

Secure Boot with i.MX28 HAB Version 4

1 Introduction

1.1 Purpose

The purpose of this application note is to explain how to perform a secure boot on i.MX28 applications processors with High Assurance Boot version 4 (HAB v4). This includes steps on how to generate signed images and configure the IC to run securely using freely available tools provided by Freescale.

Executing trusted and authentic code on an applications processor starts with secure boot provided by the on-chip boot ROM. The i.MX family of applications processors provides this capability with the High Assurance Boot (HAB) component of the on-chip ROM. HAB provides services to the ROM to authenticate software that executes immediately after ROM, which is usually a bootloader, using

Contents

1. Introduction	1
2. i.MX28 security architecture overview	4
3. Designing for code signing	8
4. Signed U-Boot and Linux kernel example	17
5. Encrypted boot and Elftosb	22
6. Manage the electrical fuses	23
7. Development and debug tips	25
8. Example CSF text files for reference	26
9. Revision history	30



digital signatures. HAB provides a mechanism to establish a root of trust for the remaining software components.

The i.MX28 ROM is architecturally quite different from other i.MX ROMs that support HAB v4. The differences in image format and encrypted boot mechanism are substantial, and hence this separate application note should be used rather than the generic application note for HAB v4. The encrypted boot for i.MX28 is independent of HAB; see [Section 5, “Encrypted boot and Elftosb,”](#) for a brief description of encrypted boot.

1.2 Scope

In this document a practical example based on u-boot and Linux is used to illustrate the construction of a secure image in addition to configuring the device to run securely.

All the following questions will be answered:

- What components are required?
 - A boot image
 - An accompanying set of signing keys and certificates
 - Resulting digital signatures
- How are each of these different components generated?
- How are all these components assembled to create an encrypted signed image?
- What are the roles of different fuses?
- What tools are available for provisioning the signed image on bootable media?
- What tools are available for programming fuses?

NOTE

This document covers the secure boot for only the i.MX28 applications processor using HAB v4.

1.3 Audience

This document is intended for those:

- Requiring an architectural-level technical understanding of how ROM/HAB works in the boot sequence.
- Designing signed software images for use with a HAB-enabled i.MX28 processor.

It is assumed that the reader is familiar with the basics of digital signatures and public key cryptography.

1.4 Definitions, acronyms, and abbreviations

Table 1. Definitions, acronyms, and abbreviations

Term/Acronym	Definition
BD file	Boot descriptor file, an input file to Elftosb that describes the flow of boot and different binary and elf images included in the final SB file.
Bootlet	A bootlet is an image that can be executed on i.MX28 processor using ROM command CALL HAB. These are generally small images that can be used to configure peripherals on board such as external memory, voltage rails, etc., before loading larger images like bootloader or operating system.
CA	Certificate Authority, the holder of a private key used to certify public keys.
CSF	Command Sequence File, a binary data structure interpreted by HAB to guide authentication operations.
CST	Code Signing Tool, an application running on a host to generate a binary CSF and associated digital signatures.
DCD	Device Configuration Data, a binary table used by the ROM code to configure the device at the early boot stage.
DCP	Data Co-Processor, a cryptographic accelerator (including hash acceleration) found on some processors including i.MX28.
Elftosb	Freescale tool available for Windows and Linux to generate i.MX28 boot images.
HAB	High Assurance Boot, a software library executed in internal ROM on the Freescale processor at boot time which, among other things, authenticates software in external memory by verifying digital signatures in accordance with a CSF. This document is limited to HAB v4, as configured on i.MX28 processors.
IVT	Image Vector Table.
OS	Operating System.
OTP	One-Time Programmable. OTP hardware includes masked ROM and electrically programmable fuses (e-fuses).
PKCS#1	Standard specifying the use of the RSA algorithm.
PKI	Public Key Infrastructure, a hierarchy of public key certificates in which each certificate (except the root certificate) can be verified using the public key above it.
RSA	Public key cryptography algorithm developed by Rivest, Shamir and Adleman.
RVT	The ROM Vector Table (RVT) contains addresses of the HAB APIs available.
SA	Signature Authority, the holder of a private key used to sign software components.
SB file	A bootable image on i.MX28. It is generated using Elftosb tool and consists of header and multiple sections including a section with ROM Boot Commands.

Table 1. Definitions, acronyms, and abbreviations (continued)

Term/Acronym	Definition
SRK	Super Root Key, an RSA key pair which forms the start of the boot-time authentication chain. The SRK private keys are held by the CA. Unless explicitly noted, SRK in this document refers to the public key only.
SRK Table	Super Root Key Table, HAB v4 uses an SRK Table with maximum length of up to four (4) keys, allowing selection of the SRK used for a particular image. The hash of the SRK Table is embedded in the processor using OTP hardware.

1.5 References

The references listed below are available for download at freescale.com using the keyword provided.

- *i.MX28 Applications Processor Reference Manual*. Keyword: *MCIMX28RM*.
- *HAB Code-Signing Tool User's Guide* available in the Code Signing Tool package. Keyword: *IMX_CST_TOOL*.
- Fuse programming guides, *Programming OTP Bits* and *OTP Burner Documentation*, are available in the OTP tools package. Keyword: *IMX_OTP_TOOLS*.
- Elftosb documentation is available in the ELFTOSB package. Keyword: *IMX_ELFTOSB_TOOL*.
- *High Assurance Boot Version 4 Application Programming Interface Reference Manual* in the Code Signing Tool package (version 2.0 and later). Keyword: *IMX_CST_TOOL*.

2 i.MX28 security architecture overview

This section gives a technical overview of the i.MX28 security architecture, providing the background information needed for understanding the use cases and processes described in later sections.

2.1 ROM bootstrap code and HAB library

To design a correctly signed boot image, it is necessary to understand both the components which make up HAB and the basic boot-time authentication process. This section gives an architectural level overview of these elements which should be sufficient for most purposes.

The ROM bootstrap code is the first software executed after reset, and controls the initial phase of the boot process, using the HAB library. HAB is used to authenticate the boot image in external memory prior to its execution.

Based on pin or fuse settings, the ROM Bootstrap executes different boot modes to locate, load and execute the boot image from various boot peripherals (for example, NAND flash, SD/MMC card, serial EEPROM/flash, and USB recovery mode).

To ensure a secure boot, correct execution of the ROM Bootstrap must be guaranteed. To this end, its integrity is protected by virtue of its location in masked processor-internal ROM. Execution of the Boot ROM is also protected through disabling of external boot modes and interrupts.

The HAB library, embedded in the processor ROM, contains functions to authenticate an image as well as initialize and test security hardware. The same library functions can be called from later boot stages to extend the boot chain past the stage immediately after the Boot ROM.

The areas of an image that HAB verifies are completely customizable through a series of commands that are interpreted by HAB. These are known as Command Sequence File (CSF) commands that define the memory locations a digital signature covers, which keys to verify the signature with, and so on. All CSF processing is done within the HAB library, including cryptographic hash and digital signature verification. When appropriate, the HAB library makes use of the on-board hardware hash accelerator DCP to improve boot performance. On i.MX28, HAB v4 uses the RSA algorithm with all signatures following the CMS format, and all certificates following the X509v3 format.

For further details, see the *i.MX28 Reference Manual* in addition to the *HAB CST User Guide* listed in [Section 1.5, “References.”](#)

NOTE

RSA public key sizes used for secure boot with HAB on i.MX28 are limited to 1024 and 2048 bits only.

2.2 Boot flow

The Boot ROM execution state diagram for i.MX28 application processor that includes HAB v4 is shown in [Figure 1](#). The boot ROM for i.MX28 begins by loading a boot image (SB file) from bootable media. The bootable section of the SB file consists of boot commands such as LOAD, LOAD DCD, CALL HAB, JUMP HAB, etc. The ROM executes these commands in the sequence they are placed in the image binary. More details are provided in the sections describing the tools to generate a bootable image.

In [Figure 1](#), “Process CSF with HAB” is the point in the ROM execution state where the digital signatures across an image are verified. When configured for secure operation, the Boot ROM on an i.MX28 device will not allow unauthenticated code to execute and access to registers is limited for the LOAD DCD command. Any signature failures or security violations force the boot ROM to enter USB recovery mode to provision a new signed image to the boot device. Note that when configured for secure operation, even images downloaded via USB must be properly signed.

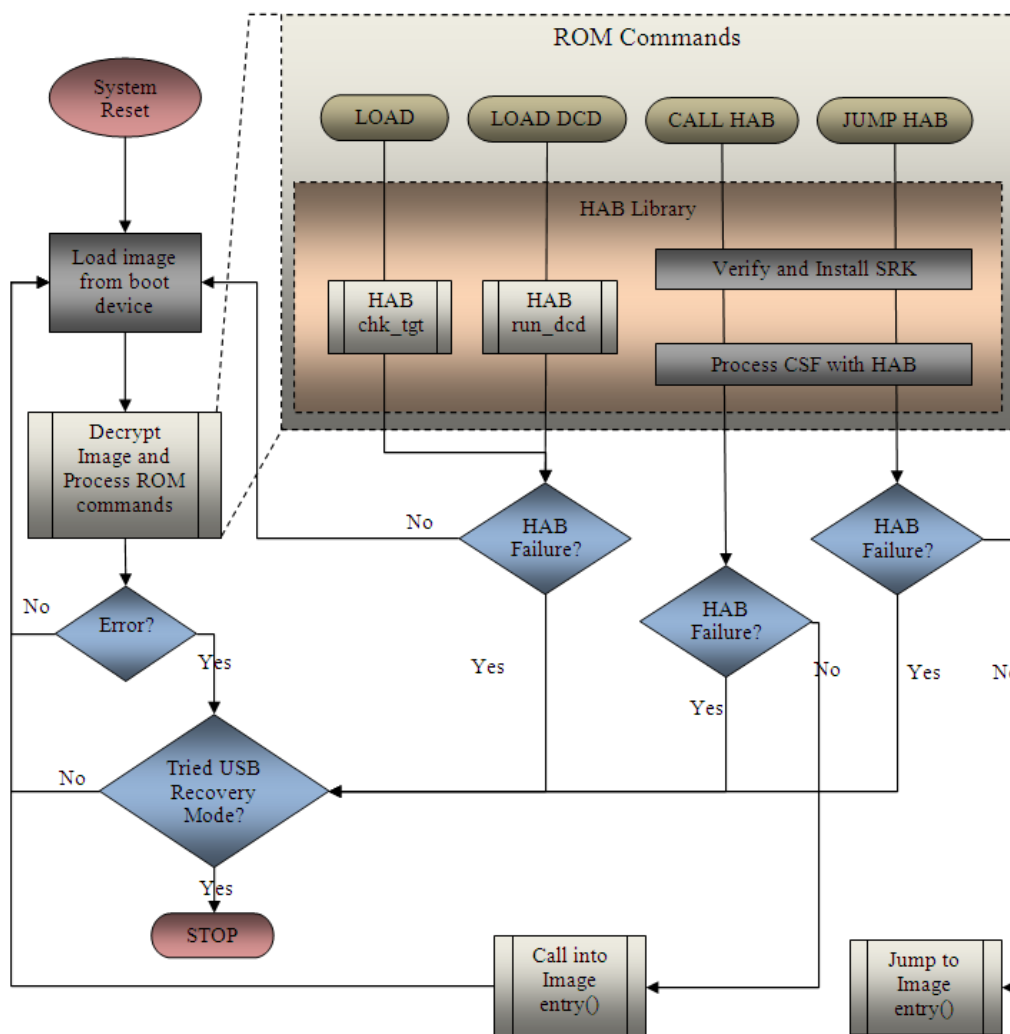


Figure 1. Secure boot flow from device

2.3 HAB Public Key Infrastructure

HAB authentication is based on public key cryptography using the RSA algorithm in which image data is signed offline using a series of private keys. The resulting signed image data then is verified on i.MX28 using the corresponding public keys. This key structure is known as a Public Key Infrastructure (PKI) tree.

Figure 2 gives an example of a typical PKI tree that is generated by the Freescale Code Signing Tools.

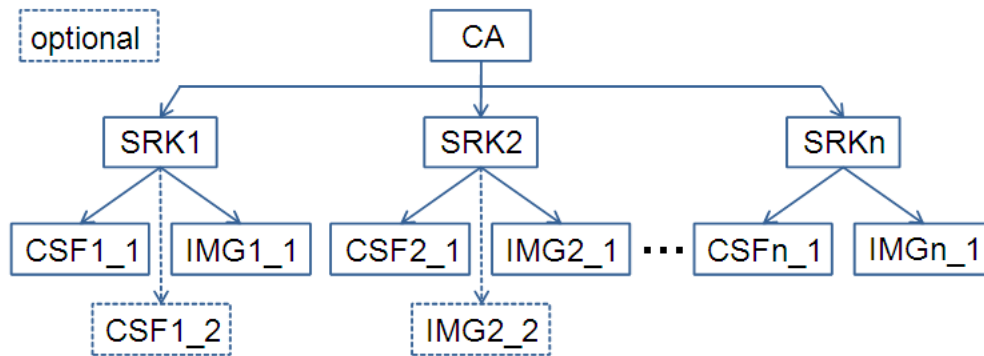


Figure 2. HAB v4 enabled devices typical PKI tree

For further information on the PKI tree used for HAB v4, see the *HAB CST User Guide* as mentioned in the [Section 1.5, “References.”](#) The details of digital signature authentication with the RSA algorithm are beyond the scope of this document.

The authentication steps performed by HAB occur in stages which are shown in [Figure 3.](#)

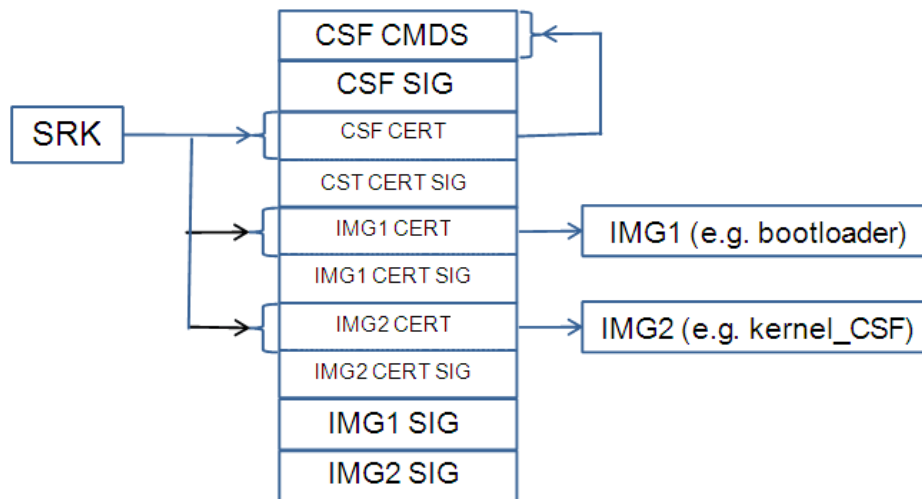


Figure 3. HAB v4 enabled devices detailed PKI tree

On the i.MX28, the authentication begins with establishing a root of trust with the Super Root Key (SRK). HAB does this by computing a cryptographic hash of the SRK Table and comparing the result with a pre-computed hash that is provisioned in OTP efuses. This ensures that the integrity of the SRK Table included in the image is intact. This is the beginning of the authentication chain in which the SRK is used to authenticate other keys which exist in the form of X509 certificates. For details on the SRK Table and how to generate it, see the *HAB CST User’s Guide*.

The arrows in [Figure 3](#) show the authentication flow. For example, the SRK is used to authenticate both the CSF key certificate and the image key certificates.

There are several important features to note. First, each key can certify multiple instances of the objects beneath it. For example, a single SRK can certify multiple CSF keys, a single CSF key can authenticate multiple CSFs (for example, on different product revisions), and a single image key can certify multiple images. Nevertheless, the CSF key can only authenticate the CSF headers and commands. The objects closer to the root of the PKI have greater impact if compromised, and require more protection. To some extent, this is offered by the CST tool, but it is important that the CST user adopt appropriate policies and processes. For example, a poorly planned CSF can open the way for malicious applications to be loaded in place of the authentic one. It is therefore prudent to plan the CSF so it does not need to change with every new version of the application, and restrict the group authorized to sign CSFs to a relatively small number of people.

Second, the authentication of an image key through the CSF may be a little different to the other links shown in [Figure 3](#). In order to provide better key separation, an image key may be bound to the CSF using a hash fingerprint embedded in the CSF. This means that it would not be possible to use the CSF with other image keys, even if they have been certified by the same SRK. The addition of the hash is optional and is dependent on whether the Hash Algorithm argument is present in the Install Key command. See the Install Key command documentation in the *HAB CST User's Guide* for further details.

Thirdly, each key type can authenticate only one data type. The SRK can authenticate only key certificates, not CSFs or images. A CSF key can authenticate only CSFs. An image key can authenticate only images.

3 Designing for code signing

3.1 What components are required?

A secure boot requires a number of data components to be added to an image. This includes certificates, signatures, Device configuration data (DCD) and CSF data.

NOTE

Although the i.MX28 ROM supports the use of DCD configuration of the chip, it is optional. On the i.MX28, device configuration is typically performed using bootlets using the Call command supported by the ROM. See section 3.1.2 for further information on DCD.

When performing a secure boot on the i.MX28, Boot ROM and HAB require the following data components to be defined in the image:

- Image Vector Table—A table of pointers used by the Boot ROM to locate other required data components.
- CSF data—A block of data containing the commands that HAB will execute during boot.
- Certificates and associated signatures HAB uses to verify an image.

In addition to the above components, the location of the ROM Vector Table (RVT) is also required. The RVT is a table of addresses defining the location of each of the HAB API functions. This is required as the HAB library will be called to authenticate the next component in the boot chain. The structure of the RVT

is defined in the *High Assurance Boot Version 4 Application Programming Interface Reference Manual* included in the Freescale Code Signing Tool release package. The memory location of the RVT differs for each member of the family. In this case, the location of the RVT for MX28 is documented in the *i.MX28 Applications Processor Reference Manual*.

3.1.1 Image Vector Table

The Image Vector Table (IVT) is a mandatory part of the boot image, and its structure is defined as:

```
typedef struct
{
    uint32_t      header;
    uint32_t      *entry;
    uint32_t      reserved1;
    uint32_t      *dcd;
    boot_data_t   *boot_data;
    uint32_t      *self;
    uint32_t      *csf;
    uint32_t      reserved2;
} hab_ivt_t;
```

Where:

uint32_t:	A type representing a 32 bit unsigned integer.
Header:	Header identifying the type of data structure (0xD1), its size (0x0020), and HAB version (0x40). For i.MX28, this is D100 2040h.
*entry:	Absolute address of the first instruction to execute from the image.
reserved1:	Reserved and should be zero.
*dcd:	Absolute address of the image Device Configuration Table (DCD). If using bootlets to configure i.MX28, this field should be set to NULL.
*boot_data:	Absolute address of the Boot Data structure. This should be set to NULL for i.MX28.
*self:	Absolute address of the IVT. Used internally by the ROM.
*csf:	Absolute address of the Command Sequence File (CSF) used by the HAB library. This field must be set to NULL when not performing a secure boot.
reserved2:	Reserved and should be zero.

The IVT is a block of data that must reside on the boot device. Every image including bootlets in the boot sequence needs an IVT for ROM to run authentication process. Systems can be designed to have a single IVT serving all the images in the boot sequence or have multiple IVTs one per image. This app note provides examples of multiple IVTs, one per image. See [Section 3.3, “How to assemble the HAB data with](#)

the boot image,” which discusses how the IVT is used in the signed image. Also see the *i.MX28 Applications Processor Reference Manual* for more detailed description of IVT data structure.

NOTE

The i.MX28 ROM requires that the IVT is followed by an unsigned 32-bit integer in memory containing the size of entire image including IVT and CSF data. See Boot Modes chapter of the *i.MX28 Reference Manual* for more details.

3.1.2 Device Configuration Data

The main purpose of the DCD is to allow peripherals to be configured for optimal performance during image authentication. A second purpose is to allow memory controllers to be configured in advance of loading the image from non-volatile storage to its run-time location in external RAM. Since DCD processing occurs prior to authentication, the scope of valid DCD operations is strictly limited to certain controllers (clock, memories, etc.). The DCD is executed using the “LOAD DCD” ROM command and is optional. For i.MX28 a bootlet, an independent image that resides in final boot image that is executed with a “CALL HAB” ROM command, can also be used to initialize external memories. If using bootlets to configure i.MX28, the use of DCD is not required.

For further details, see the Boot Modes chapter of the *i.MX28 Reference Manual*.

3.1.3 Command Sequence File

The CSF is a binary data structure interpreted by the HAB library to guide the authentication process. This CSF binary structure is created using the HAB Code Signing Tool. The CSF contains commands which determine:

- The PKI tree to be used in authentication operations.
- The physical memory regions to be authenticated, along with the authentication method and reference data.
- Device configuration operations.

Device configuration operations in the CSF are similar to those in the DCD. The important difference between the two is that DCD may configure only a limited range of peripherals (since DCD processing is performed prior to authentication) whereas device configuration commands within the CSF are unconstrained, because CSF commands are authenticated before they are executed.

With HAB, multiple non-contiguous regions of physical memory can be covered with a single digital signature. The maximum number of regions is limited by the hash computation engine used, which may also depend on the size and alignment of the images, as follows:

- When using DCP for the hash computation of digital signature verification a maximum of six (6) non-contiguous blocks are supported.
- When using DCP all blocks except the final one must be multiples of 64 bytes in length (the final data block may be an arbitrary length).
- When using the software implementation for hash computations included in HAB a maximum of 16 non-contiguous blocks are supported.

3.1.4 Image layout

When performing a secure boot on an i.MX28 processor, the image must contain a correctly formatted image vector table (IVT) with a valid header and pointers.

The loader inside ROM first loads the image from boot media. The image data is then passed through the DCP (Data Co-Processor) where it will be decrypted (if it is an encrypted image) and placed at the destination address.

As mentioned earlier in Section 2.2 the bootable section of the SB file consists of a sequence of boot commands. Typically it consists of number of LOAD commands followed by HAB CALL commands to execute bootlets and then finally a HAB JUMP command. The HAB CALL and HAB JUMP commands require an address where an IVT was loaded.

At this stage, the rest of the boot process diverges depending on the security configuration: non-secure/open or secure/closed which is determined by the SEC_CONFIG fuse field.

3.1.5 Nonsecure boot—image layout

When performing a non-secure boot with the SEC_CONFIG fuse field set to Open, it is not necessary to provide the CSF data as part of the image. When no CSF is present, the CSF field of the IVT should be set to NULL. Regardless of whether a valid CSF present or not, HAB will attempt to authenticate the image performing the same steps as it would do for a secure boot in closed configuration. If authentication fails then HAB will log events that can be later used for debugging purpose and continue execution of the normal boot flow. Eventually ROM code will jump to the image pointed by *entry.

Note that when SEC_CONFIG fuse field is set to Open, all HAB failures are considered to be non-fatal and the boot process is allowed to continue. The Open configuration should also be used for development purposes of secure products where CSFs and other data components for secure boot can be debugged. The Open configuration is the end configuration for non-secure products.

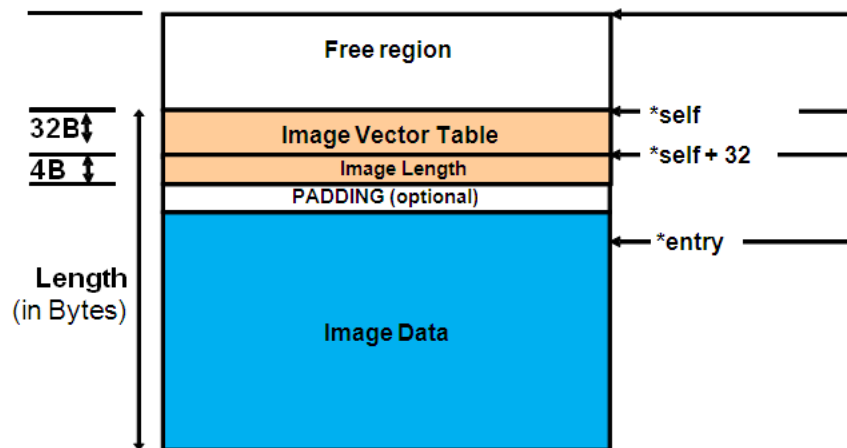


Figure 4. Typical memory layout of an unsigned image

The IVT can appear anywhere before, in between or after the Image Data but not at address 0. Otherwise *self in IVT points to NULL and is interpreted by HAB library as an invalid address.

The Image Length field as mentioned earlier must immediately follow the IVT and is the length of entire image data including IVT and CSF data.

3.1.6 Secure boot—image layout

The SEC_CONFIG fuse field tells HAB whether the device is to boot securely or not. By setting this field to Closed, the i.MX28 only allows a properly signed image to execute. In the Closed configuration the CSF data component is mandatory and must be included in the image along with valid pointers in the IVT structure. This is true regardless of which boot device is chosen, including USB recovery mode.

The first step performed by HAB when performing a secure boot is the installation of the SRK. It is important to have the SRK tied to the processor to avoid replacement with an untrusted key. Therefore, during the installation of the SRK, the ROM computes a SHA-256 hash of the SRK Table attached to the binary CSF data. The result is compared to the reference value provisioned into the OTP fuses during product manufacturing.

Next are the principal steps (not necessarily in order) involved in processing the CSF:

- Verify the CSF key certificate using the SRK.
- Verify the CSF signature using the CSF key.
- Verify image key certificates using the SRK.
- Verify image signature(s) using the image keys.
- Perform any device configuration operations specified in the CSF.

Note that not all steps apply to every CSF.

If HAB authentication is successful, ROM code jumps into the image code pointed to *entry.

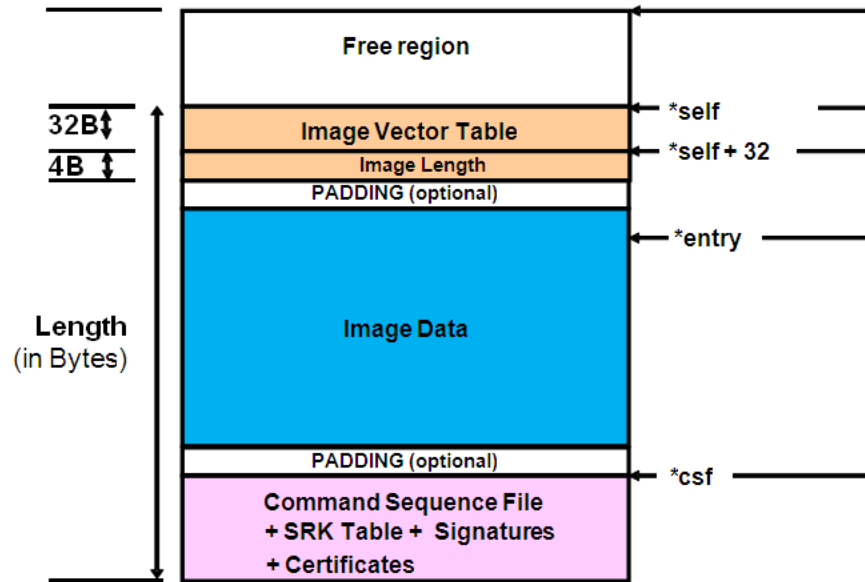


Figure 5. Typical memory layout of a signed image

The IVT can appear anywhere before, in between, or after Image Data but not at address 0. Otherwise `*self` in IVT points to NULL and that will be interpreted by HAB library as an invalid address. Also the CSF and associated data (SRK Table, Signatures and Certificates) need not be concatenated together but it is the default output of the CST.

The Size field must immediately follow the IVT and it is the length of entire image data including IVT and CSF data. See the Boot Modes chapter of the reference manual for more details.

NOTE

HAB requires that the IVT, the Size field and at minimum, the first word of the Image Data all must be covered by a digital signature. Failure to do so will result in HAB issuing an assertion audit log event and the ROM refusing to launch the image.

3.2 Generating the HAB data

3.2.1 Generating the Command Sequence File data (CSF)

The CSF contains all the commands that HAB will execute during the secure boot. These commands instruct HAB on which memory areas of the image to authenticate, which keys to install, which keys to use for signature verification, what data to write to a particular register, and so on.

Every image including bootlets in the boot sequence must be signed. There could be a single CSF for all the images in the boot sequence or multiple CSFs, one for each image. A single CSF is possible if images do not overlap in memory but the examples presented in this app note use multiple CSFs as they occupy same space in memory.

The first CSF in the boot sequence must contain an Install SRK command to install a single SRK from the SRK Table provided. Also, it must contain an Install CSFK command to install the CSF key prior to CSF authentication. Subsequent CSFs in the boot sequence do not require Install SRK and Install CSFK commands. Every CSF must contain an Authenticate CSF command to authenticate the CSF contents using the CSF key.

To facilitate well-formed CSF generation, Freescale provides a reference Code Signing Tool (IMX_CST_TOOL) for the creation of the CSF data necessary to perform a secure boot. The CST release package is available at freescale.com as shown in the list of references.

The binary output from the CST consists of the following components:

- CSF commands interpreted by HAB
- SRK Table and corresponding fuse pattern
- Public key certificates
- CSF Signature
- One or more Image signatures

NOTE

Prior to continuing with examples described below see the *CST User's Guide* available in the above mentioned package to obtain a better understanding of the code signing process and how to use the CST.

3.2.2 Generating keys and the Super Root Key (SRK) Table

To begin, HAB code signing keys are required. The CST provides scripts to generate the required private keys and public key certificates. In addition to the keys a SRK table must also be generated.

The following steps illustrate how the keys and SRK Table can be generated:

1. Generating HAB code signing keys—To generate the standard code signing keys for HAB run the following command:

```
./hab4_pki_tree.sh
```

The resulting private keys will be placed in the keys directory of the CST and the corresponding X.509 certificates will be placed in the crts directory. The private keys are stored in password protected files in PKCS#8 format but care must be taken to ensure that the confidentiality of these keys is maintained.

For details on key generation with the CST, see *HAB CST User Guide*.

2. Generating an SRK Table—The SRK Table is constructed from up to four public SRKs. A cryptographic hash of this table is generated by the CST for provisioning to the SRK_HASH field in OTP fuses during manufacturing. At boot time an Install SRK CSF command specifies the location of the SRK Table in memory as well as the index of the SRK to use for authenticating the remaining keys.

To generate an SRK Table the CST provides the srktool, which requires X.509v3 public key certificates for the SRKs as inputs. The following is an example to generate an SRK Table with four keys:

```
../linux/srktool -h 4 -t SRK_1_2_3_4_table.bin -e SRK_1_2_3_4_fuse.bin -d sha256 -c
./SRK1_sha256_2048_65537_v3_ca.crt.pem, ./SRK2_sha256_2048_65537_v3_ca.crt.pem, ./SRK3_sh
a256_2048_65537_v3_ca.crt.pem, ./ SRK4_sha256_2048_65537_v3_ca.crt.pem -f 1
```

For details on key generation with the CST, see *HAB CST User Guide*.

NOTE

[Section 6, “Manage the electrical fuses,”](#) provides guidance on how to blow fuses, and which fuses must be blown for a secure product.

3.2.3 Generating the binary CSF and signatures

The *HAB CST User Guide* (listed in [Section 1.5, “References”](#)) explains in detail how to use CSF input file with CST tool to generate CSF binary data and signatures. Refer to Section 4 of the *HAB CST User Guide (HABCST_UG_Rev_1.pdf)* available in the Code Signing Tool package, downloadable on the website freescale.com.

3.3 How to assemble the HAB data with the boot image

This section lists out typical code changes needed to accommodate HAB data (including the binary CSF, certificates and signatures) and the IVT data structure. The purpose is to create a boot image that is organized as represented by [Figure 5](#).

The following definitions will be referred to in the steps below:

- `__hab_data`: symbol name for the start of HAB data in memory
- `input_ivt`: symbol name for start of IVT data in memory

1. The first step is to modify the linker file to preserve space and a symbol name “`__hab_data`” for HAB data. Also make sure `input_ivt` and CSF are not located at address 0. Below are the typical linker file changes in bold italic, with the `__hab_data` symbol name and reserving 0x2000 bytes for `*csf`.

```
OUTPUT_ARCH(arm)
ENTRY(_start)
SECTIONS
{
    /* Image loaded at address 0x10 to avoid input_ivt at 0 */
    . = 0x00000010;
    . = ALIGN(4);
    . = BASE_ADDR;
    .text : { *(.text) }
    .rodata : { *(.rodata) }
    .data : { *(.data) }
    /* Allow the section for future growth with padding
        to a known length */
    . = BASE_ADDR + 0x2A000;
}
```

```

/* reserve this area to store HAB related data such as
 * CSF commands, certificates and signatures
 */
__hab_data = .;
. = . + 0x2000;
__hab_data_end = .;
/* place the __hab_data memory region before the .bss
 * region to avoid being over written at runtime and to
 * keep the u-boot binary as small as possible
 */
. = ALIGN(4);
.bss : { *(.bss) }
}

```

2. The next step is to add the IVT data structure, image length and symbol name `input_ivt` to locate the IVT data structure in memory. Following is a typical implementation of `input_ivt` that includes IVT data structure and followed by the “Image Length” field containing the length of the entire image including HAB data. Note the use of symbol `__hab_data` in initialization of `*csf` pointer in IVT and the use of `__hab_data_end` and `BASE_ADDR` in calculating the length of the image.

```

#include <hab.h> /* hab_ivt_t is defined in hab.h */

struct _hab_aut {
    hab_ivt_t ivt;
    uint32_t img_len;
};

const struct _hab_aut input_ivt __attribute__((section(".data"),aligned(4))) = {
    {
        // hdr word with tag #HAB_TAG_IVT, length and HAB version fields
        IVT_HDR(sizeof(struct hab_ivt), HAB_VER(4, 0)),

        // Absolute address of the first instruction to execute
        (hab_image_entry_f) (&_start),

        // Reserved in this version of HAB: should be NULL
        NULL,

        // Absolute address of the image DCD: may be NULL
        NULL,
    }
}

```



```

// Absolute address of the Boot Data: may be NULL, but not
// interpreted any further by HAB
NULL,

// Absolute address of the IVT
(const void*) (&input_ivt),

// Absolute address of the image CSF (CSF data generated by cst)
(const void*) (&__hab_data),

// Reserved in this version of HAB: should be zero.
0
},
// image length including CSF data calculated from linker symbol __hab_data_end
// and BASE_ADDR, defined in Makefile and used at compile time
(const void*) (&__hab_data_end) - BASE_ADDR;
};

```

3. Finally changes are required to the boot descriptor file (.bd or BD file) for use with Elftosb to generate a final bootable image with HAB data. For sample u-boot BD and Linux kernel BD files, refer to [Section 4.1, “Sample boot descriptor file used for u-boot Image,”](#) and [Section 4.2, “Sample boot descriptor file used for Linux kernel image.”](#)

4 Signed U-Boot and Linux kernel example

U-Boot is a bootloader commonly used to boot a Linux device and is provided in the Freescale Linux BSP. i.MX28 specific U-Boot consists of three ELF files:

- power_prep
- boot_prep
- u-boot

Power_prep and Boot_prep are bootlet images that are used to prepare the board and initialize the external memory before loading the u-boot image. Bootlets are also part of Linux BSP with imx-bootlets-src package. For secure boot we need to generate HAB data for all three ELF files. The streaming boot architecture of i.MX28 enables all three signed images with HAB data to reside in the same SB file. The boot descriptor file described in [Section 4.1, “Sample boot descriptor file used for u-boot Image,”](#) dictates the sequence of boot commands in the bootable section of u-boot SB file.

Similarly the Linux kernel of i.MX28 consists of power_prep, boot_prep, linux_prep and zImage boot components and the sequence of boot commands in the bootable section of Linux SB file is shown in [Section 4.2, “Sample boot descriptor file used for Linux kernel image.”](#)

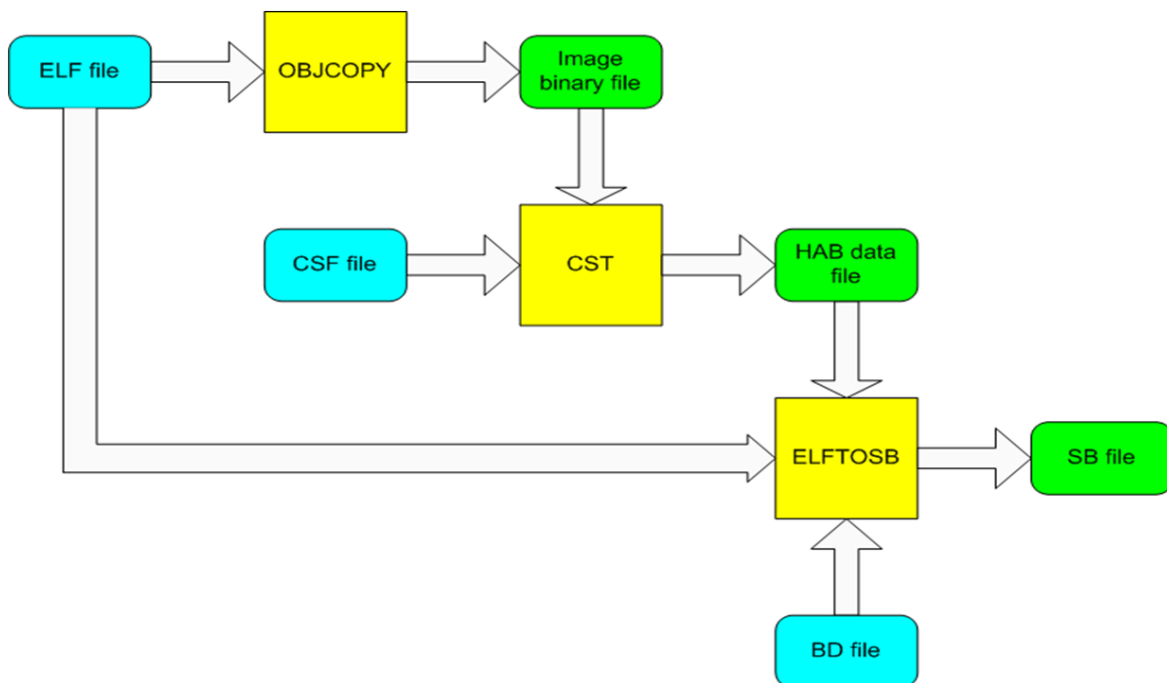


Figure 6. Players in the generation of signed boot image

Figure 6 above shows the tools and steps for code signing a bootable image for i.MX28 processor.

The prerequisites are:

- Linux machine set up to perform builds of the i.MX28 BSP
- Freescale CST
- Freescale elftosb tool
- Objcopy utility

Here are the steps to generate signed u-boot SB file:

1. The source code changes described in section 3.3 are required for power_prep, boot_prep and u-boot.
2. Build the three ELF files for power_prep, boot_prep and u-boot. Follow the instructions in the BSP guide on how to build imx-bootlets and u-boot.
3. Next step is to generate HAB data for the three ELF files using the Freescale code signing tool. The ELF files should be first converted to binary using the GNU objcopy command.

```

objcopy -I elf32-little -O binary --gap-fill 0xFF power_prep power_prep.bin
objcopy -I elf32-little -O binary --gap-fill 0xFF boot_prep boot_prep.bin
objcopy -I elf32-little -O binary --gap-fill 0xFF u-boot u-boot.bin
  
```

Also using objcopy command add padding to the binary for sufficient length to allow future expansion of the code

```

objcopy -I binary -O binary --gap-fill 0xFF --pad-to 0x2A000 u-boot.bin
u-boot_pad.bin
  
```

The HAB data is generated using the code signing tool. [Section 8, “Example CSF text files for reference,”](#) illustrates sample CSF files including u-boot.csf and boot_prep.csf.

```
cst -o boot_prep_hab_data < boot_prep.csf
cst -o power_prep_hab_data < power_prep.csf
cst -o uboot_hab_data < u-boot.csf
```

4. Finally the `elftosb` tool is used to generate the signed SB file. `ElfTosb` is described in [Section 5.2, “IMX_ELFTOSB_TOOL.”](#)

```
./elftosb -z -V -f imx28 -c ./uboot_ivt.bd -o imx28_ivt_uboot.sb
```

Here are the steps to generate a signed Linux kernel SB file.

1. The source code changes described in section 3.3 are required for all three bootlets: `power_prep`, `boot_prep` and `linux_prep`.
2. Build the three ELF files for `power_prep`, `boot_prep` and `linux_prep`. Follow the instructions in the BSP guide to build the three bootlets.
3. Next step is to generate HAB data for the Linux kernel binary file (zImage) and the 3 bootlets using the Freescale code signing tool. The ELF files should be first converted to binary using the GNU `objcopy` command.

```
objcopy -I elf32-little -O binary -gap-fill 0xFF power_prep power_prep.bin
objcopy -I elf32-little -O binary -gap-fill 0xFF boot_prep boot_prep.bin
objcopy -I elf32-little -O binary -gap-fill 0xFF linux_prep linux_prep.bin
```

The BSP design of `linux_prep` is a little complex in that it is executed twice. The first instance it is executed using the CALL HAB command and second instance using the JUMP HAB command. The execution flow can better be understood using [Section 4.2, “Sample boot descriptor file used for Linux kernel image.”](#) The first execution modifies the memory at byte offset 0x24 to 1. If we want to authenticate the entire `linux_prep` for both executions then we will have to generate two signatures. The first signature will be used with CALL HAB with offset 0x24 showing original value ‘0’ and second signature used for authenticating `linux_prep` with JUMP HAB showing a value of 1 at offset 0x24. We do this by first copying `linux_prep`, bin to `linux_kernel.bin`, then manually modify byte 0x24 to 1 using a hex editor and include `linux_kernel.bin` in `linux_kernel.csf` for signature generation.

```
cp linux_prep.bin linux_kernel.bin
using a hex editor set byte 0x24 to 1
```

The HAB data is generated using the code signing tool. [Section 8, “Example CSF text files for reference,”](#) illustrates sample CSF files including `linux_prep.csf` and `linux_kernel.csf`.

```
cst -o boot_prep_hab_data < boot_prep.csf
cst -o power_prep_hab_data < power_prep.csf
cst -o linux_prep_hab_data < linux_prep.csf
cst -o linux_kernel_hab_data < linux_kernel.csf
```

4. Finally the `elftosb` tool is used to generate the signed SB file. `ElfTosb` is described in [Section 5.2, “IMX_ELFTOSB_TOOL.”](#)

```
./elftosb -z -V -f imx28 -c ./linux_ivt.bd -o imx28_ivt_linux.sb
```

4.1 Sample boot descriptor file used for u-boot Image

```
// i.MX28 ROM command script to load and run U-Boot
options {
    flags = 0x01;
}

sources {
    power_prep = "power_prep";
    power_prep_bin="power_prep.bin";
    power_prep_hab_data="power_prep_hab_data";

    boot_prep = "boot_prep";
    boot_prep_bin = "boot_prep.bin";
    boot_prep_hab_data="boot_prep_hab_data";

    u_boot = "u-boot";
    u_boot_bin="u-boot_pad.bin";
    uboot_hab_data="uboot_hab_data";
}

section (0) {

    //-----
    // Power Supply initialization
    //-----
    load power_prep_bin > 0x10;
    load power_prep;
    load power_prep_hab_data > power_prep:__hab_data;
    hab call power_prep:input_ivt;

    //-----
    // SDRAM initialization
    //-----
    load boot_prep_bin > 0x10;
    load boot_prep;
    load boot_prep_hab_data > boot_prep:__hab_data;
    hab call boot_prep:input_ivt;

    //-----

```

```

// Load and call u_boot - ELF ARM image
//-----
load u_boot_bin > 0x41008000;
load u_boot;
load uboot_hab_data > u_boot:__hab_data;
hab jump u_boot:input_ivt;
}

```

4.2 Sample boot descriptor file used for Linux kernel image

```

// i.MX28 ROM command script to load and run Linux kernel
options {
    flags = 0x01;
}
sources {
    power_prep          = "./power_prep";
    power_prep_bin      = "./power_prep.bin";
    power_prep_hab_data = "./power_prep_hab_data";

    boot_prep           = "./boot_prep";
    boot_prep_bin       = "./boot_prep.bin";
    boot_prep_hab_data  = "./boot_prep_hab_data";

    linux_prep          = "./linux_prep";
    linux_prep_bin      = "./linux_prep.bin";
    linux_prep_hab_data = "./linux_prep_hab_data";
    linux_kernel_hab_data = "./linux_kernel_hab_data";
    zImage              = "./zImage";
}
section (0) {
    //-----
    // Power Supply initialization
    //-----
    load power_prep_bin > 0x10;
    load power_prep;
    load power_prep_hab_data > power_prep:__hab_data;
    hab call power_prep:input_ivt;

    //-----
    // SDRAM initialization

```

```

//-----
load boot_prep_bin > 0x10;
load boot_prep;
load boot_prep_hab_data > boot_prep:__hab_data;
hab call boot_prep:input_ivt;

//-----
// Prepare to boot Linux
//-----
load linux_prep_bin > 0x2000;
load linux_prep;
load linux_prep_hab_data > linux_prep:__hab_data;
hab call linux_prep:input_ivt;

//-----
// Load and start Linux kernel
//-----
load zImage > 0x40008000;
load linux_kernel_hab_data > linux_prep:__hab_data;
hab jump linux_prep:input_ivt;
}

```

5 Encrypted boot and Elftosb

5.1 i.MX28 encrypted boot in a nut-shell

i.MX28 supports boot images encrypted with AES-128. The entire image including HAB data is encrypted. The Elftosb tool from Freescale supports encryption of boot images. Elftosb generates a session key which is used to encrypt the image. The user generates one or more input OTP keys using Keygen utility. For every input OTP key, elftosb generates an entry in a key dictionary residing inside the SB file. The dictionary entry consists of CBC-MAC computed over boot image header with OTP key and the session key encrypted with the OTP key. There is no limit on number of input OTP keys or key dictionary size.

Any one of the OTP keys in the key dictionary can be burned into i.MX28 CRYPTO fuses.

At boot time, the ROM computes a CBC-MAC over the boot image header with the OTP Key, finds a matching entry in the key dictionary of the image, decrypts the session key with the OTP key and decrypts the rest of the image with decrypted session key.

5.2 IMX_ELFTOSB_TOOL

The IMX_ELFTOSB_TOOL package is available on freescale.com.

The package contains executable `elftosb.exe` for Windows and `elftosb` for UNIX. See the documentation available in the package for detailed explanation of `elftosb` and the image encryption and decryption process

6 Manage the electrical fuses

6.1 Tools to blow the fuses

For programming any fuse on i.MX28, Freescale recommends using the `IMX_OTP_TOOLS` package available on freescale.com, search for “`IMX_OTP_TOOLS`.”

The fuse programming package consists of a set of scripts, tools and relevant documentation to program any fuse including the SRK hash and CRYPTO key fuses.

Using these tools will guarantee programming of fuses in correct byte order.

6.2 Documents available in the package

- `Programming_OTP_Bits.pdf`: describes various tools available for programming OTP fuses on i.MX28.
- `OTP_Burner_Documentation.pdf`: describes the usage of `otp_burner.py` script.

6.3 List of tools available in the package

6.3.1 OTP_BURNER.PY

This is a python script to generate an `otpinit.sb` application that is downloaded on i.MX28 to program the fuses. The `otp_burner.py` script can be run on either Windows or UNIX hosts. The inputs to the script are:

- `fuses.bin` file used with `--srk` option, `fuses.bin` file is the output of `SRKTOOL` available with `CST` package. `Fuses.bin` contains the hash of SRK Table in binary format.
- encryption key with `--key` option, described in `otp_burner_documentation.pdf`
- input text file with `--input` option, described in `otp_burner_documentation.pdf`

See the documentation available with the `IMX_OTP_TOOLS` package for a detailed description on the usage of `Otp_Burner.py`.

6.3.2 BITINIT.EXE

`BitInit.exe` is a Windows application used to download and execute the `otpinit.sb` file in the internal RAM of i.MX28 when connected to PC host in USB recovery mode. The `OtpInit.sb` file is the output of `Otp_burner.py` described above.

6.3.3 KEYGEN and KEYGEN.EXE

`Keygen` is used to create random encryption keys called as input OTP keys. These keys are programmed into fuses using `otp_burner.py` and `BitInit.exe` tools.

On Windows (Keygen.exe), cryptographically secure RNG APIs in the OS are used to generate the random key.

On Linux (Keygen), /dev/random is used to generate the random key.

6.4 Recommendations on i.MX28 fuse configuration

During production, it is suggested to change the SEC_CONFIG of the chip to Closed configuration only once the programming, provisioning, validation and other pre-production steps are working successfully in Open configuration. When only secure boot is allowed, every boot image whatever the boot mode is, must be signed and authenticated correctly prior its execution so it is easier to fix any issues encountered with a chip still in Open configuration.

Some important boot parameters are set through the fuses. The fact that a fuse is only One Time Programmable is sufficient to prevent the change of a 1-bit parameter, but is not sufficient to prevent the modification of a larger value such as the hash of the SRK Table. Therefore lock fuses are dedicated to protect such information. It is recommended to blow these fuses once the value is programmed and verified to be functional.

For instance, with the i.MX28, once the SRK_HASH[255:0] is programmed, the fuse SRK LOCK bit must be programmed to disable any modification of the reference digest for the super toot key table.

For a description of the lock fuses, refer to Programming_OTP_Bits.pdf available with [IMX_OTP_TOOLS] package, listed in [Section 1.5, “References.”](#)

6.5 Programming SRK Hash fuses

This section will explain how tools provided with IMX_CST_TOOL and IMX_OTP_TOOLS packages should be used to programming SRK Hash fuses.

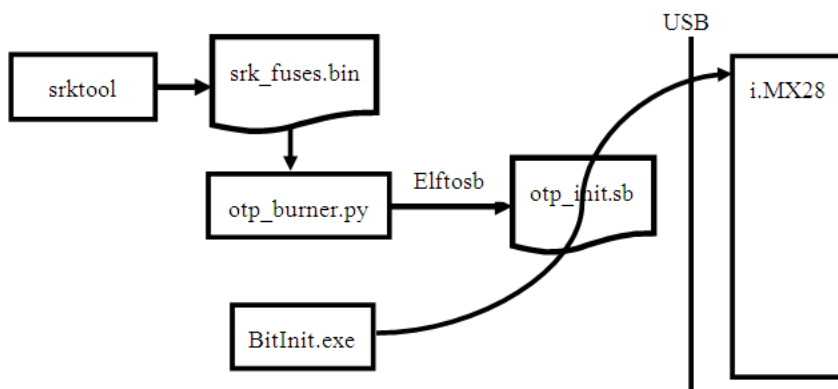


Figure 7. Fuse programming tools on i.MX28

Srktool is used to generate the HAB v4 SRK Table; the tool also outputs the cryptographic hash of the SRK Table in a binary file (srk_fuses.bin).

The `otp_burner.py` script uses the binary SRK hash file to generate an executable image that can program fuses. The output image `otp_init.sb` resulting from `otp_burner.py` is then downloaded to i.MX28 using `BitInit.exe`. The i.MX28 must be connected in USB recovery mode in order for `BitInit.exe` to download the SB file to internal RAM on the device. When executed on i.MX28 `otp_init.sb` programs the SRK fuses. Using these tools will ensure SRK and other fuses are programmed correctly.

The arguments to `otp_burner.py` to generate `otp_init.sb` with SRK fuse programming is `--srk`:

```
otp_burner.py --srk srk_fuses.bin --key encryption_key.txt -i bit_settings.txt -o
otp_init.sb
```

The `bit_settings.txt` file provided with `-i` option carries values for other fuses. The format of `bit_settings.txt` file is specified in the documentation with the `IMX_OTP_TOOLS` package.

The file `encryption_key.txt` is the 128 bit OTP key created using `keygen` utility. The 128 bit OTP key will be programmed to the fuses that ROM uses in decrypting the boot image.

7 Development and debug tips

7.1 Error logging

In development phase it is always wise to test the device in Open configuration. It is recommended for boot images to use ROM HAP API `report_event` to browse through the events created during HAB authentication. The `report_status` API can be used to determine the security configuration and security state of the system. Detailed information on HAB Event Data is available on request from Freescale representative. All FAILURE events reported by HAB in Open configuration must be resolved before moving on to Closed configuration, otherwise the image will not boot. Here is example code that can be included in u-boot to print any events occurred during the image authentication process. This example could be extended to report all warning events as well using `HAB_STS_ANY` instead of `HAB_FAILURE` in `hab_report_event`. While they do not prevent booting in Closed configuration, warning events should still be analyzed. For example, if software hash is used when DCP hash was requested, there is a warning, not a failure. Given that it slows down the boot, it is a good idea to fix all warnings before final production using the image.

```
int get_hab_status(void)
{
    uint32_t index = 0; /* Loop index */
    uint8_t event_data[128]; /* Event data buffer */
    size_t bytes = sizeof(event_data); /* Event size in bytes */
    hab_config_t config= 0;
    hab_state_t state = 0;
    /* Check HAB status */
    if (hab_rvt_report_status(&config, &state) != HAB_SUCCESS)
    {
        printf("\nHAB Configuration: 0x%02x HAB State: 0x%02x\n",
            config, state);
    }
}
```

Example CSF text files for reference

```

/* Display HAB Failure events */
while (hab_rvt_report_event(HAB_FAILURE, index, event_data, &bytes)
    == HAB_SUCCESS)
{
    printf("\n");
    printf("-----HAB Event %d -----\n", index + 1);
    printf("event data:\n");
    /* display_event will simply prints out the contents of events_data */
    display_event(event_data, bytes);
    printf("\n");
    bytes = sizeof(event_data);
    index++;
}
/* Check reason for stopping */
if (hab_rvt_report_event(HAB_STS_ANY, index, NULL, &bytes)
    == HAB_SUCCESS)
{
    printf("ERROR: Recompile with larger event data buffer - at least %d
bytes\n",
        bytes);
}
}
/* Display message if no HAB Failure events are found */
else
{
    printf("\nHAB Configuration: 0x%02x HAB State: 0x%02x\n",
        config, state);
    printf("No HAB Failure Events Found!\n\n");
}
}

```

8 Example CSF text files for reference

This section provides sample input CSF files used for u-boot, linux_kernel and boot_prep code signing.

8.1 U-boot CSF example

```

[Header]
Version = 4.0
Hash Algorithm = sha256

```

```
Engine Configuration = 0
Certificate Format = X509
Signature Format = CMS

[Install SRK]
File = "../crts/srk_tbl1_2_3_4.bin"
# Specify the index of the SRK in the SRK Table
Source index = 0

[Install CSFK]
File = "../crts/CSF1_1_sha256_2048_65537_v3_usr.crt.pem"

[Authenticate CSF]

[Install Key]
Verification index = 0
Target index = 2
File = "../crts/IMG1_1_sha256_2048_65537_v3_usr.crt.pem"

# Sign entire u-boot image
# Blocks have the following definition:
# Base address of the binary file, Offset of the block within the binary file,
# Length of block in bytes, binary file name
[Authenticate Data]
Verification index = 2
Engine = DCP
Blocks = 0x41008000 0x0 0x2A000 "u-boot_pad.bin"
```

8.2 Linux_prep CSF example

```
[Header]
Version = 4.0
Hash Algorithm = sha256
Engine Configuration = 0
Certificate Format = X509
Signature Format = CMS

[Install SRK]
File = "../crts/srk_tbl1_2_3_4.bin"
Source index = 0
```

Example CSF text files for reference

```
[Install CSFK]
    File = "../crts/CSF1_1_sha256_2048_65537_v3_usr.crt.pem"

[Authenticate CSF]

[Install Key]
    Verification index = 0
    Target index = 2
    File = "../crts/IMG1_1_sha256_2048_65537_v3_usr.crt.pem"

# Sign entire linux_prep image
# Blocks have the following definition:
#   Base address of the binary file, Offset, Length of block in bytes
[Authenticate Data]
    Verification index = 2
    Engine = DCP
    Blocks = 0x00002000 0x0 0x4000 "linux_prep.bin"
```

8.3 Linux_kernel CSF example

```
[Header]
    Version = 4.0
    Hash Algorithm = sha256
    Engine Configuration = 0
    Certificate Format = X509
    Signature Format = CMS

[Install SRK]
    File = "../crts/srk_tbl1_2_3_4.bin"
    Source index = 0

[Install CSFK]
    File = "../crts/CSF1_1_sha256_2048_65537_v3_usr.crt.pem"

[Authenticate CSF]

[Install Key]
    Verification index = 0
    Target index = 2
    File = "../crts/IMG1_1_sha256_2048_65537_v3_usr.crt.pem"
```

```
# Sign entire linux_prep image
# Sign entire zImage
# Blocks have the following definition:
#   Base address of the binary file, Offset, Length of block in bytes
[Authenticate Data]
  Verification index = 2
  Engine = DCP
  Blocks = 0x00002000 0x0 0x4000 "linux_kernel.bin", \
          0x40008000 0x0 0x2DA030 "zImage"
```

8.4 Boot_prep CSF example

```
[Header]
  Version = 4.0
  Hash Algorithm = sha256
  Engine Configuration = 0
  Certificate Format = X509
  Signature Format = CMS

[Install SRK]
  File = "../crts/srk_tbl1_2_3_4.bin"
  Source index = 0

[Install CSFK]
  File = "../crts/CSF1_1_sha256_2048_65537_v3_usr crt.pem"

[Authenticate CSF]

[Install Key]
  Verification index = 0
  Target index = 2
  File = "../crts/IMG1_1_sha256_2048_65537_v3_usr crt.pem"

# Sign entire boot_prep image
# Blocks have the following definition:
#   Base address of the binary file, Offset, Length of block in bytes
[Authenticate Data]
  Verification index = 2
  Engine = DCP
  Blocks = 0x10 0x0 0x4000 "boot_prep.bin"
```

9 Revision history

Table 2 provides a revision history for this application note.

Table 2. Document revision history

Rev. Number	Date	Substantive Change(s)
1	05/13	<ul style="list-style-type: none"> • Added RVT term and definition to Table 1, “Definitions, acronyms, and abbreviations.” • Added reference to i.MX28 Reference Manual in Section 1.5, “References.” • Added note about RSA public key sizes to Section 2.1, “ROM bootstrap code and HAB library.” • Added information regarding the RVT in Section 3.1, “What components are required?”
0	08/2012	Initial release.

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