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D. Harkins
D. Carrel
cisco Systems

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The Internet Key Exchange (IKE)

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Table Of Contents

1. Abstract

ISAKMP ([MSST98]) provides a framework for authentication and key exchange but does not define them. ISAKMP is designed to be key exchange independant; that is, it is designed to support many different key exchanges.

Oakley ([Orm96]) describes a series of key exchanges-- called "modes"-- and details the services provided by each (e.g. perfect forward secrecy for keys, identity protection, and authentication).

SKEME ([SKEME]) describes a versatile key exchange technique which provides anonymity, repudiability, and quick key refreshment.

This document describes a protocol using part of Oakley and part of SKEME in conjunction with ISAKMP to obtain authenticated keying material for use with ISAKMP, and for other security associations such as AH and ESP for the IETF IPsec DOI.

2. Discussion

This memo describes a hybrid protocol. The purpose is to negotiate, and provide authenticated keying material for, security associations in a protected manner.

Processes which implement this memo can be used for negotiating virtual private networks (VPNs) and also for providing a remote user from a remote site (whose IP address need not be known beforehand) access to a secure host or network.

Client negotiation is supported. Client mode is where the negotiating parties are not the endpoints for which security association negotiation is taking place. When used in client mode, the identities of the end parties remain hidden.

This does not implement the entire Oakley protocol, but only a subset necessary to satisfy its goals. It does not claim conformance or compliance with the entire Oakley protocol nor is it dependant in any way on the Oakley protocol.

Likewise, this does not implement the entire SKEME protocol, but only the method of public key encryption for authentication and its concept of fast re-keying using an exchange of nonces. This protocol is not dependant in any way on the SKEME protocol.

3. Terms and Definitions

3.1 Requirements Terminology

Keywords "MUST", "MUST NOT", "REQUIRED", "SHOULD", "SHOULD NOT" and "MAY" that appear in this document are to be interpreted as described in [Bra97].

3.2 Notation

The following notation is used throughout this memo.

HDR is an ISAKMP header whose exchange type is the mode. When writen as HDR* it indicates payload encryption.

SA is an SA negotiation payload with one or more proposals. An initiator MAY provide multiple proposals for negotiation; a responder MUST reply with only one.

<P>_b indicates the body of payload <P>-- the ISAKMP generic vpayload is not included.

SAi_b is the entire body of the SA payload (minus the ISAKMP generic header)-- i.e. the DOI, situation, all proposals and all transforms offered by the Initiator.

CKY-I and CKY-R are the Initiator’s cookie and the Responder’s cookie, respectively, from the ISAKMP header.

g^xi and g^xr are the Diffie-Hellman ([DH]) public values of the initiator and responder respectively.

g^xy is the Diffie-Hellman shared secret.

KE is the key exchange payload which contains the public information exchanged in a Diffie-Hellman exchange. There is no particular encoding (e.g. a TLV) used for the data of a KE payload.

Nx is the nonce payload; x can be: i or r for the ISAKMP initiator and responder respectively.

IDx is the identification payload for "x". x can be: "ii" or "ir" for the ISAKMP initiator and responder respectively during phase one negotiation; or "ui" or "ur" for the user initiator and responder respectively during phase two. The ID payload format for the Internet DOI is defined in [Pip97].

SIG is the signature payload. The data to sign is exchange-specific.

CERT is the certificate payload.

HASH (and any derivitive such as HASH(2) or HASH_I) is the hash payload. The contents of the hash are specific to the authentication method.

prf(key, msg) is the keyed pseudo-random function-- often a keyed hash function-- used to generate a deterministic output that appears pseudo-random. prf's are used both for key derivations and for authentication (i.e. as a keyed MAC). (See [KBC96]).

SKEYID is a string derived from secret material known only to the active players in the exchange.

SKEYID_e is the keying material used by the ISAKMP SA to protect the confidentiality of its messages.

SKEYID_a is the keying material used by the ISAKMP SA to authenticate its messages.

SKEYID_d is the keying material used to derive keys for non-ISAKMP security associations.

<x>y indicates that "x" is encrypted with the key "y".

--> signifies "initiator to responder" communication (requests).

<-- signifies "responder to initiator" communication (replies).

| signifies concatenation of information-- e.g. X | Y is the concatentation of X with Y.

[x] indicates that x is optional.

Message encryption (when noted by a '*' after the ISAKMP header) MUST begin immediately after the ISAKMP header. When communication is protected, all payloads following the ISAKMP header MUST be encrypted. Encryption keys are generated from SKEYID_e in a manner that is defined for each algorithm.

3.3 Perfect Forward Secrecy

When used in the memo Perfect Forward Secrecy (PFS) refers to the notion that compromise of a single key will permit access to only data protected by a single key. For PFS to exist the key used to protect transmission of data MUST NOT be used to derive any additional keys, and if the key used to protect transmission of data was derived from some other keying material, that material MUST NOT be used to derive any more keys.

Perfect Forward Secrecy for both keys and identities is provided in this protocol. (Sections 5.5 and 8).

3.4 Security Association

A security association (SA) is a set of policy and key(s) used to protect information. The ISAKMP SA is the shared policy and key(s) used by the negotiating peers in this protocol to protect their communication.

4. Introduction

Oakley and SKEME each define a method to establish an authenticated key exchange. This includes payloads construction, the information payloads carry, the order in which they are processed and how they are used.

While Oakley defines "modes", ISAKMP defines "phases". The relationship between the two is very straightforward and IKE presents different exchanges as modes which operate in one of two phases.

Phase 1 is where the two ISAKMP peers establish a secure, authenticated channel with which to communicate. This is called the ISAKMP Security Association (SA). "Main Mode" and "Aggressive Mode" each accomplish a phase 1 exchange. "Main Mode" and "Aggressive Mode" MUST ONLY be used in phase 1.

Phase 2 is where Security Associations are negotiated on behalf of services such as IPsec or any other service which needs key material and/or parameter negotiation. "Quick Mode" accomplishes a phase 2 exchange. "Quick Mode" MUST ONLY be used in phase 2.

"New Group Mode" is not really a phase 1 or phase 2. It follows phase 1, but serves to establish a new group which can be used in future negotiations. "New Group Mode" MUST ONLY be used after phase 1.

The ISAKMP SA is bi-directional. That is, once established, either party may initiate Quick Mode, Informational, and New Group Mode Exchanges. Per the base ISAKMP document, the ISAKMP SA is identified by the Initiator's cookie followed by the Responder's cookie-- the role of each party in the phase 1 exchange dictates which cookie is the Initiator's. The cookie order established by the phase 1 exchange continues to identify the ISAKMP SA regardless of the direction the Quick Mode, Informational, or New Group exchange. In other words, the cookies MUST NOT swap places when the direction of the ISAKMP SA changes.

With the use of ISAKMP phases, an implementation can accomplish very fast keying when necessary. A single phase 1 negotiation may be used for more than one phase 2 negotiation. Additionally a single phase 2 negotiation can request multiple Security Associations. With these optimizations, an implementation can see less than one round trip per SA as well as less than one DH exponentiation per SA. "Main Mode" for phase 1 provides identity protection. When identity protection is not needed, "Aggressive Mode" can be used to reduce round trips even further. Developer hints for doing these optimizations are included below. It should also be noted that using public key encryption to authenticate an Aggressive Mode exchange will still provide identity protection.

This protocol does not define its own DOI per se. The ISAKMP SA, established in phase 1, MAY use the DOI and situation from a non-ISAKMP service (such as the IETF IPSec DOI [Pip97]). In this case an implementation MAY choose to restrict use of the ISAKMP SA for establishment of SAs for services of the same DOI. Alternately, an ISAKMP SA MAY be established with the value zero in both the DOI and situation (see [MSST98] for a description of these fields) and in this case implementations will be free to establish security services for any defined DOI using this ISAKMP SA. If a DOI of zero is used for establishment of a phase 1 SA, the syntax of the identity payloads used in phase 1 is that defined in [MSST98] and not from any DOI-- e.g. [Pip97]-- which may further expand the syntax and semantics of identities.

The following attributes are used by IKE and are negotiated as part of the ISAKMP Security Association. (These attributes pertain only to the ISAKMP Security Association and not to any Security Associations that ISAKMP may be negotiating on behalf of other services.)

- encryption algorithm

- hash algorithm

- authentication method

- information about a group over which to do Diffie-Hellman.

All of these attributes are mandatory and MUST be negotiated. In addition, it is possible to optionally negotiate a psuedo-random function ("prf"). (There are currently no negotiable pseudo-random functions defined in this document. Private use attribute values can be used for prf negotiation between consenting parties). If a "prf" is not negotiation, the HMAC (see [KBC96]) version of the negotiated hash algorithm is used as a pseudo-random function. Other non-mandatory attributes are described in Appendix A. The selected hash algorithm MUST support both native and HMAC modes.

The Diffie-Hellman group MUST be either specified using a defined group description (section 6) or by defining all attributes of a group (section 5.6). Group attributes (such as group type or prime--see Appendix A) MUST NOT be offered in conjunction with a previously defined group (either a reserved group description or a private use description that is established after conclusion of a New Group Mode exchange).

IKE implementations MUST support the following attribute values:

- DES [DES] in CBC mode with a weak, and semi-weak, key check (weak and semi-weak keys are referenced in [Sch96] and listed in Appendix A). The key is derived according to Appendix B.

- MD5 [MD5] and SHA [SHA}.

- Authentication via pre-shared keys.

- MODP over default group number one (see below).

In addition, IKE implementations SHOULD support: 3DES for encryption; Tiger ([TIGER]) for hash; the Digital Signature Standard, RSA [RSA] signatures and authentication with RSA public key encryption; and MODP group number 2. IKE implementations MAY support any additional encryption algorithms defined in Appendix A and MAY support ECP and EC2N groups.

The IKE modes described here MUST be implemented whenever the IETF IPsec DOI [Pip97] is implemented. Other DOIs MAY use the modes described here.

5. Exchanges

There are two basic methods used to establish an authenticated key exchange: Main Mode and Aggressive Mode. Each generates authenticated keying material from an ephemeral Diffie-Hellman exchange. Main Mode MUST be implemented; Aggressive Mode SHOULD be implemented. In addition, Quick Mode MUST be implemented as a mechanism to generate fresh keying material and negotiate non-ISAKMP security services. In addition, New Group Mode SHOULD be implemented as a mechanism to define private groups for Diffie-Hellman exchanges. Implementations MUST NOT switch exchange types in the middle of an exchange.

Exchanges conform to standard ISAKMP payload syntax, attribute encoding, timeouts and retransmits of messages, and informational messages-- e.g a notify response is sent when, for example, a proposal is unacceptable, or a signature verification or decryption was unsuccessful, etc.

The SA payload MUST precede all other payloads in a phase 1 exchange. Except where otherwise noted, there are no requirements for ISAKMP payloads in any message to be in any particular order.

The Diffie-Hellman public value passed in a KE payload, in either a phase 1 or phase 2 exchange, MUST be the length of the negotiated Diffie-Hellman group enforced, if necessary, by pre-pending the value with zeros.

The length of nonce payload MUST be between 8 and 256 bytes inclusive.

Main Mode is an instantiation of the ISAKMP Identity Protect Exchange: The first two messages negotiate policy; the next two exchange Diffie-Hellman public values and ancillary data (e.g. nonces) necessary for the exchange; and the last two messages authenticate the Diffie-Hellman Exchange. The authentication method negotiated as part of the initial ISAKMP exchange influences the composition of the payloads but not their purpose. The XCHG for Main Mode is ISAKMP Identity Protect.

Similarly, Aggressive Mode is an instantiation of the ISAKMP Aggressive Exchange. The first two messages negotiate policy, exchange Diffie-Hellman public values and ancillary data necessary for the exchange, and identities. In addition the second message authenticates the responder. The third message authenticates the initiator and provides a proof of participation in the exchange. The XCHG for Aggressive Mode is ISAKMP Aggressive. The final message MAY NOT be sent under protection of the ISAKMP SA allowing each party to

postpone exponentiation, if desired, until negotiation of this exchange is complete. The graphic depictions of Aggressive Mode show the final payload in the clear; it need not be.

Exchanges in IKE are not open ended and have a fixed number of messages. Receipt of a Certificate Request payload MUST NOT extend the number of messages transmitted or expected.

Security Association negotiation is limited with Aggressive Mode. Due to message construction requirements the group in which the Diffie-Hellman exchange is performed cannot be negotiated. In addition, different authentication methods may further constrain attribute negotiation. For example, authentication with public key encryption cannot be negotiated and when using the revised method of public key encryption for authentication the cipher and hash cannot be negotiated. For situations where the rich attribute negotiation capabilities of IKE are required Main Mode may be required.

Quick Mode and New Group Mode have no analog in ISAKMP. The XCHG values for Quick Mode and New Group Mode are defined in Appendix A.

Main Mode, Aggressive Mode, and Quick Mode do security association negotiation. Security Association offers take the form of Tranform Payload(s) encapsulated in Proposal Payload(s) encapsulated in Security Association (SA) payload(s). If multiple offers are being made for phase 1 exchanges (Main Mode and Aggressive Mode) they MUST take the form of multiple Transform Payloads for a single Proposal Payload in a single SA payload. To put it another way, for phase 1 exchanges there MUST NOT be multiple Proposal Payloads for a single SA payload and there MUST NOT be multiple SA payloads. This document does not proscribe such behavior on offers in phase 2 exchanges.

There is no limit on the number of offers the initiator may send to the responder but conformant implementations MAY choose to limit the number of offers it will inspect for performance reasons.

During security association negotiation, initiators present offers for potential security associations to responders. Responders MUST NOT modify attributes of any offer, attribute encoding excepted (see Appendix A). If the initiator of an exchange notices that attribute values have changed or attributes have been added or deleted from an offer made, that response MUST be rejected.

Four different authentication methods are allowed with either Main Mode or Aggressive Mode-- digital signature, two forms of authentication with public key encryption, or pre-shared key. The value SKEYID is computed seperately for each authentication method.

```
  For signatures:            SKEYID = prf(Ni_b | Nr_b, g^xy)
  For public key encryption: SKEYID = prf(hash(Ni_b | Nr_b), CKY-I |
CKY-R)
  For pre-shared keys:       SKEYID = prf(pre-shared-key, Ni_b |
Nr_b)
```

The result of either Main Mode or Aggressive Mode is three groups of authenticated keying material:

```
   SKEYID_d = prf(SKEYID, g^xy | CKY-I | CKY-R | 0)
   SKEYID_a = prf(SKEYID, SKEYID_d | g^xy | CKY-I | CKY-R | 1)
   SKEYID_e = prf(SKEYID, SKEYID_a | g^xy | CKY-I | CKY-R | 2)
```

and agreed upon policy to protect further communications. The values of 0, 1, and 2 above are represented by a single octet. The key used for encryption is derived from SKEYID_e in an algorithm-specific manner (see appendix B).

To authenticate either exchange the initiator of the protocol generates HASH_I and the responder generates HASH_R where:

```
 HASH_I = prf(SKEYID, g^xi | g^xr | CKY-I | CKY-R | SAi_b | IDii_b )
 HASH_R = prf(SKEYID, g^xr | g^xi | CKY-R | CKY-I | SAi_b | IDir_b )
```

For authentication with digital signatures, HASH_I and HASH_R are signed and verified; for authentication with either public key encryption or pre-shared keys, HASH_I and HASH_R directly authenticate the exchange. The entire ID payload (including ID type, port, and protocol but excluding the generic header) is hashed into both HASH_I and HASH_R.

As mentioned above, the negotiated authentication method influences the content and use of messages for Phase 1 Modes, but not their intent. When using public keys for authentication, the Phase 1 exchange can be accomplished either by using signatures or by using public key encryption (if the algorithm supports it). Following are Phase 1 exchanges with different authentication options.

5.1 IKE Phase 1 Authenticated With Signatures

Using signatures, the ancillary information exchanged during the second roundtrip are nonces; the exchange is authenticated by signing a mutually obtainable hash. Main Mode with signature authentication is described as follows:

```
     Initiator                           Responder
     -----------                         -----------
     HDR, SA                       -->
                                   <--   HDR, SA
     HDR, KE, Ni                   -->
                                   <--   HDR, KE, Nr
     HDR*, IDii, [ CERT, ] SIG_I   -->
                                   <--   HDR*, IDir, [ CERT, ] SIG_R
```

Aggressive mode with signatures in conjunction with ISAKMP is described as follows:

```
     Initiator                           Responder
     -----------                         -----------
     HDR, SA, KE, Ni, IDii         -->
                                   <--   HDR, SA, KE, Nr, IDir,
                                              [ CERT, ] SIG_R
     HDR, [ CERT, ] SIG_I          -->
```

In both modes, the signed data, SIG_I or SIG_R, is the result of the negotiated digital signature algorithm applied to HASH_I or HASH_R respectively.

In general the signature will be over HASH_I and HASH_R as above using the negotiated prf, or the HMAC version of the negotiated hash function (if no prf is negotiated). However, this can be overridden for construction of the signature if the signature algorithm is tied to a particular hash algorithm (e.g. DSS is only defined with SHA's 160 bit output). In this case, the signature will be over HASH_I and HASH_R as above, except using the HMAC version of the hash algorithm associated with the signature method. The negotiated prf and hash function would continue to be used for all other prescribed pseudo-random functions.

Since the hash algorithm used is already known there is no need to encode its OID into the signature. In addition, there is no binding between the OIDs used for RSA signatures in PKCS #1 and those used in this document. Therefore, RSA signatures MUST be encoded as a private key encryption in PKCS #1 format and not as a signature in PKCS #1 format (which includes the OID of the hash algorithm). DSS signatures MUST be encoded as r followed by s.

One or more certificate payloads MAY be optionally passed.

5.2 Phase 1 Authenticated With Public Key Encryption

Using public key encryption to authenticate the exchange, the ancillary information exchanged is encrypted nonces. Each party's ability to reconstruct a hash (proving that the other party decrypted the nonce) authenticates the exchange.

In order to perform the public key encryption, the initiator must already have the responder's public key. In the case where the responder has multiple public keys, a hash of the certificate the initiator is using to encrypt the ancillary information is passed as part of the third message. In this way the responder can determine which corresponding private key to use to decrypt the encrypted payloads and identity protection is retained.

In addition to the nonce, the identities of the parties (IDii and IDir) are also encrypted with the other party's public key. If the authentication method is public key encryption, the nonce and identity payloads MUST be encrypted with the public key of the other party. Only the body of the payloads are encrypted, the payload headers are left in the clear.

When using encryption for authentication, Main Mode is defined as follows.

```
     Initiator                          Responder
    -----------                        -----------
     HDR, SA                    -->
                                <--     HDR, SA
     HDR, KE, [ HASH(1), ]
       <IDii_b>PubKey_r,
         <Ni_b>PubKey_r         -->
                                        HDR, KE, <IDir_b>PubKey_i,
                                <--             <Nr_b>PubKey_i
     HDR*, HASH_I               -->
                                <--     HDR*, HASH_R
```

Aggressive Mode authenticated with encryption is described as follows:

```
     Initiator                          Responder
    -----------                        -----------
     HDR, SA, [ HASH(1),] KE,
       <IDii_b>Pubkey_r,
        <Ni_b>Pubkey_r          -->
                                        HDR, SA, KE, <IDir_b>PubKey_i,
                                <--          <Nr_b>PubKey_i, HASH_R
     HDR, HASH_I                -->
```

Where HASH(1) is a hash (using the negotiated hash function) of the certificate which the initiator is using to encrypt the nonce and identity.

RSA encryption MUST be encoded in PKCS #1 format. While only the body of the ID and nonce payloads is encrypted, the encrypted data must be preceded by a valid ISAKMP generic header. The payload length is the length of the entire encrypted payload plus header. The PKCS #1 encoding allows for determination of the actual length of the cleartext payload upon decryption.

Using encryption for authentication provides for a plausably deniable exchange. There is no proof (as with a digital signature) that the conversation ever took place since each party can completely reconstruct both sides of the exchange. In addition, security is added to secret generation since an attacker would have to successfully break not only the Diffie-Hellman exchange but also both RSA encryptions. This exchange was motivated by [SKEME].

Note that, unlike other authentication methods, authentication with public key encryption allows for identity protection with Aggressive Mode.

5.3 Phase 1 Authenticated With a Revised Mode of Public Key Encryption

Authentication with Public Key Encryption has significant advantages over authentication with signatures (see section 5.2 above). Unfortunately, this is at the cost of 4 public key operations-- two public key encryptions and two private key decryptions. This authentication mode retains the advantages of authentication using public key encryption but does so with half the public key operations.

In this mode, the nonce is still encrypted using the public key of the peer, however the peer’s identity (and the certificate if it is sent) is encrypted using the negotiated symmetric encryption algorithm (from the SA payload) with a key derived from the nonce. This solution adds minimal complexity and state yet saves two costly public key operations on each side. In addition, the Key Exchange payload is also encrypted using the same derived key. This provides additional protection against cryptanalysis of the Diffie-Hellman exchange.

As with the public key encryption method of authentication (section 5.2), a HASH payload may be sent to identify a certificate if the responder has multiple certificates which contain useable public keys (e.g. if the certificate is not for signatures only, either due to certificate restrictions or algorithmic restrictions). If the HASH

payload is sent it MUST be the first payload of the second message exchange and MUST be followed by the encrypted nonce. If the HASH payload is not sent, the first payload of the second message exchange MUST be the encrypted nonce. In addition, the initiator my optionally send a certificate payload to provide the responder with a public key with which to respond.

When using the revised encryption mode for authentication, Main Mode is defined as follows.

```
     Initiator                          Responder
    -----------                        -----------
     HDR, SA                    -->
                                <--     HDR, SA
     HDR, [ HASH(1), ]
       <Ni_b>Pubkey_r,
       <KE_b>Ke_i,
       <IDii_b>Ke_i,
       [<<Cert-I_b>Ke_i]        -->
                                           HDR, <Nr_b>PubKey_i,
                                                <KE_b>Ke_r,
                                <--         <IDir_b>Ke_r,
     HDR*, HASH_I               -->
                                <--     HDR*, HASH_R
```

Aggressive Mode authenticated with the revised encryption method is described as follows:

```
     Initiator                          Responder
    -----------                        -----------
     HDR, SA, [ HASH(1),]
       <Ni_b>Pubkey_r,
       <KE_b>Ke_i, <IDii_b>Ke_i
       [, <Cert-I_b>Ke_i ]      -->
                                           HDR, SA, <Nr_b>PubKey_i,
                                                <KE_b>Ke_r, <IDir_b>Ke_r,
                                <--         HASH_R
     HDR, HASH_I                -->
```

where HASH(1) is identical to section 5.2. Ke_i and Ke_r are keys to the symmetric encryption algorithm negotiated in the SA payload exchange. Only the body of the payloads are encrypted (in both public key and symmetric operations), the generic payload headers are left in the clear. The payload length includes that added to perform encryption.

The symmetric cipher keys are derived from the decrypted nonces as follows. First the values Ne_i and Ne_r are computed:

```
Ne_i = prf(Ni_b, CKY-I)
Ne_r = prf(Nr_b, CKY-R)
```

The keys Ke_i and Ke_r are then taken from Ne_i and Ne_r respectively in the manner described in Appendix B used to derive symmetric keys for use with the negotiated encryption algorithm. If the length of the output of the negotiated prf is greater than or equal to the key length requirements of the cipher, Ke_i and Ke_r are derived from the most significant bits of Ne_i and Ne_r respectively. If the desired length of Ke_i and Ke_r exceed the length of the output of the prf the necessary number of bits is obtained by repeatedly feeding the results of the prf back into itself and concatenating the result until the necessary number has been achieved. For example, if the negotiated encryption algorithm requires 320 bits of key and the output of the prf is only 128 bits, Ke_i is the most significant 320 bits of K, where

```
K = K1 | K2 | K3 and
K1 = prf(Ne_i, 0)
K2 = prf(Ne_i, K1)
K3 = prf(Ne_i, K2)
```

For brevity, only derivation of Ke_i is shown; Ke_r is identical. The length of the value 0 in the computation of K1 is a single octet. Note that Ne_i, Ne_r, Ke_i, and Ke_r are all ephemeral and MUST be discarded after use.

Save the requirements on the location of the optional HASH payload and the mandatory nonce payload there are no further payload requirements. All payloads-- in whatever order-- following the encrypted nonce MUST be encrypted with Ke_i or Ke_r depending on the direction.

If CBC mode is used for the symmetric encryption then the initialization vectors (IVs) are set as follows. The IV for encrypting the first payload following the nonce is set to 0 (zero). The IV for subsequent payloads encrypted with the ephemeral symmetric cipher key, Ke_i, is the last ciphertext block of the previous payload. Encrypted payloads are padded up to the nearest block size. All padding bytes, except for the last one, contain 0x00. The last byte of the padding contains the number of the padding bytes used, excluding the last one. Note that this means there will always be padding.

5.4 Phase 1 Authenticated With a Pre-Shared Key

A key derived by some out-of-band mechanism may also be used to authenticate the exchange. The actual establishment of this key is out of the scope of this document.

When doing a pre-shared key authentication, Main Mode is defined as follows:

```
     Initiator                        Responder
    ----------                       -----------
     HDR, SA              -->
                          <--    HDR, SA
     HDR, KE, Ni          -->
                          <--    HDR, KE, Nr
     HDR*, IDii, HASH_I   -->
                          <--    HDR*, IDir, HASH_R
```

Aggressive mode with a pre-shared key is described as follows:

```
     Initiator                          Responder
    -----------                        -----------
     HDR, SA, KE, Ni, IDii -->
                           <--    HDR, SA, KE, Nr, IDir, HASH_R
     HDR, HASH_I           -->
```

When using pre-shared key authentication with Main Mode the key can only be identified by the IP address of the peers since HASH_I must be computed before the initiator has processed IDir. Aggressive Mode allows for a wider range of identifiers of the pre-shared secret to be used. In addition, Aggressive Mode allows two parties to maintain multiple, different pre-shared keys and identify the correct one for a particular exchange.

5.5 Phase 2 - Quick Mode

Quick Mode is not a complete exchange itself (in that it is bound to a phase 1 exchange), but is used as part of the SA negotiation process (phase 2) to derive keying material and negotiate shared policy for non-ISAKMP SAs. The information exchanged along with Quick Mode MUST be protected by the ISAKMP SA-- i.e. all payloads except the ISAKMP header are encrypted. In Quick Mode, a HASH payload MUST immediately follow the ISAKMP header and a SA payload MUST immediately follow the HASH. This HASH authenticates the message and also provides liveliness proofs.

The message ID in the ISAKMP header identifies a Quick Mode in progress for a particular ISAKMP SA which itself is identified by the cookies in the ISAKMP header. Since each instance of a Quick Mode uses a unique initialization vector (see Appendix B) it is possible to have multiple simultaneous Quick Modes, based off a single ISAKMP SA, in progress at any one time.

Quick Mode is essentially a SA negotiation and an exchange of nonces that provides replay protection. The nonces are used to generate fresh key material and prevent replay attacks from generating bogus security associations. An optional Key Exchange payload can be exchanged to allow for an additional Diffie-Hellman exchange and exponentiation per Quick Mode. While use of the key exchange payload with Quick Mode is optional it MUST be supported.

Base Quick Mode (without the KE payload) refreshes the keying material derived from the exponentiation in phase 1. This does not provide PFS. Using the optional KE payload, an additional exponentiation is performed and PFS is provided for the keying material.

The identities of the SAs negotiated in Quick Mode are implicitly assumed to be the IP addresses of the ISAKMP peers, without any implied constraints on the protocol or port numbers allowed, unless client identifiers are specified in Quick Mode. If ISAKMP is acting as a client negotiator on behalf of another party, the identities of the parties MUST be passed as IDci and then IDcr. Local policy will dictate whether the proposals are acceptable for the identities specified. If the client identities are not acceptable to the Quick Mode responder (due to policy or other reasons), a Notify payload with Notify Message Type INVALID-ID-INFORMATION (18) SHOULD be sent.

The client identities are used to identify and direct traffic to the appropriate tunnel in cases where multiple tunnels exist between two peers and also to allow for unique and shared SAs with different granularities.

All offers made during a Quick Mode are logically related and must be consistant. For example, if a KE payload is sent, the attribute describing the Diffie-Hellman group (see section 6.1 and [Pip97]) MUST be included in every transform of every proposal of every SA being negotiated. Similarly, if client identities are used, they MUST apply to every SA in the negotiation.

Quick Mode is defined as follows:

```
     Initiator                          Responder
     -----------                        -----------
     HDR*, HASH(1), SA, Ni
       [, KE ] [, IDci, IDcr ] -->
                                <--     HDR*, HASH(2), SA, Nr
                                              [, KE ] [, IDci, IDcr ]
     HDR*, HASH(3)              -->
```

Where:
HASH(1) is the prf over the message id (M-ID) from the ISAKMP header concatenated with the entire message that follows the hash including all payload headers, but excluding any padding added for encryption. HASH(2) is identical to HASH(1) except the initiator's nonce-- Ni, minus the payload header-- is added after M-ID but before the complete message. The addition of the nonce to HASH(2) is for a liveliness proof. HASH(3)-- for liveliness-- is the prf over the value zero represented as a single octet, followed by a concatenation of the message id and the two nonces-- the initiator's followed by the responder's-- minus the payload header. In other words, the hashes for the above exchange are:

HASH(1) = prf(SKEYID_a, M-ID | SA | Ni [| KE] [| IDci | IDcr)
HASH(2) = prf(SKEYID_a, M-ID | Ni_b | SA | Nr [| KE] [| IDci | IDcr)
HASH(3) = prf(SKEYID_a, 0 | M-ID | Ni_b | Nr_b)

With the exception of the HASH, SA, and the optional ID payloads, there are no payload ordering restrictions on Quick Mode. HASH(1) and HASH(2) may differ from the illustration above if the order of payloads in the message differs from the illustrative example or if any optional payloads, for example a notify payload, have been chained to the message.

If PFS is not needed, and KE payloads are not exchanged, the new keying material is defined as

KEYMAT = prf(SKEYID_d, protocol | SPI | Ni_b | Nr_b).

If PFS is desired and KE payloads were exchanged, the new keying material is defined as

KEYMAT = prf(SKEYID_d, g(qm)^xy | protocol | SPI | Ni_b | Nr_b)

where g(qm)^xy is the shared secret from the ephemeral Diffie-Hellman exchange of this Quick Mode.

In either case, "protocol" and "SPI" are from the ISAKMP Proposal Payload that contained the negotiated Transform.

A single SA negotiation results in two security assocations-- one inbound and one outbound. Different SPIs for each SA (one chosen by the initiator, the other by the responder) guarantee a different key for each direction. The SPI chosen by the destination of the SA is used to derive KEYMAT for that SA.

For situations where the amount of keying material desired is greater than that supplied by the prf, KEYMAT is expanded by feeding the results of the prf back into itself and concatenating results until the required keying material has been reached. In other words,

```
KEYMAT = K1 | K2 | K3 | ...
where
  K1 = prf(SKEYID_d, [ g(qm)^xy | ] protocol | SPI | Ni_b | Nr_b)
  K2 = prf(SKEYID_d, K1 | [ g(qm)^xy | ] protocol | SPI | Ni_b |
  Nr_b)
  K3 = prf(SKEYID_d, K2 | [ g(qm)^xy | ] protocol | SPI | Ni_b |
  Nr_b)
  etc.
```

This keying material (whether with PFS or without, and whether derived directly or through concatenation) MUST be used with the negotiated SA. It is up to the service to define how keys are derived from the keying material.

In the case of an ephemeral Diffie-Hellman exchange in Quick Mode, the exponential (g(qm)^xy) is irretreivably removed from the current state and SKEYID_e and SKEYID_a (derived from phase 1 negotiation) continue to protect and authenticate the ISAKMP SA and SKEYID_d continues to be used to derive keys.

Using Quick Mode, multiple SA's and keys can be negotiated with one exchange as follows:

```
     Initiator                          Responder
    -----------                        -----------
     HDR*, HASH(1), SA0, SA1, Ni,
       [, KE ] [, IDci, IDcr ] -->
                                <--     HDR*, HASH(2), SA0, SA1, Nr,
                                           [, KE ] [, IDci, IDcr ]
     HDR*, HASH(3)              -->
```

The keying material is derived identically as in the case of a single SA. In this case (negotiation of two SA payloads) the result would be four security associations-- two each way for both SAs.

5.6 New Group Mode

New Group Mode MUST NOT be used prior to establishment of an ISAKMP SA. The description of a new group MUST only follow phase 1 negotiation. (It is not a phase 2 exchange, though).

```
     Initiator                          Responder
    -----------                        -----------
     HDR*, HASH(1), SA        -->
                              <--       HDR*, HASH(2), SA
```

where HASH(1) is the prf output, using SKEYID_a as the key, and the message-ID from the ISAKMP header concatenated with the entire SA proposal, body and header, as the data; HASH(2) is the prf output, using SKEYID_a as the key, and the message-ID from the ISAKMP header concatenated with the reply as the data. In other words the hashes for the above exchange are:

```
HASH(1) = prf(SKEYID_a, M-ID | SA)
HASH(2) = prf(SKEYID_a, M-ID | SA)
```

The proposal will specify the characteristics of the group (see appendix A, "Attribute Assigned Numbers"). Group descriptions for private Groups MUST be greater than or equal to 2^15. If the group is not acceptable, the responder MUST reply with a Notify payload with the message type set to ATTRIBUTES-NOT-SUPPORTED (13).

ISAKMP implementations MAY require private groups to expire with the SA under which they were established.

Groups may be directly negotiated in the SA proposal with Main Mode. To do this the component parts-- for a MODP group, the type, prime and generator; for a EC2N group the type, the Irreducible Polynomial, Group Generator One, Group Generator Two, Group Curve A, Group Curve B and Group Order-- are passed as SA attributes (see Appendix A). Alternately, the nature of the group can be hidden using New Group Mode and only the group identifier is passed in the clear during phase 1 negotiation.

5.7 ISAKMP Informational Exchanges

This protocol protects ISAKMP Informational Exchanges when possible. Once the ISAKMP security association has been established (and SKEYID_e and SKEYID_a have been generated) ISAKMP Information Exchanges, when used with this protocol, are as follows:

```
     Initiator                       Responder
    -----------                     -----------
     HDR*, HASH(1), N/D      -->
```

where N/D is either an ISAKMP Notify Payload or an ISAKMP Delete Payload and HASH(1) is the prf output, using SKEYID_a as the key, and a M-ID unique to this exchange concatenated with the entire informational payload (either a Notify or Delete) as the data. In other words, the hash for the above exchange is:

HASH(1) = prf(SKEYID_a, M-ID | N/D)

As noted the message ID in the ISAKMP header-- and used in the prf computation-- is unique to this exchange and MUST NOT be the same as the message ID of another phase 2 exchange which generated this informational exchange. The derivation of the initialization vector, used with SKEYID_e to encrypt this message, is described in Appendix B.

If the ISAKMP security association has not yet been established at the time of the Informational Exchange, the exchange is done in the clear without an accompanying HASH payload.

6 Oakley Groups

With IKE, the group in which to do the Diffie-Hellman exchange is negotiated. Four groups-- values 1 through 4-- are defined below. These groups originated with the Oakley protocol and are therefore called "Oakley Groups". The attribute class for "Group" is defined in Appendix A. All values 2^15 and higher are used for private group identifiers. For a discussion on the strength of the default Oakley groups please see the Security Considerations section below.

These groups were all generated by Richard Schroeppel at the University of Arizona. Properties of these groups are described in [Orm96].

6.1 First Oakley Default Group

Oakley implementations MUST support a MODP group with the following prime and generator. This group is assigned id 1 (one).

The prime is: 2^768 - 2 ^704 - 1 + 2^64 * { [2^638 pi] + 149686 }
Its hexadecimal value is

```
      FFFFFFFF FFFFFFFF C90FDAA2 2168C234 C4C6628B 80DC1CD1
      29024E08 8A67CC74 020BBEA6 3B139B22 514A0879 8E3404DD
      EF9519B3 CD3A431B 302B0A6D F25F1437 4FE1356D 6D51C245
      E485B576 625E7EC6 F44C42E9 A63A3620 FFFFFFFF FFFFFFFF
```

The generator is: 2.

6.2 Second Oakley Group

IKE implementations SHOULD support a MODP group with the following prime and generator. This group is assigned id 2 (two).

The prime is 2^1024 - 2^960 - 1 + 2^64 * { [2^894 pi] + 129093 }. Its hexadecimal value is

```
      FFFFFFFF FFFFFFFF C90FDAA2 2168C234 C4C6628B 80DC1CD1
      29024E08 8A67CC74 020BBEA6 3B139B22 514A0879 8E3404DD
      EF9519B3 CD3A431B 302B0A6D F25F1437 4FE1356D 6D51C245
      E485B576 625E7EC6 F44C42E9 A637ED6B 0BFF5CB6 F406B7ED
      EE386BFB 5A899FA5 AE9F2411 7C4B1FE6 49286651 ECE65381
      FFFFFFFF FFFFFFFF
```

The generator is 2 (decimal)

6.3 Third Oakley Group

IKE implementations SHOULD support a EC2N group with the following characteristics. This group is assigned id 3 (three). The curve is based on the Galois Field GF[2^155]. The field size is 155. The irreducible polynomial for the field is:

```
       u^155 + u^62 + 1.
```

The equation for the elliptic curve is:

```
        y^2 + xy = x^3 + ax^2 + b.
```

```
Field Size:                          155
Group Prime/Irreducible Polynomial:
                0x080000000000000000000004000000000000001
Group Generator One:                 0x7b
Group Curve A:                       0x0
Group Curve B:                       0x07338f
```

Group Order: 0X080000000000000000057db5698537193aef944

The data in the KE payload when using this group is the value x from the solution (x,y), the point on the curve chosen by taking the randomly chosen secret Ka and computing Ka*P, where * is the repetition of the group addition and double operations, P is the curve point with x coordinate equal to generator 1 and the y

coordinate determined from the defining equation. The equation of curve is implicitly known by the Group Type and the A and B coefficients. There are two possible values for the y coordinate; either one can be used successfully (the two parties need not agree on the selection).

6.4 Fourth Oakley Group

IKE implementations SHOULD support a EC2N group with the following characteristics. This group is assigned id 4 (four). The curve is based on the Galois Field GF[2^185]. The field size is 185. The irreducible polynomial for the field is:

u^185 + u^69 + 1. The

equation for the elliptic curve is:

y^2 + xy = x^3 + ax^2 + b.

Field Size:	185
Group Prime/Irreducible Polynomial:	0x20000000000000000000000000002000000000000000001
Group Generator One:	0x18
Group Curve A:	0x0
Group Curve B:	0x1ee9

Group Order: 0X01ffffffffffffffffffffdbf2f889b73e484175f94ebc

The data in the KE payload when using this group will be identical to that as when using Oakley Group 3 (three).

Other groups can be defined using New Group Mode. These default groups were generated by Richard Schroeppel at the University of Arizona. Properties of these primes are described in [Orm96].

7. Payload Explosion for a Complete IKE Exchange

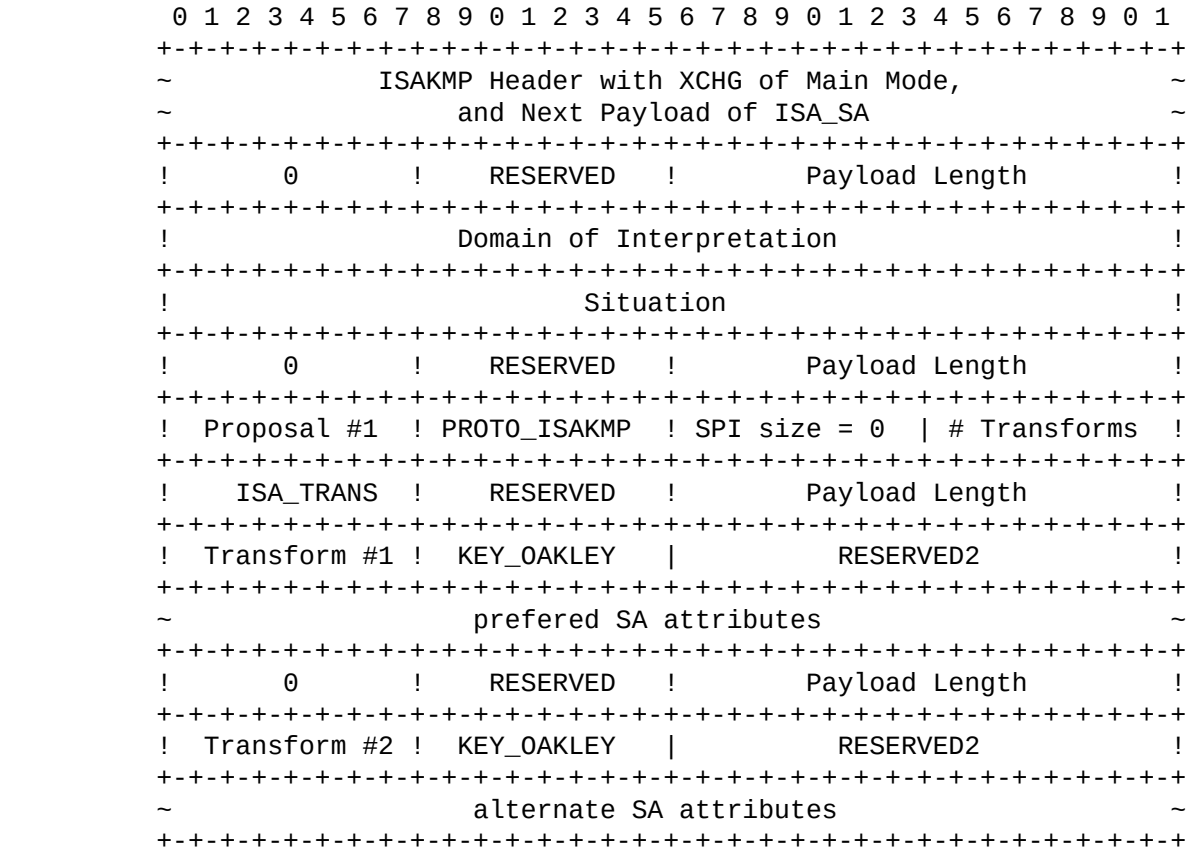
This section illustrates how the IKE protocol is used to:

- establish a secure and authenticated channel between ISAKMP processes (phase 1); and

- generate key material for, and negotiate, an IPsec SA (phase 2).

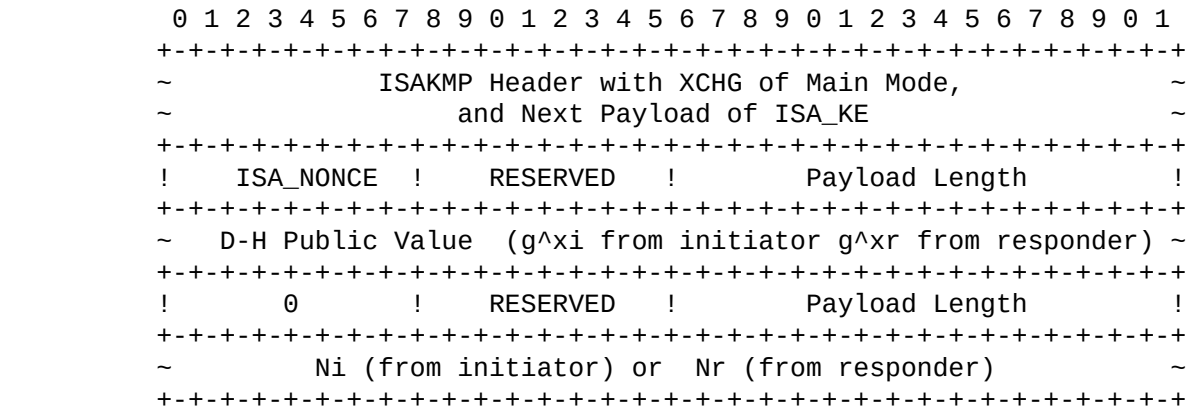
7.1 Phase 1 using Main Mode

The following diagram illustrates the payloads exchanged between the two parties in the first round trip exchange. The initiator MAY propose several proposals; the responder MUST reply with one.

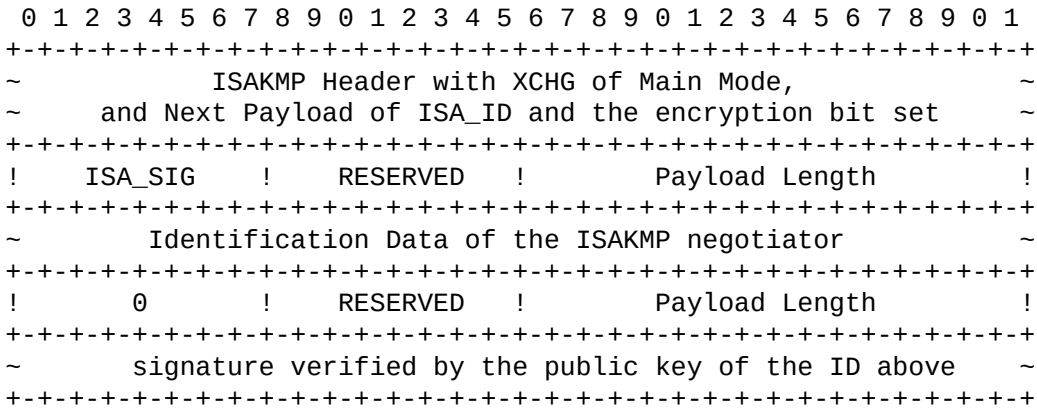


The responder replies in kind but selects, and returns, one transform proposal (the ISAKMP SA attributes).

The second exchange consists of the following payloads:



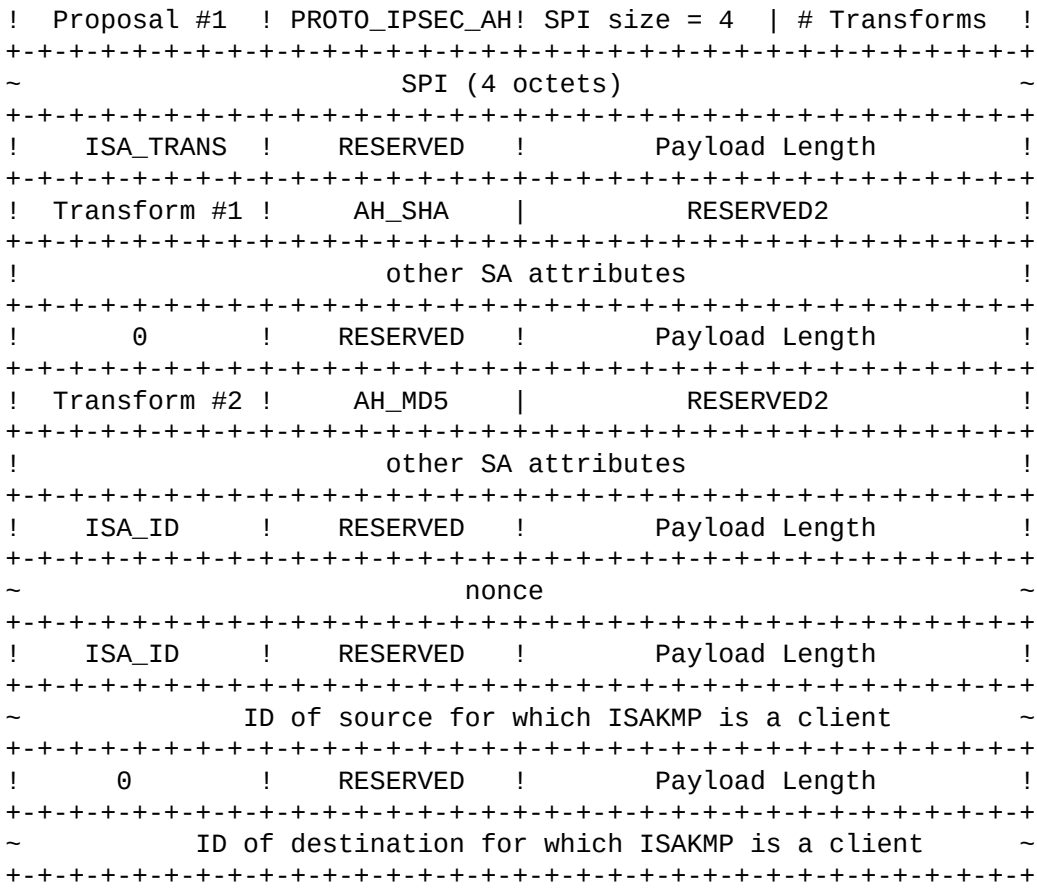
The shared keys, SKEYID_e and SKEYID_a, are now used to protect and authenticate all further communication. Note that both SKEYID_e and SKEYID_a are unauthenticated.



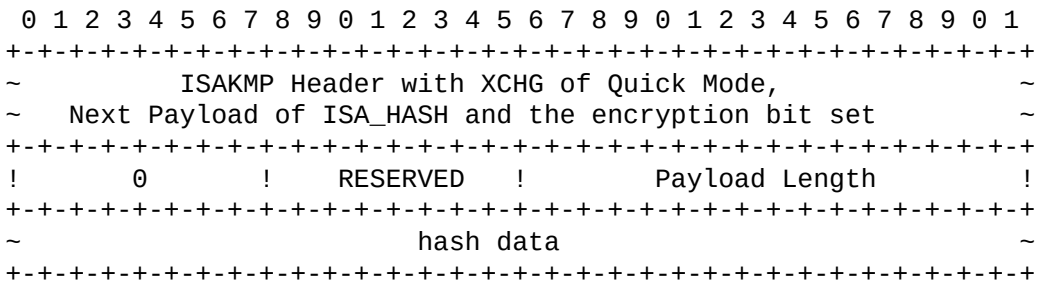
The key exchange is authenticated over a signed hash as described in section 5.1. Once the signature has been verified using the authentication algorithm negotiated as part of the ISAKMP SA, the shared keys, SKEYID_e and SKEYID_a can be marked as authenticated. (For brevity, certificate payloads were not exchanged).

7.2 Phase 2 using Quick Mode

The following payloads are exchanged in the first round of Quick Mode with ISAKMP SA negotiation. In this hypothetical exchange, the ISAKMP negotiators are proxies for other parties which have requested authentication.



where the contents of the hash are described in 5.5 above. The responder replies with a similar message which only contains one transform-- the selected AH transform. Upon receipt, the initiator can provide the key engine with the negotiated security association and the keying material. As a check against replay attacks, the responder waits until receipt of the next message.



where the contents of the hash are described in 5.5 above.

8. Perfect Forward Secrecy Example

This protocol can provide PFS of both keys and identities. The identies of both the ISAKMP negotiating peer and, if applicable, the identities for whom the peers are negotiating can be protected with PFS.

To provide Perfect Forward Secrecy of both keys and all identities, two parties would perform the following:

- A Main Mode Exchange to protect the identities of the ISAKMP peers.
  This establishes an ISAKMP SA.
- A Quick Mode Exchange to negotiate other security protocol protection.
  This establishes a SA on each end for this protocol.
- Delete the ISAKMP SA and its associated state.

Since the key for use in the non-ISAKMP SA was derived from the single ephemeral Diffie-Hellman exchange PFS is preserved.

To provide Perfect Forward Secrecy of merely the keys of a non-ISAKMP security association, it in not necessary to do a phase 1 exchange if an ISAKMP SA exists between the two peers. A single Quick Mode in which the optional KE payload is passed, and an additional Diffie-Hellman exchange is performed, is all that is required. At this point the state derived from this Quick Mode must be deleted from the ISAKMP SA as described in section 5.5.

9. Implementation Hints

Using a single ISAKMP Phase 1 negotiation makes subsequent Phase 2 negotiations extremely quick. As long as the Phase 1 state remains cached, and PFS is not needed, Phase 2 can proceed without any exponentiation. How many Phase 2 negotiations can be performed for a single Phase 1 is a local policy issue. The decision will depend on the strength of the algorithms being used and level of trust in the peer system.

An implementation may wish to negotiate a range of SAs when performing Quick Mode. By doing this they can speed up the "re-keying". Quick Mode defines how KEYMAT is defined for a range of SAs. When one peer feels it is time to change SAs they simply use the next one within the stated range. A range of SAs can be established by negotiating multiple SAs (identical attributes, different SPIs) with one Quick Mode.

An optimization that is often useful is to establish Security Associations with peers before they are needed so that when they become needed they are already in place. This ensures there would be no delays due to key management before initial data transmission. This optimization is easily implemented by setting up more than one Security Association with a peer for each requested Security Association and caching those not immediately used.

Also, if an ISAKMP implementation is alerted that a SA will soon be needed (e.g. to replace an existing SA that will expire in the near future), then it can establish the new SA before that new SA is needed.

The base ISAKMP specification describes conditions in which one party of the protocol may inform the other party of some activity-- either deletion of a security association or in response to some error in the protocol such as a signature verification failed or a payload failed to decrypt. It is strongly suggested that these Informational exchanges not be responded to under any circumstances. Such a condition may result in a "notify war" in which failure to understand a message results in a notify to the peer who cannot understand it and sends his own notify back which is also not understood.

10. Security Considerations

This entire memo discusses a hybrid protocol, combining parts of Oakley and parts of SKEME with ISAKMP, to negotiate, and derive keying material for, security associations in a secure and authenticated manner.

Confidentiality is assured by the use of a negotiated encryption algorithm. Authentication is assured by the use of a negotiated method: a digital signature algorithm; a public key algorithm which supports encryption; or, a pre-shared key. The confidentiality and authentication of this exchange is only as good as the attributes negotiated as part of the ISAKMP security association.

Repeated re-keying using Quick Mode can consume the entropy of the Diffie-Hellman shared secret. Implementors should take note of this fact and set a limit on Quick Mode Exchanges between exponentiations. This memo does not prescribe such a limit.

Perfect Forward Secrecy (PFS) of both keying material and identities is possible with this protocol. By specifying a Diffie-Hellman group, and passing public values in KE payloads, ISAKMP peers can establish PFS of keys-- the identities would be protected by SKEYID_e from the ISAKMP SA and would therefore not be protected by PFS. If PFS of both keying material and identities is desired, an ISAKMP peer MUST

establish only one non-ISAKMP security association (e.g. IPsec Security Association) per ISAKMP SA. PFS for keys and identities is accomplished by deleting the ISAKMP SA (and optionally issuing a DELETE message) upon establishment of the single non-ISAKMP SA. In this way a phase one negotiation is uniquely tied to a single phase two negotiation, and the ISAKMP SA established during phase one negotiation is never used again.

The strength of a key derived from a Diffie-Hellman exchange using any of the groups defined here depends on the inherent strength of the group, the size of the exponent used, and the entropy provided by the random number generator used. Due to these inputs it is difficult to determine the strength of a key for any of the defined groups. The default Diffie-Hellman group (number one) when used with a strong random number generator and an exponent no less than 160 bits is sufficient to use for DES. Groups two through four provide greater security. Implementations should make note of these conservative estimates when establishing policy and negotiating security parameters.

Note that these limitations are on the Diffie-Hellman groups themselves. There is nothing in IKE which prohibits using stronger groups nor is there anything which will dilute the strength obtained from stronger groups. In fact, the extensible framework of IKE encourages the definition of more groups; use of elliptical curve groups will greatly increase strength using much smaller numbers.

For situations where defined groups provide insufficient strength New Group Mode can be used to exchange a Diffie-Hellman group which provides the necessary strength. In is incumbent upon implementations to check the primality in groups being offered and independently arrive at strength estimates.

It is assumed that the Diffie-Hellman exponents in this exchange are erased from memory after use. In particular, these exponents must not be derived from long-lived secrets like the seed to a pseudo-random generator.

IKE exchanges maintain running initialization vectors (IV) where the last ciphertext block of the last message is the IV for the next message. To prevent retransmissions (or forged messages with valid cookies) from causing exchanges to get out of sync IKE implementations SHOULD NOT update their running IV until the decrypted message has passed a basic sanity check and has been determined to actually advance the IKE state machine-- i.e. it is not a retransmission.

While the last roundtrip of Main Mode (and optionally the last message of Aggressive Mode) is encrypted it is not, strictly speaking, authenticated. An active substitution attack on the ciphertext could result in payload corruption. If such an attack corrupts mandatory payloads it would be detected by an authentication failure, but if it corrupts any optional payloads (e.g. notify payloads chained onto the last message of a Main Mode exchange) it might not be detectable.

11. IANA Considerations

This document contains many "magic numbers" to be maintained by the IANA. This section explains the criteria to be used by the IANA to assign additional numbers in each of these lists.

11.1 Attribute Classes

Attributes negotiated in this protocol are identified by their class. Requests for assignment of new classes must be accompanied by a standards-track RFC which describes the use of this attribute.

11.2 Encryption Algorithm Class

Values of the Encryption Algorithm Class define an encryption algorithm to use when called for in this document. Requests for assignment of new encryption algorithm values must be accompanied by a reference to a standards-track or Informational RFC or a reference to published cryptographic literature which describes this algorithm.

11.3 Hash Algorithm

Values of the Hash Algorithm Class define a hash algorithm to use when called for in this document. Requests for assignment of new hash algorithm values must be accompanied by a reference to a standards-track or Informational RFC or a reference to published cryptographic literature which describes this algorithm. Due to the key derivation and key expansion uses of HMAC forms of hash algorithms in IKE, requests for assignment of new hash algorithm values must take into account the cryptographic properties-- e.g it’s resistance to collision-- of the hash algorithm itself.

11.4 Group Description and Group Type

Values of the Group Description Class identify a group to use in a Diffie-Hellman exchange. Values of the Group Type Class define the type of group. Requests for assignment of new groups must be accompanied by a reference to a standards-track or Informational RFC which describes this group. Requests for assignment of new group

types must be accompanied by a reference to a standards-track or Informational RFC or by a reference to published cryptographic or mathmatical literature which describes the new type.

11.5 Life Type

Values of the Life Type Class define a type of lifetime to which the ISAKMP Security Association applies. Requests for assignment of new life types must be accompanied by a detailed description of the units of this type and its expiry.

12. Acknowledgements

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We would also like to thank the many members of the IPSec working group that contributed to the development of this protocol over the past year.

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Appendix A

This is a list of DES Weak and Semi-Weak keys. The keys come from [Sch96]. All keys are listed in hexidecimal.

DES Weak Keys
0101 0101 0101 0101
1F1F 1F1F E0E0 E0E0
E0E0 E0E0 1F1F 1F1F
FEFE FEFE FEFE FEFE

DES Semi-Weak Keys
01FE 01FE 01FE 01FE
1FE0 1FE0 0EF1 0EF1
01E0 01E0 01F1 01F1
1FFE 1FFE 0EFE 0EFE
011F 011F 010E 010E
E0FE E0FE F1FE F1FE

FE01 FE01 FE01 FE01
E01F E01F F10E F10E
E001 E001 F101 F101
FE1F FE1F FE0E FE0E
1F01 1F01 0E01 0E01
FEE0 FEE0 FEF1 FEF1

Attribute Assigned Numbers

Attributes negotiated during phase one use the following definitions. Phase two attributes are defined in the applicable DOI specification (for example, IPsec attributes are defined in the IPsec DOI), with the exception of a group description when Quick Mode includes an ephemeral Diffie-Hellman exchange. Attribute types can be either Basic (B) or Variable-length (V). Encoding of these attributes is defined in the base ISAKMP specification as Type/Value (Basic) and Type/Length/Value (Variable).

Attributes described as basic MUST NOT be encoded as variable. Variable length attributes MAY be encoded as basic attributes if their value can fit into two octets. If this is the case, an attribute offered as variable (or basic) by the initiator of this protocol MAY be returned to the initiator as a basic (or variable).

Attribute Classes

class	value	type
Encryption Algorithm	1	B
Hash Algorithm	2	B
Authentication Method	3	B
Group Description	4	B
Group Type	5	B
Group Prime/Irreducible Polynomial	6	V
Group Generator One	7	V
Group Generator Two	8	V
Group Curve A	9	V
Group Curve B	10	V
Life Type	11	B
Life Duration	12	V
PRF	13	B
Key Length	14	B
Field Size	15	B
Group Order	16	V

values 17-16383 are reserved to IANA. Values 16384-32767 are for private use among mutually consenting parties.

Class Values

- Encryption Algorithm

		Defined In
DES-CBC	1	RFC 2405
IDEA-CBC	2	
Blowfish-CBC	3	
RC5-R16-B64-CBC	4	
3DES-CBC	5	
CAST-CBC	6	

values 7-65000 are reserved to IANA. Values 65001-65535 are for private use among mutually consenting parties.

- Hash Algorithm

		Defined In
MD5	1	RFC 1321
SHA	2	FIPS 180-1
Tiger	3	See Reference [TIGER]

values 4-65000 are reserved to IANA. Values 65001-65535 are for private use among mutually consenting parties.

- Authentication Method

pre-shared key	1
DSS signatures	2
RSA signatures	3
Encryption with RSA	4
Revised encryption with RSA	5

values 6-65000 are reserved to IANA. Values 65001-65535 are for private use among mutually consenting parties.

- Group Description

default 768-bit MODP group (section 6.1)	1
alternate 1024-bit MODP group (section 6.2)	2
EC2N group on GP[2^155] (section 6.3)	3
EC2N group on GP[2^185] (section 6.4)	4

values 5-32767 are reserved to IANA. Values 32768-65535 are for private use among mutually consenting parties.

- Group Type

MODP (modular exponentiation group)	1
ECP (elliptic curve group over GF[P])	2
EC2N (elliptic curve group over GF[2^N])	3

values 4-65000 are reserved to IANA. Values 65001-65535 are for private use among mutually consenting parties.

- Life Type

seconds	1
kilobytes	2

values 3-65000 are reserved to IANA. Values 65001-65535 are for private use among mutually consenting parties. For a given "Life Type" the value of the "Life Duration" attribute defines the actual length of the SA life-- either a number of seconds, or a number of kbytes protected.

- PRF

There are currently no pseudo-random functions defined.

values 1-65000 are reserved to IANA. Values 65001-65535 are for private use among mutually consenting parties.

- Key Length

  When using an Encryption Algorithm that has a variable length key, this attribute specifies the key length in bits. (MUST use network byte order). This attribute MUST NOT be used when the specified Encryption Algorithm uses a fixed length key.

- Field Size

  The field size, in bits, of a Diffie-Hellman group.

- Group Order

  The group order of an elliptical curve group. Note the length of this attribute depends on the field size.

Additional Exchanges Defined-- XCHG values

Quick Mode	32
New Group Mode	33

Appendix B

This appendix describes encryption details to be used ONLY when encrypting ISAKMP messages. When a service (such as an IPSEC transform) utilizes ISAKMP to generate keying material, all encryption algorithm specific details (such as key and IV generation, padding, etc...) MUST be defined by that service. ISAKMP does not purport to ever produce keys that are suitable for any encryption algorithm. ISAKMP produces the requested amount of keying material from which the service MUST generate a suitable key. Details, such as weak key checks, are the responsibility of the service.

Use of negotiated PRFs may require the PRF output to be expanded due to the PRF feedback mechanism employed by this document. For example, if the (ficticious) DOORAK-MAC requires 24 bytes of key but produces only 8 bytes of output, the output must be expanded three times before being used as the key for another instance of itself. The output of a PRF is expanded by feeding back the results of the PRF into itself to generate successive blocks. These blocks are concatenated until the requisite number of bytes has been acheived. For example, for pre-shared key authentication with DOORAK-MAC as the negotiated PRF:

```
  BLOCK1-8 = prf(pre-shared-key, Ni_b | Nr_b)
  BLOCK9-16 = prf(pre-shared-key, BLOCK1-8 | Ni_b | Nr_b)
  BLOCK17-24 = prf(pre-shared-key, BLOCK9-16 | Ni_b | Nr_b)
and
  SKEYID = BLOCK1-8 | BLOCK9-16 | BLOCK17-24
```

so therefore to derive SKEYID_d:

```
  BLOCK1-8 = prf(SKEYID, g^xy | CKY-I | CKY-R | 0)
  BLOCK9-16 = prf(SKEYID, BLOCK1-8 | g^xy | CKY-I | CKY-R | 0)
  BLOCK17-24 = prf(SKEYID, BLOCK9-16 | g^xy | CKY-I | CKY-R | 0)
and
  SKEYID_d = BLOCK1-8 | BLOCK9-16 | BLOCK17-24
```

Subsequent PRF derivations are done similarly.

Encryption keys used to protect the ISAKMP SA are derived from SKEYID_e in an algorithm-specific manner. When SKEYID_e is not long enough to supply all the necessary keying material an algorithm requires, the key is derived from feeding the results of a pseudo-random function into itself, concatenating the results, and taking the highest necessary bits.

For example, if (ficticious) algorithm AKULA requires 320-bits of key (and has no weak key check) and the prf used to generate SKEYID_e only generates 120 bits of material, the key for AKULA, would be the first 320-bits of Ka, where:

```
    Ka = K1 | K2 | K3
and
    K1 = prf(SKEYID_e, 0)
    K2 = prf(SKEYID_e, K1)
    K3 = prf(SKEYID_e, K2)
```

where prf is the negotiated prf or the HMAC version of the negotiated hash function (if no prf was negotiated) and 0 is represented by a single octet. Each result of the prf provides 120 bits of material for a total of 360 bits. AKULA would use the first 320 bits of that 360 bit string.

In phase 1, material for the initialization vector (IV material) for CBC mode encryption algorithms is derived from a hash of a concatenation of the initiator's public Diffie-Hellman value and the responder's public Diffie-Hellman value using the negotiated hash algorithm. This is used for the first message only. Each message should be padded up to the nearest block size using bytes containing 0x00. The message length in the header MUST include the length of the pad since this reflects the size of the ciphertext. Subsequent messages MUST use the last CBC encryption block from the previous message as their initialization vector.

In phase 2, material for the initialization vector for CBC mode encryption of the first message of a Quick Mode exchange is derived from a hash of a concatenation of the last phase 1 CBC output block and the phase 2 message id using the negotiated hash algorithm. The IV for subsequent messages within a Quick Mode exchange is the CBC output block from the previous message. Padding and IVs for subsequent messages are done as in phase 1.

After the ISAKMP SA has been authenticated all Informational Exchanges are encrypted using SKEYID_e. The initiaization vector for these exchanges is derived in exactly the same fashion as that for a Quick Mode-- i.e. it is derived from a hash of a concatenation of the last phase 1 CBC output block and the message id from the ISAKMP header of the Informational Exchange (not the message id from the message that may have prompted the Informational Exchange).

Note that the final phase 1 CBC output block, the result of encryption/decryption of the last phase 1 message, must be retained in the ISAKMP SA state to allow for generation of unique IVs for each Quick Mode. Each post- phase 1 exchange (Quick Modes and

Informational Exchanges) generates IVs independantly to prevent IVs from getting out of sync when two different exchanges are started simultaneously.

In all cases, there is a single bidirectional cipher/IV context. Having each Quick Mode and Informational Exchange maintain a unique context prevents IVs from getting out of sync.

The key for DES-CBC is derived from the first eight (8) non-weak and non-semi-weak (see Appendix A) bytes of SKEYID_e. The IV is the first 8 bytes of the IV material derived above.

The key for IDEA-CBC is derived from the first sixteen (16) bytes of SKEYID_e. The IV is the first eight (8) bytes of the IV material derived above.

The key for Blowfish-CBC is either the negotiated key size, or the first fifty-six (56) bytes of a key (if no key size is negotiated) derived in the aforementioned pseudo-random function feedback method. The IV is the first eight (8) bytes of the IV material derived above.

The key for RC5-R16-B64-CBC is the negotiated key size, or the first sixteen (16) bytes of a key (if no key size is negotiated) derived from the aforementioned pseudo-random function feedback method if necessary. The IV is the first eight (8) bytes of the IV material derived above. The number of rounds MUST be 16 and the block size MUST be 64.

The key for 3DES-CBC is the first twenty-four (24) bytes of a key derived in the aforementioned pseudo-random function feedback method. 3DES-CBC is an encrypt-decrypt-encrypt operation using the first, middle, and last eight (8) bytes of the entire 3DES-CBC key. The IV is the first eight (8) bytes of the IV material derived above.

The key for CAST-CBC is either the negotiated key size, or the first sixteen (16) bytes of a key derived in the aforementioned pseudo-random function feedback method. The IV is the first eight (8) bytes of the IV material derived above.

Support for algorithms other than DES-CBC is purely optional. Some optional algorithms may be subject to intellectual property claims.

Authors' Addresses

Dan Harkins
cisco Systems
170 W. Tasman Dr.
San Jose, California, 95134-1706
United States of America

Phone: +1 408 526 4000
EMail: dharkins@cisco.com

Dave Carrel
76 Lippard Ave.
San Francisco, CA 94131-2947
United States of America

Phone: +1 415 337 8469
EMail: carrel@ipsec.org

Authors' Note

The authors encourage independent implementation, and interoperability testing, of this hybrid protocol.

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