Intel® Trust Domain CPU Architectural Extensions
### Revision History

<table>
<thead>
<tr>
<th>Revision</th>
<th>Description</th>
<th>Date</th>
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<tbody>
<tr>
<td>343754-001</td>
<td>Initial release.</td>
<td>September 2020</td>
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Ref. # 343754-001
REVISION HISTORY

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1.1 OVERVIEW

Secure Arbitration Mode (SEAM) is an extension to the Virtual Machines Extension (VMX) architecture to define a new, VMX root operation called SEAM VMX root and a new VMX non-root operation called SEAM VMX non-root. Collectively, the SEAM VMX root and SEAM VMX non-root execution are called operation in SEAM.

SEAM VMX root operation is designed to host a CPU-attested, software module called the Intel® Trust Domain Extensions (Intel® TDX) module to manage virtual machine (VM) guests called Trust Domains (TD). Virtual machines launched/resumed from SEAM VMX root operation are TDs, and VMs launched/resumed from legacy VMX root operation are legacy VMs. Intel TDX modules use the SEAM instruction set extensions to help protect the confidentiality and integrity of TD memory contents and CPU state from all other software, including the hosting Virtual Machine Monitor (VMM), unless explicitly shared by the TD itself.

The SEAMCALL instruction is used by the VMM to help transition the logical processor from legacy VMX root operation to SEAM VMX root operation. The Intel TDX module uses the SEAMRET instruction to help transition the logical processor from SEAM VMX root operation to legacy VMX root operation. The VMRESUME/VMLAUNCH instructions are used to help transition to the SEAM VMX non-root operation from SEAM VMX root operation. VM is designed to then exit from the SEAM VMX non-root transition to SEAM VMX root operation.

The transitions are shown in Figure 1-2.
1.2 INTEL® TDX MODULE

The Intel TDX module implements the functions to build, tear down, and start execution of TD VMs. The VMM provides memory resources to build the TD, and the VMM helps schedule the TD executions using the API provided by the Intel TDX module.

The Intel TDX module executes out of a range of memory defined using a SEAM range register (SEAMRR) interface. By design, access to this range is restricted to SEAM VMX root operation. Code fetches outside of SEAMRR when in SEAM VMX root operation are meant to be disallowed and lead to an unbreakable shutdown.

If the SEAMRR bit (bit 15) of the IA32_MTRRCAP MSR is set, the processor supports the SEAMRR interface to restrict access to a specified memory address range used by the Intel TDX module when executing in SEAM VMX root operation. The SEAM range registers consist of a pair of MSRs. The IA32_SEAMRR_PHYS_BASE MSR is intended to define the 32-MB aligned base address for the SEAM memory range. The IA32_SEAMRR_PHYS_MASK MSR contains a mask that helps determine the address range protected by the SEAMRR interface. The smallest address range that should be specified by the SEAM range registers is 32 MB. The intention is that the MSRs may be written only by boot BIOS and before the lock bit has been set; an attempt to write them outside of boot BIOS or after the lock bit has been set would cause a general-protection exception.

<table>
<thead>
<tr>
<th>Register Address</th>
<th>Register Name / Bit Fields</th>
<th>Scope</th>
<th>Bit Description</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:0</td>
<td>Reserved</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>When set, indicates the range is configured.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24:4</td>
<td>Reserved</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(MAXPHYADDR-1):25</td>
<td>SEAMRR base address.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>63: MAXPHYADDR</td>
<td>Reserved</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Starting at offset 4K from the SEAMRR base, a 4K page per addressable logical processor ID is used to host a SEAM transfer VMCS structure used by the SEAMCALL instruction to aid the transfer from legacy VMX-root operation to SEAM VMX-root operation as a VM exit. The SEAMRET instruction uses this VMCS to aid transfer from the SEAM VMX-root operation to legacy VMX-root operation as a VM entry. The address of the SEAM transfer VMCS for a given, logical processor is IA32_SEAMRR_PHYS_BASE + 4096 + CPUID.B.0.EDX [31:0] * 4096.

Intel provides a Secure Arbitration Mode Loader (SEAMLDR) ACM to help initialize the SEAM range, set up the SEAM transfer VMCS structure, and load the Intel TDX module into this protected range of memory. The OS can launch the SEAMLDR ACM using the GETSEC[ENTERACCS] instruction if the SEAMRR range enable bit (bit 11) of IA32_SEAMRR_PHYS_MASK MSR is 1. The SEAMLDR aims to measure and verify the Intel TDX module against its signature structure and record its security version number (SVN), measurements, and identity into CPU registers that are accessible only to the SEAMLDR ACM.

The SEAMCALL instruction is meant to return VMFailInvalid if invoked when the Intel TDX module is not ready due to i) either the SEAMLDR not having been invoked to successfully initialize and load the Intel TDX module, or ii) the Intel TDX module is not ready due to entering a shutdown when in SEAM.

The SVN of the SEAMLDR ACM itself is reported in the IA32_SGX_SVN_STATUS MSR. OS/VMMs that launch an ACM such as SINIT or SEAMLDR are expected to read the IA32_SGX_SVN_STATUS MSR to determine whether the ACM can be launched or if a new ACM is needed.

• If either the Intel® Software-Guard-Extensions (Intel® SGX) SVN of the ACM value in the ACM’s header is greater than the value reported by IA32_SGX_SVN_STATUS or the lock bit in the IA32_SGX_SVN_STATUS is not set, then the OS/VMM can launch the ACM.

• If the Intel SGX SVN value reported in the corresponding component of the IA32_SGX_SVN_STATUS MSR is greater than the Intel SGX SVN value in the ACM’s header, and if bit 0 of the IA32_SGX_SVN_STATUS MSR is 1, then the OS/VMM would not launch that version of the ACM. It would obtain an updated version of the ACM either from the BIOS or from an external resource.

However, OSVs/VMMs are strongly advised to update their version of the ACM any time they detect that the Intel SGX SVN of the ACM carried by the OS/VMM is lower than that reported by the IA32_SGX_SVN_STATUS MSR, irrespective of the setting of the lock bit.
1.3 SEAM VMX ROOT OPERATION

The Intel TDX module uses the SEAM VMX root operation to help arbitrate resource allocation to the TD VMs and transition to SEAM VMX non-root operations to execute the TD VMs. The Intel TDX module uses Multi-Key, Total-Memory-Encryption (MKTME) technology to aid protection of the confidentiality and integrity of the TD VMs' private memory. The Intel® Architecture Memory Encryption Technologies Specification is specified at: https://software.intel.com/content/dam/develop/external/us/en/documents/multi-key-total-memory-encryption-spec-753926.pdf.

Leaving VMX operation using VMXOFF or invoking SMM-monitor using VMCALL instructions is not supported and would result in a General-Protection fault (#GP(0)) in SEAM VMX root operation. This section discusses the SEAM VMX root operation differences compared to the legacy VMX root operation.

If a logical processor enters a shutdown state when in SEAM VMX root or non-root operation, the processor is designed to mark the Intel TDX module state as not loaded prior to entering shutdown, such that all subsequent, SEAMCALL invocations on any logical processor return VMFailInvalid.

1.3.1 TDX Private KeyID

The TD VM private memory contents are meant to be encrypted and integrity protected using the MKTME technology by associating each TD VM with a different MKTME key identifier (KeyID). Protecting the confidentiality and

<table>
<thead>
<tr>
<th>Register Address</th>
<th>Register Name / Bit Fields</th>
<th>Scope</th>
<th>Bit Description</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Lock</td>
<td></td>
<td></td>
<td>If 1, indicates that a non-faulting Intel SGX instruction or SEAMOPS instruction has been executed. Consequently, launching a properly signed ACM but with Intel SGX SVN value less than the BIOS specified Intel SGX SVN threshold would lead to an Intel TXT shutdown. If 0, indicates that the processor will allow a properly signed ACM to launch irrespective of the Intel SGX SVN value of the ACM.</td>
</tr>
<tr>
<td>15:1</td>
<td>Reserved</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23:16</td>
<td>SGX_SVN_SINIT</td>
<td></td>
<td></td>
<td>If CPUID. (EAX=01H, ECX=0H): ECX[SMX] =1, this field reflects the expected threshold of Intel SGX SVN for the SINIT ACM. If CPUID. (EAX=01H, ECX=0H): ECX[SMX] =0, this field is reserved (0).</td>
</tr>
<tr>
<td>63:56</td>
<td>SGX_SVN_SEAMLDR</td>
<td></td>
<td></td>
<td>This field reflects the expected threshold of Intel SGX SVN for the SEAMLDR ACM. On parts that do not support SEAM operation, this field is reserved (0).</td>
</tr>
</tbody>
</table>
SECURE ARBITRATION MODE (SEAM)

The integrity of the TD memory can require that the key associated with a KeyID assigned to a TD cannot be tampered by untrusted software. Likewise, untrusted software should not be allowed to read or write memory using the KeyID assigned to a TD.

Intel Trust Domain Extensions enable reservation of a configurable number of KeyIDs as private KeyIDs that can be used only in SEAM.

MKTME on an SOC that supports SEAM might support an integrity protected, memory encryption mode. When using keys with integrity enabled, the MKTME associates a message authentication code (MAC) with each cache line. By design, when reading a cache line using a KeyID with integrity enabled, if the MAC stored in the metadata does not match the MAC regenerated by the MKTME, then the cache line is marked poisoned to prevent the data from being consumed. Integrity protected memory must be initialized before being read, and such initialization must be performed using 64-bytes direct-store with 64-byte write atomicity using the MOVDIR64B instruction.

The maximum number of KeyIDs supported by the MKTME and the maximum number of upper physical address bits that can be configured to be used as KeyIDs are enumerated by the IA32_TME_CAPABILITY MSR. As part of activating the MKTME, BIOS is meant to use the IA32_TME_ACTIVATE MSR to configure the number of upper physical address bits to be used as KeyIDs and thereby activate the number of KeyIDs that are usable on that platform. The partitioning of this activated number of KeyIDs into shared and TDX private KeyIDs can also be performed by the boot BIOS using the IA32_TME_ACTIVATE MSR. The IA32_MKTME_KEYID_PARTITIONING MSR enables reading the KeyID partitioning done by the BIOS. The MKTME programming interface extensions are described in Table 1-3.

### Table 1-3. MKTME Programming Interface Extensions

<table>
<thead>
<tr>
<th>Register Address</th>
<th>Register Name / Bit Fields</th>
<th>Scope</th>
<th>Bit Description</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>87H 135</td>
<td>IA32_MKTME_KEYID_PARTITIONING</td>
<td>Package</td>
<td>Multi-Key Total Memory Encryption (MKTME) KeyID Partitioning Enumeration MSR</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NUM_MKTME_KIDS</td>
<td>Total Number of activated MKTME KeyIDs. If the LOCK field in IA32_TME_ACTIVATE is 0, this field reports 0. MKTME KeyIDs span the KID range 1 through NUM_MKTME_KIDS.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NUM_TDX_PRIV_KIDS - Number of TDX Private KeyIDs</td>
<td>If the LOCK field in IA32_TME_ACTIVATE is 0, this field reports 0. TDX private KeyIDs span the range (NUM_MKTME_KIDS + 1) through (NUM_MKTME_KIDS + NUM_TDX_PRIV_KIDS).</td>
</tr>
<tr>
<td>981H 2433</td>
<td>IA32_TME_CAPABILITY</td>
<td>Package</td>
<td>Total Memory Encryption (TME) / Multi-Key Total Memory Encryption (MKTME) Capability Reporting MSR</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>When set to 1, AES-XTS 128-bit encryption algorithm supported.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>When set to 1, AES-XTS 128-bit encryption with at least 28-bits of integrity algorithm supported.</td>
</tr>
</tbody>
</table>
SECURE ARBITRATION MODE (SEAM)

The keys for the MKTME KeyID are programmed using the PCONFIG instruction. The PCONFIG instruction is designed to allow key programming for TDX private KeyID only in SEAM.

When MKTME is activated, the plan intends the upper bits of platform physical address (starting with the highest order bit available as enumerated by the CPUID MAXPA info) be repurposed for usage as a KeyID. When the KeyID space is partitioned, the TDX_RESERVED_KEYID_BITS number of bits, starting with the highest order bit of the physical address, is meant to be used to encode TDX private KeyID, and, if any of these bits are set, then the KeyID specified would be a TDX private KeyID.

MKTME usage for TD memory protection might require the Intel TDX module to write-back and invalidate caches for certain, maintenance operations. For some maintenance operations, the Intel TDX module might need to write-back the caches but not require invalidation of the cache contents. The WBINVD/WBNOINVD instructions may be used by the Intel TDX module to help perform these operations.

The processor can provide an alternate, cache management interface to SEAM VMX root operation through MSR_WBINVD and MSR_WBNOINVD. WRMSR to MSR_WBINVD and MSR_WBNOINVD can do write-back of one cache sub-block specified by software in EDX: EAX. The WRMSR to MSR_WBINVD can additionally invalidate the specified, cache sub-block. The maximum of cache sub-blocks (NUM_CACHE_SUB_BLOCKS) is meant to be read by software using RDMSR to MSR_WBINVD or MSR_WBNOINVD. Software should invoke

---

### Table 1-3. MKTME Programming Interface Extensions (Continued)

<table>
<thead>
<tr>
<th>Register Address</th>
<th>Register Name / Bit Fields</th>
<th>Scope</th>
<th>Bit Description</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hex</td>
<td>Dec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>982H</td>
<td>2434</td>
<td>IA32_TME_ACTIVATE</td>
<td>Package</td>
<td>Total Memory Encryption (TME) / Multi-Key Total Memory Encryption (MKTME) Activation MSR</td>
</tr>
<tr>
<td>35:32</td>
<td></td>
<td>MK_TME_KEYID_BITS</td>
<td>The number of KeyID bits to allocate to MKTME usage. Like enumeration, this is an encoded value. Writing a value greater than MK_TME_MAX_KEYID_BITS will result in #GP(0). Writing a non-zero value to this field will #GP(0) if bit 1 of EAX (TME Enable) is not also set to 1, as TME must be enabled to use MKTME.</td>
<td></td>
</tr>
<tr>
<td>39:36</td>
<td></td>
<td>TDX_RESERVED_KEYID_BITS</td>
<td>The number of physical address bits starting at (MAXPHYADDR - 1) that are reserved for Intel TDX use to encode TDX private KeyID.</td>
<td>The value in this field cannot exceed the value in bits 35:32 of this MSR.</td>
</tr>
</tbody>
</table>

The keys for the MKTME KeyID are programmed using the PCONFIG instruction. The PCONFIG instruction is designed to allow key programming for TDX private KeyID only in SEAM.

When MKTME is activated, the plan intends the upper bits of platform physical address (starting with the highest order bit available as enumerated by the CPUID MAXPA info) be repurposed for usage as a KeyID. When the KeyID space is partitioned, the TDX_RESERVED_KEYID_BITS number of bits, starting with the highest order bit of the physical address, is meant to be used to encode TDX private KeyID, and, if any of these bits are set, then the KeyID specified would be a TDX private KeyID.

### Table 1-4. Encoding KeyID in Physical Address

|---------|----------------|-------------------------------------------|----------------------------------------|-------------------------|

**NOTES:**

1. L represents TDX_RESERVED_KEYID_BITS.
2. N represents MK_TME_KEYID_BITS.

MKTME usage for TD memory protection might require the Intel TDX module to write-back and invalidate caches for certain, maintenance operations. For some maintenance operations, the Intel TDX module might need to write-back the caches but not require invalidation of the cache contents. The WBINVD/WBNOINVD instructions may be used by the Intel TDX module to help perform these operations.

The processor can provide an alternate, cache management interface to SEAM VMX root operation through MSR_WBINVD and MSR_WBNOINVD. WRMSR to MSR_WBINVD and MSR_WBNOINVD can do write-back of one cache sub-block specified by software in EDX: EAX. The WRMSR to MSR_WBINVD can additionally invalidate the specified, cache sub-block. The maximum of cache sub-blocks (NUM_CACHE_SUB_BLOCKS) is meant to be read by software using RDMSR to MSR_WBINVD or MSR_WBNOINVD. Software should invoke...
SECURE ARBITRATION MODE (SEAM)

MSR_WBINVDP/MSR_WBNOINVDP with EDX:EAX at least once with a sub-block number between 0 and (MAX_CACHE_SUB_BLOCKS - 1) to operate on the entire cache. Specifying an invalid cache sub-block number, i.e., a number greater than or equal to MAX_CACHE_SUB_BLOCKS, can cause a General-Protection fault (#GP(0)). The operation of these WRMSR and RDMSR to MSR_WBINVDP and MSR_WBNOINVDP is designed as follows:

```
IF RDMSR
  IF inSEAM==0 THEN #GP(0);
  IF invoked from VMX load/store list THEN #GP(0);
  EDX:EAX = MAX CACHE_SUB_BLOCKS;
ENDIF

IF WRMSR
  IF inSEAM==0 THEN #GP(0);
  IF invoked from VMX load/store list THEN #GP(0);
  IF EDX:EAX >= MAX_CACHE_SUB_BLOCKS THEN #GP(0);
  Flush cache sub-block indexed by EDX:EAX
  IF ECX == MSR_WBINVDP THEN Invalidate cache sub-block indexed by EDX:EAX;
ENDIF
```

### 1.3.2 Memory Typing

In SEAM VMX root operation, the determination of memory type for an access is designed as follows:

- If CR0.CD is 1, then the effective memory type is UC.
- If CR0.CD is 0, then the effective memory type depends on the physical address that is accessed and the KeyID used for the access.
  - If the access is to the SEAMRR, then the MTRRs do not contribute to the memory typing, and the effective, memory type for the access is determined by the PAT alone.
  - If the access is to physical memory outside SEAMRR and the access uses a TDX private KeyID, then the MTRRs do not contribute to the memory typing. The memory type is determined by the PAT alone.
  - If the access is to physical memory outside SEAMRR and the access does not use a TDX private KeyID, then the memory type for the access is determined based on the MTRR matching the physical address and the PAT.

Special operations that explicitly force a memory type (e.g., fast strings, MOVDIR64, etc.) continue to operate with their special memory type as defined by those instructions.

### 1.3.3 Caching Translation Information

The address translation caching architecture is augmented with an in-SEAM state to support SEAM. When in SEAM VMX root operation, in-SEAM is 1. In SEAM VMX root operation, a logical processor might cache and use cached mappings for linear addresses derived from the paging structure referenced (directly or indirectly) by the current value of CR3 and associate them with:

- Current VPID.
- Current PCID (non-global translations) or any PCID (global translations).
- Current In-SEAM.
1.3.4 Event Handling

On transition to SEAM VMX root operation, the processor can inhibit NMI and SMI. While inhibited, if these events occur, then they are tailored to stay pending and be delivered when the inhibit state is removed. NMI and external interrupts can be uninhibited in SEAM VMX-root operation. In SEAM VMX-root operation, MSR_INTR_PENDING can be read to help determine status of any pending events.

On transition to SEAM VMX non-root operation using a VM entry, NMI and INTR inhibit states are, by design, updated based on the configuration of the TD VMCS used to perform the VM entry.

SMIs that are incident to SEAM VMX non-root operation or were pending from prior to transition to SEAM VMX non-root operation can cause a VM to exit to the SEAM root-mode operation with the exit reason set to "IO SMI" or "Other SMI". The exit qualification bit 0 is meant to be set to 1, if the SMI is a machine check initiated SMI (MSMI). The SMI would then remain pending following the VM exit.

On transition to legacy VMX root operation using SEAMRET, the NMI and SMI inhibit state can be restored to the inhibit state at the time of the previous SEAMCALL and any pending NMI/SMI would be delivered if not inhibited.

The layout of the MSR_INTR_PENDING is described in Table 1-5.

<table>
<thead>
<tr>
<th>Register Address</th>
<th>Register Name / Bit Fields</th>
<th>Scope</th>
<th>Bit Description</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>981H 2433</td>
<td>MSR_INTR_PENDING</td>
<td>Thread</td>
<td>Determine if there are pending interrupts or events. (RO)</td>
<td>Not allowed in VMX MSR store list. Not readable outside SEAM VMX-root operation.</td>
</tr>
<tr>
<td>0</td>
<td>INTR pending</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>NMI pending</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>SMI pending</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Other/unspecified event pending</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Other/unspecified event pending</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>63:5</td>
<td>Reserved</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The reporting of these pending events in MSR_INTR_PENDING is designed not to be affected by:
- EFLAGS.IF.
- NMI blocking.
- SEAM blocking of SMI, or NMI.
- SMI inhibited by SENTER.
- MOV-SS/POP-SS blocking.
- CLI blocking.

1.4 SEAM VMX NON-ROOT OPERATION

The TD VMs execute in SEAM VMX non-root operation. This section discusses the SEAM VMX non-root operation differences compared to the legacy VMX non-root operation.

1.4.1 SEAM VMX Non-Root Execution Controls

Each TD VM is associated with a VMCS that manages transitions into and out of SEAM VMX non-root operation (VM entries and VM exits) as well as processor behavior in SEAM VMX non-root operation.
When in SEAM non-root operation, the processor uses the following, additional controls to help accomplish its aim:

1. **Shared EPT Pointer (Shared-EPTP):** A 64-bit execution control field (encoding pair 203CH/203DH) to specify the Shared-EPT pointer. In SEAM VMX non-root operation, the plan dictates two EPTs be active: the private EPT specified using the EPTP field of the VMCS and a Shared-EPT specified using the Shared-EPTP field of the VMCS.
   a. Bits 11:0 are reserved.
   b. Bits (MAXPHYADDR - 1):12 contain bits (MAXPHYADDR - 1):12 of the physical address of the 4-Kbyte aligned EPT PML4/PML5 table.
   c. Bits 63:MAXPHYADDR are reserved.

2. **TD Key identifier (TD-KeyID) (encoding 4026H):** A 32-bit execution control field to help specify the TD assigned, MKTME KeyID. The processor is meant to use this TD-KeyID to access EPT paging structures referenced by EPT as the physical addresses obtained as a result of translation through the EPT referenced by the EPTP.

3. **Guest Physical Address Width (GPAW):** GPAW execution control (bit position 5) in the tertiary, processor-based execution controls (encoding 2034H) that, along with the EPT walk levels (4 or 5 level), is used to assist in determining the GPA width and thus a SHARED bit position in the GPA. The GPA space of a TD is partitioned into two halves: a shared GPA range and a private GPA range. The GPA range where a SHARED bit is 0 is TD private memory, and the EPT determined by the EPTP is used to help translate the GPA to a physical address. The processor uses the TD-KeyID to aid gaining access to the physical address as a result of translation through the EPT referenced by the EPTP.
   a. When 4-level EPT is active, the SHARED bit position would always be bit 47.
   b. When 5-level EPT is active, the SHARED bit position would be bit 47 if GPAW is 0. Otherwise, else it would be bit 51.

The tertiary, processor-based execution control is designed to be activated by bit 17 of the primary, processor-based execution control, and the IA32_VMX_PROCBASED_CTLS3 MSR (index 492H) would then indicate the bits that can be set to 1 in the tertiary, processor-based execution control field in the VMCS. Bit position 5 of IA32_VMX_PROCBASED_CTLS3 MSR aims to report if the GPAW execution control in tertiary, processor-based execution controls field of the VMCS can be set to 1. When the GPAW execution control can be set to 1, the processor also supports programming the Shared-EPTP and TD-KeyID execution controls in the VMCS. These VMCS fields would be ignored by VM entry when not in SEAM VMX root operation.

### 1.4.2 Guest Physical Address Translation

Transition to SEAM VMX non-root operation is formatted to require Extended Page Tables (EPT) to be enabled. In SEAM VMX non-root operation, there should be two EPTs active: the private EPT specified using the EPTP field of the VMCS and a shared EPT specified using the Shared-EPT field of the VMCS.

When translating a GPA using the shared EPT, an EPT misconfiguration can occur if the entry is present and the physical address bits in the range (MAXPHYADDR-1) to (MAXPHYADDR-TDX_RESERVED_KEYID_BITS) are set, i.e., if configured with a TDX private KeyID.

If the CPU's maximum physical-address width (MAXPA) is 52 and the guest physical address width is configured to be 48, accesses with GPA bits 51:48 not all being 0 can cause an EPT-violation, where such EPT-violations are not mutated to #VE, even if the “EPT-violations #VE” execution control is 1.

If the CPU's physical-address width (MAXPA) is less than 48 and the SHARED bit is configured to be in bit position 47, GPA bit 47 would be reserved, and GPA bits 46:MAXPA would be reserved. On such CPUs, setting bits 51:48 or bits 46:MAXPA in any paging structure can cause a reserved bit page fault on access.

### 1.4.3 Linear Address Translation

In SEAM VMX non-root operation, all paging structures used to translate linear addresses to GPA should be in private GPA space. Setting a SHARED bit to 1 in CR3 or paging structures that reference another paging structure can cause a reserved bit page fault exception.
SECURE ARBITRATION MODE (SEAM)

In SEAM VMX non-root operation, attempting to execute out of a page in TD shared memory, i.e., page mapped with a SHARED bit set to 1, can cause a page fault exception.

### 1.4.4 Memory Typing

For translated, guest physical accesses, the memory type should normally be determined based on CR0.CD, PAT memory type, and EPT memory type. The EPT memory type provided by the EPT (shared or private) helps to perform the translation.

Special operations that explicitly force a memory type (e.g., fast strings, MOVDIR64, etc.) are intended to continue to operate with their respective, special memory type.

The memory type for accessing VMCS linked data structures using a TDX private KeyID (MSR bitmaps, VAPIC page, etc.) would be UC if CR0.CD is 1. Otherwise, it would be WB.

### 1.4.5 Caching Translations Information

When in SEAM VMX non-root operations, EPT is intended to always be in use. Address translation caching architecture is augmented with an additional in-SEAM state to support SEAM. When in SEAM VMX root or VMX non-root operation, in-SEAM would be 1 (otherwise, it would be 0) and augment the caching architecture as follows:

- For accesses using linear addresses, the processor can create combined mappings. Combined mappings would be derived from the EPT paging structures referenced (directly or indirectly) by the current EP4TA (when 4-level EPT is active) or current EP5TA (when 5-level EPT is active). The EPT4TA/EP5TA are from the EPTP field of the VMCS. If CR0.PG = 1, the combined mappings can also be derived from the paging structures referenced (directly or indirectly) by the current value of CR3. No combined, paging-structure-cache entries would be created if CR0.PG = 0. The combined mappings are associated with:
  - Current VPID.
  - Current PCID (non-global translations) or any PCID (global translations).
  - Current EP4TA (when 4-level EPT is active) or current EP5TA (when 5-level EPT is active) from the EPTP field of the VMCS.
  - Current In-SEAM.

- For guest-physical address accesses, a processor can use guest-physical mappings derived from the EPT paging structures referenced (directly or indirectly) by bits 51:12 of the current EPTP or current Shared-EPTP, depending on the EPT used to perform the translation. Newly created, guest-physical mappings are associated with current EP4TA or current EP5TA from the EPTP field of the VMCS.

Combined and guest-physical mappings obtained through EPT referenced by Shared EPTP are also associated with the EP4TA/EP5TA from the EPTP field of the VMCS. To invalidate guest-physical or combined mappings created in SEAM, software (including the VMM executing outside SEAM operation) would use the EPTP (not Shared-EPTP). INVVPID or INVPCID are designed to invalidate combined mappings created in SEAM only when invoked in SEAM.

### 1.4.6 Virtual Interrupt Delivery

Virtual interrupt delivery in SEAM VMX non-root operation aims to ignore bits corresponding to vectors 0 through 30 in the virtual interrupt-request register (VIRR) in the virtual-APIC page when computing the requesting, virtual interrupt (RVI). These vectors are formatted not to be delivered as virtual interrupts through virtual interrupt delivery.

### 1.5 OPERATION OUTSIDE SEAM

The physical address bits reserved for encoding TDX private KeyID are meant to be treated as reserved bits when not in SEAM operation.

When translating a linear address outside SEAM, if any paging structure entry has bits reserved for TDX private KeyID encoding in the physical address set, then the processor helps generate a reserved bit page fault exception.
When translating a guest physical address outside SEAM, if any EPT structure entry has bits reserved for TDX private KeyID encoding in the physical address set, then the processor helps generate an EPT misconfiguration. Instructions that accept physical address operands when invoked with physical addresses that set bits reserved for encoding TDX private KeyID are designed to generate a failure or exception as described in Table 1-6.

### Table 1-6. Encoding KeyID in Physical Address

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMXON</td>
<td>VMFailInvalid: the physical address sets reserved bits.</td>
</tr>
<tr>
<td>VMPTRLD</td>
<td>VMFail with reason &quot;VMPTRLD with invalid physical address&quot;.</td>
</tr>
<tr>
<td>VMCLEAR</td>
<td>VMFail with reason &quot;VMCLEAR with invalid physical address&quot;.</td>
</tr>
<tr>
<td>VMLAUNCH</td>
<td>Treat any VMCS linked physical address with bits reserved for encoding TDX private KeyID set, i.e., specifying a TDX private KeyID as invalid. The treatment is like programming these fields with a physical address with bits set beyond the maximum physical address width of the processor. Examples of such VMCS fields are MSR bitmap pointer, PML buffer, VAPIC page, etc.</td>
</tr>
<tr>
<td>VMRESUME</td>
<td></td>
</tr>
<tr>
<td>MOV to CR3</td>
<td>General Protection Fault (#GP(0)).</td>
</tr>
</tbody>
</table>
| WRMSR       | Programming control registers and MSRs outside SEAM with physical addresses that have bits reserved for encoding TDX private KeyID set to 1 are treated as errors and cause a #GP(0) exception. Examples of such MSRs and CRs include:  
  - IA32_APIC_BASE.  
  - IA32_RTIT_OUTPUT_BASE.  
  - MTRR and PRMRR base and mask registers.  
  - IA32_Hw_FEEDBACK_PTR.  
  - IA32_TME_EXCLUDE_BASE. |

PCONFIG invoked outside SEAM can fail with error code INVALID_KEYID (encoding 3; KeyID not valid) if the KeyID operand is a private KeyID.
Instructions described in this document follow the general documentation convention established in *Intel® 64 and IA-32 Architectures Software Developer’s Manual Volume 2A*. Additionally, some instructions use notation conventions as described below.

## 2.1 CONVENTIONS

The operation sections for the VMX instructions in Section 2.3 use the pseudo-function VMexit, which indicates that the logical processor performs a VM exit.

The operation sections also use the pseudo-functions VMsucceed, VMfail, VMfailInvalid, and VMfailValid. These pseudo-functions can signal instruction success or failure by setting or clearing bits in RFLAGS and, in some cases, by writing the VM-instruction error field. The following pseudocode fragments detail these functions:

**VMsucceed:**
- \( CF := 0; \)
- \( PF := 0; \)
- \( AF := 0; \)
- \( ZF := 0; \)
- \( SF := 0; \)
- \( OF := 0; \)

**VMfail(ErrorNumber):**
- If VMCS pointer is valid
  - Then VMfailValid(ErrorNumber);
  - Else VMfailInvalid;
- FI;

**VMfailInvalid:**
- \( CF := 1; \)
- \( PF := 0; \)
- \( AF := 0; \)
- \( ZF := 0; \)
- \( SF := 0; \)
- \( OF := 0; \)

**VMfailValid(ErrorNumber):**  // executed only if there is a current VMCS
- \( CF := 0; \)
- \( PF := 0; \)
- \( AF := 0; \)
- \( ZF := 0; \)
- \( SF := 0; \)
- \( OF := 0; \)
- Set the VM-instruction error field to ErrorNumber;

The different VM-instruction error numbers are enumerated in Section 2.2, “VM Instruction Error Numbers”.
### 2.2 VM INSTRUCTION ERROR NUMBERS

For certain error conditions, the VM-instruction error field is loaded with an error number to indicate the source of the error. Table 2-1 lists VM instruction error numbers.

<table>
<thead>
<tr>
<th>Error Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VMCALL executed in VMX root operation.</td>
</tr>
<tr>
<td>2</td>
<td>VMCLEAR with invalid physical address.</td>
</tr>
<tr>
<td>3</td>
<td>VMCLEAR with VMXON pointer.</td>
</tr>
<tr>
<td>4</td>
<td>VMLAUNCH with non-clear VMCS.</td>
</tr>
<tr>
<td>5</td>
<td>VMRESUME with non-launched VMCS.</td>
</tr>
<tr>
<td>6</td>
<td>VMRESUME after VMXOFF (VMXOFF and VMXON between VMLAUNCH and VMRESUME).</td>
</tr>
<tr>
<td>7</td>
<td>VM entry with invalid control field(s)(^1,2).</td>
</tr>
<tr>
<td>8</td>
<td>VM entry with invalid host-state field(s)(^1).</td>
</tr>
<tr>
<td>9</td>
<td>VMPTRLD with invalid physical address.</td>
</tr>
<tr>
<td>10</td>
<td>VMPTRLD with VMXON pointer.</td>
</tr>
<tr>
<td>11</td>
<td>VMPTRLD with incorrect VMCS revision identifier.</td>
</tr>
<tr>
<td>12</td>
<td>VMREAD/VMWRITE from/to unsupported VMCS component.</td>
</tr>
<tr>
<td>13</td>
<td>VMWRITE to read-only VMCS component.</td>
</tr>
<tr>
<td>15</td>
<td>VMXON executed in VMX root operation.</td>
</tr>
<tr>
<td>16</td>
<td>VM entry with invalid executive-VMCS pointer(^1).</td>
</tr>
<tr>
<td>17</td>
<td>VM entry with non-launched executive VMCS(^1).</td>
</tr>
<tr>
<td>18</td>
<td>VM entry with executive-VMCS pointer not VMXON pointer (when attempting to deactivate the dual-monitor treatment of SMIs and SMM)(^1).</td>
</tr>
<tr>
<td>19</td>
<td>VMCALL with non-clear VMCS (when attempting to activate the dual-monitor treatment of SMIs and SMM).</td>
</tr>
<tr>
<td>20</td>
<td>VMCALL with invalid VM-exit control fields.</td>
</tr>
<tr>
<td>22</td>
<td>VMCALL with incorrect MSEG revision identifier (when attempting to activate the dual-monitor treatment of SMIs and SMM).</td>
</tr>
<tr>
<td>23</td>
<td>VMXOFF under dual-monitor treatment of SMIs and SMM.</td>
</tr>
<tr>
<td>24</td>
<td>VMCALL with invalid SMM-monitor features (when attempting to activate the dual-monitor treatment of SMIs and SMM).</td>
</tr>
<tr>
<td>25</td>
<td>VM entry with invalid VM-execution control fields in executive VMCS (when attempting to return from SMM)(^1,2).</td>
</tr>
<tr>
<td>26</td>
<td>VM entry with events blocked by MOV SS.</td>
</tr>
<tr>
<td>28</td>
<td>Invalid operand to INVEPT/INVVPID.</td>
</tr>
</tbody>
</table>

**NOTES:**

1. VM-entry checks on control fields and host-state fields can be performed in any order. Thus, an indication by error number of one cause does not imply that there are not also other errors. Different processors might give different error numbers for the same VMCS.

2. Error number 7 is not designed to be used for VM entries that return from SMM that fail due to invalid VM-execution control fields in the executive VMCS. Error number 25 is intended to be used for these cases.

### 2.3 INSTRUCTION SET REFERENCE
SEAMCALL — Call to SEAM VMX Root Operation

<table>
<thead>
<tr>
<th>Opcode/ Instruction</th>
<th>Op/ En</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>66 0F 01 CF</td>
<td>ZO</td>
<td>Call to SEAM VMX root operation.</td>
</tr>
</tbody>
</table>

**Instruction Operand Encoding**

<table>
<thead>
<tr>
<th>Op/En</th>
<th>Operand 1</th>
<th>Operand 2</th>
<th>Operand 3</th>
<th>Operand 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZO</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

**Description**

When invoked in legacy VMX-root operation, this instruction can cause a VM exit (exit reason 4CH - SEAMCALL) to SEAM VMX root operation using the SEAM transfer VMCS of the logical processor on which the instruction was invoked. Bit 29 of the exit reason (VM exit from VMX root operation) would be set to 1 on such VM exits.

When invoked in SEAM VMX non-root operation or legacy VMX non-root operation, this instruction can cause a VM exit (exit reason 4CH - SEAMCALL). Bit 29 of the exit reason (VM exit from VMX root operation) would be set to 0 on such VM exits.

**Operation**

IF not in VMX operation or inSMM or inSEAM or ((IA32_EFER.LMA & CS.L) == 0)
THEN #UD;
ELSIF in VMX non-root operation
THEN VMexit("basic reason" = SEAMCALL,
"VM exit from VMX root operation" (bit 29) = 0);
ELSIF CPL > 0 or IA32_SEAMRR_MASK.VALID == 0 or "events blocking by MOV-SS"
THEN #GP(0);

// Certain events/conditions that could affect security of SEAM could disable SEAM execution
IF "Intel TDX module not loaded or disabled"
THEN VMfailInvalid
  RFLAGS.{CF, OF, SF, PF, AF, ZF} = 0

// Exiting from legacy VMX root operation
inSEAM = 1
SEAM_CVP = (SEAMRR.BASE + 4K) + CPUID.B0.EDX[31:0] * 4K
controlling-VMCS = SEAM_CVP
Save VMM state in controlling-VMCS based on its VM-exit controls
Save event inhibits in VMM interruptibility status - SMI inhibit, NMI inhibit
Load/force SEAM state based on VM-exit controls and host-state area
// Further details of the operation of the VM-exit appear in Chapter 27 "VM Exits" of Intel® 64 and IA-32 Architectures Software
Inhibit SMI and NMI
controlling-VMCS.exit_reason.basic_reason = SEAMCALL
controlling-VMCS.exit_reason."VM exit from VMX root operation" (bit 29) = 1
controlling-VMCS.exit_qualification = 0
controlling-VMCS.VMCS_link_pointer = working-VMCS
working-VMCS = controlling-VMCS
controlling-VMCS = vmxon-VMCS
VMX INSTRUCTION SET EXTENSIONS

Flags Affected
The operation section uses the pseudo-functions VMsucceed and VMfailInvalid. See the operation section and Section 2.1.

Protected Mode Exceptions
#UD The SEAMCALL instruction is not designed to be recognized in protected mode.

Real-Address Mode Exceptions
#UD The SEAMCALL instruction is not designed to be recognized in real-address mode.

Virtual-8086 Mode Exceptions
#UD The SEAMCALL instruction is not designed to be recognized in virtual-8086 mode.

Compatibility Mode Exceptions
#UD The SEAMCALL instruction is not designed to be recognized in compatibility mode.

64-Bit Mode Exceptions
#GP(0) If CPL > 0.
If IA32_SEAMRR_MASK.VALID is 0.
If events are being blocked by MOV SS.
#UD If executed outside VMX operation.
If executed in SEAM VMX root operation.
If logical processor is in SMM.
If IA32_VMX_PROCBASED_CTLS3[5] is 0.
SEAMOPS — Invoke SEAM Operations

<table>
<thead>
<tr>
<th>Opcode/Instruction</th>
<th>Op/En</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>66 0F 01 CE SEAMOPS</td>
<td>ZO</td>
<td>Invoke SEAM specific operations.</td>
</tr>
</tbody>
</table>

### Instruction Operand Encoding

<table>
<thead>
<tr>
<th>Op/En</th>
<th>Operand 1</th>
<th>Operand 2</th>
<th>Operand 3</th>
<th>Operand 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZO</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

### Description

The SEAMOPS instruction is used to help execute SEAM-specific operations in SEAM VMX root operation. The SEAMOPS instruction is designed to only be executed by privileged software running in SEAM VMX root operation and invoke leaf functions for performing the requested functionality. Software would select the leaf function by setting the appropriate value in register RAX. Other registers might have leaf-specific purposes. The instruction would be used only in 64-bit mode.

Two leaf functions are currently defined:

- **CAPABILITIES (RAX == 0):** Returns a bitmap of the supported SEAMOPS leaves.
- **SEAMREPORT (RAX == 1):** Generate SEAMREPORT structure.

The instruction is formatted to return the outcome of execution of leaf-specific function in RAX register. Leaf specific functions might return information in additional GPR.

SEAMOPS is intended to lock CRPL_CPUSVN and BIOS_SE_SVN, if CRPL_CPUSVN is not already locked, if the SEAMREPORT leaf is enabled. Once locked, the CPU helps prevent any further modifications to these registers. Thus, CRPL_CPUSVN might be locked by either the first, non-faulting Intel SGX instruction or the first, SEAMOPS instruction that executes with SEAMREPORT_ENABLED, i.e., the CAPABILITIES leaf reports support for the SEAMREPORT leaf.

### Operation

IF inSEAM==0 or ((IA32_EFER.LMA & CS.L) == 0) or in VMX non-root operation or lock-prefix-used
THEN #UD;
ELSIF CPL > 0
THEN #GP(0);
IF SEAMREPORT_ENABLED == 1 and CRPL_CPUSVN not locked
   Lock CRPL_CPUSVN and BIOS_SE_SVN
ENDIF
SWITCH RAX
   CASE 0: RAX = SEAMREPORT_ENABLED ? 0x3 : 0x1;break; // SEAMREPORT (leaf 1) is supported if
          // only if SEAMREPORT enabled
   DEFAULT: #GP(0); break;
ENDSWITCH

### Flags Affected

None.

### Protected Mode Exceptions

#UD The SEAMOPS instruction is not designed to be recognized in protected mode.

### Real-Address Mode Exceptions

#UD The SEAMOPS instruction is not designed to be recognized in real-address mode.
VMX INSTRUCTION SET EXTENSIONS

Virtual-8086 Mode Exceptions
#UD The SEAMOPS instruction is not designed to be recognized in virtual-8086 mode.

Compatibility Mode Exceptions
#UD The SEAMOPS instruction is not designed to be recognized in compatibility mode.

64-Bit Mode Exceptions
#GP(0): If CPL > 0.
Illegal leaf function specified in RAX.
Leaf specific exceptions.
If any leaf-specific memory operand is in CS, DS, ES, FS, or GS segment and memory address is non-canonical.
#SS(0): If any leaf-specific memory operand is in SS segment and memory address is non-canonical.
#UD: If not in SEAM root operation.
If LOCK prefix is used.
If IA32_VMX_PROCBASED_CTLS3[5] is 0.
#PF(PFEC): If a page fault occurs in accessing a leaf-specific memory operand.

SEAMOPS Data Structures

Table 2-2. TEE_TCB_SVN

<table>
<thead>
<tr>
<th>Name</th>
<th>Offset (Bytes)</th>
<th>Size (Bytes)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEAM</td>
<td>0</td>
<td>2</td>
<td>Intel TDX module SVN.</td>
</tr>
<tr>
<td>RESERVED</td>
<td>2</td>
<td>14</td>
<td>Must be zero.</td>
</tr>
</tbody>
</table>

Table 2-3. TEE_TCB_INFO Structure

<table>
<thead>
<tr>
<th>Name</th>
<th>Offset (Bytes)</th>
<th>Size (Bytes)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VALID</td>
<td>0</td>
<td>8</td>
<td>Indicates TEE_TCB_INFO fields which are valid.</td>
</tr>
<tr>
<td>TEE_TCB_SVN</td>
<td>8</td>
<td>16</td>
<td>TEE_TCB_SVN array.</td>
</tr>
<tr>
<td>MRSIGNERSEAM</td>
<td>72</td>
<td>48</td>
<td>Measurement of TDX module signer if valid.</td>
</tr>
<tr>
<td>ATTRIBUTES</td>
<td>120</td>
<td>8</td>
<td>Additional configuration ATTRIBUTES if valid.</td>
</tr>
<tr>
<td>RESERVED</td>
<td>128</td>
<td>111</td>
<td>Must be zero.</td>
</tr>
</tbody>
</table>
### Table 2-4. REPORTTYPE

<table>
<thead>
<tr>
<th>Name</th>
<th>Offset (Bytes)</th>
<th>Size (Bytes)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPE</td>
<td>0</td>
<td>1</td>
<td>TEE Type</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0x00: SGX</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0x7F - 0x01: RESERVED</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0xFF - 0x80: SEAM Defined</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Note: Bit 7 defines either hardware implementation (0) or Intel TDX module implementation (1).</td>
</tr>
<tr>
<td>SUBTYPE</td>
<td>1</td>
<td>1</td>
<td>TYPE-specific subtype.</td>
</tr>
<tr>
<td>VERSION</td>
<td>2</td>
<td>1</td>
<td>TYPE-specific version. Must be 0 for Intel SGX.</td>
</tr>
<tr>
<td>RESERVED</td>
<td>3</td>
<td>1</td>
<td>Must be zero.</td>
</tr>
</tbody>
</table>

### Table 2-5. REPORTMACSTRUCT

<table>
<thead>
<tr>
<th>Name</th>
<th>Offset (Bytes)</th>
<th>Size (Bytes)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPORTTYPE</td>
<td>0</td>
<td>4</td>
<td>Type Header Structure</td>
</tr>
<tr>
<td>RESERVED</td>
<td>4</td>
<td>12</td>
<td>Must be zero.</td>
</tr>
<tr>
<td>CPUSVN</td>
<td>16</td>
<td>16</td>
<td>CPUSVN</td>
</tr>
<tr>
<td>TEE_TCB_INFO_HASH</td>
<td>32</td>
<td>48</td>
<td>SHA384 of TEE_TCB_INFO</td>
</tr>
<tr>
<td>TEE_INFO_HASH</td>
<td>80</td>
<td>48</td>
<td>SHA384 of TEE_INFO (or 0x00 if no TEE is represented)</td>
</tr>
<tr>
<td>REPORTDATA</td>
<td>128</td>
<td>64</td>
<td>A set of data used for communication between the caller and the target.</td>
</tr>
<tr>
<td>RESERVED</td>
<td>192</td>
<td>32</td>
<td>Must be zero.</td>
</tr>
<tr>
<td>MAC</td>
<td>224</td>
<td>32</td>
<td>The MAC over the REPORTMACSTRUCT with report-type specific MAC key.</td>
</tr>
</tbody>
</table>

### Table 2-6. SEAMREPORT

<table>
<thead>
<tr>
<th>Name</th>
<th>Offset (Bytes)</th>
<th>Size (Bytes)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPORTMACSTRUCT</td>
<td>0</td>
<td>256</td>
<td>REPORTMAC Structure for REPORT.</td>
</tr>
<tr>
<td>TEE_TCB_INFO</td>
<td>256</td>
<td>239</td>
<td>TEE_TCB_INFO whose HASH is found in the REPORTMACSTRUCT.</td>
</tr>
</tbody>
</table>
SEAMOPS Leaf Functions

SEAMREPORT Leaf

Helps create a SEAMREPORT structure that contains the measurements/configuration information of the SEAM and, when invoked on behalf of a TEE, it includes the TEE measurements. The SEAMREPORT operands are described in Table 2-7.

Table 2-7. SEAMREPORT Operands

<table>
<thead>
<tr>
<th>Operand</th>
<th>In / Out</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAX</td>
<td>In</td>
<td>1 (SEAMOPS instruction leaf number).</td>
</tr>
<tr>
<td></td>
<td>Out</td>
<td>Leaf-specific return code.</td>
</tr>
<tr>
<td>RCX</td>
<td>In</td>
<td>1024B-aligned linear address, of newly created SEAMREPORT structures.</td>
</tr>
<tr>
<td>RDX</td>
<td>In</td>
<td>Report Type Header in the low order 32 bits. Upper 32 bits must be zero.</td>
</tr>
<tr>
<td>R8</td>
<td>In</td>
<td>64B-aligned linear address of REPORTDATA to be signed.</td>
</tr>
<tr>
<td>R9</td>
<td>In</td>
<td>64B-aligned linear address of TEE_INFO_HASH to be signed.</td>
</tr>
</tbody>
</table>

SEAMREPORT Leaf Description

This instruction is used by the Intel TDX module and helps create a report, SEAMREPORT, of the Intel TDX module or a TEE (e.g., TD) hosted by the Intel TDX module. The SEAMREPORT structure can contain the measurements/configuration information of the TEE, the Intel TDX module, and any additional components in the TEE TCB. The SEAMREPORT has a REPORTMACSTRUCT that is designed to be integrity protected with a MAC that covers the TEE_TCB_INFO_HASH, TEE_INFO_HASH (when provided), and the REPORTDATA. The TEE_TCB_INFO_HASH is meant as the SHA384 hash of the TEE_TCB_INFO structure, which reflects the measurement/configuration of the TEE and other elements in the TCB of all instances of TEE hosted by the SEAM. The VALID field contains an array of flags that can indicate which fields have been populated, as not all fields apply to all reports. When used by the Intel TDX module to create a TEE report, the TEE_INFO_HASH is expected to be a SHA384 hash of measurement and configuration of the TEE being reported. When used to report just the Intel TDX module, TEE_INFO_HASH might be a string of zeros.

The Intel TDX module can select the report type values, however, all valid values for REPORTTYPE.TYPE should have the high order bit set to 1. Failure to set this bit will result in a SEAM_INVALID_REPORT_TYPE error. The Intel TDX module additionally helps provide the REPORTDATA, a 64-byte value to be included in the SEAMREPORT and, eventually, the quote. This aids the caller of the instruction in associating data with the Intel TDX module or the TEE it reports.

To assist verification of the integrity of the SEAMREPORT, software should help verify any hashes present in the report. The REPORTMACSTRUCT.TEE_TCB_INFO_HASH should match the hash of SEAMREPORT.TEAMINFO. If the REPORTMACSTRUCT.TEE_INFO_HASH is non-zero, it should match the hash of the separate, TEE_INFO structure. By design, if either value does not match, the report has been tampered. Software uses ENCLU[EVERIFYREPORT] to help verify the integrity of the REPORTMACSTRUCT itself.

Table 2-8. SEAMREPORT Memory Operands

<table>
<thead>
<tr>
<th>Explicit / Implicit</th>
<th>Linear Address</th>
<th>Name</th>
<th>Access Permissions</th>
<th>Alignment</th>
<th>Concurrency Restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explicit</td>
<td>RCX</td>
<td>SEAMREPORT</td>
<td>RW</td>
<td>1024B</td>
<td>None</td>
</tr>
<tr>
<td>Explicit</td>
<td>R8</td>
<td>REPORTDATA</td>
<td>R</td>
<td>64B</td>
<td>None</td>
</tr>
<tr>
<td>Explicit</td>
<td>R9</td>
<td>TEE_INFO_HASH</td>
<td>R</td>
<td>64B</td>
<td>None</td>
</tr>
</tbody>
</table>
VMX INSTRUCTION SET EXTENSIONS

SEAMREPORT Leaf Operation

// Temporary Variables setup with input register operands
SEAMREPORT *tmp_seamreport_la = RCX; // Linear address of SEAMREPORT
uint64_t tmp_report_type = RDX; // Report type
void *tmp_reportdata_la = R8; // Linear address of REPORTDATA
SHA384_HASH_t *tmp_tee_info_hash_la = R9; // Linear address of TEE_INFO_HASH
KEY256_t tmp_report_key; // 256b report key
RAX = SEAM_SUCCESS;
RFLAGS.{ZF, CF, PF, AF, OF, SF} = 0;

// Ensure SEAMREPORT pointer is 1024B aligned and read/write accessible
IF (tmp_seamreport_la is not 1024B aligned) #GP(0);
<<tmp_seamreport_la must be read/write accessible>>

// Ensure TEE_INFO_HASH pointer is 64B aligned and read accessible
IF (tmp_tee_info_hash_la is not 64B aligned) #GP(0);
<<tmp_tee_info_hash_la must be read accessible>>

// Ensure REPORTDATA pointer is 64B aligned and read accessible
IF (tmp_reportdata_la is not 64B aligned) #GP(0);
<<tmp_reportdata_la must be read accessible>>

// Check reserved bit in REPORT TYPE and that TYPE reflects SEAM implementation
IF ((tmp_report_type & 0xFFFFFFFFFF000000) != 0) || (tmp_report_type & 0x0000000000000080) == 0)
{
  RAX = SEAM_INVALID_REPORT_TYPE;
  RFLAGS.ZF = 1;
  GOTO END;
}

// Create SEAMREPORT in a temporary buffer
tmp_seamreport = 0;
tmp_seamreport.REPORTMACSTRUCT.REPORTTYPE = tmp_report_type[31:0];
tmp_seamreport.REPORTMACSTRUCT.RESERVED = 0x00;
tmp_seamreport.REPORTMACSTRUCT.CPUSVN = CRPL_CPUSVN;

// Populate TEE_TCB_INFO depending on the Intel TDX module type
tmp_seamreport.TEE_TCB_INFO.TEE_TCB_SVN = CRPL_TEE_TCB_INFO.TEE_TCB_SVN;
tmp_seamreport.TEE_TCB_INFO.MRSEAM = CRPL_TEE_TCB_INFO.MRSEAM;
IF (<Intel SEAM>)
{
  tmp_seamreport.TEE_TCB_INFO.VALID = 111111111b;
}
ELSE
{
  tmp_seamreport.TEE_TCB_INFO.VALID = 1111111111111111b;
  tmp_seamreport.TEE_TCB_INFO.MRSIGNERSEAM = CRPL_TEE_TCB_INFO.MRSIGNERSEAM;
  tmp_seamreport.TEE_TCB_INFO.ATTRIBUTES = CRPL_TEE_TCB_INFO.ATTRIBUTES;
}
tmp_seamreport.REPORTMACSTRUCT.TEE_TCB_INFO_HASH = SHA384(tmp_seamreport.TEE_TCB_INFO);
VMX INSTRUCTION SET EXTENSIONS

// Copy TEE_INFO_HASH and REPORTDATA from memory
tmp_seamreport.REPORTMACSTRUCT.TEE_INFO_HASH = *tmp_tee_info_hash_la;
tmp_seamreport.REPORTMACSTRUCT.REPORTDATA = *tmp_reportdata_la;

// Compute MAC on the first 224B of REPORTMACSTRUCT
tmp_report_key = CR_REPORT_KEY2;
tmp_seamreport.REPORTMACSTRUCT.MAC = HMAC-SHA256(tmp_report_key, &tmp_tdreport.REPORTMACSTRUCT, 224);

// Copy out report to memory
*tmp_seamreport_la = tmp_seamreport;
END:

Flags Affected
ZF: Set if failed due to an error (see error codes below); otherwise, it is cleared to zero.
CF, PF, AF, OF, SF: Cleared to zero.

Error Codes
• SEAM_SUCCESS (0x00): SEAMREPORT is successful.
• SEAM_INVALID_REPORT_TYPE (0x01): Invalid report type.

64-Bit Mode Exceptions
#GP(0): If a memory address is non-canonical form.
#PF(fault-code): If a page fault occurs in accessing memory operands.
SEAMRET — Return to Legacy VMX Root Operation

<table>
<thead>
<tr>
<th>Opcode/ Instruction</th>
<th>Op/ En</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>66 0F 01 CD SEAMRET</td>
<td>ZO</td>
<td>Return to legacy VMX root operation from SEAM VMX root operation.</td>
</tr>
</tbody>
</table>

**Instruction Operand Encoding**

<table>
<thead>
<tr>
<th>Op/En</th>
<th>Operand 1</th>
<th>Operand 2</th>
<th>Operand 3</th>
<th>Operand 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZO</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

**Description**
This instruction helps the SEAM VMX root software exit from SEAM VMX root operation and resume execution of the VMM software in legacy VMX root operation.

**Operation**
IF inSEAM==0 or ((IA32_EFER.LMA & CS.L) == 0) or in VMX non-root operation
    THEN #UD;
ELSIF CPL > 0
    THEN #GP(0);
ELSIF current-VMCS pointer is not valid
    THEN VMfailInvalid;
Check settings of VMX controls and host-state area;
IF invalid settings
    THEN
        VMfailValid(VM entry with invalid VMX-control field(s)) or
        VMfailValid(VM entry with invalid host-state field(s)) as appropriate;
ELSE
    Attempt to load guest state including event inhibits (NMI, SMI, etc.)
    and PDPTRs as appropriate based on entry controls;
    Clear address-range monitoring;
    IF failure in checking guest state or PDPTRs
        THEN VM entry fails // see Section 26.8 of the Intel® 64 and IA-32 Architectures Software Developer's Manual Volume 3C
    ELSE
        Attempt to load MSRs from VM-entry MSR-load area;
        IF failure
            THEN VM entry fails // see Section 26.8 of the Intel® 64 and IA-32 Architectures Software Developer's Manual Volume 3C
            ELSE
                working-VMCS = working-VMCS.VMCS-link-pointer
                controlling-VMCS = vmxon-VMCS
                inSEAM = 0 // Closes SEAMRR access
                VM entry succeeds;
        FI;
    FI;
FI;


**Flags Affected**
The operation section uses the pseudo-functions VMsucceed, VMfail(ErrorCode), VMfailInvalid, and VMfailValid(ErrorCode). See the operation section and Section 2.1. See Section 2.2 for error numbers. The following error numbers can be reported by SEAMRET: 7, 8, and 26.
VMX INSTRUCTION SET EXTENSIONS

Protected Mode Exceptions
#UD The SEAMRET instruction is not designed to be recognized in protected mode.

Real-Address Mode Exceptions
#UD The SEAMRET instruction is not designed to be recognized in real-address mode.

Virtual-8086 Mode Exceptions
#UD The SEAMRET instruction is not designed to be recognized in virtual-8086 mode.

Compatibility Mode Exceptions
#UD The SEAMRET instruction is not designed to be recognized in compatibility mode.

64-Bit Mode Exceptions
#GP(0) If CPL > 0.
#UD If logical processor is not in SEAM VMX root operation.
If IA32_VMX_PROCBASED_CTLS3[5] is 0.
TDCALL — Call to VM Monitor from TD Guest

<table>
<thead>
<tr>
<th>Opcode/Instruction</th>
<th>Op/En</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>66 0F 01 CC TDCALL</td>
<td>ZO</td>
<td>Call to VM monitor by causing a VM exit.</td>
</tr>
</tbody>
</table>

Instruction Operand Encoding

<table>
<thead>
<tr>
<th>Op/En</th>
<th>Operand 1</th>
<th>Operand 2</th>
<th>Operand 3</th>
<th>Operand 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZO</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Description

This instruction is designed to allow guest privileged software to make a call for service into a VM monitor. The details of the programming interface for such calls are Intel TDX module-specific; this instruction can cause a VM exit, registering the appropriate, exit reason. Use of this instruction outside VMX non-root operation can cause #UD fault.

Operation

IF not in VMX non-root operation THEN #UD;
ELSEIF CPL > 0 THEN #GP(0);
ELSE VM exit with exit reason TDCALL (4DH) and zero exit qualification

Flags Affected

None.

Protected Mode Exceptions

#GP(0) If CPL > 0.
#UD If logical processor is not in VMX non-root operation.

Real-Address Mode Exceptions

#GP(0) If CPL > 0.
#UD If logical processor is not in VMX non-root operation.

Virtual-8086 Mode Exceptions

#GP(0) If CPL > 0.
#UD If logical processor is not in VMX non-root operation.

Compatibility Mode Exceptions

#GP(0) If CPL > 0.
#UD If logical processor is not in VMX non-root operation.

64-Bit Mode Exceptions

#GP(0) If CPL > 0.
#UD If logical processor is not in VMX non-root operation.

If IA32_VMX_PROCBASED_CTLS[5] is 0.
VMRESUME/VMLAUNCH — Resume/Launch Virtual Machine

The following additional actions can be performed by VMRESUME/VMLAUNCH in SEAM VMX root operation:

1. If the “enable EPT” VM-execution control is 0, then cause a VM entry failure due to invalid control field.
2. Shared-EPTP execution control must not set any reserved bits.
The ENCLU instruction defines a new leaf, EVERIFYREPORT2, that can be used to help verify the MAC on reports generated using SEAMOPS[SEAMREPORT]. CPUID leaf 12, sub-leaf 0, EAX bit 7 is set to 1 to help enumerate support for the EVERIFYREPORT2 leaf of ENCLU. The EVERIFYREPORT2 instruction layout is described in Table 3-1.

### Table 3-1. EVERIFYREPORT2 Instruction Layout

<table>
<thead>
<tr>
<th>Instruction</th>
<th>EAX</th>
<th>RBX</th>
<th>RCX</th>
<th>RDX</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVERIFYREPORT2</td>
<td>08H</td>
<td>REPORTMACSTRUCT</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3.1 EVERIFYREPORT2 LEAF DESCRIPTION

**Description**

This enclave mode instruction enables verification of a cryptographic REPORTMACSTRUCT that describes the contents of a TD, and the REPORTMACSTRUCT can be used to determine that the TEE described in the TDREPORT was running on the same platform.

**Table 3-2. EVERIFYREPORT2 Memory Parameter Information**

<table>
<thead>
<tr>
<th>Memory Parameter</th>
<th>Permissions</th>
<th>Semantics</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RBX]REPORTMACSTRUCT</td>
<td>R</td>
<td>Enclave Access</td>
</tr>
</tbody>
</table>

The instruction flow is designed as follows:

1. Verify alignment requirements of the operands.
2. Validate the operand (RBX) is inside the enclave.
3. Compute a MAC over REPORTMACSTRUCT structure.
4. Determine if the computed MAC matches the MAC attached to the REPORTMACSTRUCT structure.

**Operation**

**Table 3-3. Temp Variables in EVERIFYREPORT2 Operational Flow**

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Type</th>
<th>Size</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMP_CURRENTSECS</td>
<td>Effective Address</td>
<td>32/64 Bytes</td>
<td>The address of the SECS for the currently executing enclave.</td>
</tr>
<tr>
<td>TMPREPORTMACSTRUCT</td>
<td>REPORTMACSTRUCT</td>
<td>256 Bytes</td>
<td>Cryptographic Report of the TEE.</td>
</tr>
<tr>
<td>TMP_MAC</td>
<td>MAC</td>
<td>32 Bytes</td>
<td>MAC over REPORT calculated by instruction.</td>
</tr>
</tbody>
</table>
// check alignment of REPORTMACSTRUCT
IF (DS:RBX is not 256 Byte aligned) #GP(0);

// check to see if REPORTMACSTRUCT is inside the current enclave
IF (DS:RBX is not within CR_ELRANGE) #GP(0);

// make sure DS:RBX is read accessible
<< DS:RBX should be read accessible >>

// read EPCM VALID, PENDING, MODIFIED, BLOCKED, PT, R, W, X, and ENCLAVESECS
// fields atomically check that DS:RBX is a valid and accessible EPC page
IF ((DS:RBX does not resolve to an EPC address) OR
    (EPCM(DS:RBX).VALID = 0) OR
    (EPCM(DS:RBX).PENDING = 1) OR
    (EPCM(DS:RBX).MODIFIED = 1) OR
    (EPCM(DS:RBX).BLOCKED = 1) OR
    (EPCM(DS:RBX).R is 0) OR
    (EPCM(DS:RBX).PT != PT_REG) OR
    (EPCM(DS:RBX).ENCLAVESECS != CR_ACTIVE_SECS) OR
    (EPCM(DS:RBX).ENCLAVEADDRESS != (DS:RBX & ~0xFFF)))
{
    #PF(DS:RBX);
}

// Create local/protected copy of REPORTMACSTRUCT
TMP_REPORTMACSTRUCT[255:0B] = DS:RBX[255:0B];

// Verify REPORTMACSTRUCT header
IF ((TMP_REPORTMACSTRUCT.TYPE != 0x81) OR  // TDX implemented by Intel TDX module
    (TMP_REPORTMACSTRUCT.REPORTTYPE.SUBTYPE != 0x00) OR
    (TMP_REPORTMACSTRUCT.REPORTTYPE.VERSION != 0x00) OR
    (TMP_REPORTMACSTRUCT.RESERVED != 0))
{
    RFLAGS.ZF = 1;
    RAX = SGX_INVALID_REPORTMACSTRUCT;
    goto EXIT;
}

// Verify CPUSVN is a valid value
IF ((TMP_REPORTMACSTRUCT.CPUSVN is unsupported by the CPU) {
    RFLAGS.ZF = 1;
    RAX = SGX_INVALID_CPUSVN;
    goto EXIT
}

// Verify MAC on REPORTMACSTRUCT
TMP_MAC = MAC(CR_REPORT_KEY2, TMP_REPORTMACSTRUCT[223:0B], 224);
IF (TMP_MAC != TMP_REPORTMACSTRUCT.MAC)
{
    RFLAGS.ZF = 1;
    RAX = SGX_INVALID_REPORTMACSTRUCT;
    goto EXIT
}

RAX=0;
RFLAGS.ZF=0;
EXIT:
RFLAGS.CF=0;
RFLAGS.PF=0;
RFLAGS.AF=0;
RFLAGS.OF=0;
RFLAGS.SF=0;

Flags Affected
None.

Error Codes
• SGX_INVALID_CPUSVN (32): If REPORTMACSTRUCT.CPUSVN is an unsupported value.
• SGX_INVALID_REPORTMACSTRUCT (28): REPORTMACSTRUCT included illegal values or MAC verification failed.

Protected Mode Exceptions
#GP(0) If a memory operand effective address is outside the DS segment limit.
   If the DS segment is unusable.
   If a memory operand is not properly aligned.
#PF(fault-code) If a page fault occurs in accessing memory operands.

64-Bit Mode Exceptions
#GP(0) If a memory address is in a non-canonical form.
   If a memory operand is not properly aligned.
#PF(fault-code) If a page fault occurs in accessing memory operands.