate when the payload will be decrypted in full or streamed sequentially.

16384: Smaller chunks reduce the cost of partial updates. Re-encrypting a modified chunk requires reading and rewriting only that chunk; at 16384 bytes the I/O cost per edit is one quarter of the default. Applications that perform random-access writes to encrypted data SHOULD use Block-Size 16384.

Both values align to hardware page boundaries. Block-Size 16384 is one page on systems with 16 KiB pages (e.g., Apple Silicon) and four pages on systems with 4 KiB pages (e.g., x86-64). Block-Size 65536 is four pages and sixteen pages, respectively. This alignment avoids page-crossing penalties with direct I/O or memory-mapped access.

The sender selects Block-Size at encryption time. The value is recorded in the SAFE config and applies to all recipients. There is no mechanism to change Block-Size after encryption without re-encrypting the entire payload.

## 6.2. SAFE LOCK

A LOCK block defines the unlock steps for a single recipient and carries the artifacts needed to recover the CEK. Each LOCK contains one or more steps and exactly one Encrypted-CEK.

Steps are evaluated in the order they appear. Step-specific inputs are carried as parameters (e.g., salt= for pass, kemct= for hpke). See Section 5.6.2 and Section 5.6.3 for step-specific requirements.

The Encrypted-CEK is the concatenation of lock_nonce and the AEAD ciphertext of the CEK under the derived KEK with empty associated data (Section 5.7.2). The lock_nonce length is the AEAD’s nonce size (Nn) as specified in Section 9.1. Encryptors MUST generate a fresh lock_nonce per LOCK using a cryptographically secure random number generator.

Decryptors MUST skip LOCK blocks containing unknown KEM identifiers or unknown step types, and attempt other LOCKs (if available).

Implementations SHOULD bound the number of LOCK blocks; Decryptors MAY reject files containing more than 1024 LOCK blocks to prevent resource exhaustion.

Two Lock-Encoding values are defined: readable (text) and armored (binary). Both produce the same binding step_tokens for the KEK schedule (Section 5.6).

#### 6.2.1. Readable Format

The readable format uses text step tokens and colon-delimited fields:

```
-----BEGIN SAFE LOCK-----
Step: pass(kdf=argon2id, salt=<Base64>)
Step: hpke(kem=x25519, id=<Base64>, kemct=<Base64>)
Encrypted-CEK: <Base64>
-----END SAFE LOCK-----
```

Field names are case-sensitive. Encryptors MUST NOT include fields other than Step and Encrypted-CEK. Encryptors MUST include at least one Step line and exactly one Encrypted-CEK line. Decryptors MUST reject LOCK blocks containing multiple Encrypted-CEK lines or unknown field names. Optional whitespace (OWS) after colons and commas is permitted for readability.

##### 6.2.1.1. Step Syntax

Each Step line declares a single cryptographic step. Multiple steps form an ordered sequence with AND semantics: all steps MUST be satisfied to derive the KEK. The syntax follows this ABNF, which applies after Decryptors perform line unfolding (concatenating continuation lines and stripping leading whitespace per Section 6.2.1.2):

```
step-line       = "Step:" OWS step-token LF
step-token      = step-name "(" step-params ")"
step-name       = 1*( ALPHA / DIGIT / "-" )
step-params     = param *( "," OWS param )
param           = param-name "=" param-value
param-name      = 1*( ALPHA / DIGIT / "-" )
param-value     = 1*PCHAR
PCHAR           = %x21-28 / %x2A-2B / %x2D-7E
                    ; VCHAR except SP, ")", ","
OWS             = *( SP / HTAB )
```

The binding step_token used in the KEK schedule (Section 5.7.1) is derived per Section 5.6: extract the binding fields and encode them with Encode().

Each Step line contains exactly one step token. LOCK blocks with multiple steps use multiple Step lines. Step-specific inputs are carried as step token parameters (e.g., salt= for pass, kemct= for hpke).

The param-value production forbids spaces (SP, 0x20) and tabs (HTAB, 0x09). Percent-encoding is not supported; all parameter values MUST be literal UTF-8 printable characters excluding whitespace.

Encryptors MUST emit parameters in the order specified by the step definition. Decryptors MUST reject step tokens containing duplicate parameter names within a single step.

See Section 5.7 for how step secrets are combined to derive the KEK. See Section 5.6.3 for the HPKE step format and Section 5.6.2 for the passphrase step format.

#### 6.2.1.2. Line Wrapping

Field values MAY wrap across multiple lines. Continuation lines MUST be indented with at least two spaces. Decryptors MUST unfold wrapped values by concatenating continuation lines and stripping leading whitespace.

* Step tokens MAY wrap at parameter boundaries (after commas). Encryptors SHOULD insert a space after the comma at each wrap point. Continuation lines use 4-space indent.

* Encrypted-CEK values use 2-space indent for continuation lines.

Encryptors SHOULD wrap lines at 64 characters. Decryptors MUST accept any line length.

A field value extends from immediately after the colon (and any following whitespace) until one of:

1. A line starting with "Step:" (unindented)

2. A line starting with "Encrypted-CEK:" (unindented)

3. A fence line "-----END SAFE LOCK-----"

Trailing whitespace on individual lines SHOULD be avoided; Decryptors MUST strip trailing spaces and tabs from each line before concatenation.

Example with wrapped HPKE step token:

```
Step: hpke(kem=ml-kem-768, hint=4217,
    kemct=bWxrZW03NjhrZW1jaXBoZXJ0ZXh0
    ZXh0cmVtZWx5bG9uZ2JhY2U2NGVuY29kZW
    RkYXRhYXBwcm94aW1hdGVseTEwODhvY3Rl
    dHNmb3JwcXNlY3VyaXR5)
```

Decryptors parse the text, extract field values, and produce the step Encode form for binding.

#### 6.2.2. Armored Format

When Lock-Encoding is armored, the SAFE LOCK block contains a single Base64 value. The value is the Base64 encoding of the Encode-serialized LOCK:

```
armored_lock = Base64(
    Encode(step_1, step_2, ..., encrypted_cek))
```

Each step_i is the binding Encode form (excluding display-only fields) as defined in the step's specification. The encrypted_cek is the raw Encrypted-CEK bytes (lock_nonce || ciphertext).

Decryptors decode the Base64, split the outer Encode into lp16-framed elements. The last element is the Encrypted-CEK; preceding elements are step tokens. Each step token is itself an Encode whose first element is the step name.

Encryptors MUST use Base64 with padding per [RFC4648]. The Base64 value MAY wrap across multiple lines; continuation lines MUST be indented with at least two spaces. Decryptors MUST concatenate continuation lines (stripping leading whitespace) before decoding.

#### 6.2.3. LOCK Selection

A decryptor determines candidate LOCK blocks without touching the SAFE data block.

##### 6.2.3.1. Candidate Selection

For each LOCK block, determine candidacy as follows:

1. Parse the Step tokens. If any token references an unsupported step type, the LOCK is not a candidate.

2. For each hpke(...) step, determine candidate keys based on mode:

   Identified (id present): Compute the key identifier for locally available public keys using LabeledDerive("SAFE-SPKI-v1", spki_der, "", 32) with the configured Hash (default: sha-256). Keys whose identifier matches the id parameter are candidates.

   Hinted (hint present): Look up keys in local storage associated with this hint value. Keys with matching hint are candidates.

Anonymous (neither id nor hint): All local keys matching the kem type are candidates.

If no local recipient keys are candidates, the LOCK is not a candidate.

For auth-mode hpke(...) steps (sid or shint present), also determine candidate sender keys:

Identified (sid with Base64 value): Keys whose identifier matches sid are candidates.

Hinted (shint present): Keys with matching shint are candidates.

Anonymous (sid=anon): All locally known sender keys matching the kem type are candidates.

If no sender keys are candidates for an auth-mode step, the LOCK is not a candidate.

3. For pass(...) steps: the LOCK is a candidate if the implementation supports passphrase entry.

4. For other registered steps: the LOCK is a candidate if the implementation supports them and local policy permits.

#### 6.2.3.2. Attempt Order

Among remaining candidates, Decryptors SHOULD attempt LOCKs in order of confidence:

1. LOCKs where all hpke steps are identified or hinted; the decryptor has confirmed it holds matching keys.

2. LOCKs with anonymous hpke steps; requires trial decryption across all keys of the matching KEM type.

3. LOCKs with pass steps; may require user interaction, so defer until key-only LOCKs are exhausted.

Encryptors MAY include multiple pass(...)-only LOCK blocks if they use different KDF variants (e.g., one pass(kdf=argon2id, ...) and one pass(kdf=pbkdf2, ...) for the same passphrase). This enables interoperability between implementations with different passphrase KDF support. Encryptors MUST NOT include duplicate pass(...)-only LOCKs with the same KDF variant. Decryptors MUST stop at the first successful CEK recovery. Decryptors MAY attempt multiple candidates in parallel.

#### 6.2.3.3. Trial Decryption

For hinted or anonymous step sequences, Decryptors iterate through candidate key combinations. For composable step sequences (multiple hpke steps with AND semantics), trial decryption MUST consider the combinatorial product of candidates for each step. For auth-mode steps, the product includes sender key candidates in addition to recipient key candidates. For each combination:

1. Establish an HPKE context for each hpke(...) step via SetupBaseR (or SetupAuthR with the candidate sender key for auth-mode steps) and call Export per Section 5.6.3.4

2. Derive the KEK by aggregating step secrets per Section 5.7.1

3. Attempt to open Encrypted-CEK with the derived KEK

A candidate succeeds when AEAD tag verification passes on Encrypted-CEK. If the KEK is wrong, the tag will not verify.

## 6.3. Data Encoding

The Data-Encoding CONFIG field specifies how the payload is represented. SAFE defines two payload layouts: linear concatenates encrypted blocks sequentially, while aligned adds padding for block-aligned random access. Three encoding values are defined:

| Value | Layout | Representation |
|---|---|---|
| armored | linear | Base64 within fence markers |
| binary | aligned | Raw binary, block-aligned |
| binary-linear | linear | Raw binary, sequential |

Table 10

The default is "armored" when Data-Encoding is omitted.

### 6.3.1. Armored Encoding

Armored encoding wraps the linear layout (Section 6.4.1) in Base64 with fence markers:

```
-----BEGIN SAFE DATA-----
<Base64: linear_payload>
-----END SAFE DATA-----
```

The Base64 string MAY be wrapped across multiple lines for readability. When wrapped, each line break MUST be a single LF character. For length calculations and random-access arithmetic, Decryptors MUST first remove all line breaks (LF and CRLF) and CR octets (0x0D), then strip trailing whitespace from the result. The normalized string length determines padding and block offset computations. Decryptors MUST ignore these characters during Base64 decoding and concatenate all lines before decoding.

Encryptors SHOULD wrap Base64 lines at 64 characters. Decryptors MUST accept any line length.

Implementations MAY enforce an upper bound on payload size to prevent over-allocation; Decryptors MAY reject payloads exceeding 64 TiB of ciphertext.

Armored data arithmetic (computing block count, byte-to-Base64 offsets, and per-block decryption) is detailed in Appendix F.

#### 6.3.2. Binary Encoding

Binary encoding omits fence markers; raw bytes follow the last -----END SAFE ...----- line (typically the final LOCK block). Binary data ends at EOF.

Two variants exist:

Data-Encoding: binary Uses the aligned layout (Section 6.4.2). Optimized for random access to large files via memory-mapped I/O or O_DIRECT.

Data-Encoding: binary-linear Uses the linear layout (Section 6.4.1). Suitable for streaming or simple implementations that do not require block-aligned random access.

Implementations that do not support binary encoding MUST fail when encountering Data-Encoding: binary or Data-Encoding: binary-linear, consistent with the handling of unknown AEAD or Hash values.

Encryptors SHOULD prefer armored encoding for maximum compatibility. Binary encoding is intended for performance-critical applications or programmatic access where human readability is not required.

### 6.4. Payload Layouts

SAFE defines two payload layouts that describe how encrypted blocks are structured.

#### 6.4.1. Linear Layout

The linear layout concatenates encrypted blocks sequentially with no padding or alignment constraints:

[commitment] [eb_0] [eb_1] [eb_2] ...

For non-NMR AEADs:

```
eb_i = nonce_i || ciphertext_i || tag_i    (Nn + len(pt_i) + 16)
```

For NMR AEADs:

```
eb_i = ciphertext_i || tag_i               (len(pt_i) + 16)
```

The commitment prefix is always present (32 octets for SHA-256).

For non-NMR AEADs, each encrypted block (eb_i) is Nn + len(plaintext_i) + 16 octets. For NMR AEADs, each encrypted block is len(plaintext_i) + 16 octets (nonces are derived, not stored).

The payload begins with a 32-octet commitment derived per Section 5.7.3. Decryptors MUST verify the commitment before decryption. See Section 8.12.

All blocks except the final block contain Block-Size octets of plaintext. The final block MAY be smaller. For non-NMR AEADs, each encrypted block consists of a nonce (Nn octets), ciphertext (same length as the plaintext), and authentication tag (16 octets). For NMR AEADs, each encrypted block consists of ciphertext and authentication tag only.

Zero-length plaintexts are allowed. A zero-length plaintext produces N = 1, L_final = 0. For non-NMR AEADs, C_final = Nn + 16 (nonce plus AEAD tag); for AEADs with Nn = 12, the minimum payload is 60 octets (32-octet commitment + 28-octet encrypted block). For NMR AEADs, C_final = 16 (AEAD tag only).

Decryptors MUST reject payloads with unexpected structure: incorrect commitment length, trailing bytes after the final block, or block boundaries that do not align with the expected sizes.

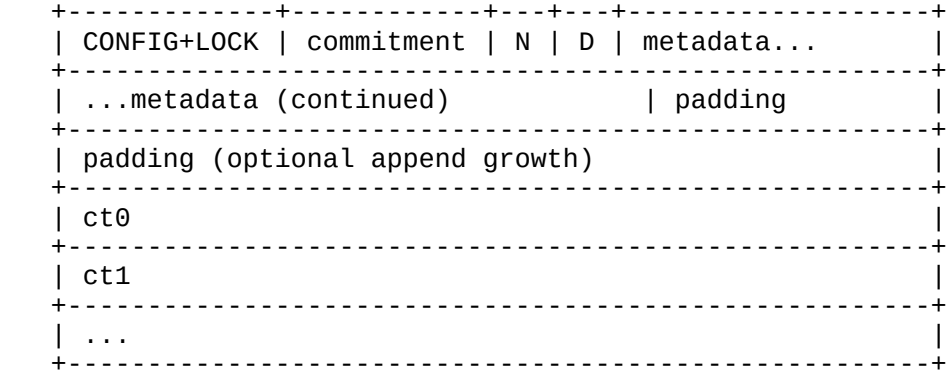
### 6.4.2. Aligned Layout

The aligned layout structures the file so that every ciphertext block begins at an offset that is an exact multiple of the Block-Size B. This alignment enables efficient memory-mapped I/O and O_DIRECT access, since the operating system can read any block without copying data across page boundaries.

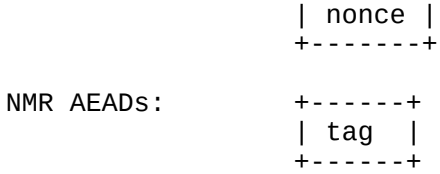
The file begins with a header section containing the text headers (CONFIG and LOCK blocks) followed by binary fields: commitment, block count N, first ciphertext index D, and per-block metadata (nonces and tags). The header is padded with zeros to a block boundary, followed by zero or more padding blocks for append growth, then ciphertext blocks.

Let B denote the Block-Size in octets (16384 or 65536). Let Nn be the nonce size (12 for AES-GCM and ChaCha20, 32 for AEGIS-256 and AEGIS-256X2). N is the block count (uint32), and D is the first ciphertext block index (uint32). Let meta_len be the per-block metadata size: Nn + 16 for non-NMR AEADs, or 16 for NMR AEADs.

Each row below represents one Block-Size:




Per-block metadata entry:




The binary portion immediately follows the text headers:

* commitment (32 bytes)

* N: block count (uint32, big-endian)

* D: first ciphertext block index (uint32, big-endian)

* metadata: N entries, each meta_len bytes

* padding to block boundary, then zero or more padding blocks

* ciphertext blocks starting at offset (D × B)

#### 6.4.2.1. Reading

To read an aligned-layout file:

1. Parse CONFIG and LOCK text to determine AEAD and Block-Size.

2. Read the 32-byte commitment, N, and D.

3. Read N metadata entries, each meta_len bytes.

4. Ciphertext block i is at offset (D + i) × B.

To read only block i: for NMR AEADs, compute nonce_i from nonce_base and the block index; for non-NMR AEADs, read the nonce from the metadata entry. Read the tag from the metadata entry in both cases. Then read B bytes (or fewer for the final block) at offset (D + i) x B.

## 7. Compatibility and Migration

### 7.1. Handling Unknown Elements

Decryptors processing SAFE-encoded data MUST:

* Fail if they encounter an unknown AEAD identifier in the SAFE config.

* Fail if they encounter an unknown Data-Encoding or Lock-Encoding value in the SAFE config.

* Reject Block-Size values other than 16384 or 65536.

* Skip LOCKs containing unknown field names, KEM identifiers, or step types and attempt other LOCKs (if available).

* Fail if a CONFIG block contains unknown field names.

* Fail if the payload has unexpected structure (wrong commitment length, trailing bytes, misaligned block boundaries).

* Skip unknown block types if the IANA SAFE Block Types registry (Section 9.6) marks them as Ignorable; otherwise fail.

### 7.2. Versioning

This document defines SAFE version 1, identified by fence markers ("-----BEGIN SAFE CONFIG-----", etc.). Future incompatible versions would use different fence markers or a new media type. New features SHOULD be added through IANA registries rather than format version changes.

### 7.3. Extension Points

SAFE provides IANA registries for AEADs (Section 9.1), KEMs (Section 9.2), step types (Section 9.4), and block types (Section 9.6).

Unknown block types are critical by default: Decryptors MUST fail if they encounter an unrecognized block. The IANA SAFE Block Types registry (Section 9.6) MAY mark specific block types as Ignorable, enabling forward-compatible optional extensions such as metadata or signatures that older implementations can safely skip.

### 7.4. Application Profiles

This section is informative. It describes three parameter combinations for common deployment scenarios. These profiles compose the CONFIG fields defined in Section 6.1; they do not introduce new protocol elements.

#### 7.4.1. Objects

Applications that prioritize text-safe output and maximum interoperability SHOULD use the default parameters (Section 5.1). No CONFIG block is required. The resulting SAFE object is entirely printable ASCII and can be embedded in email, JSON, YAML, or version-controlled files. AES-256-GCM is the mandatory-to-implement AEAD, ensuring the widest recipient support.

#### 7.4.2. Streaming

Applications that process data sequentially at high throughput SHOULD consider:

```
-----BEGIN SAFE CONFIG-----
AEAD: aegis-256
Data-Encoding: binary-linear
-----END SAFE CONFIG-----
```

AEGIS-256 offers high throughput and a 32-octet nonce that simplifies nonce management. Combined with binary-linear encoding (Section 6.4.1), this yields minimal framing overhead and sequential I/O without alignment padding. Encryptors using this profile SHOULD apply the hedged nonce construction (Appendix C.2) or plaintext-bound nonce construction (Appendix D.2) per Section 8.9.

AEGIS-256 is not mandatory-to-implement. Encryptors targeting broad interoperability SHOULD verify recipient support before selecting this profile.

#### 7.4.3. Edit

Applications that perform random-access reads and writes on encrypted data SHOULD consider:

```
-----BEGIN SAFE CONFIG-----
AEAD: aes-256-gcm-siv
Block-Size: 16384
Data-Encoding: binary
-----END SAFE CONFIG-----
```

AES-256-GCM-SIV is nonce-misuse resistant (Section 5.2.1), so per-block nonces are derived rather than stored (Section 5.7.4). This reduces per-block metadata from Nn + 16 octets to 16 octets. Block-Size 16384 aligns each block to a single page on 16 KiB-page systems, minimizing page faults per edit (Section 6.1.1). Binary aligned encoding (Section 6.4.2) enables O(1) random access to any block via memory-mapped I/O.

Re-encrypting a modified block reuses the derived nonce for that block index. Because AES-256-GCM-SIV is nonce-misuse resistant, this degrades to deterministic encryption for unchanged blocks rather than catastrophic nonce reuse (Section 8.9.1).

## 8. Security Considerations

SAFE provides:

Confidentiality: IND-CCA2 security for the payload, assuming IND-CCA2-secure AEAD.

Authentication: Each LOCK’s Encrypted-CEK is authenticated via AEAD

under derived_kek, which binds step tokens and step secrets through the KEK schedule. Block AEAD with index-bound AAD (Section 8.3) prevents reordering, modification, and splicing.

Binding: The KEK schedule binds encryption_parameters at initialization and final derivation (Section 5.7.1). Step tokens and per-step secrets are folded into the aggregator via sequential LabeledDerive chaining. Payload keys inherit suite binding from their own LabeledDerive calls (Section 5.7.3).

SAFE does NOT provide:

Encryptor authentication (Base mode): Without a sender parameter (sid or shint), any party with recipient public keys can create SAFE-encoded data. See Section 8.2 for Auth mode authentication properties.

Forward secrecy: CEK compromise exposes all recipients' copies. This is inherent to stored-object encryption, which has no interactive key exchange.

Unlinkability: Key identifiers enable linking SAFE-encoded data to the same recipient. See Section 8.6 for privacy modes.

SAFE assumes secure key storage, side-channel resistant implementations, and trusted cryptographic primitives. A functioning CSPRNG is REQUIRED. See Section 8.9 for defenses against RNG weakness or state duplication.

## 8.1. Threat Model

SAFE defends against:

Compromised storage provider (confidentiality): An adversary with read access to stored SAFE-encoded data cannot decrypt without valid credentials (passphrase or private key) for at least one LOCK. The adversary can observe approximate file size, recipient count, and key identifier linkability. SAFE does not protect against modification or deletion by an adversary with write access.

SAFE does NOT defend against:

Compromised recipient: If a recipient's credentials (passphrase or private key) are compromised, the adversary can decrypt the payload. All recipients share the same CEK; compromise of one recipient's KEK does not expose other recipients' KEKs, but does expose the shared CEK and payload.

Active attacker with key compromise: If an attacker compromises a recipient's private key and can modify files, they can create valid SAFE-encoded data for that recipient (in Base mode). Auth mode (Section 5.6.3.1) mitigates this for steps where the attacker does not also hold the sender's private key; see Section 8.2.

Side-channel attacks: SAFE assumes implementations do not intentionally leak secrets. Timing attacks on Argon2id, HPKE, or AEAD operations are out of scope for this document.

## 8.2. Sender Authentication Properties

When sid or shint is present in an hpke(...) step, SAFE uses HPKE Auth mode (mode_auth, [RFC9180]). Auth mode defends against forgery by parties who do not hold the sender's private key: a decryptor who successfully processes an auth-mode step is assured that the encapsulation was produced by a holder of skS. This closes the "encryptor authentication" gap identified above for Base mode, within the following limits:

Non-repudiation: Auth mode authenticates the sender only to the holder of the recipient's private key. The recipient cannot prove to a third party that the sender created the SAFE object. Applications requiring non-repudiation MUST use external signatures.

Sender identity confidentiality: The sid parameter (when a Base64 value) reveals the sender's key identifier to any observer. shint narrows the sender's identity. Anonymous auth mode (sid=anon) avoids explicit sender identification, at the cost of trial decryption across all candidate sender keys.

Sender key trust: SAFE does not define a trust model for sender public keys. Decryptors MUST independently verify that a sender's public key is authentic (e.g., via a certificate, TOFU, or out-of-band verification) before relying on auth-mode authentication.

## 8.3. Integrity and Authenticity

The KEK schedule binds encryption_parameters at initialization and final derivation, with step tokens and per-step secrets folded via sequential LabeledDerive chaining. The payload schedule binds payload_key to encryption_parameters independently, tying block encryption to the negotiated AEAD and Block-Size. Payload AEAD authenticates each block with index-bound AAD, preventing reordering and cross-file splicing. SAFE detects truncation and extension at block boundaries via is_final in block AAD (Section 5.7.6). Applications requiring third-party verifiability (e.g., signatures)

MUST use external signatures.

### 8.4. Implementation Considerations

The step sequence has AND semantics; security equals the weakest step. Nonces MUST be unique: fresh lock_nonce per LOCK, and fresh random nonce per block. Implementations MUST zeroize sensitive values (CEK, KEK, PRKs) immediately after use. To prevent error oracles, implementations exposing decryption to untrusted callers (e.g., network services, APIs) MUST return a single generic "decryption failed" error rather than distinguishing between wrong passphrase, wrong key, commitment mismatch, or AEAD failure. Local tools (e.g., CLI applications, test harnesses) MAY use the detailed error codes in Appendix E for diagnostics. Implementations MUST use constant-time AEAD, KEM, and KDF operations. Trial decryption loops (Section 8.6.3) MUST NOT leak timing information about which candidate key succeeded.

### 8.5. Passphrase KDF Selection

SAFE supports two passphrase KDF variants with different security properties:

pass(kdf=argon2id, ...): Memory-hard function that resists GPU and ASIC attacks. The default parameters (64 MiB memory, 2 iterations) provide strong resistance to offline attacks. Recommended for most deployments.

pass(kdf=pbkdf2, ...): Widely deployed function using PBKDF2-HMAC-SHA-256. Lacks memory-hardness, making it more vulnerable to GPU and ASIC attacks than Argon2id. The 600,000 iteration count provides equivalent CPU-based attack resistance but does not mitigate hardware-based attacks. Use only when policy prohibits memory-hard KDFs.

Encryptors targeting Decryptors with mixed policy constraints MAY include two pass(...) LOCK blocks: one with pass(kdf=argon2id, ...) and one with pass(kdf=pbkdf2, ...), using the same passphrase but fresh salts for each.

Multiple LOCK blocks allow observers to infer shared payload access. HPKE key identifiers link files to the same recipient across objects. The Base64 length reveals approximate payload size; LOCK count reveals recipient count. Applications concerned about traffic analysis SHOULD pad payloads.

### 8.6. Recipient Anonymity and Trial Decryption

SAFE supports three levels of recipient identification for hpke(...) steps:

Identified mode: The id parameter uniquely identifies the recipient's public key. Observers can link SAFE-encoded data encrypted to the same recipient.

Hinted mode: The hint parameter is a recipient-assigned value (not cryptographically derived). It filters candidates locally while revealing nothing about the key itself. Multiple keys may share the same hint.

Anonymous mode: No identifier is present. Decryptors MUST trial-decrypt against all local keys matching the kem type. Provides maximum privacy at the cost of increased decryptor computation.

#### 8.6.1. Privacy Benefits

Omitting or replacing the key identifier with a hint prevents passive observers from mapping SAFE-encoded data to specific public keys. This is valuable when file-recipient associations are sensitive metadata.

#### 8.6.2. Sender Anonymity

Auth-mode hpke(...) steps support the same three levels of sender identification via sid and shint:

Identified (sid present): The sid parameter identifies the sender's public key using the same Hash as id. Observers can link SAFE objects to the same sender across files.

Hinted (shint present): The shint parameter is a sender-assigned value that filters candidates locally. It reveals less than sid but still narrows the sender's identity.

Anonymous (neither sid nor shint): Decryptors trial-decrypt against all locally known sender keys matching the kem type. Provides sender privacy at the cost of increased trial decryption (see Section 8.6.3).

Encryptors SHOULD prefer sid unless sender privacy is required. The same trade-offs between identification, hinting, and anonymity apply to sender keys as to recipient keys.

#### 8.6.3. Trial Complexity

Anonymous mode with composable step sequences (multiple hpke steps) requires combinatorial trial decryption. For a step sequence with two anonymous hpke(...) steps, where the decryptor holds K1 keys for step 1 and K2 keys for step 2, up to K1 x K2 combinations may be attempted. Auth-mode steps add a further multiplicative factor: if an auth-mode step has no sid or shint, the decryptor MUST try all S candidate sender keys, multiplying the search space by S.

Implementations MUST set a MaxTrialAttempts limit to bound computation and MUST reject LOCK blocks that would exceed this limit.

### 8.7. Denial of Service Considerations

An attacker can craft SAFE-encoded data with many anonymous LOCK blocks to force Decryptors into expensive cryptographic operations. Implementations MUST:

* Limit the number of LOCK blocks processed per object
* Prioritize identified blocks over hinted blocks over anonymous blocks
* Abort early when resource limits are exceeded

ML-KEM decapsulation is significantly more expensive than X25519; anonymous ML-KEM steps amplify the DoS potential.

### 8.8. Hint Assignment

The hint is a 4-digit decimal value (0000-9999) assigned by the recipient; it is not solely dependent on the public key. Recipients communicate their hint to Encryptors out-of-band. Multiple keys MAY share the same hint.

Encryptors MUST NOT assume the hint uniquely identifies a key. Decryptors MAY reassign hints at any time; Encryptors SHOULD refresh hint values periodically through out-of-band communication.

Encryptors SHOULD prefer identified mode unless recipient privacy is required.

### 8.9. Nonce Generation and CEK Reuse

Encryptors SHOULD use the hedged construction (Appendix C.2) when a private key is available, the plaintext-bound nonce construction (Appendix D.2) when RNG state duplication is a concern, and an NMR AEAD (Section 5.2.1) for additional protection. The following cases describe the resulting security properties.

With private key, working RNG: Full protection. The block nonce base is derived from both fresh randomness and the hedge key. Nonces are unique across files and within files.

With private key, duplicated RNG state: Deterministic encryption per encryptor. Different encryptors (with different private keys) produce different hedge keys and therefore different CEKs and nonce bases. Within a single file, block indices guarantee nonce uniqueness. Across files from the same encryptor, the CEK and nonce base repeat, producing identical ciphertext for identical plaintext blocks at the same index. This leaks equality but not content. The plaintext-bound nonce construction (Appendix D.2) further limits exposure: nonces differ when plaintext differs, even across files.

Without private key, working RNG: Full protection. SafeRandom returns raw CSPRNG output. Nonce uniqueness depends on the RNG.

Without private key, duplicated RNG state: No defense. CEKs and nonce bases repeat across files. Within a file, block indices still provide distinct nonces. Across files, nonce reuse under distinct plaintext permits key recovery attacks against AES-GCM, ChaCha20-Poly1305, AEGIS-256, and AEGIS-256X2. AES-256-GCM-SIV limits the damage to deterministic encryption (leaks equality). The plaintext-bound nonce construction also limits nonce reuse to identical blocks at the same index.

A functioning CSPRNG is REQUIRED when no private key is available.

Encryptors operating in environments where RNG state duplication is possible (VM snapshots, process forks without reseed, container cloning) SHOULD use the plaintext-bound nonce construction (Appendix D.2). Because the plaintext-bound construction incorporates a plaintext-dependent derivation via LabeledDerive("SAFE-NONCE", plaintext_i, encryption_parameters, 32) into nonce derivation, two instances that share identical key material still produce distinct nonces whenever plaintext differs. The two-pass cost of this construction is justified by the defense it provides against state duplication.

Within a single file, block indices are bounded by the plaintext length and Block-Size. Encryptors MUST ensure block indices remain below 2^64. Practical implementations SHOULD enforce a lower bound; for example, rejecting plaintexts exceeding 2^48 blocks (approximately 4 petabytes at the default Block-Size of 65536 octets) provides a conservative margin while supporting files far larger than current storage systems.

#### 8.9.1. Derived Nonces

For NMR AEADs, per-block nonces are derived deterministically from nonce_base and the block index rather than generated randomly and stored. This is restricted to NMR AEADs for the following reasons:

Uniqueness: The LabeledDerive output is unique per CEK (each CEK produces a distinct nonce_base). XOR with distinct block indices yields distinct nonces for all i < 2^64.

Nonce reuse tolerance: Re-encrypting block i with the same CEK reuses nonce_i. NMR AEADs degrade gracefully to deterministic encryption: identical plaintext at the same index produces identical ciphertext, but no additional information is leaked. Non-NMR AEADs would suffer catastrophic nonce reuse, which is why derived nonces are not used with them.

### 8.10. Selective Editing Security

Per-block random nonces and the is_final flag enable selective editing: individual blocks can be re-encrypted without affecting other blocks or LOCK blocks. When editing:

* Generate a fresh random nonce for any re-encrypted block

* Update the is_final flag if the last block changes

* Blocks not being edited retain their original nonces and ciphertexts

The is_final flag prevents truncation and extension attacks:

* Truncation: decrypting a block with is_final=0 when no successor exists indicates malicious or accidental truncation

* Extension: appending blocks after a block with is_final=1 will fail AEAD verification because the original final block’s AAD included is_final=1

### 8.11. Key Identifier Collisions

Key identifiers are 32-octet hashes of SPKI DER encodings (Section 5.6.3.3). Both registered Hash algorithms (sha-256 and turboshake256) produce 32-octet output, giving a birthday bound on collision probability of approximately N^2 / 2^257 for a deployment with N keys. This is negligible for any practical key population.

Implementers MUST NOT rely solely on key identifier matching for authorization; successful HPKE decapsulation and AEAD verification of Encrypted-CEK are required.

### 8.12. Key Commitment

SAFE supports multiple LOCK blocks that can be added or removed independently. Without key commitment, an adversary could craft LOCK blocks that decrypt to different CEKs and exploit AEAD malleability to create payload ciphertext valid under multiple keys:

1. Creates LOCK that wraps CEK for recipient A

2. Creates LOCK that wraps CEK for recipient B

3. Crafts payload ciphertext C that decrypts to plaintext P under payload_key (derived from CEK) and to P under payload_key (derived from CEK)

None of the AEADs registered for SAFE provide key commitment from the AEAD mechanism alone at the 128-bit security level (AES-GCM and ChaCha20-Poly1305 are well-known to lack this property; AEGIS-256 with 128-bit tags provides only birthday-bound commitment at approximately 2^64).

The commitment prefix in the SAFE DATA block (Section 6.4.1) provides uniform key commitment for all AEAD choices. The commitment is always 32 octets, derived via LabeledDerive("commit", CEK, encryption_parameters, 32) per Section 5.7.3. Recipients verify that the derived commitment equals the prefix before block decryption. This binds the ciphertext to both the CEK and the negotiated algorithm parameters (via encryption_parameters in info), providing 2^128 key-commitment security and preventing cross-algorithm commitment collisions. The security relies on collision resistance of LabeledDerive: the Encode() framing ensures unambiguous parsing of all inputs, so distinct (encryption_parameters, CEK) pairs cannot produce the same commitment.

### 8.13. Algorithm Agility and Post-Quantum Support

SAFE accommodates post-quantum KEMs without format changes. ML-KEM-768 (HPKE KEM ID 0x0041) is registered and MAY be used as kem=ml-kem-768.

Hybrid post-quantum constructions require no protocol extensions. An encryptor lists both a classical and a post-quantum hpke(...) step in the same step sequence:

```
Step: hpke(kem=x25519, kemct=<Base64>, id=<classical-id>)
Step: hpke(kem=ml-kem-768, kemct=<Base64>, id=<pq-id>)
```

The KEK schedule (Section 5.7.1) folds each step's secret into the aggregator in order, so the derived KEK depends on both the X25519 and ML-KEM-768 shared secrets. An attacker must break both KEMs to recover the KEK. Because the KEK schedule folds each step secret sequentially, the derived KEK's security is additive: an attacker must break every step. Hybrid post-quantum protection follows naturally from combining classical and post-quantum steps.

The decryptor evaluates both decapsulations during CEK recovery. Each KEM ciphertext is carried in the kemct parameter of its corresponding hpke(...) step token. See Appendix A for a complete example.

Implementations planning PQ migration SHOULD ensure kemct parsing does not impose unnecessary length limits (ML-KEM-768 ciphertexts are 1088 octets).

### 8.14. Downgrade Resistance

SAFE has no algorithm negotiation: the encryptor selects encryption_parameters unilaterally, and the decryptor either accepts them or fails. An active attacker who modifies encryption_parameters (e.g., substituting a weaker AEAD) changes the derived KEK (Section 5.7.1) and payload keys (Section 5.7.3), causing CEK unwrapping or block decryption to fail. Forging a valid SAFE object with altered parameters requires the attacker to also hold valid credentials for the target LOCK.

Decryptors that operate in constrained environments MAY reject encryption_parameters containing algorithms outside a locally configured allowlist.

The symmetric components of SAFE (HPKE export-only key schedules, LabeledDerive-based KEK aggregation, commitment prefixes, and AEAD encryption) are not vulnerable to quantum attacks. Grover's

algorithm provides at most a quadratic speedup against symmetric primitives, leaving all symmetric operations at or above 128-bit security. The post-quantum migration surface is limited to KEM selection.

DHKEM-based KEMs (x25519, p-256) internally use HKDF-SHA256 regardless of the Hash parameter; this is an HPKE design property, not a SAFE limitation. A deployment using only ML-KEM-768 with Hash=turboshake256 eliminates all SHA-256 dependencies.

# 9. IANA Considerations

## 9.1. SAFE AEAD Identifiers Registry

IANA is requested to create a SAFE AEAD Identifiers registry. Registration policy is Specification Required. Designated Experts should verify that proposed AEADs provide [RFC5116] semantics with a 16-octet authentication tag, that identifiers are at most 255 octets of lowercase ASCII, and that the algorithm is appropriate for general-purpose use in encrypted data formats.

Initial entries:

| Identifier | Nk | Nn | NMR | MTI | Reference |
|---|---|---|---|---|---|
| aes-256-gcm | 32 | 12 | No | Yes | [NIST-SP-800-38D] |
| chacha20-poly1305 | 32 | 12 | No | No | [RFC8439] |
| aes-256-gcm-siv | 32 | 12 | Yes | No | [RFC8452] |
| aegis-256 | 32 | 32 | No | No | [I-D.irtf-cfrg-aegis-aead] |
| aegis-256x2 | 32 | 32 | No | No | [I-D.irtf-cfrg-aegis-aead] |

Table 11

Nk/Nn are key/nonce sizes in octets. Nn is required to compute block boundaries (Section 5.7.4). "NMR" indicates nonce-misuse resistance. Conforming implementations MUST support aes-256-gcm (MTI=Yes). All other AEADs are OPTIONAL.

### 9.2. SAFE KEM Identifiers Registry

IANA is requested to create a SAFE KEM Identifiers registry. This registry maps SAFE's string identifiers (used in kem= parameters) to HPKE KEM IDs. Registration policy is Specification Required. Designated Experts should verify that the KEM is registered in the IANA HPKE KEM Identifiers registry, is compatible with HPKE export-only mode (AEAD ID 0xFFFF) as specified in Section 5.6.3, and that a specification for SPKI encoding of public keys is provided. The Auth column indicates whether the KEM supports AuthEncap/AuthDecap for HPKE Auth mode. Encryptors MUST NOT include sid or shint with KEMs where Auth=No.

Initial entries:

| Identifier | HPKE KEM ID | Encap Size | Auth | SPKI Encoding | MTI |
|---|---|---|---|---|---|
| x25519 | 0x0020 | 32 octets | Yes | [RFC8410] | Yes |
| p-256 | 0x0010 | 65 octets | Yes | [RFC5480] | No |
| ml-kem-768 | 0x0041 | 1088 octets | No | [I-D.ietf-lamps-kyber-certificates] | No |

Table 12

HPKE KEM IDs are defined in the IANA HPKE KEM Identifiers registry established by [RFC9180]. Conforming implementations MUST support x25519 (MTI=Yes). All other KEMs are OPTIONAL.

### 9.3. SAFE KDF Identifiers Registry

IANA is requested to create a SAFE KDF Identifiers registry. Registration policy is Specification Required. Designated Experts should verify that identifiers are at most 255 octets of lowercase ASCII, that the underlying KDF provides at least 128-bit security, and that the entry references a KDF registered in the HPKE KDF Identifiers registry ([RFC9180] Section 7.2).

Each entry MUST reference a KDF registered in the HPKE KDF Identifiers registry. Two-stage KDFs provide Extract(salt, ikm), Expand(prk, info, L), and Nh. Single-stage KDFs ([I-D.ietf-hpke-pq]) provide Derive(ikm, L). The Class column determines which LabeledDerive instantiation is used (see Section 5.4).

The CONFIG field name remains "Hash" for wire compatibility.

All conforming implementations MUST implement sha-256, which is the default when Hash is omitted from the SAFE config. Implementations MAY implement turboshake256.

Initial entries:

| Identifier | HPKE KDF ID | Class | Reference |
|---|---|---|---|
| sha-256 | 0x0001 | two-stage | [RFC5869] |
| turboshake256 | TBD | single-stage | [I-D.ietf-hpke-pq] |

Table 13

## 9.4. SAFE Step Names Registry

IANA is requested to create a SAFE Step Names registry. Each registration defines a step type conforming to the interface in Section 5.6. The registry has the following columns:

Step Name: Unique ASCII identifier for the step type (e.g., "pass", "hpke").

Parameters Grammar: ABNF grammar for step-specific parameters in the token, or "None" if no parameters.

Inputs: Description of required inputs (e.g., "user passphrase, salt", "recipient private key, kemct").

Secret Length: MUST be 32 octets for all registered steps.

Reference: Document specifying the step’s derivation algorithm.

Registration policy is Specification Required. Designated Experts MUST verify:

* The derivation algorithm is deterministic and produces exactly 32 octets

* Parameter names do not conflict with existing registrations

* The specification provides complete implementation guidance including the Encode binding form

Initial entries:

| Step Name | Algorithms | Secret Length | Reference |
|---|---|---|---|
| pass | argon2id, pbkdf2 | 32 octets | Section 5.6.2 |
| hpke | (see kem values) | 32 octets | Section 5.6.3 |

Table 14

The pass step requires: user passphrase and the salt parameter from the pass(...) step token as inputs. The algorithm variant (argon2id or pbkdf2) is specified in the step token's kdf parameter. pass(kdf=argon2id, ...) is MTI; pass(kdf=pbkdf2, ...) is OPTIONAL for environments where policy prohibits Argon2id.

The hpke step requires: recipient private key, kemct, and the step token itself as inputs. When sid or shint is present, the sender's private key (for encryption) or public key (for decryption) is also required. Supported kem values are defined in Section 5.6.3.2; key identifier computation is defined in Section 5.6.3. hpke(...) without auth is MTI; hpke(...) with sid or shint is OPTIONAL and limited to DHKEM-based KEMs (x25519, p-256).

Future registrations MAY define additional step types (e.g., hardware token, OPRF) or variant algorithms for existing step names (subject to Designated Expert review for interoperability impact). A registration request MUST include:

* Step Name and Parameters Grammar (ABNF)

* Complete list of Inputs with their sources

* Derivation algorithm producing exactly 32 octets

* Definition of any step-specific parameters (name, encoding, semantics)

* Security considerations for the step type

See Appendix K for an illustrative example.

### 9.5. SAFE Config Options Registry

IANA is requested to create a SAFE Config Options registry. Each registration defines a CONFIG field name and the registry or value set that defines its legal values. The registry has the following columns:

Field Name: Case-sensitive ASCII field name used in SAFE CONFIG.

Value Definition: Registry or fixed set of values allowed for the field.

Reference: Document specifying the field and its semantics.

Registration policy is Specification Required.

Initial entries:

| Field Name | Value Definition | Reference |
|---|---|---|
| AEAD | SAFE AEAD Identifiers registry | Section 9.1 |
| Block-Size | 16384, 65536 | Section 6.1 |
| Hash | SAFE KDF Identifiers registry | Section 9.3 |
| Lock-Encoding | armored (MTI), readable (optional) | Section 6.2 |
| Data-Encoding | armored (MTI), binary, binary-linear (optional) | Section 6.3 |

Table 15

The default encoding is "armored" when the Data-Encoding field is omitted. The default Lock-Encoding is "armored" when omitted.

### 9.6. SAFE Block Types Registry

IANA is requested to create a SAFE Block Types registry. This registry lists the block types that may appear in SAFE-encoded data, identified by their fence markers. The registry has the following columns:

Block Type: The block type name as it appears in fence markers (e.g., "CONFIG", "LOCK", "DATA").

Fence Marker: The opening fence marker string (e.g., "-----BEGIN SAFE CONFIG-----").

Ignorable: "Yes" if Decryptors MAY skip unrecognized instances of this block type without failing; "No" if Decryptors MUST fail when encountering an unrecognized block of this type.

Reference: Document defining the block's semantics.

Registration policy is Specification Required. Designated Experts MUST verify:

* The block type name does not conflict with existing registrations

* The specification clearly defines the block's syntax and semantics

* Blocks marked Ignorable=Yes do not affect security or correctness if omitted

Initial entries:

| Block Type | Fence Marker | Ignorable | Reference |
|---|---|---|---|
| CONFIG | -----BEGIN SAFE CONFIG----- | No | Section 6.1 |
| LOCK | -----BEGIN SAFE LOCK----- | No | Section 6.2 |
| DATA | -----BEGIN SAFE DATA----- | No | Section 6.3.1 |

Table 16

All initial block types are critical (Ignorable=No). Future extensions MAY register new block types with Ignorable=Yes for optional features such as detached signatures, metadata, or recipient hints.

## 9.7. Media Type Registration

IANA is requested to register the following media type per [RFC6838]:

Type name: application

Subtype name: safe

Required parameters: None

Optional parameters: None

Encoding considerations: Binary or 7bit. Armored-encoded SAFE data (the default) consists of ASCII printable characters and line feeds, with Base64 encoding for payload data. Binary-encoded SAFE data have ASCII headers followed by raw binary payload data.

Security considerations: SAFE-encoded data contain encrypted content. See Section 8 of this document.

Interoperability considerations: SAFE-encoded data are ASCII-armored with PEM-style fence markers. Line wrapping of Base64 content is permitted; Decryptors MUST accept any line length.

Published specification: This document

Applications that use this media type: File encryption, secure file sharing, encrypted backups

Fragment identifier considerations: None

Additional information: Deprecated alias names for this type: None

Magic number(s): Files begin with "-----BEGIN SAFE" (ASCII)

File extension(s): .safe

Macintosh file type code(s): None

Person & email address to contact for further information: IETF CFRG WG (cfrg@ietf.org)

Intended usage: COMMON

Restrictions on usage: None

Author: See Authors' Addresses section

Change controller: IETF

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## Appendix A. Examples

This appendix is informative.

Note: The examples in this section illustrate structure and formatting only. The Base64 values are placeholders and do not represent valid cryptographic outputs. Implementers requiring test vectors with known inputs and outputs should consult the Test Vectors appendix (Appendix I).

A minimal object with readable LOCK format (Lock-Encoding set to readable; aes-256-gcm, commitment prefix):

```
-----BEGIN SAFE CONFIG-----
Lock-Encoding: readable
-----END SAFE CONFIG-----
-----BEGIN SAFE LOCK-----
Step: pass(kdf=argon2id, salt=c2FsdHZhbHVlMTIzNDU2Nzg=)
Encrypted-CEK:
  MTIzNDU2Nzg5MDEyM0FCQ0RFRkdISUpLTE1OT1BRUlNU
  VVZXWFlaYWJjZGVmZ2hpamtsbW5vcHFyc3R1dnd4eXowMTIzNA==
-----END SAFE LOCK-----
-----BEGIN SAFE DATA-----
cGxhY2Vob2xkZXJjZWtjb21taXRtZW50aGFzaDEyMzQ1Njc4YWJjZGVmZ2hpamts
bW5vcHFyc3R1dnd4eXpBQkNERUZHSElKS0xNTk9QUVJTVFVWV1hZWjAxMjM0NTY3
ODkrLz09
-----END SAFE DATA-----
```

A LOCK block encoded as armored (default Lock-Encoding):

```
-----BEGIN SAFE LOCK-----
U3RlcDpwYXNzKGtkZj1hcmdvbjJpZCxzYWx0PWMyRnNkSFpoYkhWbE1USXpORFUy
TnpnPSlFbmNyeXB0ZWQtQ0VLOk1USXpORFUyTnpnNU1ERXlNMEZDUTBSRlJrZElT
VXBMVEUxT1QxQlJVbE5VVlZaWFdGbGFZV0pqWkdWbVoyaHBhbXRzYlc1dmNIRnlj
M1IxZG5kNGVYb3dNVEl6TkE9PQ==
-----END SAFE LOCK-----
-----BEGIN SAFE DATA-----
YmFzZTY0bG9ja2V4YW1wbGVkYXRhY2h1bmtwbGFjZWhvbG
RlcmV4YW1wbGVkYXRhMTIzNDU2
-----END SAFE DATA-----
```

HPKE recipient in armored format (derived from the readable example above):

```
-----BEGIN SAFE CONFIG-----
Block-Size: 16384
-----END SAFE CONFIG-----
-----BEGIN SAFE LOCK-----
U3RlcDpocGtlKGtlbT14MjU1MTksaWQ9Wmk2bVFuWTVqOHBJWXEzbzZyV2dOdz09
LGtlbWN0PVlXSmpaR1ZtWjJocGFtdHNiVzV2Y0hGeWMzUjFkbmQ0ZVhveE1qTTBO
VFkzT0RrdylFbmNyeXB0ZWQtQ0VLOmNHRnpjM2R2Y21ReE1qTTBOVFkzT0Rrd1lX
SmpaR1ZtWjJocGFtdHNiVzV2Y0hGeWMzUjFkbmQ0ZVhveE1qTTBOVFkzT0Rrd1lX
SmpaR1ZtWjJocGFnPT0=
-----END SAFE LOCK-----
-----BEGIN SAFE DATA-----
aHBrZWV4YW1wbGVjZWtjb21taXRtZW50aGFzaHZhbHVlMTJWR2hwY3lCcGN5QmhJ
SE5oYlhCc1pTQmxibU55ZVhCMFpXUWdjR0Y1Ykc5aFpDQjNhWFJvSUcxMWJIUnBj
R3hsSUdOb2RXNXJjdz09
-----END SAFE DATA-----
```

A HPKE recipient with non-default Block-Size (AEAD omitted, uses default aes-256-gcm with commitment prefix):

```
-----BEGIN SAFE CONFIG-----
Block-Size: 16384
Lock-Encoding: readable
-----END SAFE CONFIG-----
-----BEGIN SAFE LOCK-----
Step: hpke(kem=x25519, id=Zi6mQnY5j8pIYq3o6rWgNw==,
  kemct=YWJjZGVmZ2hpamtsbW5vcHFyc3R1dnd4eXoxMjM0NTY3ODkw)
Encrypted-CEK:
  cGFzc3dvcmQxMjM0NTY3ODkwYWJjZGVmZ2hpamtsbW5vcHFy
  c3R1dnd4eXoxMjM0NTY3ODkwYWJjZGVmZ2hpag==
-----END SAFE LOCK-----
-----BEGIN SAFE DATA-----
aHBrZWV4YW1wbGVjZWtjb21taXRtZW50aGFzaHZhbHVlMTJWR2hwY3lCcGN5QmhJ
SE5oYlhCc1pTQmxibU55ZVhCMFpXUWdjR0Y1Ykc5aFpDQjNhWFJvSUcxMWJIUnBj
R3hsSUdOb2RXNXJjdz09
-----END SAFE DATA-----
```

HPKE recipient with Hash: turboshake256 (32-octet key identifier, default aes-256-gcm with commitment prefix):

```
-----BEGIN SAFE CONFIG-----
Hash: turboshake256
Lock-Encoding: readable
-----END SAFE CONFIG-----
-----BEGIN SAFE LOCK-----
Step: hpke(kem=x25519,
  id=dHVyYm9zaGFrZTI1NmV4YW1wbGVoYXNoMzJvY3RldHM=,
  kemct=dHVyYm9zaGFrZWtlbWNpcGhlcnRleHRleGFtcGxlMTIz)
Encrypted-CEK:
  dHVyYm9ub25jZTEyMzQ1Njc4OWFiY2RlZmdoaWprbG1u
  b3BxcnN0dXZ3eHl6MDEyMzQ1Njc4OTBhYmNkZWZnaGk=
-----END SAFE LOCK-----
-----BEGIN SAFE DATA-----
dHVyYm9zaGFrZWNla2NvbW1pdG1lbnRleGFtcGxlaGFzaDFSeGhiWEJzWlNCMWMy
bHVaeUJ6Y0d0cExYUjFjbUp2YzJoaGEyVXlOVFlnYTJWNUlHbGtaVzUwYVdacFpY
SWdkMmwwYUNBek1pMXZZM1JsZENBPT0=
-----END SAFE DATA-----
```

AEGIS-256 with TurboShake key identifier (commitment prefix in DATA):

```
-----BEGIN SAFE CONFIG-----
AEAD: aegis-256
Hash: turboshake256
Lock-Encoding: readable
-----END SAFE CONFIG-----
-----BEGIN SAFE LOCK-----
Step: hpke(kem=x25519,
  id=YWVnaXN0dXJib3NoYWtlaWRlbnRpZmllcjMyYnl0ZXM=,
  kemct=YWVnaXNrZW1jaXBoZXJ0ZXh0ZXhhbXBsZTEyMzQ1Njc4)
Encrypted-CEK:
  YWVnaXNub25jZTEyMzQ1Njc4OTAxMjM0NTY3ODkwMTIz
  YWJjZGVmZ2hpamtsbW5vcHFyc3R1dnd4eXowMTIzNDU2
  Nzg5MGFiY2RlZmdoaWprbG1ub3BxcnN0dXZ3eHl6
-----END SAFE LOCK-----
-----BEGIN SAFE DATA-----
YWVnaXNub2NvbW1pdG1lbnRjaHVua2NpcGhlcnRleHRvbmx5ZXhhbXBsZWRhdGE=
-----END SAFE DATA-----

Anonymous X25519 recipient (trial decryption required):

-----BEGIN SAFE CONFIG-----
Lock-Encoding: readable
-----END SAFE CONFIG-----
-----BEGIN SAFE LOCK-----
Step: hpke(kem=x25519,
  kemct=YW5vbnltb3VzZW5jYXBzdWxhdGVka2V5bWF0ZXJpYWwx
  MjM0NTY3ODkwYWJjZGVmZ2hpamtsbW5vcHFyc3R1dg==)
Encrypted-CEK:
  YW5vbnltb3VzZW5jcnlwdGVkY2VrZGF0YTEyMzQ1Njc4
  OTBhYmNkZWZnaGlqa2xtbm9wcXJzdHV2d3h5ejAxMg==
-----END SAFE LOCK-----
-----BEGIN SAFE DATA-----
YW5vbnltb3VzY2VrY29tbWl0bWVudGhhc2h2YWx1ZXBheWxvYWRjaHVua2RhdGE=
-----END SAFE DATA-----

Hinted ML-KEM-768 recipient (4-digit hint for candidate filtering):
```

```
-----BEGIN SAFE CONFIG-----
Lock-Encoding: readable
-----END SAFE CONFIG-----
-----BEGIN SAFE LOCK-----
Step: hpke(kem=ml-kem-768, hint=4217,
  kemct=bWxrZW1jaXBoZXJ0ZXh0d2l0aGhpbnRlZHJlY2lwaWVu
  dGZpbHRlcmluZ2V4YW1wbGVkYXRhMTIzNDU2Nzg5MA==)
Encrypted-CEK:
  aGludGVkZW5jcnlwdGVkY2VrZGF0YWV4YW1wbGUxMjM0
  NTY3ODkwYWJjZGVmZ2hpamtsbW5vcHFyc3R1dnd4eXo=
-----END SAFE LOCK-----
-----BEGIN SAFE DATA-----
aGludGVkY2VrY29tbWl0bWVudGhhc2h2YWx1ZXBheWxvYWRjaHVua2RhdGFoZXJl
-----END SAFE DATA-----
```

Two recipients, one passphrase-only and one HPKE (default aes-256-gcm):

```
-----BEGIN SAFE CONFIG-----
Lock-Encoding: readable
-----END SAFE CONFIG-----
-----BEGIN SAFE LOCK-----
Step: pass(kdf=argon2id, salt=cHdkc2FsdDEyMzQ1Njc4OTA=)
Encrypted-CEK:
  cHdkbm9uY2UxMjM0NTY3ODkwYWJjZGVmZ2hpamtsbW5vcHFy
  c3R1dnd4eXowMTIzNDU2Nzg5MGFiY2RlZmdoaWo=
-----END SAFE LOCK-----
-----BEGIN SAFE LOCK-----
Step: hpke(kem=p-256, id=Z1d0u6QG0cB2a4nM3Kp2Ww==,
  kemct=QUJDREVGR0hJSktMTU5PUFFSU1RVVldYWVphYmNkZWZnaGlq
  a2xtbm9wcXJzdHV2d3h5ejAxMjM0NTY3ODkwYWJjZGVmZ2hp
  amtsbW5vcHFyc3R1dnd4eXo=)
Encrypted-CEK:
  aHBrZW5vbmNlMTIzNDU2Nzg5MGFiY2RlZmdoaWprbG1ub3Bx
  cnN0dXZ3eHl6MDEyMzQ1Njc4OTBhYmNkZWZnaGlq
-----END SAFE LOCK-----
-----BEGIN SAFE DATA-----
bXVsdGlyZWNpcGllbnRjZWtjb21taXRtZW50aGFzaHZhbHVlVFhWc2RHa3RjbVZq
YVhCcFpXNTBJR1Y0WVcxd2JHVWdkMmwwYUNCemFHRnlaV1FnY0dGNWJHOWhaQ0Js
Ym1OeWVYQjBaV1FnYjI1alpRPT0=
-----END SAFE DATA-----
```

Multi-step step sequence with AND semantics (passphrase AND HPKE, chacha20-poly1305 with commitment prefix):

```
-----BEGIN SAFE CONFIG-----
AEAD: chacha20-poly1305
Block-Size: 16384
Lock-Encoding: readable
-----END SAFE CONFIG-----
-----BEGIN SAFE LOCK-----
Step: pass(kdf=argon2id, salt=bXVsdGlzdGVwc2FsdDEyMzQ=)
Step: hpke(kem=x25519, id=eEF3bXlyT3BWbXpLUjRCdz09,
  kemct=bXVsdGlzdGVwZXhhbXBsZWtlbWNpcGhlcnRleHQxMjM0NTY3)
Encrypted-CEK:
  bXVsdGlzdGVwbm9uY2UxMjM0NTY3ODkwYWJjZGVmZ2hpamts
  bW5vcHFyc3R1dnd4eXowMTIzNDU2Nzg5MGFiYw==
-----END SAFE LOCK-----
-----BEGIN SAFE DATA-----
bXVsdGlzdGVwY2VrY29tbWl0bWVudGhhc2h2YWx1ZTEyMzQ1VW1WeGRXbHlaWE1n
WW05MGFDQndZWE56ZDI5eVpDQkJUa1FnV0RJMU5URTVJSEJ5YVhaaGRHVWdhMlY1
SUhSdklHUmxZM0o1Y0hRPQ==
-----END SAFE DATA-----
```

Same multi-step example in armored format (default Lock-Encoding):

```
-----BEGIN SAFE CONFIG-----
AEAD: chacha20-poly1305
Block-Size: 16384
-----END SAFE CONFIG-----
-----BEGIN SAFE LOCK-----
U3RlcDpwYXNzKGtkZj1hcmdvbjJpZCxzYWx0PWJYVnNkR2x6ZEdWd2MyRnNkREV5
TXpRPSlTdGVwOmhwa2Uoa2VtPXgyNTUxOSxpZD1lRUYzYlhseVQzQldiWHBMVWpS
Q2R6MDksa2VtY3Q9YlhWc2RHbHpkR1Z3WlhoaGJYQnNaV3RsYldOcGNHaGxjblJs
ZUhReE1qTTBOVFkzKUVuY3J5cHRlZC1DRUs6YlhWc2RHbHpkR1Z3Ym05dVkyVXhN
ak0wTlRZM09Ea3dZV0pqWkdWbVoyaHBhbXRzYlc1dmNIRnljM1IxZG5kNGVYb3dN
VEl6TkRVMk56ZzVNR0ZpWXc9PQ==
-----END SAFE LOCK-----
-----BEGIN SAFE DATA-----
bXVsdGlzdGVwY2VrY29tbWl0bWVudGhhc2h2YWx1ZTEyMzQ1VW1WeGRXbHlaWE1n
WW05MGFDQndZWE56ZDI5eVpDQkJUa1FnV0RJMU5URTVJSEJ5YVhaaGRHVWdhMlY1
SUhSdklHUmxZM0o1Y0hRPQ==
-----END SAFE DATA-----
```

Note: The armored LOCK examples above use placeholder Base64 values. The armored payload is Base64(Encode(step_1, ..., encrypted_cek)) per Section 6.2.2.

Two-passphrase step sequence (requires both passphrases to decrypt):

```
-----BEGIN SAFE CONFIG-----
Lock-Encoding: readable
-----END SAFE CONFIG-----
-----BEGIN SAFE LOCK-----
Step: pass(kdf=argon2id, salt=Zmlyc3RwYXNzd29yZHNhbHQ=)
Step: pass(kdf=pbkdf2, salt=c2Vjb25kcGFzc3dvcmRzYWx0)
Encrypted-CEK:
  dHdvcGFzc3dvcmRub25jZTEyMzQ1Njc4OTBhYmNkZWZnaGlq
  a2xtbm9wcXJzdHV2d3h5ejAxMjM0NTY3ODkwYWI=
-----END SAFE LOCK-----
```

Hybrid post-quantum step sequence (X25519 AND ML-KEM-768, default aes-256-gcm with commitment prefix):

```
-----BEGIN SAFE CONFIG-----
Lock-Encoding: readable
-----END SAFE CONFIG-----
-----BEGIN SAFE LOCK-----
Step: hpke(kem=x25519, id=cHF6RmlucHJpbnQxMjM0NTY3,
  kemct=eDI1NTE5a2VtY2lwaGVydGV4dDEyMzQ1Njc4OTBhYmNkZWY=)
Step: hpke(kem=ml-kem-768, id=bWxrZW1maW5nZXJwcmludDEyMw==,
  kemct=bWxrZW03NjhrZW1jaXBoZXJ0ZXh0ZXh0cmVtZWx5bG9uZ2Jh
  c2U2NGVuY29kZWRkYXRhYXBwcm94aW1hdGVseTEwODhvY3Rl
  dHNmb3JwcXNlY3VyaXR5dGhpc2lzZHVtbXlkYXRhZm9yZGVt
  ...
  NzY4a2VtY2lwaGVydGV4dGVuY2Fwc3VsYXRpb25kYXRh)
Encrypted-CEK:
  aHlicmlkbm9uY2UxMjM0NTY3ODkwYWJjZGVmZ2hpamtsbW5v
  cHFyc3R1dnd4eXowMTIzNDU2Nzg5MGFiY2RlZmc=
-----END SAFE LOCK-----
-----BEGIN SAFE DATA-----
aHlicmlkcHFjZWtjb21taXRtZW50aGFzaHZhbHVlMTIzNDU2VUc5emRDMXhkV0Z1
ZEhWdElHaDVZbkpwWkNCbGVHRnRjR3hsSUdSbGJXOXVjM1J5WVhScGJtY2dZMjl0
WW1sdVpXUWdXREkxTlRFNUlHRnVaQ0JOVEMxTFJVMHQ=
-----END SAFE DATA-----
```

## Appendix B. Implementation Guide

This appendix is informative. For a concise summary of the encryptor and decryptor flows, see Section 3.

### B.1. Encryptor Processing

Encryptor processing proceeds in three phases: setup, recipient key wrapping, and content encryption.

During setup, the encryptor:

1. Selects an AEAD algorithm and Block-Size (or accepts defaults)

2. Emits a SAFE config block if using non-default values

3. Generates a random 32-octet CEK: SafeRandom(32, "SAFE-CEK")

Encryptors MUST NOT reuse a CEK across multiple files; each SAFE encoding requires a fresh CEK. Reusing a CEK weakens unlinkability: an adversary observing multiple files encrypted with the same CEK can determine they share the same content encryption key by comparing derived payload keys or nonces.

For each recipient, the encryptor wraps the CEK by:

1. Emitting Step lines with required step parameters (salt for pass steps, kemct for hpke steps)

2. Generating a fresh lock_nonce: SafeRandom(Nn, "SAFE-LOCK-NONCE")

3. Deriving step secrets and computing the KEK per Section 5.7.1

4. Emitting the Encrypted-CEK field

To encrypt content, the encryptor:

1. Derives payload_key from the CEK and encryption_parameters per Section 5.7.3

2. Splits the plaintext into Block-Size blocks (N blocks total)

3. For NMR AEADs, derives nonce_base per Section 5.7.3 and computes nonce_i = nonce_base XOR pad(uint64(i)) for each block. For non-NMR AEADs, generates per-block nonces using one of the constructions in Appendix D.

4. For each block i: a. Computes nonce_i per the chosen construction b. Determines is_final = 1 if i == N - 1, else 0 c. Constructs data_aad(i, is_final) per Section 5.7.6 d. For non-NMR AEADs: emits nonce_i || AEAD.Seal(payload_key, nonce_i, aad, block). For NMR AEADs: emits AEAD.Seal(payload_key, nonce_i, aad, block) (ciphertext and tag only; nonce is not stored).

## B.2. Decryptor Processing

Decryptor processing proceeds in three phases: configuration, CEK recovery, and content decryption.

During configuration, the decryptor reads the SAFE config (if present) to learn non-default values and constructs encryption_parameters from AEAD, Block-Size, and Hash.

To recover the CEK, the decryptor:

1. Selects a LOCK block per Section 6.2.3

2. Parses lock_nonce (first Nn octets) from the Encrypted-CEK field

3. Evaluates steps to derive the KEK per Section 5.7.1

4. Decrypts Encrypted-CEK to recover the 32-octet CEK

Decryptors MUST reject Encrypted-CEK values that do not decode to exactly Nn octets (wrap nonce) plus a ciphertext whose plaintext length is exactly 32 octets, where Nn is the AEAD nonce size from Section 9.1.

To decrypt content, the decryptor derives payload_key from the CEK and encryption_parameters per Section 5.7.3. For NMR AEADs, the decryptor also derives nonce_base and computes nonce_i = nonce_base XOR pad(uint64(i)) for each block. For non-NMR AEADs, the decryptor reads each nonce from the stored metadata. Each block is decrypted using its nonce, ciphertext, tag, and data_aad(i, is_final) per Section 5.7.6. The location of these components depends on the layout:

* Linear layout (Section 6.4.1): for non-NMR AEADs, each encrypted block contains nonce, ciphertext, and tag concatenated; for NMR AEADs, ciphertext and tag only.

* Aligned layout (Section 6.4.2): for non-NMR AEADs, nonces and tags are in the header metadata array; for NMR AEADs, only tags are stored. Ciphertext blocks are at aligned offsets.

See Appendix G for offset calculations.

# Appendix C. Random Generation

This appendix defines SafeRandom, the random generation function used for all encryptor-generated random values in SAFE.

## C.1. Base Construction

```
SafeRandom(n, label):
    return CSPRNG(n)
```

When no private key is available, SafeRandom returns raw CSPRNG output. The label parameter is reserved for use by the hedged construction (Appendix C.2).

### C.2. Hedged Construction

When a long-term private key sk is available, the encryptor SHOULD mix it into SafeRandom to defend against a weak or attacker-influenced RNG. The construction follows [RFC8937]: hedge_key is a deterministic function of sk (replacing the signature in [RFC8937] with a KDF, since SAFE does not require a signature scheme), and SafeRandom combines it with CSPRNG output via LabeledDerive.

```
hedge_key = LabeledDerive("SAFE-HEDGE", sk, "", 32)

SafeRandom(n, label):
    return LabeledDerive(label,
        [hedge_key, CSPRNG(n)], "", n)
```

An adversary who can predict CSPRNG output but does not know sk cannot predict the hedged values. Hedging does not prevent repeated output from RNG state duplication (VM snapshot restore, process fork without reseed); identical CSPRNG output produces identical hedged output regardless of the private key.

Suitable private keys include any long-term key held by the encryptor (an HPKE sender private key, an application-provided signing key, or similar). The key need not correspond to any LOCK step.

Encryptors MUST use SafeRandom for all random values generated during SAFE encoding: CEK, passphrase salt, lock_nonce, and block nonce base. HPKE internal randomness (Encap) is not hedged by default. Implementations whose HPKE library accepts an external randomness source SHOULD supply SafeRandom(Nrand, "SAFE-ENCAP") instead of raw CSPRNG output, where Nrand is the randomness length required by the KEM.

A functioning CSPRNG is REQUIRED when no private key is available. See Section 8.9 for the security analysis.

## Appendix D. Nonce Constructions

This appendix describes two nonce constructions for block encryption. Both produce Nn-octet nonces suitable for use with the configured AEAD. Decryptors read the stored nonce from each block and do not need to know which construction was used.

### D.1. Base-XOR Construction

```
base    = SafeRandom(Nn, "SAFE-NONCE")
nonce_i = base XOR uint64(i)
```

Where uint64(i) is the block index in network byte order (see Section 4.1). The XOR is applied to the last eight octets of base, with the remaining leading octets unchanged. Within a single file, the XOR with distinct block indices guarantees nonce uniqueness.

This construction is one-pass and supports parallel block encryption.

### D.2. Plaintext-Bound Construction

Encryptors SHOULD incorporate plaintext into per-block nonce derivation for SIV-like nonce-misuse resistance when RNG state duplication is a concern (e.g., VM snapshots, process forks without reseed). This requires two passes over each block (hash then encrypt).

```
nonce_i = LabeledDerive("nonce",
    [SafeRandom(Nn, "SAFE-NONCE"),
     payload_key],
    [...encryption_parameters,
     Encode("SAFE-NONCE", I2OSP(i, 8),
        LabeledDerive("SAFE-NONCE",
            plaintext_i,
            encryption_parameters, 32))],
    Nn)
```

Under RNG state duplication, this construction produces different nonces when plaintext differs, limiting exposure to leaking equality of identical blocks at the same index. The two-pass cost is the trade-off for this property.

## Appendix E. Error Codes for Testing

This appendix is informative.

For interoperability testing, implementations MAY use the following error identifiers to categorize failures:

| Error Code | Description | When to Emit |
|---|---|---|
| ERR_UNSUPPORTED_AEAD | Unknown AEAD algorithm | Parsing SAFE config |

| | | |
|---|---|---|
| ERR_UNSUPPORTED_KEM | Unknown KEM identifier | Parsing hpke(...) step |
| ERR_INVALID_BLOCK_SIZE | Invalid Block-Size value | Parsing SAFE config |
| ERR_HPKE_NO_MATCH | No matching private key | Recipient discovery |
| ERR_HPKE_DECAP_FAILED | HPKE decapsulation error | CEK recovery |
| ERR_LOCK_AEAD_FAILED | Encrypted-CEK decryption failed | CEK recovery |
| ERR_PAYLOAD_AEAD_FAILED | Block decryption failed | Content decryption |
| ERR_BLOCK_OUT_OF_RANGE | Block index invalid | Content decryption |
| ERR_MALFORMED_BASE64 | Base64 decoding error | Any Base64 field |
| ERR_DUPLICATE_FIELD | Repeated field name | Parsing SAFE config |
| ERR_DUPLICATE_PARAM | Repeated step parameter | Parsing Step lines |
| ERR_MISSING_SALT | pass(...) without salt | Parsing LOCK |
| ERR_MISSING_KEMCT | hpke(...) without kemct | Parsing LOCK |
| ERR_MULTIPLE_PASS_ONLY_LOCK | Multiple same-variant pass-only LOCKs | Discovery |
| ERR_NON_ASCII_HEADER | Non-ASCII in header | Parsing any header |
| ERR_RESOURCE_LIMIT | Size/count limit exceeded | Parsing any block |

| | | |
|---|---|---|
| ERR_INVALID_SALT_LENGTH | salt not exactly 16 octets | Parsing salt |

Table 17

## Appendix F. Armored Data Arithmetic

This appendix is informative.

In armored mode, Decryptors compute the block count N and final block size from the Base64 payload length. Let S_b64 be the payload string between the fences, len_b64 its length in characters, pad the number of trailing = signs (0, 1, or 2), and len_bin_total = 3 * floor(len_b64 / 4) - pad. The commitment prefix is always 32 octets. The encrypted block region is len_bin_ciphertext = len_bin_total - 32. Let B = Block-Size and Nn = AEAD nonce length. Define:

```
C          = Nn + B + 16
N_nonfinal = floor( len_bin_ciphertext / C )
rem        = len_bin_ciphertext - N_nonfinal * C
if rem == 0:
    N       = N_nonfinal
    C_final = C
else if rem < Nn + 16:
    reject as malformed
else:
    N       = N_nonfinal + 1
    C_final = rem
L_final  = C_final - Nn - 16
```

A decryptor decrypting block index i computes byte offsets relative to the start of the encrypted block region (after any commitment):

```
block_byte_start = i * C
block_byte_len   = C if i < N - 1 else C_final
byte_start       = 32 + block_byte_start
byte_len         = block_byte_len
char_start       = 4 * floor( byte_start / 3 )
char_end         = 4 * ceil( (byte_start + byte_len) / 3 )
```

For each block index i, the decryptor:

1. Extracts S_b64[char_start:char_end]

2. Base64-decodes to a temporary buffer tmp

3. Computes skip = byte_start mod 3

4. Selects encrypted_block = tmp[skip : skip + byte_len]

5. Parses nonce_i = encrypted_block[0:Nn] and ciphertext_i = encrypted_block[Nn:]

6. Determines is_final = 1 if i == N - 1 else 0

7. Constructs data_aad(i, is_final) per Section 5.7.6

8. AEAD-opens ciphertext_i under payload_key with nonce_i and data_aad

# Appendix G. Selective Decryption

This appendix is informative.

To decrypt block index i from a long object, a decryptor first selects a candidate LOCK per Section 6.2.3. The decryptor constructs encryption_parameters from the SAFE config or from defaults, parses lock_nonce from Encrypted-CEK, evaluates the step sequence to derive the KEK, and opens Encrypted-CEK to recover the CEK. The decryptor derives payload_key from the CEK and encryption_parameters, then locates block i in the payload. No other blocks need to be read or decoded.

For binary encoding, read N and D from the header, then compute block i's ciphertext offset as (D + i) × B. The nonce and tag are at offset header_len + 32 + 8 + i × (Nn + 16). See Section 6.4.2.

For armored encoding, the decryptor must compute the Base64 character window covering block i and decode only that window, as described below.

## G.1. Example: Armored Selective Block Decryption

Consider Block-Size=16384, Nn=12 (AES-256-GCM nonce size), and three blocks: two full blocks plus a 5000-octet final block.

```
C       = Nn + B + 16 = 12 + 16384 + 16 = 16412 octets (full block)
C_final = Nn + 5000 + 16 = 12 + 5000 + 16 = 5028 octets (final block)
total_binary = 32 + 16412 + 16412 + 5028 = 37884 octets
Base64 len   = ceil(37884 / 3) * 4 = 50512 characters
```

To decrypt block i=0, compute byte and character offsets:

```
byte_start  = 32 + (0 * C) = 32
byte_len    = C = 16412
char_start  = floor(byte_start / 3) * 4 = 40
char_end    = ceil((byte_start + byte_len) / 3) * 4 = 21928
skip        = byte_start mod 3 = 2
```

Extract S_b64[40:21928], Base64-decode, skip first 2 bytes of decoded output, then take 16412 bytes as the encrypted block. Parse the first 12 bytes as the nonce, AEAD-open the remaining bytes under payload_key with the extracted nonce and block AAD.

## Appendix H. Design Rationale

This appendix is informative.

SAFE's design choices reflect trade-offs between flexibility, performance, and simplicity. This section explains the rationale behind key architectural decisions.

### H.1. Two-Tier Key Hierarchy

SAFE separates the Content-Encryption Key (CEK) from the Key-Encryption Key (KEK) to enable multi-recipient encryption without duplicating payload ciphertexts.

#### H.1.1. Benefits

A single CEK is generated once and used to encrypt the payload; each recipient's LOCK derives a KEK that wraps the same CEK. This design offers several advantages:

1. Storage and bandwidth efficiency: Adding recipients requires only adding LOCK blocks (typically < 1 KB each), not duplicating the entire payload. For large files, this is critical.

2. Key rotation: Recipients can be added or removed by re-wrapping the CEK under new KEKs without re-encrypting the payload.

3. Operational flexibility: The CEK remains constant while KEKs rotate, simplifying key management.

#### H.1.2. Trade-offs

This design implies that all recipients share the same payload_key. Encryptors who require per-recipient payload keys (e.g., for fine-grained access control that survives CEK compromise) would need to encrypt multiple independent payloads.

If recipients directly decrypted the payload with their KEK, each recipient would require a distinct copy of the ciphertext, multiplying storage and bandwidth costs.

### H.2. Minimal Block AAD

Block associated data is defined as Encode("SAFE-DATA", I2OSP(i, 8), I2OSP(is_final, 1)), binding each block to its position and finality. Suite parameters and LOCK-specific data are excluded from block AAD.

#### H.2.1. Rationale

This choice prioritizes simplicity and O(1) random access:

1. Selective decryption: payload_key already depends on encryption_parameters, so block AAD need not repeat them. This avoids requiring every block decryption to reference the SAFE config.

2. Multi-recipient caching: Including LOCK-specific data (Step lines, kemct) would couple block decryption to a specific LOCK, preventing efficient caching of payload_key across multiple recipients.

#### H.2.2. Security Properties

Suite and LOCK binding is indirect through the key hierarchy:

* The KEK schedule binds encryption_parameters at initialization and final derivation, with all step_tokens folded between; Encrypted-CEK AEAD authenticates the CEK under this KEK.

* The payload schedule binds payload_key to encryption_parameters via LabeledDerive.

* Block AAD includes the block index and finality flag, preventing reordering, splicing, truncation, and extension within a file.

#### H.2.3. Alternative Designs Considered

An alternative design could include a "recipient_id" in block AAD, but this would require additional per-recipient metadata and complicate multi-recipient scenarios. SAFE’s choice favors performance and simplicity for the common case of single-recipient or trust-equivalent multi-recipient files, while accepting that ciphertext blocks alone do not directly identify which LOCK unlocked them.

SAFE provides built-in truncation and extension detection via the is_final flag in block AAD (Section 5.7.6). The final block is marked with is_final=1; all preceding blocks use is_final=0. This design, inspired by the STREAM construction [STREAM], enables:

* Truncation detection: a block with is_final=0 and no successor indicates truncation

* Extension prevention: appending after is_final=1 fails AEAD verification

* Streaming writes: encryptors buffer the last block until the stream closes, then encrypt it with is_final=1

Per-block random nonces (Section 5.7.4) enable selective editing: individual blocks can be re-encrypted without affecting LOCK blocks or other blocks. This design trades a small storage overhead (Nn bytes per block) for flexibility in payload modification.

## Appendix I. Test Vectors

This appendix provides a complete known-answer test for a passphrase-based SAFE encoding using default parameters (aes-256-gcm, Block-Size=65536, Hash=sha-256, Data-Encoding=armored). All values are hex unless noted.

```
## Inputs
Passphrase:  "correct horse battery staple" (UTF-8, 28 octets)
Salt:        01010101010101010101010101010101
CEK:         aaaaaaaa...aa (32 octets of 0xAA)
lock_nonce:  020202020202020202020202
Plaintext:   "Hello, SAFE!" (12 octets)

## encryption_parameters
encryption_parameters = ["aes-256-gcm", "65536", "sha-256"]

## KEK Schedule
step_token:       000470617373000861726 76f6e326964
                  001001010101010101010101010101010101
    Encode("pass", "argon2id", salt)
step_secret:      7d3491ac8af1b54526792869b7257f5dbf7cc3c20929417bb193e396c51d7965
agg_init:         1b257512ce57328cbb04bbf80b4b3aa220d875832c8439c0cdda85e1e4f8428b
    LabeledDerive("kek_init", "",
    encryption_parameters, 32)
agg_step:         596a483b938ad11da3369007f1b7f073502101879eb257f0f4b22c0758fdee21
    LabeledDerive("kek_step",
    [agg, secret], token, 32)
derived_kek:      bfedcafd41d9da3c1c77f73358b973a4ececfbc212ae558eed0dfba709cdc24e
```

```
    LabeledDerive("kek", agg,
    encryption_parameters, 32)

## Encrypted-CEK
aad:              "" (empty)
Encrypted-CEK:    02020202020202020202020352cbe85
                  a8e4434e5cd98d6507c80759dfe41fbe
                  13a649df57a9f7f46d1a7f90c60e1531
                  92ecb8c83a649656a6785487

## Payload Schedule
commitment:       4a3a59d10a797e3fd0ea54ab2ca4e9b6d2ba6116475981fc2b7c1ec88c8bfacc
    LabeledDerive("commit", CEK,
    encryption_parameters, 32)
payload_key:      3888f12793448b662f9b2b85c5e3e9f9256d08cc6cbe29699038808accd2aa7a
    LabeledDerive("payload_key", CEK,
    encryption_parameters, 32)

## Block Encryption (block 0, is_final=1)
raw_random:       030303030303030303030303
uint64(0):        0000000000000000
nonce0:           030303030303030303030303 (= raw_random XOR 0)
data_aad:         0009534146452d444154410008000000000000000000000101
    Encode("SAFE-DATA",
    I2OSP(0, 8), I2OSP(1, 1))
ciphertext+tag:   c6d28185d04caa07e012e4dd30e6be6337c9e04493504427888ee386
encrypted_block:  030303030303030303030303c6d28185
                  d04caa07e012e4dd30e6be6337c9e044
                  93504427888ee386

## Complete SAFE Object
SAFE DATA = commitment (32) + encrypted_block (40)
= 72 octets, 96 Base64 chars.

   Readable format: ~~~~ -----BEGIN SAFE CONFIG----- Lock-Encoding:
   readable -----END SAFE CONFIG----- -----BEGIN SAFE LOCK----- Step:
   pass(kdf=argon2id, salt=AQEBAQEBAQEBAQEBAQEBAQ==) Encrypted-CEK:
   AgICAgICAgICAgICNSy+hajkQ05c2Y1lB8gHWd/kH74TpknfV6n39G0af5DGDhUx
   kuy4yDpkllameFSH -----END SAFE LOCK----- -----BEGIN SAFE DATA-----
   SjpZ0Qp5fj/Q6lSrLKTpttK6YRZHWYH8K3weyIyL+swDAwMDAwMDAwMDAwPG0oGF
   0EyqB+AS5N0w5r5jN8ngRJNQRCeIjuOG -----END SAFE DATA----- ~~~~
```

Same object in armored format (default Lock-Encoding). The armored LOCK body is Base64(Encode(step, ecek)) per Section 6.2.2:

```
-----BEGIN SAFE LOCK-----
ACIABHBhc3MACGFyZ29uMmlkABABAQEBAQEBAQEBAQEBADwCAgICAgICAgIC
AgI1LL6FqORDTlzZjWUHyAdZ3+QfvhOmSd9Xqff0bRp/kMYOFTGS7LjIOmSWVqZ4
VIc=
-----END SAFE LOCK-----
-----BEGIN SAFE DATA-----
SjpZ0Qp5fj/Q6lSrLKTpttK6YRZHWYH8K3weyIyL+swDAwMDAwMDAwMDAwPG0oGF
0EyqB+AS5N0w5r5jN8ngRJNQRCeIjuOG
-----END SAFE DATA-----
```

## Appendix J. LabeledDerive Test Vectors

This appendix is informative. These vectors validate the LabeledDerive function in isolation, independent of the SAFE protocol. Inputs are deliberately short for readability. See Section 5.4.1 for the definition.

Common inputs for all vectors:

```
label:  "SAFE-TEST" (9 octets, hex: 534146452d54455354)
ikm:    0a0b0c0d0e0f (6 octets)
info:   "" (0 octets)
```

### J.1. Hash=sha-256, L=32

```
Extract salt = "SAFE-v1":
  534146452d7631

Extract ikm = Encode("SAFE-v1",
    label, ...ikm):
  0007534146452d763100095341464 52d5445535400060a0b0c0d0e0f

prk = Extract(salt, ikm):
  983d59830192955caf33fff4056ed415e2cd1cef7fe3072e075cf90903c97146

Expand info = Encode("SAFE-v1",
    label, ...info,
    I2OSP(32, 2)):
  0007534146452d763100095341464 52d54455354000000020020

output = Expand(prk, info, 32):
  d7413c70bb7bde999f5e543c0796d63a0af6839ebbe5203cc526776b978ba147
```

### J.2. Hash=sha-256, L=16

```
output = LabeledDerive(label, ikm, info, 16):
  e190628e91995808047c49a7269b9d3b
```

### J.3. Hash=turboshake256, L=32

```
Derive(Encode("SAFE-v1",
              label, ...ikm,
              I2OSP(32, 2), ...info), 32):
  input:  0007534146452d763100095341464 52d5445535400060a0b0c0d0e0f00020020
          0000
  output: 0394158419b3a24cb4f29376ada39b833f100a1825bfac7bc64f4f2ca9ff8a50
```

### J.4. Hash=turboshake256, L=16

```
   output = LabeledDerive(label, ikm, info, 16):
     f1c0c2cd38c6b0cbd0fa6a986b12c82d
```

## Appendix K. Defining New Step Types

This appendix is informative.

New step types can be defined and registered to extend SAFE with additional authentication mechanisms. This section illustrates the process using three hypothetical steps: two PPKDF steps for token-gated key derivation (Appendix K.1), and a WebAuthn PRF step for hardware token authentication.

### K.1. Example: Privacy Pass Steps

Privacy Pass [RFC9578] type 0x0001 tokens use a VOPRF [RFC9497]. The client constructs a TokenInput containing a nonce, blinds it, and sends the blinded element to the issuer. The issuer evaluates its PRF on the blinded element and returns the result. The client unblinds to obtain the authenticator, which is a deterministic function of the TokenInput and the issuer’s secret key.

In normal issuance the nonce is random, making each token unique. PPKDF sets the nonce to a deterministic value derived from the SAFE context, so the authenticator is reproducible and serves as step key material. The issuer’s behavior is unchanged and cannot distinguish a PPKDF request from normal token issuance.

Two step types use this mechanism:

* ppkdf: token-gated key derivation with application-supplied context.

* ppkdf-pass: token-gated key derivation with password-derived context for online throttling.

### K.1.1. Shared Parameters

issuer (REQUIRED): Server name (host or host:port) of the Privacy Pass token issuer. The issuer holds the VOPRF key pair; its public key pkI MUST be known to the client.

salt (REQUIRED): Base64-encoded salt. MUST decode to exactly 32 octets. Generated at encryption time using SafeRandom.

The binding step_token uses the Encode form (Section 5.6):

* ppkdf: Encode("ppkdf", issuer, salt)

* ppkdf-pass: Encode("ppkdf-pass", issuer, kdf, salt)

where issuer and kdf are UTF-8 strings and salt is the raw decoded 32 octets.

### K.1.2. ppkdf Step

The ppkdf step provides token-gated key derivation with application-supplied context.

Token form:

ppkdf(issuer=tokens.example.com,salt=<Base64>)

Grammar:

```
ppkdf-step    = "ppkdf(" ppkdf-params ")"
ppkdf-params  = "issuer=" pp-host "," "salt=" salt
pp-host       = host [ ":" port ]
host          = 1*( ALPHA / DIGIT / "-" / "." )
port          = 1*DIGIT
salt          = 1*BASE64CHAR    ; 44 chars = 32 octets
```

Derivation:

Decode salt to salt_bytes (32 octets). Compute a deterministic nonce for the TokenInput:

```
nonce = LabeledDerive("SAFE-PPKDF",
    "", [...encryption_parameters,
         binding_step_token, salt_bytes], 32)
```

where binding_step_token is the Encode-based binding form defined in Section 5.6. Construct a type 0x0001 TokenInput ([RFC9578], Section 5.1) with nonce as above. Set challenge_digest to

LabeledDerive("SAFE-PPKDF", TokenChallenge, encryption_parameters, 32), using a TokenChallenge with issuer_name = issuer and empty redemption_context and origin_info.

Blind the TokenInput and send in a standard type 0x0001 TokenRequest. The issuer evaluates the VOPRF and returns a TokenResponse. Verify the VOPRF proof and unblind to obtain the authenticator (32 octets). Set step_secret = authenticator.

#### K.1.3. ppkdf-pass Step

The ppkdf-pass step adds password-derived input. Each password guess requires a VOPRF evaluation from the issuer.

Token form:

ppkdf-pass(issuer=tokens.example.com,kdf=argon2id,salt=<Base64>)

Grammar:

```
ppkdf-pass-step  = "ppkdf-pass(" ppkdf-pass-params ")"
ppkdf-pass-params = "issuer=" pp-host ","
                    "kdf=" kdf-name "," "salt=" salt
kdf-name          = "argon2id" / "pbkdf2"
```

The kdf parameter selects the password KDF using the same algorithms and default parameters as the pass() step (Section 5.6.2).

Derivation:

Decode salt to salt_bytes (32 octets). Derive pw32 from the user's password using the KDF indicated by the kdf parameter, with salt_bytes as salt input and the default parameters defined in Section 5.6.2. Compute the deterministic nonce:

```
nonce = LabeledDerive("SAFE-PPKDF-PASS",
    pw32, [...encryption_parameters,
           binding_step_token], 32)
```

Execute the PPKDF protocol as in the ppkdf step using this nonce. Set step_secret = authenticator.

#### K.1.4. IANA Registry Entries

A registration for these steps would include:

| Step Name | Parameters | Inputs | Secret | Ref |
|---|---|---|---|---|
| ppkdf | issuer=X, salt=X | PPKDF token | 32 octets | (this doc) |
| ppkdf-pass | issuer=X, kdf=X, salt=X | PPKDF token, password | 32 octets | (this doc) |

Table 18

### K.1.5. Security Considerations for Privacy Pass Steps

For ppkdf:

The issuer sees only the blinded_element. It cannot learn context, step_secret, or anything about the SAFE file. The VOPRF proof lets the client detect the wrong issuer key. Compromise of skI enables offline computation of step_secret for any context, breaking the online-gating property.

For ppkdf-pass:

Each password guess requires a VOPRF evaluation; issuer rate limits control guessing frequency. The issuer never sees the password-derived context. Compromise of skI still requires inverting the memory-hard KDF to recover the password.

Example LOCK block:

```
-----BEGIN SAFE CONFIG-----
Lock-Encoding: readable
-----END SAFE CONFIG-----
-----BEGIN SAFE LOCK-----
Step: ppkdf(issuer=tokens.example.com,salt=<Base64>)
Encrypted-CEK:
  Base64-encoded encrypted CEK
-----END SAFE LOCK-----
```

## K.2. Example: WebAuthn PRF Step

A WebAuthn-based step would allow hardware token authentication using the PRF extension defined in Web Authentication Level 3 [W3C.webauthn-3]. Unlike WebAuthn assertions (signatures), the PRF extension provides deterministic output suitable for SAFE's step model.

### K.2.1. Step Definition

Step name: webauthn-prf

The webauthn-prf step token has three forms:

```
webauthn-prf(rpid=example.com,salt=xyz...)           ; Identified RP
webauthn-prf(salt=xyz...)                            ; Anonymous RP
webauthn-prf(rpid=example.com,salt=xyz...,label=YubiKey) ; With label
```

The parameters are:

rpid (OPTIONAL): The WebAuthn relying party identifier. When present, the Decryptor uses this rpId for the WebAuthn ceremony. When omitted, selects anonymous RP mode.

salt (REQUIRED): The Base64-encoded PRF salt. MUST decode to exactly 32 octets. Generated at encryption time using SafeRandom.

label (OPTIONAL): A human-readable display name for this credential (e.g., "YubiKey", "Phone"). Not included in the binding step_token; see Section 5.6.

Credential selection is delegated to the authenticator via WebAuthn's allowCredentials mechanism. The Decryptor passes all candidate credential IDs for the rpId; the authenticator selects the matching credential internally.

Grammar:

```
webauthn-prf-step = "webauthn-prf(" webauthn-params ")"
webauthn-params   = [ "rpid=" rpid "," ] "salt=" salt
                    [ "," "label=" label-value ]
rpid              = 1*( ALPHA / DIGIT / "-" / "." )
salt              = 1*BASE64CHAR    ; 44 chars = 32 octets
label-value       = 1*( ALPHA / DIGIT / "-" )
```

Anonymous RP mode: When rpid is omitted from the token, the Decryptor tries each rpId for which it holds credentials. Each rpId requires a separate WebAuthn ceremony (and potentially a user prompt). Privacy benefit: hides the relying party from passive observers. Cost: one ceremony per candidate rpId.

Derivation: The authenticator evaluates the PRF extension with the selected credential and the decoded salt:

```
      prf_salt = decode(salt)      ; 32 octets

      prf_output = WebAuthn_PRF(credential, prf_salt)

      step_secret = LabeledDerive(
          "webauthn-prf", prf_output,
          encryption_parameters, 32)
```

Inputs: credential (local, selected by authenticator for the rpId), prf_salt (from token).

Encode form: Encode("webauthn-prf", rpid, salt). rpid is UTF-8; salt is the raw decoded 32 octets. rpid is always present in the binding form even when omitted on-wire; when omitted, the Encryptor or Decryptor uses the rpId from the WebAuthn ceremony. Label is not included in binding.

Validation: salt MUST decode to exactly 32 octets. rpid, when present, MUST match the hostname grammar 1*(ALPHA / DIGIT / "-" / ".").

Example LOCK:

```
-----BEGIN SAFE CONFIG-----
Lock-Encoding: readable
-----END SAFE CONFIG-----
-----BEGIN SAFE LOCK-----
Step: webauthn-prf(rpid=example.com,salt=xyz...)
Encrypted-CEK:
  Base64-encoded encrypted CEK
-----END SAFE LOCK-----
```

#### K.2.2. IANA Registry Entry

| Step Name | Parameters | Inputs | Secret | Ref |
|---|---|---|---|---|
| webauthn-prf | rpid=X, salt=X | Credential, rpId | 32 octets | (this doc) |

Table 19

#### K.2.3. Security Considerations for WebAuthn PRF Step

The WebAuthn PRF step provides hardware-bound key material (the authenticator holds the secret), user presence verification (touch required), phishing resistance (rpid binding), and offline decryption capability once the PRF output is computed.

The PRF extension requires WebAuthn Level 3 support in the browser. Non-discoverable credentials wrap key material in the credential ID; losing the credential ID means losing access to the encrypted file. Unlike the Privacy Pass steps, no server-side rate limiting is possible.

Privacy: rpid in cleartext reveals the relying party to passive observers. Anonymous RP mode (rpid omitted) hides this but the rpId may still be guessable from context.

Trial bounds: anonymous RP mode requires one WebAuthn ceremony per candidate rpId. Decryptors SHOULD impose a local bound on the number of rpIds to try. Prefer identified mode when privacy is not required.

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