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M. Ounsworth
J. Gray
Entrust
M. Pala
OpenCA Labs
J. Klaussner
Bundesdruckerei GmbH
S. Fluhrer
Cisco Systems

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Composite ML-KEM for use in X.509 Public Key Infrastructure
draft-ietf-lamps-pq-composite-kem-08

Abstract

This document defines combinations of ML-KEM [FIPS.203] in hybrid with traditional algorithms RSA-OAEP, ECDH, X25519, and X448. These combinations are tailored to meet security best practices and regulatory guidelines. Composite ML-KEM is applicable in any application that uses X.509 or PKIX data structures that accept ML-KEM, but where the operator wants extra protection against breaks or catastrophic bugs in ML-KEM.

About This Document

This note is to be removed before publishing as an RFC.

The latest revision of this draft can be found at https://lamps-wg.github.io/draft-composite-kem/draft-ietf-lamps-pq-composite-kem.html. Status information for this document may be found at https://datatracker.ietf.org/doc/draft-ietf-lamps-pq-composite-kem/.

Discussion of this document takes place on the LAMPS Working Group mailing list (mailto:spams@ietf.org), which is archived at https://datatracker.ietf.org/wg/lamps/about/. Subscribe at https://www.ietf.org/mailman/listinfo/spams/.

Source for this draft and an issue tracker can be found at https://github.com/lamps-wg/draft-composite-kem.

Status of This Memo

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1. Changes in version -08

Interop-affecting changes:

* Changed the private key serialization to carry the TradPK.

* Fixed the ASN.1 module for the pk-CompositeKEM and kema-CompositeKEM to indicate no ASN.1 wrapping is used. This simply clarifies the intended encoding but could be an interop-affecting change for implementations that built encoders / decoders from the ASN.1 and ended up with a non-intended encoding.

* Changed the domain separator strings to match draft-irtf-cfrg-concrete-hybrid-kems-00, but no reference to it because I don't want this to get stuck in MISREF.

* Added a normative section saying that the composite MUST forward any errors produced by the component primitives.

* Fully removed SHA2; changed all HMACSHA2 to SHA3.

Editorial changes:

* Clarified that the ECDSA public key is raw X9.62 with no OCTET STRING wrapping. Test vectors were already correct.

A full review was performed of the encoding of each component:

* ML-KEM:

  - pub key, priv key, ct value: Raw, according to FIPS 203. Test vectors appear to match.

* RSA:

  - pub key: ASN.1 RSAPublicKey. Test vectors appear to match (manually inspected "id-MLKEM768-RSA2048-HMAC-SHA256")

  - priv key: RSAPrivateKey (CRT). Test vectors appear to match (manually inspected "id-MLKEM768-RSA2048-HMAC-SHA256")

  - ct value: length of ct for "id-MLKEM768-RSA2048-HMAC-SHA256" verified to be 256 bytes, format hard to manually inspect.

* ECDH: Inspected test vector for "id-MLKEM768-ECDH-P256-HMAC-SHA256".

  - pub key: The wording of the pub key format in Section 2.2 of RFC5480 is extremely confusing in how it would apply outside of a SubjectPublicKeyInfo. The Composite author's interpretation was for it to be raw X9.62, which is what is already in the test vectors: verified to be raw X9.62 with a leading byte of 0x04 (uncompressed). Normative text in Section 5 is incorrect and has been changed.

* priv key: This is the ASN.1 structure ECPrivateKey [RFC5915] as intended, however, as Dan Van Geest points out, the parameters field, while marked OPTIONAL is actually required by Section 3 of RFC5915. That means the private keys here are invalid. This has been corrected in the test vectors.

  - ct value: A raw X9.62 public key, as intended.

* XDH:

  - pub key: 32 byte raw.

  - priv key: Had been wrapped in OCTET STRING to match CurvePrivateKey (RFC8410). This has been changed to 32/57 byte raw.

  - ct value: 32 byte raw.

2. Introduction

The advent of quantum computing poses a significant threat to current cryptographic systems. Traditional cryptographic key establishment algorithms such as RSA-OAEP, Diffie-Hellman and its elliptic curve variants are vulnerable to quantum attacks. During the transition to post-quantum cryptography (PQC), there is considerable uncertainty regarding the robustness of both existing and new cryptographic algorithms. While we can no longer fully trust traditional cryptography, we also cannot immediately place complete trust in post-quantum replacements until they have undergone extensive scrutiny and real-world testing to uncover and rectify both algorithmic weaknesses as well as implementation flaws across all the new implementations.

Unlike previous migrations between cryptographic algorithms, the decision of when to migrate and which algorithms to adopt is far from straightforward. For instance, the aggressive migration timelines may require deploying PQC algorithms before their implementations have been fully hardened or certified, and dual-algorithm data protection may be desirable over a longer time period to hedge against CVEs and other implementation flaws in the new implementations.

Cautious implementers may opt to combine cryptographic algorithms in such a way that an attacker would need to break all of them simultaneously to compromise the protected data. These mechanisms are referred to as Post-Quantum/Traditional (PQ/T) Hybrids [I-D.ietf-pquip-pqt-hybrid-terminology].

Certain jurisdictions are already recommending or mandating that PQC lattice schemes be used exclusively within a PQ/T hybrid framework. The use of a composite scheme provides a straightforward implementation of hybrid solutions compatible with (and advocated by) some governments and cybersecurity agencies [BSI2021], [ANSSI2024].

This specification defines a specific instantiation of the PQ/T Hybrid paradigm called "composite" where multiple cryptographic algorithms are combined to form a single key encapsulation mechanism (KEM) presenting a single public key and ciphertext such that it can be treated as a single atomic algorithm at the protocol level; a property referred to as "protocol backwards compatibility" since it can be applied to protocols that are not explicitly hybrid-aware. Composite algorithms retain some security even if one of their component algorithms is broken. Concrete instantiations of composite ML-KEM algorithms are provided based on ML-KEM, RSA-OAEP and ECDH. Backwards compatibility in the sense of upgraded systems continuing to inter-operate with legacy systems is not directly covered in this specification, but is the subject of Section 11.2. The idea of a composite was first presented in [Bindel2017].

Composite ML-KEM is applicable in any PKIX-related application that would otherwise use ML-KEM.

2.1. Conventions and Terminology

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. These words may also appear in this document in lower case as plain English words, absent their normative meanings.

This specification is consistent with all terminology from [I-D.ietf-pquip-pqt-hybrid-terminology]. In addition, the following terms are used in this specification:

ALGORITHM: The usage of the term "algorithm" within this specification generally refers to any function which has a registered Object Identifier (OID) for use within an ASN.1 AlgorithmIdentifier. This loosely, but not precisely, aligns with the definitions of "cryptographic algorithm" and "cryptographic scheme" given in [I-D.ietf-pquip-pqt-hybrid-terminology].

COMBINER: A combiner specifies how multiple shared secret keys are combined into a single shared secret key.

COMPONENT / PRIMITIVE: The words "component" or "primitive" are used interchangeably to refer to a cryptographic algorithm that is used internally within a composite algorithm. For example this could be an asymmetric algorithm such as "ML-KEM-768" or "RSA-OAEP".

DER: Distinguished Encoding Rules as defined in [X.690].

KEM: A key encapsulation mechanism as defined in Section 3.

PKI: Public Key Infrastructure, as defined in [RFC5280].

SHARED SECRET KEY: A value established between two communicating parties for use as cryptographic key material suitable for direct use by symmetric cryptographic algorithms. This specification is concerned with shared secrets established via public key cryptographic operations.

Notation: The algorithm descriptions use python-like syntax. The following symbols deserve special mention:

* || represents concatenation of two byte arrays.

* [:] represents byte array slicing.

* (a, b) represents a pair of values a and b. Typically this indicates that a function returns multiple values; the exact conveyance mechanism -- tuple, struct, output parameters, etc -- is left to the implementer.

* (a, _): represents a pair of values where one -- the second one in this case -- is ignored.

* Func<TYPE>(): represents a function that is parametrized by <TYPE> meaning that the function’s implementation will have minor differences depending on the underlying TYPE. Typically this means that a function will need to look up different constants or use different underlying cryptographic primitives depending on which composite algorithm it is implementing.

2.2. Composite Design Philosophy

[I-D.ietf-pquip-pqt-hybrid-terminology] defines composites as:

> _Composite Cryptographic Element_: A cryptographic element that incorporates multiple component cryptographic elements of the same type in a multi-algorithm scheme.

Composite algorithms, as defined in this specification, follow this definition and should be regarded as a single key that performs a single cryptographic operation typical of a key establishment mechanism such as key generation, encapsulating, or decapsulating -- using its internal concatenation of component keys as if they form a single key. This generally means that the complexity of combining algorithms can and should be handled by the cryptographic library or cryptographic module, and the single composite public key, private key, and ciphertext can be carried in existing fields in protocols such as PKCS#10 [RFC2986], CMP [RFC4210], X.509 [RFC5280], CMS [RFC5652], and the Trust Anchor Format [RFC5914]. In this way, composites achieve "protocol backwards-compatibility" in that they will drop cleanly into any protocol that accepts an analogous single-algorithm cryptographic scheme without requiring any modification of the protocol to handle multiple algorithms.

Discussion of the specific choices of algorithm pairings can be found in Section 7.2.

3. Overview of the Composite ML-KEM Scheme

Composite ML-KEM is a PQ/T hybrid Key Encapsulation Mechanism (KEM) which combines ML-KEM as specified in [FIPS.203] and [I-D.ietf-lamps-kyber-certificates] with one of RSA-OAEP defined in [RFC8017], the Elliptic Curve Diffie-Hellman key agreement schemes ECDH defined in section 5.7.1.2 of [SP.800-56Ar3], and X25519 / X448 defined in [RFC8410]. A KEM combiner function is used to combine the two component shared secret keys into a single shared secret key.

Composite Key Encapsulation Mechanisms are defined as cryptographic primitives that consist of three algorithms. These definitions are borrowed from [RFC9180].

* KeyGen() -> (pk, sk): A probabilistic key generation algorithm, which generates a public key pk and a secret key sk. Some cryptographic modules may also expose a KeyGen(seed) -> (pk, sk), which generates pk and sk deterministically from a seed. This specification assumes a seed-based keygen for ML-KEM.

* Encap(pk) -> (ss, ct): A probabilistic encapsulation algorithm, which takes as input a public key pk and outputs a ciphertext ct and shared secret key ss. Note: this specification uses Encap() to conform to [RFC9180], but [FIPS.203] uses Encaps().

* Decap(sk, ct) -> ss: A decapsulation algorithm, which takes as input a secret key sk and ciphertext ct and outputs a shared secret ss, or in some cases a distinguished error value. Note: this specification uses Decap() to conform to [RFC9180], but [FIPS.203] uses Decaps().

The KEM interface defined above differs from both traditional key transport mechanism (for example for use with KeyTransRecipientInfo defined in [RFC5652]), and key agreement (for example for use with KeyAgreeRecipientInfo defined in [RFC5652]) and thus Composite ML-KEM MUST be used with KEMRecipientInfo defined in [RFC9629], however full conventions for use of Composite ML-KEM within the Cryptographic Message Syntax will be included in a separate specification.

The KEM interface was chosen as the interface for a composite key establishment because it allows for arbitrary combinations of component algorithm types since both key transport and key agreement mechanisms can be promoted into KEMs as described in Section 3.1 and Section 3.2 below.

The following algorithms are defined for serializing and deserializing component values. These algorithms are inspired by similar algorithms in [RFC9180].

* SerializePublicKey(mlkemPK, tradPK) -> bytes: Produce a byte string encoding of the component public keys.

* DeserializePublicKey(bytes) -> (mlkemPK, tradPK): Parse a byte string to recover the component public keys.

* SerializeCiphertext(mlkemCT, tradCT) -> bytes: Produce a byte string encoding of the component ciphertexts.

* DeserializeCiphertext(bytes) -> (mlkemCT, tradCT): Parse a byte string to recover the component ciphertexts.

* SerializePrivateKey(mlkemSeed, tradPK, tradSK) -> bytes: Produce a byte string encoding of the component private keys.

* DeserializePrivateKey(bytes) -> (mlkemSeed, tradPK, tradSK): Parse a byte string to recover the component private keys.

Full definitions of serialization and deserialization algorithms can be found in Section 5.

3.1. Promotion of RSA-OAEP into a KEM

The RSA Optimal Asymmetric Encryption Padding (OAEP), as defined in section 7.1 of [RFC8017] is a public key encryption algorithm used to transport key material from a sender to a receiver. A "key transport" type algorithm has the following API:

* Encrypt(pk, ss) -> ct: Take an existing shared secret key ss and encrypt it for pk.

* Decrypt(sk, ct) -> ss: Decrypt the ciphertext ct to recover ss.

Note the difference between the API of RSA.Encrypt(pk, ss) -> ct and KEM.Encap(pk) -> (ss, ct) presented above. For this reason, RSA-OAEP cannot be directly combined with ML-KEM. Fortunately, a key transport mechanism such as RSA-OAEP can be easily promoted into a KEM by having the sender generate a random 256 bit shared secret key and encrypt it.

```
RSAOAEPKEM.Encap(pkR):
  shared_secret = SecureRandom(ss_len)
  enc = RSAES-OAEP-ENCRYPT(pkR, shared_secret)

  return shared_secret, enc
```

Acceptable public key encodings for pkR are described in Section 5.

Note that the OAEP label L is left to its default value, which is the empty string as per [RFC8017]. The shared secret key output by the overall Composite ML-KEM already binds a composite KEM Combiner Label, so there is no need to also use the component Label.

The value of ss_len as well as concrete values for all the RSA-OAEP parameters used within this specification can be found in Section 7.1.

Decap(sk, ct) -> ss is accomplished by direct use of OAEP Decrypt.

```
RSAOAEPKEM.Decap(skR, enc):
  shared_secret = RSAES-OAEP-DECRYPT(skR, enc)

  return shared_secret
```

A quick note on the choice of RSA-OAEP as the supported RSA encryption primitive. RSA-KEM [RFC5990] is cryptographically robust and is more straightforward to work with, but it has fairly limited adoption and therefore is of limited value as a PQ migration mechanism. Also, while RSA-PKCS#1v1.5 [RFC8017] is still widely used, it is hard to make secure and no longer FIPS-approved as of the end of 2023 [SP800-131Ar2], so it is of limited forwards value. This leaves RSA-OAEP [RFC8017] as the remaining choice. See Section 7.2 for further discussion of algorithm choices.

Note that, at least at the time of writing, the algorithm RSAOAEPKEM is not defined as a standalone algorithm within PKIX standards and it does not have an assigned algorithm OID, so it cannot be used directly with CMS KEMRecipientInfo [RFC9629]; it is merely a building block for the composite algorithm.

3.2. Promotion of ECDH into a KEM

The elliptic curve Diffie-Hellman algorithm identified by the OID id-ecDH as defined in [RFC5480] and [SEC1] is a key agreement algorithm requiring both parties to contribute an asymmetric keypair to the derivation of the shared secret key. A "key agreement" type algorithm has the following API:

* DH(skX, pkY) -> ss: Each party combines their secret key skX with the other party’s public key pkY.

Note the difference between the API of DH(skX, pkY) -> ss and KEM.Encap(pk) -> (ss, ct) presented above. For this reason, a Diffie-Hellman key exchange cannot be directly combined with ML-KEM. Fortunately, a Diffie-Hellman key agreement can be easily promoted into a KEM Encap(pk) -> (ss, ct) by having the sender generate an ephemeral keypair for themself and sending their public key as the ciphertext ct. Composite ML-KEM uses a simplified version of the DHKEM definition from [RFC9180]:

```
DHKEM.Encap(pkR):
  (skE, pkE) = GenerateKeyPair()
  ss = DH(skE, pkR)
  ct = SerializePublicKey(pkE)

  return ss, ct
```

Decap(sk, ct) -> ss is accomplished in the analogous way.

```
DHKEM.Decap(skR, ct):
  pkE = DeserializePublicKey(ct)
  ss = DH(skR, pkE)

  return ss
```

This construction applies for all variants of elliptic curve Diffie-Hellman used in this specification: ECDH, X25519, and X448.

For ECDH, DH() yields the value Z as described in section 5.7.1.2 of [SP.800-56Ar3]. Acceptable public key encodings for enc and pkE are described in Section 5.

For X25519 and X448, DH() yields the value K as described in section 6 of [RFC7748]. Acceptable public key encodings for enc and pkE are described in Section 5.

The promotion of DH to a KEM is similar to the DHKEM functions in [RFC9180], but it is simplified in the following ways:

1. Notation has been aligned to the notation used in this specification.

2. Since a KEM Combiner Label is included explicitly in the Composite ML-KEM combiner, there is no need to perform the labeled steps of ExtractAndExpand().

3. Since the ciphertext and receiver’s public key are included explicitly in the Composite ML-KEM combiner, there is no need to construct the kem_context object.

Note that here, SerializePublicKey() and DeserializePublicKey() refer to the underlying encoding of the DH primitive, and not to the composite serialization functions defined in Section 5. Acceptable serializations for the underlying DH primitives are described in Section 5.

Note that, at least at the time of writing, the algorithm DHKEM is not defined as a standalone algorithm within PKIX standards and it does not have an assigned algorithm OID, so it cannot be used directly with CMS KEMRecipientInfo [RFC9629]; it is merely a building block for the composite algorithm.

4. Composite ML-KEM Functions

This section describes the composite ML-KEM functions needed to instantiate the public API of a Key Encapsulation Mechanism as defined in Section 3.

4.1. Key Generation

In order to maintain security properties of the composite, applications that use composite keys MUST always perform fresh key generations of both component keys and MUST NOT reuse existing key material. See Section 10.3 for a discussion.

To generate a new keypair for composite schemes, the KeyGen() -> (pk, sk) function is used. The KeyGen() function calls the two key generation functions of the component algorithms independently. Multi-threaded, multi-process, or multi-module applications might choose to execute the key generation functions in parallel for better key generation performance or architectural modularity.

The following describes how to instantiate a KeyGen() function for a given composite algorithm represented by <OID>.

```
Composite-ML-KEM<OID>.KeyGen() -> (pk, sk)

Explicit Inputs:
     None

Implicit Inputs mapped from <OID>:

  ML-KEM     The underlying ML-KEM algorithm and
             parameter set, for example, could be "ML-KEM-768".

  Trad       The underlying traditional algorithm and
             parameter, for example "RSA-OAEP"
             or "X25519".

Output:
  (pk, sk)  The composite keypair.

Key Generation Process:

  1. Generate component keys

    mlkemSeed = Random(64)
    (mlkemPK, mlkemSK) = ML-KEM.KeyGen(mlkemSeed)
    (tradPK, tradSK) = Trad.KeyGen()

  2. Check for component key gen failure
    if NOT (mlkemPK, mlkemSK) or NOT (tradPK, tradSK):
      output "Key generation error"

  3. Output the composite public and private keys

    pk = SerializePublicKey(mlkemPK, tradPK)
    sk = SerializePrivateKey(mlkemSeed, tradPK, tradSK)
    return (pk, sk)
```

In order to ensure fresh keys, the key generation functions MUST be executed for both component algorithms. Compliant parties MUST NOT use, import or export component keys that are used in other contexts, combinations, or by themselves as keys for standalone algorithm use. For more details on the security considerations around key reuse, see Section 10.3.

Note that this keygen routine outputs a serialized composite key, which contains only the ML-KEM seed. Implementations should feel free to modify this routine to output the expanded mlkemSK or to make free use of ML-KEM.KeyGen(mldsaSeed) as needed to expand the ML-KEM seed into an expanded prior to performing a decapsulation operation.

Variations in the keygen process above and decapsulation processes below to accommodate particular private key storage mechanisms or alternate interfaces to the underlying cryptographic modules are considered to be conformant to this specification so long as they produce the same output and error handling.

For example, component private keys stored in separate software or hardware modules where it is not possible to do a joint simultaneous keygen would be considered compliant so long as both keys are freshly generated. It is also possible that the underlying cryptographic module does not expose a ML-KEM.KeyGen(seed) that accepts an externally-generated seed, and instead an alternate keygen interface must be used. Note however that cryptographic modules that do not support seed-based ML-KEM key generation will be incapable of importing or exporting composite keys in the standard format since the private key serialization routines defined in Section 5.2 only support ML-KEM keys as seeds.

Errors produced by the component KeyGen() routines MUST be forwarded on to the calling application. Further discussion can be found below in Section 4.5.

4.2. Encapsulation

The Encap(pk) of a Composite ML-KEM algorithm is designed to behave exactly the same as ML-KEM.Encaps(ek) defined in Algorithm 20 in Section 7.2 of [FIPS.203]. Specifically, Composite-ML-KEM.Encap(pk) produces a 256-bit shared secret key that can be used directly with any symmetric-key cryptographic algorithm. In this way, Composite ML-KEM can be used as a direct drop-in replacement anywhere that ML-KEM is used.

The following describes how to instantiate a Encap(pk) function for a given composite algorithm represented by <OID>.

Composite-ML-KEM<OID>.Encap(pk) -> (ss, ct)

Explicit Inputs:

pk Composite public key consisting of encryption public keys for each component.

Implicit inputs mapped from <OID>:

ML-KEM The underlying ML-KEM algorithm and parameter set, for example "ML-KEM-768".

Trad The underlying ML-KEM algorithm and parameter set, for example "RSA-OAEP" or "X25519".

KDF The KDF specified for the given Composite ML-KEM algorithm. See algorithm specifications below.

Label KEM Combiner Label value for binding the ciphertext to the Composite OID. See section on KEM Combiner Labels below.

Output:

ss The shared secret key, a 256-bit key suitable for use with symmetric cryptographic algorithms.

ct The ciphertext, a byte string.

Encap Process:

1. Separate the public keys.

```
(mlkemPK, tradPK) = DeserializePublicKey(pk)
```

2. Perform the respective component Encap operations according to their algorithm specifications.

```
(mlkemCT, mlkemSS) = ML-KEM.Encaps(mlkemPK)
(tradCT, tradSS) = TradKEM.Encap(tradPK)
```

3. If either ML-KEM.Encaps() or TradKEM.Encap() return an error, then this process must return an error.

```
if NOT (mlkemCT, mlkemSS) or NOT (tradCT, tradSS):
  output "Encapsulation error"
```

4. Encode the ciphertext

```
ct = SerializeCiphertext(mlkemCT, tradCT)
```

5. Combine the KEM secrets and additional context to yield the composite shared secret key.

```
ss = KemCombiner<KDF>(mlkemSS, tradSS, tradCT, tradPK, Label)
```

6. Output composite shared secret key and ciphertext.

```
return (ss, ct)
```

Depending on the security needs of the application, it MAY be advantageous to perform steps 2, 3, and 5 in a timing-invariant way to prevent side-channel attackers from learning which component algorithm failed and from learning any of the inputs or output of the KEM combiner.

The specific values for KDF and the specific values for Label are defined per Composite ML-KEM algorithm in Section 7.

Errors produced by the component Encaps() routines MUST be forwarded on to the calling application. Further discussion can be found below in Section 4.5.

4.3. Decapsulation

The Decap(sk, ct) -> ss of a Composite ML-KEM algorithm is designed to behave exactly the same as ML-KEM.Decaps(dk, c) defined in Algorithm 21 in Section 7.3 of [FIPS.203]. Specifically, Composite-ML-KEM.Decap(sk, ct) produces a 256-bit shared secret key that can be used directly with any symmetric-key cryptographic algorithm. In this way, Composite ML-KEM can be used as a direct drop-in replacement anywhere that ML-KEM is used.

The following describes how to instantiate a Decap(sk, ct) function for a given composite algorithm represented by <OID>.

```
Composite-ML-KEM<OID>.Decap(sk, ct) -> ss
```

Explicit inputs

- sk   Composite private key consisting of decryption private keys for each component.

- ct   The ciphertext, a byte string.

Implicit inputs mapped from <OID>:

ML-KEM The underlying ML-KEM algorithm and parameter set, for example, could be "ML-KEM-768".

Trad The underlying traditional algorithm and parameter set, for example "RSA-OAEP" or "X25519".

tradPK The traditional public key is required for the KEM combiner.
The suggested algorithm below extracts the tradPK from sk, however implementations that use a non-standard private key encoding will need to obtain the traditional public key some other way.

KDF The KDF specified for the given Composite ML-KEM algorithm. See algorithm specifications below.

Label KEM Combiner Label value for binding the ciphertext to the Composite ML-KEM OID.
See section on KEM Combiner Labels below.

Output:

ss The shared secret key, a 256-bit key suitable for use with symmetric cryptographic algorithms.

Decap Process:

1. Separate the private keys and ciphertexts

```
(mlkemSeed, tradPK, tradSK) = DeserializePrivateKey(sk)
(_, mlkemSK) = ML-KEM.KeyGen(mlkemSeed)
(mlkemCT, tradCT) = DeserializeCiphertext(ct)
```

2. Perform the respective component Encap operations according to their algorithm specifications.

```
mlkemSS = ML-KEM.Decaps(mlkemSK, mlkemCT)
tradSS  = TradKEM.Decap(tradSK, tradCT)
```

3. If either ML-KEM.Decaps() or TradKEM.Decap() return an error, then this process must return an error.

```
if NOT mlkemSS or NOT tradSS:
  output "Encapsulation error"
```

4. Combine the KEM secrets and additional context to yield the composite shared secret key.

```
ss = KemCombiner<KDF>(mlkemSS, tradSS, tradCT, tradPK, Label)
```

5. Output composite shared secret key.

```
return ss
```

Steps 2, 3, and 4 SHOULD be performed in a timing-invariant way to prevent side-channel attackers from learning which component algorithm failed and from learning any of the inputs or output of the KEM combiner.

It is possible to use component private keys stored in separate software or hardware keystores. Variations in the process to accommodate particular private key storage mechanisms are considered to be conformant to this specification so long as it produces the same output and error handling as the process sketched above.

In order to properly achieve its security properties, the KEM combiner requires that all inputs are fixed-length. Since each Composite ML-KEM algorithm fully specifies its component algorithms, including key sizes, all inputs should be fixed-length in non-error scenarios except for minor variations introduced by encoding. However some implementations may choose to perform additional checking to handle certain error conditions. In particular, the KEM combiner step should not be performed if either of the component decapsulations returned an error condition indicating malformed inputs. For timing-invariance reasons, it is RECOMMENDED to perform both decapsulation operations and check for errors afterwards to prevent an attacker from using a timing channel to tell which component failed decapsulation. Also, RSA-based composites MUST ensure that the modulus size (i.e. the size of tradCT and tradPK) matches that specified for the given Composite ML-KEM algorithm in Section 7; depending on the cryptographic library used, this check may be done by the library or may require an explicit check as part of the Composite-ML-KEM.Decap() routine. Implementers should keep in mind that some instances of tradCT and tradPK will be DER-encoded which could introduce minor length variations such as dropping leading zeroes; since these variations are not attacker-controlled they are considered benign.

Errors produced by the component Decaps() routines MUST be forwarded on to the calling application. Further discussion can be found below in Section 4.5.

4.4. KEM Combiner Function

As noted in the Encapsulation and Decapsulation procedures above, the KEM combiner is parameterized by the choice of underlying KDF. This specification provides a combiner construction with SHA3-256 for all combinations of algorithms.

```
KemCombiner(mlkemSS, tradSS, tradCT, tradPK, Label) -> ss
```

Explicit inputs:

The list of input values to be combined.

Output:

ss The shared secret key, a 256-bit key suitable for use with symmetric cryptographic algorithms.

Process:

```
ss = SHA3-256(mlkemSS || tradSS || tradCT || tradPK || Label)

return ss
```

4.5. Error Handling and Explicit Rejection

ML-KEM, particularly its Decaps() defined in Algorithms 18 and 21 of [FIPS.203], is designed to be implicitly rejecting, meaning that a failure within the underlying PKE scheme due to a mangled ciphertext will not cause ML-KEM.Decaps() to return an error, but instead any errors encountered during decapsulation are handled by producing a pseudo-randomized shared secret that does not match the intended shared secret. ML-KEM.Decaps() can, however return errors for example if the provided ciphertext or decapsulation private key is the wrong size.

In Composite ML-KEM, not all component algorithms will be implicitly rejecting, for example RSA-OAEP’s Decrypt() can return an error if the padding is incorrect. In general, in the case that one of the component primitives generates an error during Composite ML-KEM KeyGen, Encaps, or Decaps, if a component primitive returns an error, Composite ML-KEM MUST clear all buffers containing key material and forward the error to its caller; I.E. Composite ML-KEM MUST be explicitly rejecting whenever one of its components is. The same applies to Composite ML-KEM KeyGen() and Encaps(): Composite KEM MUST forward any errors produced by component algorithms.

5. Serialization

This section presents routines for serializing and deserializing composite public keys, private keys, and ciphertext values to bytes via simple concatenation of the underlying encodings of the component algorithms. The functions defined in this section are considered internal implementation detail and are referenced from within the public API definitions in Section 4.

Deserialization is possible because ML-KEM has fixed-length public keys, private keys (seeds), and ciphertext values as shown in the following table.

Algorithm	Public Key	Private Key	Ciphertext
ML-KEM-768	1184	64	1088
ML-KEM-1024	1568	64	1568

Table 1: ML-KEM Sizes

For all serialization routines below, when these values are required to be carried in an ASN.1 structure, they are wrapped as described in Section 6.1.

While ML-KEM has a single fixed-size representation for each of public key, private key, and ciphertext, the traditional component might allow multiple valid encodings; for example an elliptic curve public key, and therefore also ciphertext, might be validly encoded as either compressed or uncompressed [SEC1], or an RSA private key could be encoded in Chinese Remainder Theorem form [RFC8017]. In order to obtain interoperability, composite algorithms MUST use the following encodings of the underlying components:

* *ML-KEM*: MUST be encoded as specified in sections 7.1 and 7.2 of [FIPS.203], using a 64-byte seed as the private key.

* *RSA*: the public key MUST be encoded as RSAPublicKey with the (n,e) public key representation as specified in A.1.1 of [RFC8017] and the private key representation as RSAPrivateKey specified in A.1.2 of [RFC8017] with version 0 and 'otherPrimeInfos' absent. An RSA-OAEP ciphertext MUST be encoded as specified in section 7.1.1 of [RFC8017]

* *ECDH*: public key MUST be encoded as an uncompressed X9.62 [X9.622005], including the leading byte 0x04 indicating uncompressed. This is consistent with the encoding of ECPoint as specified in section 2.2 of [RFC5480] when no ASN.1 OCTET STRING wrapping is present. The private key MUST be encoded as ECPrivateKey specified in [RFC5915] with 'NamedCurve' parameter set to the OID of the curve, but without the 'publicKey' field.

* *X25519 and X448*: the public key MUST be encoded as per section 5 of [RFC7748] and the private key is a 32 or 57 byte raw value for Ed25519 and Ed448 respectively, which can be converted to a CurvePrivateKey specified in [RFC8410] by the addition of an OCTET STRING wrapper.

All ASN.1 objects SHALL be encoded using DER on serialization.

Even with fixed encodings for the traditional component, there may be slight differences in size of the encoded value due to, for example, encoding rules that drop leading zeroes. See Appendix A for further discussion of encoded size of each composite algorithm.

The deserialization routines described below do not check for well-formedness of the cryptographic material they are recovering. It is assumed that underlying cryptographic primitives will catch malformed values and raise an appropriate error.

5.1. SerializePublicKey and DeserializePublicKey

The serialization routine for keys simply concatenates the public keys of the component algorithms, as defined below:

Composite-ML-KEM.SerializePublicKey(mlkemPK, tradPK) -> bytes

Explicit inputs:

mlkemPK The ML-KEM public key, which is bytes.

tradPK The traditional public key in the appropriate encoding for the underlying component algorithm.

Implicit inputs:

None

Output:

bytes The encoded composite public key.

Serialization Process:

1. Combine and output the encoded public key

   output mlkemPK || tradPK

Deserialization reverses this process. Each component key is deserialized according to their respective specification as shown in Appendix B.

The following describes how to instantiate a DeserializePublicKey(bytes) function for a given composite algorithm represented by <OID>.

Composite-ML-KEM<OID>.DeserializePublicKey(bytes) -> (mlkemPK, tradPK)

Explicit inputs:

bytes An encoded composite public key.

Implicit inputs mapped from <OID>:

ML-KEM The underlying ML-KEM algorithm and parameter, for example, could be "ML-KEM-768".

Output:

mlkemPK The ML-KEM public key, which is bytes.

tradPK The traditional public key in the appropriate encoding for the underlying component algorithm.

Deserialization Process:

1. Parse each constituent encoded public key.
   The length of the mlkemPK is known based on the size of
   the ML-KEM component key length specified by the Object ID.

```
switch ML-KEM do
   case ML-KEM-768:
     mlkemPK = bytes[:1184]
     tradPK  = bytes[1184:]
   case ML-KEM-1024:
     mlkemPK = bytes[:1568]
     tradPK  = bytes[1568:]
```

   Note that while ML-KEM has fixed-length keys, RSA and ECDH may not, depending on encoding, so rigorous length-checking of the overall composite key is not always possible.

2. Output the component public keys

```
output (mlkemPK, tradPK)
```

5.2. SerializePrivateKey and DeserializePrivateKey

The serialization routine for keys simply concatenates the private keys of the component algorithms, as defined below:

```
Composite-ML-KEM.SerializePrivateKey(mlkemSeed, tradPK, tradSK)
                                       -> bytes
```

Explicit inputs:

mlkemSeed The ML-KEM private key, which is the bytes of the seed.

tradPK   The traditional public key in the appropriate encoding for the underlying component algorithm. This is required by the decapsulater for inclusion in the KEM combiner.

tradSK   The traditional private key in the appropriate encoding for the underlying component algorithm.

Implicit inputs:

None

Output:

bytes   The encoded composite private key.

Serialization Process:

1. Compute the length of tradPK

   ```
   lenTradPK = IntegerToBytes( len(tradPK), 2 )
   ```

2. Combine and output the encoded private key.

   ```
   output mlkemSeed || lenTradPK || tradPK || tradSK
   ```

The function IntegerToBytes(x, a) is defined in Algorithm 11 of [FIPS.204], which is the usual little-endian encoding of an integer. Encoding to 2 bytes allows for traditional public keys up to 65 kb.

Deserialization reverses this process. Each component key is deserialized according to their respective specification as shown in Appendix B.

The following describes how to instantiate a DeserializePrivateKey(bytes) function. Since ML-KEM private keys are 64 bytes for all parameter sets, this function does not need to be parametrized.

```
Composite-ML-KEM.DeserializePrivateKey(bytes)
                                       -> (mlkemSeed, tradPK, tradSK)
```

Explicit inputs:

bytes   An encoded composite private key.

Implicit inputs:

That an ML-KEM private key is 64 bytes for all parameter sets.

Output:

mlkemSeed The ML-KEM private key, which is the bytes of the seed.

tradSK   The traditional private key in the appropriate encoding for the underlying component algorithm.

Deserialization Process:

1. Parse the ML-DSA seed, which is always a 64 byte seed for all parameter sets.

   ```
   mlkemSeed = bytes[:64]
   ```

2. Parse the traditional public and private key

   ```
   lenTradPK = BytesToInteger( bytes[64:66] )
   tradPK = bytes[66: 66+lenTradPK]

   tradSK  = bytes[66+lenTradPK:]
   ```

   Note that while ML-KEM has fixed-length keys, RSA and ECDH may not, depending on encoding, so rigorous length-checking of the overall composite key is not always possible.

2. Output the component private keys

   ```
   output (mlkemSeed, tradPK, tradSK)
   ```

The function BytesToInteger(x) is not defined in [FIPS.204], but is the obvious inverse of the defined IntegerToBytes() which is the usual little-endian encoding of an integer.

5.3. SerializeCiphertext and DeserializeCiphertext

The serialization routine for the composite ciphertext value simply concatenates the fixed-length ML-KEM ciphertext with the ciphertext from the traditional algorithm, as defined below:

```
Composite-ML-KEM.SerializeCiphertext(mlkemCT, tradCT) -> bytes

Explicit inputs:

  mlkemCT  The ML-KEM ciphertext, which is bytes.

  tradCT   The traditional ciphertext in the appropriate
           encoding for the underlying component algorithm.

Implicit inputs:

  None

Output:

  bytes   The encoded composite ciphertext value.


Serialization Process:

  1. Combine and output the encoded composite ciphertext

     output mlkemCT || tradCT
```

Deserialization reverses this process. Each component ciphertext is deserialized according to their respective specification as shown in Appendix B.

The following describes how to instantiate a DeserializeCiphertext(bytes) function for a given composite algorithm represented by <OID>.

```
Composite-ML-KEM<OID>.DeserializeCiphertext(bytes)
                                          -> (mldkemCT, tradCT)
```

Explicit inputs:

bytes   An encoded composite ciphertext value.

Implicit inputs mapped from <OID>:

ML-KEM   The underlying ML-KEM algorithm and parameter, for example, could be "ML-KEM-768".

Output:

mlkemCT The ML-KEM ciphertext, which is bytes.

tradCT   The traditional ciphertext in the appropriate encoding for the underlying component algorithm.

Deserialization Process:

1. Parse each constituent encoded ciphertext. The length of the mlkemCT is known based on the size of the ML-KEM component ciphertext length specified by the Object ID.

   ```
   switch ML-KEM do
      case ML-KEM-768:
        mlkemCT = bytes[:1088]
        tradCT  = bytes[1088:]
      case ML-KEM-1024:
        mlkemCT= bytes[:1568]
        tradCT  = bytes[1568:]
   ```

   Note that while ML-KEM has fixed-length ciphertexts, RSA and ECDH may not, depending on encoding, so rigorous length-checking is not always possible here.

2. Output the component ciphertext values

   ```
   output (mlkemCT, tradCT)
   ```

6. Use within X.509 and PKIX

The following sections provide processing logic and the necessary ASN.1 modules necessary to use composite ML-KEM within X.509 and PKIX protocols. Use within the Cryptographic Message Syntax (CMS) will be covered in a separate specification.

While composite ML-KEM keys and ciphertext values MAY be used raw, the following sections provide conventions for using them within X.509 and other PKIX protocols such that Composite ML-KEM can be used as a drop-in replacement for KEM algorithms in PKCS#10 [RFC2986], CMP [RFC4210], X.509 [RFC5280], and related protocols.

6.1. Encoding to DER

The serialization routines presented in Section 5 produce raw binary values. When these values are required to be carried within a DER-encoded message format such as an X.509's subjectPublicKey and signatureValue BIT STRING [RFC5280] or a OneAsymmetricKey.privateKey OCTET STRING [RFC5958], then the BIT STRING or OCTET STRING contains this raw byte string encoding of the public key.

When a Composite ML-KEM public key appears outside of a SubjectPublicKeyInfo type in an environment that uses ASN.1 encoding, it could be encoded as an OCTET STRING by using the Composite-ML-KEM-PublicKey type defined below.

```
Composite-ML-KEM-PublicKey ::= OCTET STRING
```

Size constraints MAY be enforced, as appropriate as per Appendix A.

6.2. Key Usage Bits

When any Composite ML-KEM Object Identifier appears within the SubjectPublicKeyInfo.AlgorithmIdentifier field of an X.509 certificate [RFC5280], the key usage certificate extension MUST only contain:

keyEncipherment

Composite ML-KEM keys MUST NOT be used in a "dual usage" mode because even if the traditional component key supports both signing and encryption, the post-quantum algorithms do not and therefore the overall composite algorithm does not. Implementations MUST NOT use one component of the composite for the purposes of digital signature and the other component for the purposes of encryption or key establishment.

6.3. ASN.1 Definitions

Composite ML-KEM uses a substantially non-ASN.1 based encoding, as specified in Section 5. However, as composite algorithms will be used within ASN.1-based X.509 and PKIX protocols, some conventions for ASN.1 wrapping are necessary.

The following ASN.1 Information Object Classes are defined to allow for compact definitions of each composite algorithm, leading to a smaller overall ASN.1 module.

```
pk-CompositeKEM {OBJECT IDENTIFIER:id}
  PUBLIC-KEY ::= {
    IDENTIFIER id
    -- KEY without ASN.1 wrapping --
    PARAMS ARE absent
    CERT-KEY-USAGE { keyEncipherment }
  }

kema-CompositeKEM {
  OBJECT IDENTIFIER:id,
    PUBLIC-KEY:publicKeyType }
    KEM-ALGORITHM ::= {
         IDENTIFIER id
         -- VALUE without ASN.1 wrapping --
         PARAMS ARE absent
         PUBLIC-KEYS { publicKeyType }
         SMIME-CAPS { IDENTIFIED BY id }
        }
```

Figure 1: ASN.1 Object Information Classes for Composite ML-KEM

As an example, the public key and KEM algorithm types associated with id-MLKEM768-ECDH-P256-SHA3-256 are defined as:

```
pk-MLKEM768-ECDH-P256-SHA3-256 PUBLIC-KEY ::=
  pk-CompositeKEM {
    id-MLKEM768-ECDH-P256-SHA3-256 }

kema-MLKEM768-ECDH-P256-SHA3-256 KEM-ALGORITHM ::=
    kema-CompositeKEM{
      id-MLKEM768-ECDH-P256-SHA3-256,
      pk-MLKEM768-ECDH-P256-SHA3-256 }
```

The full set of key types defined by this specification can be found in the ASN.1 Module in Section 8.

Use cases that require an interoperable encoding for composite private keys will often need to place a composite private key inside a OneAsymmetricKey structure defined in [RFC5958], such as when private keys are carried in PKCS #12 [RFC7292], CMP [RFC4210] or CRMF [RFC4211]. The definition of OneAsymmetricKey is copied here for convenience:

```
    OneAsymmetricKey ::= SEQUENCE {
          version                  Version,
          privateKeyAlgorithm      PrivateKeyAlgorithmIdentifier,
          privateKey               PrivateKey,
          attributes           [0] Attributes OPTIONAL,
          ...,
          [[2: publicKey       [1] PublicKey OPTIONAL ]],
          ...
        }

     ...
     PrivateKey ::= OCTET STRING
                           -- Content varies based on type of key.  The
                           -- algorithm identifier dictates the format of
                           -- the key.
```

Figure 2: OneAsymmetricKey as defined in [RFC5958]

When a composite private key is conveyed inside a OneAsymmetricKey structure (version 1 of which is also known as PrivateKeyInfo) [RFC5958], the privateKeyAlgorithm field SHALL be set to the corresponding composite algorithm identifier defined according to Section 7 and its parameters field MUST be absent. The privateKey field SHALL contain the OCTET STRING representation of the serialized composite private key as per Section 5.2. The publicKey field remains OPTIONAL. If the publicKey field is present, it MUST be a composite public key as per Section 5.1.

Some applications might need to reconstruct the SubjectPublicKeyInfo or OneAsymmetricKey objects corresponding to each component key individually, for example if this is required for invoking the underlying primitive. Section 7 provides the necessary mapping between composite and their component algorithms for doing this reconstruction.

Component keys of a composite private key MUST NOT be used in any other type of key or as a standalone key. For more details on the security considerations around key reuse, see Section 10.3.

7. Algorithm Identifiers and Parameters

This section lists the algorithm identifiers and parameters for all Composite ML-KEM algorithms.

Full specifications for the referenced algorithms can be found in Appendix B.

As the number of algorithms can be daunting to implementers, see Section 11.3 for a discussion of choosing a subset to support.

Each Composite ML-KEM algorithm has a unique Label which is used in constructing the KEM combiner in (Section 4.4). This helps protect against a different algorithm arriving at the same shared secret key even if all inputs are the same.

Label values are provided as ASCII strings, but MUST be converted into binary strings in the obvious way. For example:

* ".//^" in hexadecimal is "5c2e2f2f5e5c"

* "QSF-MLKEM768-P256-SHA3-256" in hexadecimal is "5153462d4d4c4b454d3736382d503235362d534841332d323536"

EDNOTE: the OIDs listed below are prototyping OIDs defined in Entrust’s 2.16.840.1.114027.80.9.1 arc but will be replaced by IANA.

Composite KEM algorithm list:

* id-MLKEM768-RSA2048-SHA3-256
  - OID: 2.16.840.1.114027.80.5.2.62
  - Label: "QSF-MLKEM768-RSAOAEP2048-SHA3256"
  - Key Derivation Function (KDF): SHA3-256
  - ML-KEM variant: ML-KEM-768
  - Traditional Algorithm: RSA
    o Traditional KEM Algorithm: id-RSAES-OAEP
    o RSA size: 2048
    o RSAES-OAEP parameters: See Table 2
* id-MLKEM768-RSA3072-SHA3-256
  - OID: 2.16.840.1.114027.80.5.2.63
  - Label: "QSF-MLKEM768-RSAOAEP3072-SHA3256"
  - Key Derivation Function (KDF): SHA3-256
  - ML-KEM variant: ML-KEM-768

      - Traditional Algorithm: RSA

         o Traditional KEM Algorithm: id-RSAES-OAEP

         o RSA size: 3072

         o RSAES-OAEP parameters: See Table 2

   * id-MLKEM768-RSA4096-SHA3-256

      - OID: 2.16.840.1.114027.80.5.2.64

      - Label: "QSF-MLKEM768-RSAOAEP4096-SHA3256"

      - Key Derivation Function (KDF): SHA3-256

      - ML-KEM variant: ML-KEM-768

      - Traditional Algorithm: RSA

         o Traditional KEM Algorithm: id-RSAES-OAEP

         o RSA size: 4096

         o RSAES-OAEP parameters: See Table 2

   * id-MLKEM768-X25519-SHA3-256

      - OID: 2.16.840.1.114027.80.5.2.65

      - Label: "\.//^\"

      - Key Derivation Function (KDF): SHA3-256

      - ML-KEM variant: ML-KEM-768

      - Traditional Algorithm: X25519

         o Traditional KEM Algorithm: id-X25519

   * id-MLKEM768-ECDH-P256-SHA3-256

      - OID: 2.16.840.1.114027.80.5.2.66

      - Label: "QSF-MLKEM768-P256-SHA3256"

      - Key Derivation Function (KDF): SHA3-256

    - ML-KEM variant: ML-KEM-768

    - Traditional Algorithm: ECDH

      o Traditional KEM Algorithm: id-ecDH

      o ECDH curve: secp256r1

* id-MLKEM768-ECDH-P384-SHA3-256

  - OID: 2.16.840.1.114027.80.5.2.67

  - Label: "QSF-MLKEM768-P384-SHA3256"

  - Key Derivation Function (KDF): SHA3-256

  - ML-KEM variant: ML-KEM-768

  - Traditional Algorithm: ECDH

    o Traditional KEM Algorithm: id-ecDH

    o ECDH curve: secp384r1

* id-MLKEM768-ECDH-brainpoolP256r1-SHA3-256

  - OID: 2.16.840.1.114027.80.5.2.68

  - Label: "QSF-MLKEM768-BP256-SHA3256"

  - Key Derivation Function (KDF): SHA3-256

  - ML-KEM variant: ML-KEM-768

  - Traditional Algorithm: ECDH

    o Traditional KEM Algorithm: id-ecDH

    o ECDH curve: brainpoolP256r1

* id-MLKEM1024-RSA3072-SHA3-256

  - OID: 2.16.840.1.114027.80.5.2.69

  - Label: "QSF-MLKEM1024-RSAOAEP3072-SHA3256"

  - Key Derivation Function (KDF): SHA3-256

    - ML-KEM variant: ML-KEM-1024

    - Traditional Algorithm: RSA

        o Traditional KEM Algorithm: id-RSAES-OAEP

        o RSA size: 3072

        o RSAES-OAEP parameters: See Table 2

* id-MLKEM1024-ECDH-P384-SHA3-256

    - OID: 2.16.840.1.114027.80.5.2.70

    - Label: "QSF-MLKEM1024-P384-SHA3256"

    - Key Derivation Function (KDF): SHA3-256

    - ML-KEM variant: ML-KEM-1024

    - Traditional Algorithm: ECDH

        o Traditional KEM Algorithm: id-ecDH

        o ECDH curve: secp384r1

* id-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256

    - OID: 2.16.840.1.114027.80.5.2.71

    - Label: "QSF-MLKEM1024-BP384-SHA3256"

    - Key Derivation Function (KDF): SHA3-256

    - ML-KEM variant: ML-KEM-1024

    - Traditional Algorithm: ECDH

        o Traditional KEM Algorithm: id-ecDH

        o ECDH curve: brainpoolP384r1

* id-MLKEM1024-X448-SHA3-256

    - OID: 2.16.840.1.114027.80.5.2.72

    - Label: "QSF-MLKEM1024-X448-SHA3256"

  - Key Derivation Function (KDF): SHA3-256

  - ML-KEM variant: ML-KEM-1024

  - Traditional Algorithm: X448

    - Traditional KEM Algorithm: id-X448

* id-MLKEM1024-ECDH-P521-SHA3-256

  - OID: 2.16.840.1.114027.80.5.2.73

  - Label: "QSF-MLKEM1024-P521-SHA3256"

  - Key Derivation Function (KDF): SHA3-256

  - ML-KEM variant: ML-KEM-1024

  - Traditional Algorithm: ECDH

    - Traditional KEM Algorithm: id-ecDH

    - ECDH curve: secp521r1

In alignment with ML-KEM [FIPS.203], Composite KEM algorithms output a 256-bit shared secret key at all security levels, truncating is necessary as described in Section 4.4.

For all RSA key types and sizes, the exponent is RECOMMENDED to be 65537. Implementations MAY support only 65537 and reject other exponent values. Legacy RSA implementations that use other values for the exponent MAY be used to within a composite, but need to be careful when interoperating with other implementations.

The KDFs were chosen to roughly match the security level of the stronger component. In the case of X25519 and X448 SHA3-256 is used to match the construction in [X-Wing].

7.1. RSA-OAEP Parameters

Use of RSA-OAEP [RFC8017] requires additional parameters to be specified.

The RSA component keys MUST be generated at the specified 2048-bit, 3072-bit, 4096-bit key sizes respectively (up to small differences such as dropping leading zeros); intermediate sizes are not acceptable.

As with the other Composite ML-KEM algorithms, AlgorithmIdentifier parameters MUST be absent. The RSA-OAEP primitive SHALL be instantiated with the following hard-coded parameters which are the same for the 2048, 3072 and 4096 bit security levels since the objective is to carry and output a 256-bit shared secret key at all security levels.

RSAES-OAEP-params	Value
hashAlgorithm	id-sha256
MaskGenAlgorithm.algorithm	id-mgf1
maskGenAlgorithm.parameters	id-sha256
pSourceAlgorithm	pSpecifiedEmpty
ss_len	256 bits

Table 2: RSA-OAEP Parameters

Full specifications for the referenced algorithms can be found in Appendix B.

Note: The mask length, according to [RFC8017], is k - hLen - 1, where k is the size of the RSA modulus. Since the choice of hash function and the RSA key size is fixed for each composite algorithm, implementations could choose to pre-compute and hard-code the mask length.

7.2. Rationale for choices

In generating the list of composite algorithms, the idea was to provide composite algorithms at various security levels with varying performance characteristics.

The main design consideration in choosing pairings is to prioritize providing pairings of each ML-KEM security level with commonly-deployed traditional algorithms. This supports the design goal of using composites as a stepping stone to efficiently deploy post-quantum on top of existing hardened and certified traditional algorithm implementations. This was prioritized rather than attempting to exactly match the security level of the post-quantum and traditional components -- which in general is difficult to do since there is no academic consensus on how to compare the "bits of security" against classical attackers and "qubits of security" against quantum attackers.

While it may seem odd to use 256-bit outputs at all security levels, this aligns with ML-KEM [FIPS.203] which produces a 256-bit shared secret key at all security levels. All hash functions used have >= 256 bits of (2nd) pre-image resistance, which is the required property for a KDF to provide 128 bits of security, as allowed in Table 3 of [SP.800-57pt1r5]. Composite algorithms at higher security levels use a larger hash function in order to preserve internal collision resistance of the hash function at a comparable strength to the underlying component algorithms up to the point where truncation to a 256-bit output is performed.

8. ASN.1 Module

```
<CODE STARTS>

Composite-MLKEM-2025
      { iso(1) identified-organization(3) dod(6) internet(1)
        security(5) mechanisms(5) pkix(7) id-mod(0)
        id-mod-composite-mlkem-2025(TBDMOD) }

DEFINITIONS IMPLICIT TAGS ::= BEGIN

EXPORTS ALL;

IMPORTS

PUBLIC-KEY, AlgorithmIdentifier{}, SMIME-CAPS
  FROM AlgorithmInformation-2009  -- RFC 5912 [X509ASN1]
      { iso(1) identified-organization(3) dod(6) internet(1)
        security(5) mechanisms(5) pkix(7) id-mod(0)
        id-mod-algorithmInformation-02(58) }

KEM-ALGORITHM
  FROM KEMAlgorithmInformation-2023
      { iso(1) identified-organization(3) dod(6) internet(1)
        security(5) mechanisms(5) pkix(7) id-mod(0)
```

```
          id-mod-kemAlgorithmInformation-2023(109) }
   ;


   --
   -- Object Identifiers
   --

   --
   -- Information Object Classes
   --

   pk-CompositeKEM {OBJECT IDENTIFIER:id}
     PUBLIC-KEY ::= {
       IDENTIFIER id
       -- KEY without ASN.1 wrapping --
       PARAMS ARE absent
       CERT-KEY-USAGE { keyEncipherment }
     }

   kema-CompositeKEM {
     OBJECT IDENTIFIER:id,
       PUBLIC-KEY:publicKeyType }
       KEM-ALGORITHM ::= {
            IDENTIFIER id
            -- VALUE without ASN.1 wrapping --
            PARAMS ARE absent
            PUBLIC-KEYS { publicKeyType }
            SMIME-CAPS { IDENTIFIED BY id }
           }



   --
   -- Composite KEM Algorithms
   --


   -- TODO: OID to be replaced by IANA
   id-MLKEM768-RSA2048-SHA3-256 OBJECT IDENTIFIER ::= {
     joint-iso-itu-t(2) country(16) us(840) organization(1)
     entrust(114027) algorithm(80) explicitcomposite(5) kem(2) 62 }

   pk-MLKEM768-RSA2048-SHA3-256 PUBLIC-KEY ::=
     pk-CompositeKEM {
       id-MLKEM768-RSA2048-SHA3-256 }

   kema-MLKEM768-RSA2048-SHA3-256 KEM-ALGORITHM ::=
```

```
    kema-CompositeKEM{
      id-MLKEM768-RSA2048-SHA3-256,
      pk-MLKEM768-RSA2048-SHA3-256 }



-- TODO: OID to be replaced by IANA
id-MLKEM768-RSA3072-SHA3-256 OBJECT IDENTIFIER ::= {
  joint-iso-itu-t(2) country(16) us(840) organization(1)
  entrust(114027) algorithm(80) explicitcomposite(5) kem(2) 63 }

pk-MLKEM768-RSA3072-SHA3-256 PUBLIC-KEY ::=
  pk-CompositeKEM {
    id-MLKEM768-RSA3072-SHA3-256 }

kema-MLKEM768-RSA3072-SHA3-256 KEM-ALGORITHM ::=
    kema-CompositeKEM{
      id-MLKEM768-RSA3072-SHA3-256,
      pk-MLKEM768-RSA3072-SHA3-256 }



-- TODO: OID to be replaced by IANA
id-MLKEM768-RSA4096-SHA3-256 OBJECT IDENTIFIER ::= {
  joint-iso-itu-t(2) country(16) us(840) organization(1)
  entrust(114027) algorithm(80) explicitcomposite(5) kem(2) 64 }

pk-MLKEM768-RSA4096-SHA3-256 PUBLIC-KEY ::=
  pk-CompositeKEM {
    id-MLKEM768-RSA4096-SHA3-256 }

kema-MLKEM768-RSA4096-SHA3-256 KEM-ALGORITHM ::=
    kema-CompositeKEM{
      id-MLKEM768-RSA4096-SHA3-256,
      pk-MLKEM768-RSA4096-SHA3-256 }



-- TODO: OID to be replaced by IANA
id-MLKEM768-X25519-SHA3-256 OBJECT IDENTIFIER ::= {
  joint-iso-itu-t(2) country(16) us(840) organization(1)
  entrust(114027) algorithm(80) explicitcomposite(5) kem(2) 65 }

pk-MLKEM768-X25519-SHA3-256 PUBLIC-KEY ::=
  pk-CompositeKEM {
    id-MLKEM768-X25519-SHA3-256 }

kema-MLKEM768-X25519-SHA3-256 KEM-ALGORITHM ::=
```

```
    kema-CompositeKEM{
      id-MLKEM768-X25519-SHA3-256,
      pk-MLKEM768-X25519-SHA3-256 }


-- TODO: OID to be replaced by IANA
id-MLKEM768-ECDH-P256-SHA3-256 OBJECT IDENTIFIER ::= {
  joint-iso-itu-t(2) country(16) us(840) organization(1)
  entrust(114027) algorithm(80) explicitcomposite(5) kem(2) 66 }

pk-MLKEM768-ECDH-P256-SHA3-256 PUBLIC-KEY ::=
  pk-CompositeKEM {
    id-MLKEM768-ECDH-P256-SHA3-256 }

kema-MLKEM768-ECDH-P256-SHA3-256 KEM-ALGORITHM ::=
    kema-CompositeKEM{
      id-MLKEM768-ECDH-P256-SHA3-256,
      pk-MLKEM768-ECDH-P256-SHA3-256 }



-- TODO: OID to be replaced by IANA
id-MLKEM768-ECDH-P384-SHA3-256 OBJECT IDENTIFIER ::= {
  joint-iso-itu-t(2) country(16) us(840) organization(1)
  entrust(114027) algorithm(80) explicitcomposite(5) kem(2) 67 }

pk-MLKEM768-ECDH-P384-SHA3-256 PUBLIC-KEY ::=
  pk-CompositeKEM {
    id-MLKEM768-ECDH-P384-SHA3-256 }

kema-MLKEM768-ECDH-P384-SHA3-256 KEM-ALGORITHM ::=
    kema-CompositeKEM{
      id-MLKEM768-ECDH-P384-SHA3-256,
      pk-MLKEM768-ECDH-P384-SHA3-256 }



-- TODO: OID to be replaced by IANA
id-MLKEM768-ECDH-brainpoolP256r1-SHA3-256 OBJECT IDENTIFIER ::= {
  joint-iso-itu-t(2) country(16) us(840) organization(1)
  entrust(114027) algorithm(80) explicitcomposite(5) kem(2) 68 }

pk-MLKEM768-ECDH-brainpoolP256r1-SHA3-256 PUBLIC-KEY ::=
  pk-CompositeKEM {
    id-MLKEM768-ECDH-brainpoolP256r1-SHA3-256 }

kema-MLKEM768-ECDH-brainpoolP256r1-SHA3-256 KEM-ALGORITHM ::=
    kema-CompositeKEM{
```

```
        id-MLKEM768-ECDH-brainpoolP256r1-SHA3-256,
        pk-MLKEM768-ECDH-brainpoolP256r1-SHA3-256 }


  -- TODO: OID to be replaced by IANA
  id-MLKEM1024-RSA3072-SHA3-256 OBJECT IDENTIFIER ::= {
    joint-iso-itu-t(2) country(16) us(840) organization(1)
    entrust(114027) algorithm(80) explicitcomposite(5) kem(2) 69 }

  pk-MLKEM1024-RSA3072-SHA3-256 PUBLIC-KEY ::=
    pk-CompositeKEM {
      id-MLKEM1024-RSA3072-SHA3-256 }

  kema-MLKEM1024-RSA3072-SHA3-256 KEM-ALGORITHM ::=
      kema-CompositeKEM{
        id-MLKEM1024-RSA3072-SHA3-256,
        pk-MLKEM1024-RSA3072-SHA3-256 }


  -- TODO: OID to be replaced by IANA
  id-MLKEM1024-ECDH-P384-SHA3-256 OBJECT IDENTIFIER ::= {
    joint-iso-itu-t(2) country(16) us(840) organization(1)
    entrust(114027) algorithm(80) explicitcomposite(5) kem(2) 70 }

  pk-MLKEM1024-ECDH-P384-SHA3-256 PUBLIC-KEY ::=
    pk-CompositeKEM {
      id-MLKEM1024-ECDH-P384-SHA3-256 }

  kema-MLKEM1024-ECDH-P384-SHA3-256 KEM-ALGORITHM ::=
      kema-CompositeKEM{
        id-MLKEM1024-ECDH-P384-SHA3-256,
        pk-MLKEM1024-ECDH-P384-SHA3-256 }


  -- TODO: OID to be replaced by IANA
  id-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256 OBJECT IDENTIFIER ::= {
    joint-iso-itu-t(2) country(16) us(840) organization(1)
    entrust(114027) algorithm(80) explicitcomposite(5) kem(2) 71 }

  pk-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256 PUBLIC-KEY ::=
    pk-CompositeKEM{
      id-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256 }

  kema-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256 KEM-ALGORITHM ::=
      kema-CompositeKEM{
        id-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256,
        pk-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256 }
```

```
-- TODO: OID to be replaced by IANA
id-MLKEM1024-X448-SHA3-256 OBJECT IDENTIFIER ::= {
  joint-iso-itu-t(2) country(16) us(840) organization(1)
  entrust(114027) algorithm(80) explicitcomposite(5) kem(2) 72 }

pk-MLKEM1024-X448-SHA3-256 PUBLIC-KEY ::=
  pk-CompositeKEM {
    id-MLKEM1024-X448-SHA3-256 }

kema-MLKEM1024-X448 KEM-ALGORITHM ::=
    kema-CompositeKEM{
      id-MLKEM1024-X448-SHA3-256,
      pk-MLKEM1024-X448-SHA3-256 }


-- TODO: OID to be replaced by IANA
id-MLKEM1024-ECDH-P521-SHA3-256 OBJECT IDENTIFIER ::= {
  joint-iso-itu-t(2) country(16) us(840) organization(1)
  entrust(114027) algorithm(80) explicitcomposite(5) kem(2) 73 }

pk-MLKEM1024-ECDH-P521-SHA3-256 PUBLIC-KEY ::=
  pk-CompositeKEM {
    id-MLKEM1024-ECDH-P521-SHA3-256 }

kema-MLKEM1024-ECDH-P521-SHA3-256 KEM-ALGORITHM ::=
    kema-CompositeKEM{
      id-MLKEM1024-ECDH-P521-SHA3-256,
      pk-MLKEM1024-ECDH-P521-SHA3-256 }

END
```

<CODE ENDS>

9. IANA Considerations

9.1. Object Identifier Allocations

EDNOTE to IANA: OIDs will need to be replaced in both the ASN.1 module and in Section 7.

9.1.1. Module Registration

The following is to be registered in "SMI Security for PKIX Module Identifier":

* Decimal: IANA Assigned - *Replace TBDMOD*

* Description: Composite-KEM-2023 - id-mod-composite-kems

* References: This Document

9.1.2. Object Identifier Registrations

The following is to be registered in "SMI Security for PKIX Algorithms":

* id-MLKEM768-RSA2048-SHA3-256
  - Decimal: IANA Assigned
  - Description: id-MLKEM768-RSA2048-SHA3-256
  - References: This Document
* id-MLKEM768-RSA3072-SHA3-256
  - Decimal: IANA Assigned
  - Description: id-MLKEM768-RSA3072-SHA3-256
  - References: This Document
* id-MLKEM768-RSA4096-SHA3-256
  - Decimal: IANA Assigned
  - Description: id-MLKEM768-RSA4096-SHA3-256
  - References: This Document
* id-MLKEM768-ECDH-P256-SHA3-256
  - Decimal: IANA Assigned
  - Description: id-MLKEM768-ECDH-P256-SHA3-256
  - References: This Document
* id-MLKEM768-ECDH-P384-SHA3-256
  - Decimal: IANA Assigned
  - Description: id-MLKEM768-ECDH-P384-SHA3-256
  - References: This Document
* id-MLKEM768-ECDH-brainpoolP256r1-SHA3-256

   - Decimal: IANA Assigned

   - Description: id-MLKEM768-ECDH-brainpoolP256r1-SHA3-256

   - References: This Document

* id-MLKEM768-X25519-SHA3-256

   - Decimal: IANA Assigned

   - Description: id-MLKEM768-X25519-SHA3-256

   - References: This Document

* id-MLKEM1024-RSA3072-SHA3-256

   - Decimal: IANA Assigned

   - Description: id-MLKEM1024-RSA3072-SHA3-256

   - References: This Document

* id-MLKEM1024-ECDH-P384-SHA3-256

   - Decimal: IANA Assigned

   - Description: id-MLKEM1024-ECDH-P384-SHA3-256

   - References: This Document

* id-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256

   - Decimal: IANA Assigned

   - Description: id-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256

   - References: This Document

* id-MLKEM1024-X448-SHA3-256

   - Decimal: IANA Assigned

   - Description: id-MLKEM1024-X448-SHA3-256

   - References: This Document

* id-MLKEM1024-ECDH-P521-SHA3-256

- Decimal: IANA Assigned

- Description: id-MLKEM1024-ECDH-P521-SHA3-256

- References: This Document

10. Security Considerations

10.1. Why Hybrids?

In broad terms, a PQ/T Hybrid can be used either to provide dual-algorithm security or to provide migration flexibility. Let’s quickly explore both.

Dual-algorithm security. The general idea is that the data is protected by two algorithms such that an attacker would need to break both in order to compromise the data. As with most of cryptography, this property is easy to state in general terms, but becomes more complicated when expressed in formalisms. The following sections go into more detail here.

Migration flexibility. Some PQ/T hybrids exist to provide a sort of "OR" mode where the application can choose to use one algorithm or the other or both. The intention is that the PQ/T hybrid mechanism builds in backwards compatibility to allow legacy and upgraded applications to co-exist and communicate. The composite algorithms presented in this specification do not provide this since they operate in a strict "AND" mode. They do, however, provide codebase migration flexibility. Consider that an organization has today a mature, validated, certified, hardened implementation of RSA or ECC; composites allow them to add an ML-KEM implementation which immediately starts providing benefits against harvest-now-decrypt-later attacks even if that ML-KEM implementation is still an experimental, non-validated, non-certified, non-hardened implementation. More details of obtaining FIPS certification of a composite algorithm can be found in Section 11.1.

10.2. KEM Combiner

The KEM combiner from Section 4.4 is reproduced here for reference.

```
KDF(mlkemSS || tradSS || tradCT || tradPK || Label)
```

Figure 3: KEM combiner construction

The primary security property of the KEM combiner is that it preserves IND-CCA2 of the overall Composite ML-KEM so long as at least one component is IND-CCA2 [X-Wing] [GHP18]. Additionally, we also need to consider the case where one of the component algorithms is completely broken; that the private key is known to an attacker, or worse that the public key, private key, and ciphertext are manipulated by the attacker. In this case, we rely on the construction of the KEM combiner to ensure that the value of the other shared secret key cannot be leaked or the combined shared secret key predicted via manipulation of the broken algorithm.

Each registered Composite ML-KEM algorithm specifies the choice of KDF and Label -- see Section 7. Given that each Composite ML-KEM algorithm fully specifies the component algorithms, including for example the size of the RSA modulus, all inputs to the KEM combiner are fixed-size and thus do not require length-prefixing.

* mlkemSS is always 32 bytes.

* tradSS in the case of DH this is derived by the decapsulator and therefore the length is not controlled by the attacker, however in the case of RSA-OAEP this value is directly chosen by the sender and both the length and content could be freely chosen by an attacker.

* tradCT is either an elliptic curve public key or an RSA-OAEP ciphertext which is required to have its length checked by step 1b of RSAES-OAEP-DECRYPT in [RFC8017].

* tradPK is the public key of the traditional component (elliptic curve or RSA) and therefore fixed-length.

* Label is a fixed value specified in this document.

10.2.1. IND-CCA Security of the hybrid scheme

Informally, a Composite ML-KEM algorithm is secure if the combiner (SHA3) is secure, and either ML-KEM is secure or the traditional component (RSA-OAEP, ECDH, X25519 or X448) is secure.

The security of ML-KEM and DH hybrids is covered in [X-Wing] and requires that the first KEM component (ML-KEM in this construction) is IND-CCA and second ciphertext preimage resistant (C2PRI) and that the second traditional component is IND-CCA. This design choice improves performance by not including the large ML-KEM public key and ciphertext, but means that an implementation error in the ML-KEM component that affects the ciphertext check step of the FO transform could result in the overall composite no longer achieving IND-CCA2 security. Note that ciphertext collisions exist in the traditional component by the composite design choice to support any underlying encoding of the traditional component, such as compressed vs uncompressed EC points as the DH KEM ciphertext. This solution remains IND-CCA due to binding the tradPK and tradCT in the KEM combiner.

The QSF framework presented in [X-Wing] is extended to cover RSA-OAEP as the traditional algorithm in place of DH by noting that RSA-OAEP is also IND-CCA secure [RFC8017].

The composite combiner cannot be assumed to be secure when used with different KEMs and a more cautious approach would bind the public key and ciphertext of the first KEM as well.

10.2.2. Second pre-image resistance of component KEMs

The notion of a "ciphertext second pre-image resistant KEM" is defined in [X-Wing] as being the property that it is computationally difficult to find two different ciphertexts c != c′ that will decapsulate to the same shared secret key under the same public key. For the purposes of a hybrid KEM combiner, this property means that given two composite ciphertexts (c1, c2) and (c1′, c2′), we must obtain a unique overall shared secret key so long as either c1 != c1′ or c2 != c2′ -- i.e. the overall Composite ML-KEM is ciphertext second pre-image resistant, and therefore secure so long as one of the component KEMs is secure.

In [X-Wing] it is proven that ML-KEM is a second pre-image resistant KEM and therefore the ML-KEM ciphertext can safely be omitted from the KEM combiner. Note that this makes a fundamental assumption on ML-KEM remaining ciphertext second pre-image resistant, and therefore this formulation of KEM combiner does not fully protect against implementation errors in the ML-KEM component -- particularly around the ciphertext check step of the Fujisaki-Okamoto transform -- which could trivially lead to second ciphertext pre-image attacks that break the IND-CCA2 security of the ML-KEM component and of the overall Composite ML-KEM. This could be more fully mitigated by binding the ML-KEM ciphertext in the combiner, but a design decision was made to settle for protection against algorithmic attacks and not implementation attacks against ML-KEM in order to increase performance.

However, since neither RSA-OAEP nor DH guarantee second pre-image resistance at all, even in a correct implementation, these ciphertexts are bound to the key derivation in order to guarantee that c != c′ will yield a unique ciphertext, and thus restoring second pre-image resistance to the overall Composite ML-KEM.

10.2.3. Generifying this construction

It should be clear that the security analysis of the presented KEM combiner construction relies heavily on the specific choices of component algorithms and combiner KDF, and this combiner construction SHOULD NOT by applied to any other combination of ciphers without performing the appropriate security analysis.

10.3. Key Reuse

While conformance with this specification requires that both components of a composite key MUST be freshly generated, the designers are aware that some implementers may be forced to break this rule due to operational constraints. This section documents the implications of doing so.

When using single-algorithm cryptography, the best practice is to always generate fresh keying material for each purpose, for example when renewing a certificate, or obtaining both a TLS and S/MIME certificate for the same device. However, in practice key reuse in such scenarios is not always catastrophic to security and therefore often tolerated. However this reasoning does not hold in the PQ/T hybrid setting.

Within the broader context of PQ/T hybrids, we need to consider new attack surfaces that arise due to the hybrid constructions and did not exist in single-algorithm contexts. One of these is key reuse where the component keys within a hybrid are also used by themselves within a single-algorithm context. For example, it might be tempting for an operator to take already-deployed RSA keys and add an ML-KEM key to them to form a hybrid. Within a hybrid signature context this leads to a class of attacks referred to as "stripping attacks" where one component signature can be extracted and presented as a single-algorithm signature. Hybrid KEMs using a concatenation-style KEM combiner, as is done in this specification, do not have the analogous attack surface because even if an attacker is able to extract and decrypt one of the component ciphertexts, this will yield a different shared secret key than the overall shared secret key derived from the composite, so any subsequent symmetric cryptographic operations will fail.

In addition, there is a further implication to key reuse regarding certificate revocation. Upon receiving a new certificate enrolment request, many certification authorities will check if the requested public key has been previously revoked due to key compromise. Often a CA will perform this check by using the public key hash. Therefore, if one, or even both, components of a composite have been previously revoked, the CA may only check the hash of the combined composite key and not find the revocations. Therefore, because the possibility of key reuse exists even though forbidden in this specification, CAs performing revocation checks on a composite key SHOULD also check both component keys independently to verify that the component keys have not been revoked.

10.4. Decapsulation failure

Provided all inputs are well-formed, the key establishment procedure of ML-KEM will never explicitly fail. Specifically, the ML-KEM.Encaps() and ML-KEM.Decaps() algorithms from [FIPS.203] will always output a value with the same data type as a shared secret key, and will never output an error or failure symbol. However, it is possible (though extremely unlikely) that the process will fail in the sense that ML-KEM.Encaps() and ML-KEM.Decaps() will produce different outputs, even though both of them are behaving honestly and no adversarial interference is present. This is due to the lattice arithmetic for decapsulation with the secret key having hit an unrecoverable degenerate case that could not have been predicted by the encapsulator without knowledge of the secret key. In this case, the sender and recipient clearly did not succeed in producing a shared secret key. This event is called a decapsulation failure. Estimates for the decapsulation failure probability (or rate) for each of the ML-KEM parameter sets are provided in Table 1 of [FIPS.203] and reproduced here in Table 3.

Parameter set	Decapsulation failure rate
ML-KEM-512	2^(-139)
ML-KEM-768	2^(-164)
ML-KEM-1024	2^(-174)

Table 3: ML-KEM decapsulation failure rates

In the case of ML-KEM decapsulation failure, Composite ML-KEM MUST preserve the same behavior and return a well-formed output shared secret key.

10.5. Policy for Deprecated and Acceptable Algorithms

Traditionally, a public key or certificate contains a single cryptographic algorithm. If and when an algorithm becomes deprecated (for example, RSA-512, or SHA1), the path to deprecating it through policy and removing it from operational environments is, at least is principle, straightforward.

In the composite model this is less obvious since a PQ/T hybrid is expected to still be considered valid after the traditional component is deprecated for individual use. As such, a single composite public key or certificate may contain a mixture of deprecated and non-deprecated algorithms. In general this should be manageable through policy by removing OIDs for the standalone component algorithms while still allowing OIDs for composite algorithms. However, complications may arise when the composite implementation needs to invoke the cryptographic module for a deprecated component algorithm. In particular, this could lead to complex Cryptographic Bills of Materials that show implementations of deprecated algorithms still present and being used.

11. Implementation Considerations

11.1. FIPS Certification

The following sections give guidance to implementers wishing to FIPS-certify a composite implementation.

This guidance is not authoritative and has not been endorsed by NIST.

Implementers seeking FIPS certification of a composite KEM algorithm where only one of the component algorithms has been FIPS-validated or FIPS-approved should credit the FIPS-validated component algorithm with full security strength, the non-FIPS-validated component algorithm with zero security, and the overall composite should be considered at least as strong and thus FIPS-approved.

The composite algorithm has been designed to treat the underlying primitives as "black-box implementations" and not impose any additional requirements on them that could require an existing implementation of an underlying primitive to run in a mode different from the one under which it was certified. For example, the KeyGen defined in Section 4.1 invokes ML-KEM.KeyGen(seed) which might not be available in a cryptographic module running in FIPS-mode, but Section 4.1 is only a suggested implementation and the composite KeyGen MAY be implemented using a different available interface for ML-KEM.KeyGen.

The authors wish to note that composite algorithms provide a design pattern to provide utility in future situations that require care to remain FIPS-compliant, such as future cryptographic migrations as well as bridging across jurisdictions with non-intersecting cryptographic requirements.

The following sections go into further detail on specific issues that relate to FIPS certification.

11.1.1. Combiner Function

For reference, the KEM combiner used in Composite ML-KEM is:

```
ss = SHA3-256(mlkemSS || tradSS || tradCT || tradPK || Label)
```

NIST SP 800-227 [SP-800-227] allows hybrid key combiners of the following form:

```
K <- KDM((S1,S2,...,St), OtherInput)          (14)
```

Composite ML-KEM maps cleanly into this since it places the two shared secret keys mlkemSS || tradSS at the beginning of the KDF input such that all other inputs tradCT || tradPK || Label can be considered part of OtherInput for the purposes of FIPS certification.

For the detailed steps of the Key Derivation Mechanism KDM, [SP-800-227] refers to [SP.800-56Cr2].

Compliance of the Composite ML-KEM variants is achieved in the following way:

The Composite ML-KEM algorithms use SHA3, and so can be certified under [SP.800-56Cr2] One-Step Key Derivation Option 1: H(x) = hash(x).

[SP.800-56Cr2] section 4 "One-Step Key Derivation" requires a counter which begins at the 4-byte value 0x00000001. However, the counter is allowed to be omitted when the hash function is executed only once, as specified on page 159 of the FIPS 140-3 Implementation Guidance [FIPS-140-3-IG].

11.1.2. Order of KDF inputs with Non-Approved Algorithms

[SP-800-227] adds an important stipulation that was not present in earlier NIST specifications:

> This publication approves the use of the key combiner (14) for any t > 1, so long as at least one shared secret (i.e., S_j for some j) is a shared secret generated from the key- establishment methods of SP 800-56A or SP 800-56B, or an approved KEM.

This means that although Composite ML-KEM always places the shared secret key from ML-KEM in the first slot, a Composite ML-KEM can be FIPS certified so long as either component is FIPS certified. This is important for several reasons. First, in the early stages of PQC migration, composites allow for a non-FIPS certified ML-KEM implementation to be added to a module that already has a FIPS certified traditional component, and the resulting composite can be FIPS certified. Second, when eventually RSA and Elliptic Curve are no longer FIPS-allowed, the composite can retain its FIPS certified status on the strength of the ML-KEM component. Third, while this is outside the scope of this specification, the general composite construction could be used to create FIPS certified algorithms that contain a component algorithm from a different jurisdiction. Third, a composite where both components are FIPS-certified could allow an implementer to patch one component algorithm while awaiting re-certification while continuing to use the overall composite in FIPS mode.

At the time of writing, [SP-800-227] is in its public draft period and not yet in force. A Composite ML-KEM implementation using a FIPS-certified traditional component and a non-FIPS certified ML-KEM is not believed to be certifiable under [SP.800-56Cr2] since this requires the shared secret key from the certified algorithm to be in the first slot.

11.2. Backwards Compatibility

The term "backwards compatibility" is used here to mean that existing systems as they are deployed today can interoperate with the upgraded systems of the future. This draft explicitly does not provide backwards compatibility, only upgraded systems will understand the OIDs defined in this specification.

These migration and interoperability concerns need to be thought about in the context of various types of protocols that make use of X.509 and PKIX with relation to key establishment and content encryption, from online negotiated protocols such as TLS 1.3 [RFC8446] and IKEv2 [RFC7296], to non-negotiated asynchronous protocols such as S/MIME signed email [RFC8551], as well as myriad other standardized and proprietary protocols and applications that leverage CMS [RFC5652] encrypted structures.

11.3. Profiling down the number of options

One daunting aspect of this specification is the number of composite algorithm combinations. Each option has been specified because there is a community that has a direct application for it; typically because the traditional component is already deployed in a change-managed environment, or because that specific traditional component is required for regulatory reasons.

However, this large number of combinations leads either to fracturing of the ecosystem into non-interoperable sub-groups when different communities choose non-overlapping subsets to support, or on the other hand it leads to spreading development resources too thin when trying to support all options.

This specification does not list any particular composite algorithm as mandatory-to-implement, however organizations that operate within specific application domains are encouraged to define profiles that select a small number of composites appropriate for that application domain. For applications that do not have any regulatory requirements or legacy implementations to consider, it is RECOMMENDED to focus implementation effort on:

```
id-MLKEM768-X25519-SHA3-256  (aka "X-Wing")
id-MLKEM768-ECDH-P256-SHA3-256
```

In applications that only allow NIST PQC Level 5, it is RECOMMENDED to focus implementation effort on:

```
id-MLKEM1024-ECDH-P384-SHA3-256
```

11.4. Decapsulation Requires the Public Key

ML-KEM always requires the public key in order to perform various steps of the Fujisaki-Okamoto decapsulation [FIPS.203], and for this reason the private key encoding specified in FIPS 203 includes the public key.

Moreover, the KEM combiner as specified in Section 4.4 requires the public key of the traditional component in order to achieve the public-key binding property and ciphertext collision resistance as described in Section 10.2. For this reason, the private key serialization defined in Section 5.2 carries the traditional public key so that it is easily available to the decapsulater.

Implementers who choose to use a different private key encoding than the one specified in this document MUST consider how to provide the component public keys to the decapsulate routine. This includes, for example, implementations that use a hardware security module to hold the private key. While some implementations might contain routines to computationally derive the public key from the private key, it is not guaranteed that all implementations will support this. In some implementations, the application might be required to cache the public key or certificate associated with the private key so that the public key can be retrieved for the purposes of decapsulation.

12. References

12.1. Normative References

[FIPS.202] National Institute of Standards and Technology (NIST), "SHA-3 Standard: Permutation-Based Hash and Extendable-Output Functions", August 2015, <https://nvlpubs.nist.gov/nistpubs/FIPS/NIST.FIPS.202.pdf>.

[FIPS.203] National Institute of Standards and Technology (NIST), "Module-Lattice-based Key-Encapsulation Mechanism Standard", August 2024, <https://nvlpubs.nist.gov/nistpubs/FIPS/NIST.FIPS.203.pdf>.

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Appendix A. Maximum Key and Ciphertext Sizes

The sizes listed below are maximum values: several factors could cause fluctuations in the size of the traditional component. For example, this could be due to:

* Compressed vs uncompressed EC point.

* The RSA public key (n, e) allows e to vary is size between 3 and n - 1 [RFC8017]. Note that the size table below assumes the recommended value of e = 65537, so for RSA combinations it is in fact not a true maximum.

* When the underlying RSA or EC value is itself DER-encoded, integer values could occasionally be shorter than expected due to leading zeros being dropped from the encoding.

By contrast, ML-KEM values are always fixed size, so composite values can always be correctly de-serialized based on the size of the ML-KEM component.

Size values marked with an asterisk in the table are not fixed but maximum possible values for the composite key or ciphertext. Implementations MUST NOT perform strict length checking based on such values.

Non-hybrid ML-KEM is included for reference.

Algorithm	Public key	Private key	Ciphertext	SS
id-alg-ml-kem-768	1184	64	1088	32
id-alg-ml-kem-1024	1568	64	1568	32
id-MLKEM768-RSA2048-SHA3-256	1454*	1530*	1344	32
id-MLKEM768-RSA3072-SHA3-256	1582*	2234*	1472	32
id-MLKEM768-RSA4096-SHA3-256	1710*	2943*	1600	32
id-MLKEM768-X25519-SHA3-256	1216	130	1120	32
id-MLKEM768-ECDH-P256-SHA3-256	1249	182	1153	32
id-MLKEM768-ECDH-P384-SHA3-256	1281	227	1185	32
id-MLKEM768-ECDH-brainpoolP256r1-SHA3-256	1249	183	1153	32
id-MLKEM1024-RSA3072-SHA3-256	1966*	2234*	1952	32
id-MLKEM1024-ECDH-P384-SHA3-256	1665	227	1665	32
id-MLKEM1024-ECDH-brainpoolP384r1-SHA3-256	1665	231	1665	32
id-MLKEM1024-X448-SHA3-256	1624	178	1624	32
id-MLKEM1024-ECDH-P521-SHA3-256	1701	281	1701	32

Table 4: Maximum size values of composite ML-KEM

Appendix B. Component Algorithm Reference

This section provides references to the full specification of the algorithms used in the composite constructions.

Component KEM Algorithm ID	OID	Specification
id-ML-KEM-768	2.16.840.1.101.3.4.4.2	[FIPS.203]
id-ML-KEM-1024	2.16.840.1.101.3.4.4.3	[FIPS.203]
id-X25519	1.3.101.110	[RFC7748], [RFC8410]
id-X448	1.3.101.111	[RFC7748], [RFC8410]
id-ecDH	1.3.132.1.12	[RFC5480], [RFC5915], [SEC1]
id-RSAES-OAEP	1.2.840.113549.1.1.7	[RFC8017]

Table 5: Component Encryption Algorithms used in Composite Constructions

Elliptic CurveID	OID	Specification
secp256r1	1.2.840.10045.3.1.7	[RFC6090], [SEC2]
secp384r1	1.3.132.0.34	[RFC6090], [SEC2]
secp521r1	1.3.132.0.35	[RFC6090], [SEC2]
brainpoolP256r1	1.3.36.3.3.2.8.1.1.7	[RFC5639]
brainpoolP384r1	1.3.36.3.3.2.8.1.1.11	[RFC5639]

Table 6: Elliptic Curves used in Composite Constructions

HashID	OID	Specification
id-sha256	2.16.840.1.101.3.4.2.1	[RFC6234]
id-sha512	2.16.840.1.101.3.4.2.3	[RFC6234]
id-sha3-256	2.16.840.1.101.3.4.2.8	[FIPS.202]

Table 7: Hash algorithms used in Composite Constructions

Appendix C. Fixed Component Algorithm Identifiers

Many cryptographic libraries are X.509-focused and do not expose interfaces to instantiate a public key from raw bytes, but only from a SubjectPublicKeyInfo structure as you would find in an X.509 certificate, therefore implementing composite in those libraries requires reconstructing the SPKI for each component algorithm. In order to aid implementers and reduce interoperability issues, this section lists out the full public key and signature AlgorithmIdentifiers for each component algorithm.

ML-KEM-768

ASN.1:
```
algorithm AlgorithmIdentifier ::= {
  algorithm id-alg-ml-kem-768   -- (2.16.840.1.101.3.4.4.2)
  }
```

DER:
```
30 0B 06 07 60 86 48 01 65 03 04 04 02
```

ML-KEM-1024

ASN.1:

ASN.1:
```
algorithm AlgorithmIdentifier ::= {
  algorithm id-alg-ml-kem-1024   -- (2.16.840.1.101.3.4.4.3)
  }
```

DER:
```
30 0B 06 07 60 86 48 01 65 03 04 04 03
```

RSA-OAEP - all sizes

ASN.1:

```
algorithm AlgorithmIdentifier ::= {
  algorithm id-RSAES-OAEP,   -- (1.2.840.113549.1.1.7)
  parameters RSAES-OAEP-params {
       hashFunc      [0] id-sha256,  -- (2.16.840.1.101.3.4.2.1)
       maskGenFunc   [1] mgf1SHA256Identifier,
       pSourceFunc   [2] pSpecifiedEmpty  }
  }
```

where

```
      mgf1SHA256Identifier  AlgorithmIdentifier  ::=  {
                            algorithm id-mgf1,  -- (1.2.840.113549.1.1.8)
                            parameters sha256Identifier }


      sha256Identifier  AlgorithmIdentifier  ::=  { id-sha256, NULL }
```

DER:

```
 30 4D 06 09 2A 86 48 86 F7 0D 01 01 07 30 40 A0 0F 30 0D 06 09 60 86
 48 01 65 03 04 02 01 05 00 A1 1C 30 1A 06 09 2A 86 48 86 F7 0D 01 01
 08 30 0D 06 09 60 86 48 01 65 03 04 02 01 05 00 A2 0F 30 0D 06 09 2A
 86 48 86 F7 0D 01 01 09 04 00
```

ECDH NIST-P-256

ASN.1:

```
algorithm AlgorithmIdentifier ::= {
  algorithm id-ecPublicKey   -- (1.2.840.10045.2.1)
  parameters ANY ::= {
    AlgorithmIdentifier ::= {
      algorithm secp256r1    -- (1.2.840.10045.3.1.7)
      }
    }
  }
```

DER:

```
30 13 06 07 2A 86 48 CE 3D 02 01 06 08 2A 86 48 CE 3D 03 01 07
```

ECDH NIST-P-384

```
ASN.1:
  algorithm AlgorithmIdentifier ::= {
    algorithm id-ecPublicKey   -- (1.2.840.10045.2.1)
    parameters ANY ::= {
      AlgorithmIdentifier ::= {
        algorithm secp384r1    -- (1.3.132.0.34)
        }
      }
    }

DER:
  30 10 06 07 2A 86 48 CE 3D 02 01 06 05 2B 81 04 00 22
```

ECDH NIST-P-521

```
ASN.1:
  algorithm AlgorithmIdentifier ::= {
    algorithm id-ecPublicKey   -- (1.2.840.10045.2.1)
    parameters ANY ::= {
      AlgorithmIdentifier ::= {
        algorithm secp521r1    -- (1.3.132.0.35)
        }
      }
    }

DER:
  30 10 06 07 2A 86 48 CE 3D 02 01 06 05 2B 81 04 00 23
```

ECDH Brainpool-256

```
ASN.1:
  algorithm AlgorithmIdentifier ::= {
    algorithm id-ecPublicKey   -- (1.2.840.10045.2.1)
    parameters ANY ::= {
      AlgorithmIdentifier ::= {
        algorithm brainpoolP256r1   -- (1.3.36.3.3.2.8.1.1.7)
        }
      }
    }

DER:
  30 14 06 07 2A 86 48 CE 3D 02 01 06 09 2B 24 03 03 02 08 01 01 07
```

ECDH Brainpool-384

```
ASN.1:
  algorithm AlgorithmIdentifier ::= {
    algorithm id-ecPublicKey   -- (1.2.840.10045.2.1)
    parameters ANY ::= {
      AlgorithmIdentifier ::= {
        algorithm brainpoolP384r1   -- (1.3.36.3.3.2.8.1.1.11)
        }
      }
    }

DER:
  30 14 06 07 2A 86 48 CE 3D 02 01 06 09 2B 24 03 03 02 08 01 01 0B
```

X25519

```
ASN.1:
  algorithm AlgorithmIdentifier ::= {
    algorithm id-X25519   -- (1.3.101.110)
    }

DER:
  30 05 06 03 2B 65 6E
```

X448

```
ASN.1:
  algorithm AlgorithmIdentifier ::= {
    algorithm id-X448   -- (1.3.101.111)
    }

DER:
  30 05 06 03 2B 65 6F
```

Appendix D. Comparison with other Hybrid KEMs

D.1. X-Wing

This specification borrows extensively from the analysis and KEM combiner construction presented in [X-Wing]. In particular, X-Wing and id-MLKEM768-X25519-SHA3-256 are largely interchangeable. The one difference is that X-Wing uses a combined KeyGen function to generate the two component private keys from the same seed, which gives some additional binding properties. However, using a derived value as the seed for ML-KEM.KeyGen_internal() is, at time of writing, explicitly disallowed by [FIPS.203] which makes it impossible to create a FIPS-compliant implementation of X-Wing’s KeyGen or private key import functionality. For this reason, this specification keeps the key generation for both components separate and only loosely-specified so that implementers are free to use an existing certified hardware or software module for one or both components.

Due to the difference in key generation and security properties, X-Wing and id-MLKEM768-X25519-SHA3-256 have been registered as separate algorithms with separate OIDs, and they use a different KEM Combiner Label in order to ensure that their ciphertexts are not inter-compatible.

D.2. ETSI CatKDF

[ETSI.TS.103.744] section 8.2.3 defines CatKDF as:

```
1) Form secret = psk || k1 || k 2.
2) Set context = f(info, MA, MB), where f is a context formatting
   function.
3) key_material = KDF(secret, label, context, length).
4) Return key_material.

MA shall contain all of the public keys.
MB shall contain all of the corresponding public keys and ciphertexts.
```

The main difference between the Composite ML-KEM combiner and the ETSI CatKDF combiner is that CatKDF makes the more conservative choice to bind the public keys and ciphertexts of both components, while Composite ML-KEM follows the analysis presented in [X-Wing] that while preserving the security properties of the traditional component requires binding the public key and ciphertext of the traditional component, it is not necessary to do so for ML-KEM thanks to the rejection sampling step of the Fujisaki-Okamoto transform.

Additionally, ETSI CatKDF can be instantiated with either HMAC [RFC2104], KMAC [SP.800-185] or HKDF [RFC5869] as KDF. Since this specification uses SHA3-256 as the KDF for all variants, there is no equivalent construction of CatKDF.

Appendix E. Examples of KEM Combiner Intermediate Values

This section provides examples of constructing the input for the KEM Combiner, showing all intermediate values. This is intended to be useful for debugging purposes. See Section 4.4 for additional information.

Each input component is shown. Note that values are shown hex-encoded for display purposes only, they are actually raw binary values.

* mlkemSS is the shared secret produced by the ML-KEM encapsulate or decapsulate function which is always 32 bytes.

* tradSS is the shared secret produce by the traditional algorithm.

* tradCT is either an elliptic curve public key or an RSA-OAEP ciphertext depending on the algorithm chosen.

* tradPK is the public key of the traditional component (elliptic curve or RSA) and therefore fixed-length.

* Label is the specific KEM Combiner Label for this composite algorithm. See Section 7

Next, the Combined KDF Input is given, which is simply the concatenation of the above values.

Finally, the KDF Function and the ss Output are shown as outputs. The ss is the Composite ML-KEM shared-secret generated by applying the KDF to the Combined KDF Input.

Examples are given for each recommended Composite ML-KEM algorithm from Section 11.3, which happens to demonstrate all three combiner functions.

Example 1:

Example of id-MLKEM768-ECDH-P256-SHA3-256 Combiner function output.

```
# Inputs
mlkemSS:
8e85b00024a24039c5da29c22772d11bb4759e14345c0d0ff7a41502ffe26d68

tradSS:
124b95eff40dbe5e109d934593935cbfcaad65068cba7363a0c57b3a41b59651

tradCT:  04bf0749b0989f902446576b10282c29b2dde656a47e4380ebda4b215c
0185caf4b65ddc3d407757fb7d12f01fb3a95de13588c2949c8c48c039732192223
1e5d4

tradPK:  0468e89465c288edbac25623e558f9be99d15380ffec9442b0aeb3abf0
67b2234fc410a2e81a464441fc2e83b4152192ab60796542168b2c599348432ef6a
d5b2d

Label:  5153462d4d4c4b454d3736382d503235362d53484133323536

        (ascii: "QSF-MLKEM768-P256-SHA3256")


# Combined KDF Input:
#  mlkemSS || tradSS || tradCT || tradPK || Label

Combined KDF Input: 8e85b00024a24039c5da29c22772d11bb4759e14345c0d0
ff7a41502ffe26d68124b95eff40dbe5e109d934593935cbfcaad65068cba7363a0
c57b3a41b5965104bf0749b0989f902446576b10282c29b2dde656a47e4380ebda4
b215c0185caf4b65ddc3d407757fb7d12f01fb3a95de13588c2949c8c48c0397321
922231e5d40468e89465c288edbac25623e558f9be99d15380ffec9442b0aeb3abf
067b2234fc410a2e81a464441fc2e83b4152192ab60796542168b2c599348432ef6
ad5b2d5153462d4d4c4b454d3736382d503235362d53484133323536


# Outputs
# ss = SHA3-256(Combined KDF Input)

ss:
87c945015f267ca3a96f794c9dfce00b4bdb4596030e034d0c04cdc5dcf50065
```

Example 2:

```
Example of id-MLKEM768-X25519-SHA3-256 Combiner function output.

# Inputs
mlkemSS:
b191c0384d3a5c3921fd2fe63fdb87a9156d3e73efb9c5ebf0e2cc00a2087643

tradSS:
e8247eb791cc06cb8e50d404058c820ad1b44e02d39b855c041a03cf03ebe44a

tradCT:
6da0261f94959c4da892dbaf5680af92d962b0b59befae895f44b95bdcbbae1e

tradPK:
c5c26f76e6232e48aa2d1a87ced73f275a4031cdf83aff90c26d036d12611977

Label:  5c2e2f2f5e5c

        (ascii: "\.//^\")


# Combined KDF Input:
#  mlkemSS || tradSS || tradCT || tradPK || Label

Combined KDF Input: b191c0384d3a5c3921fd2fe63fdb87a9156d3e73efb9c5e
bf0e2cc00a2087643e8247eb791cc06cb8e50d404058c820ad1b44e02d39b855c04
1a03cf03ebe44a6da0261f94959c4da892dbaf5680af92d962b0b59befae895f44b
95bdcbbae1ec5c26f76e6232e48aa2d1a87ced73f275a4031cdf83aff90c26d036d
126119775c2e2f2f5e5c


# Outputs
# ss = SHA3-256(Combined KDF Input)

ss:
ff15da0b25b55c8971b5e088cd4fba3e6f90c848cb9c068c24ac701e487eb9c4
```

Example 3:

```
Example of id-MLKEM1024-ECDH-P384-SHA3-256 Combiner function output.

# Inputs
mlkemSS:
27ee13466bb4c2b72bb0dbac9fb9f8cd17425218eb52ec6a92490196bfacb90e

tradSS:  6d9358552851d7681a2ba7f6d266bc5ddc89308496545a29462b15f645
9638572705f43f01d902447a83702a7a91dc19

tradCT:  0494a8920eb2b023ddf72f5f04d49a6b9e2af047578bfac37b097f2ba8
19cb3e35634595ee95b909e556a3ebc90d658814f714a71fa89bcd99e6ebc31414b
3b7bc9625c2f5fd8a4ced073759bc0fa21a2e5bb9914d2ca28ef6e6b12bff0901ce
f1

tradPK:  043d8dd898d42b7787278c8affb0148cc158f577b9ff67d4a43f4edfb4
a685bfe23efebef57501fecf4098a0db033a0a58f9b8f62ed88379318486070b0aa
624c8de78dbfd746d21aa4c8582364ed969a854ec423ebc5b9fae9912611fddea83
2e

Label:  5153462d4d4c4b454d313032342d503338342d53484133323536

        (ascii: "QSF-MLKEM1024-P384-SHA3256")


# Combined KDF Input:
#  mlkemSS || tradSS || tradCT || tradPK || Label

Combined KDF Input: 27ee13466bb4c2b72bb0dbac9fb9f8cd17425218eb52ec6
a92490196bfacb90e6d9358552851d7681a2ba7f6d266bc5ddc89308496545a2946
2b15f6459638572705f43f01d902447a83702a7a91dc190494a8920eb2b023ddf72
f5f04d49a6b9e2af047578bfac37b097f2ba819cb3e35634595ee95b909e556a3eb
c90d658814f714a71fa89bcd99e6ebc31414b3b7bc9625c2f5fd8a4ced073759bc0
fa21a2e5bb9914d2ca28ef6e6b12bff0901cef1043d8dd898d42b7787278c8affb0
148cc158f577b9ff67d4a43f4edfb4a685bfe23efebef57501fecf4098a0db033a0
a58f9b8f62ed88379318486070b0aa624c8de78dbfd746d21aa4c8582364ed969a8
54ec423ebc5b9fae9912611fddea832e5153462d4d4c4b454d313032342d5033383
42d53484133323536


# Outputs
# ss = SHA3-256(Combined KDF Input)

ss:
d776982891626f4e4804969ff858120b87d8f8abda7d21ee241b3589d23f8ac4
```

Appendix F. Test Vectors

The following test vectors are provided in a format similar to the NIST ACVP Known-Answer-Tests (KATs).

The structure is that a global cacert is provided which is used to sign each KEM certificate.

Within each test case there are the following values:

* tcId the name of the algorithm.

* ek the encapsulation public key.

* x5c the X.509 certificate of the encapsulation key, signed by the cacert.

* dk the raw decapsulation private key.

* dk_pkcs8 the decapsulation private key in a PKCS#8 object.

* c the ciphertext.

* k the derived shared secret key.

Implementers should be able to perform the following tests using the test vectors below:

1. Load the public key ek or certificate x5c and perform an encapsulation for it (you should obtain valid ct and k values, but they will not match the ones in the test vector since Encap() is randomized.)

2. Load the decapsulation private key dk or dk_pkcs8 and the ciphertext c and perform a Decaps() operation to ensure that the same shared secret key k is derived.

Test vectors are provided for each underlying ML-KEM algorithm in isolation for the purposes of debugging.

Due to the length of the test vectors, some readers will prefer to retrieve the non-word-wrapped copy from GitHub. The reference implementation written in python that generated them is also available.

https://github.com/lamps-wg/draft-composite-kem/tree/main/src

```
{
"cacert": "MIIVpzCCCKSgAwIBAgIULtrNBeQEwwJaM4oDWYvBU60jS3owCwYJYIZ
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wPTENMAsGA1UECgwESUVURjEOMAwGA1UECwwFTEFNUFMxHDAaBgNVBAMME0NvbXBvc2l
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Nl7urRYp6KtiEibS95s/Y4+TI77XKJQsq/xIJmJvSHWgxrPELvMaH3wC742AJ45kL6OY
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ykQJwaXFTc97OVcqKelnIV0Av0EYUyjgbWbfBloLkBVKAAfaIdJi+pJZI7p7K9gjia3r
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```

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Appendix G. Contributors and Acknowledgments

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Authors' Addresses

Mike Ounsworth
Entrust Limited
2500 Solandt Road Suite 100
Ottawa, Ontario K2K 3G5
Canada
Email: mike.ounsworth@entrust.com

John Gray
Entrust Limited
2500 Solandt Road Suite 100
Ottawa, Ontario K2K 3G5
Canada
Email: john.gray@entrust.com

Massimiliano Pala
OpenCA Labs
New York City, New York,
United States of America
Email: director@openca.org

Jan Klaussner
Bundesdruckerei GmbH
Kommandantenstr. 18
10969 Berlin
Germany
Email: jan.klaussner@bdr.de

Scott Fluhrer
Cisco Systems
Email: sfluhrer@cisco.com