12 Thermal Shields

12.1 Functions, Basic Configuration and System Boundaries

12.1.1 Functions

The thermal shield system:

- provides an effective optically opaque barrier for total and local thermal loads transferred from warm components to the superconducting coils and structures operating at 4.5K, by thermal radiation and conduction during normal operation and vacuum vessel (VV) baking;
- withstands gravity, thermal and electromagnetic loads, deflection of support components, loads experienced during assembly and disassembly, tests, seismic events and postulated accidents, without damage requiring repair;
- provides access ports for in-cryostat components, maintenance equipment and diagnostics;
- provides a low enough thermal radiation emissivity for the 80K and 4.5K heat loads to be handled cost-effectively by the cryo-plant.

12.1.2 Basic Configuration and System Boundaries

The thermal shields form an optically opaque reflector between all warm (room temperature and above) surfaces with the potential for emitting thermal radiation to the liquid helium temperature magnet structures.

The overall thermal shield system consists of four sub-systems, corresponding to the parts of the warm emitting surfaces that they shield. These four sub-systems are the vacuum vessel thermal shield (VVTS), the cryostat thermal shield (CTS), the transition thermal shield (TTS) and the support thermal shield (STS). The VVTS is interposed between the VV exterior and the adjacent TF coil surfaces, and completely envelopes the VV and VV ports, which constitute the system boundary. The CTS basically covers the interior surfaces of the cryostat, and has many penetrations to allow passage of equipment connecting to the tokamak and to in-cryostat destinations (for example the bellows connecting the VV ports to the cryostat), and for maintenance access. The TTS shields the VV port connection ducts which connect the VV ports to the cryostat, and the in-cryostat TCWS pipes, and interface with the VVTS at the end of the VV ports, and with the CTS adjacent to the cryostat wall. These interface locations are also the system boundaries. The final sub-system is the STS, which surrounds unshielded warm parts of the tokamak gravity supports, and connects with the other thermal shield sub-systems to form the required continuous optically opaque reflective barrier between warm and cold zones. All the aforementioned thermal shield subsystems are provided with gravity supports which are adequate to resist all the designated load combinations, have sufficient thermal impedance to limit heat conduction to the cold structures to acceptable values, and are flexible enough to accommodate thermal movements.

The thermal shield coolant pipes are routed from two cold valve boxes (located at the magnet and TCWS vault level) and penetrate the cryostat through two penetrations at the magnet and TCWS vault level. The thermal shield coolant lines penetrate the cryostat by way of 2 standpipes, which are part of the cryostat, and projects out from the cryostat cylinder to just beyond the bioshield outer wall, to which they are sealed by bellows. These standpipes and bellows are part of the cryostat pressure boundary, and connect with the vacuum jacket of the helium coolant lines by means of a welded sleeve joint, which bridges a gap left between the cryostat standpipe and the thermal shield coolant pipe vacuum jacket. Before the sleeve is welded, it is displaced axially along the vacuum jacket to allow access for butt welding of the internal coolant pipes. When these butt welds are completed, the sleeve is displaced to bridge the gap between the vacuum jacket and the cryostat standpipe, and welded to both. The sleeve is part of the cryostat, and the weld between the sleeve and the vacuum jacket is the boundary between the cryostat and the thermal shield systems (the internal 80K pipes are part of the thermal shield system).

Outboard of the cryostat interface joint, the thermal shield coolant pipes are routed to the two U-bend boxes and further to the two thermal shield valve boxes, which are part of the thermal shield system. The boundary between the cryo-distribution and the thermal shield systems is at the connection location of the cryolines coming from cryosystem with the two cold valve boxes. The connections between thermal shield coolant manifold and valve boxes as well as between valve box and cryosystem manifolds are made with welded sleeve joints the same as at the cryostat connection.

12.2 Design Requirements

12.2.1 General

The thermal shield shall be designed to set up upper limit for both total and local thermal loads applied to the surface of components operating at 4.5K, by conduction and thermal radiation.

At normal operation conditions, when plasma operation is required, the thermal loads to the surfaces at 4.5K shall be limited to 9 kW total as follows:

1. Radiation from warm components, thermal shield surface, conductance through thermal shield supports and residual gas conduction 5.0 kW
2. From thermal anchor in the VV supports to TF coil cases 2.0 kW
3. From thermal anchor in the gravity supports to TF coil cases 2.0 kW

During VV baking, when plasma operation is not required, the total heat load on the magnet system may be increased by a value less than nuclear heating during the plasma operation state. The nuclear heating of the magnet system is defined in section 1.15 (Table 1.15-5) of DRG1.

In addition, the maximum surface heat loads on 4.5K surfaces shall be limited to 40 W/m^2 locally, provided the above totals are not exceeded.

At thermal shield conditioning and during abnormal events, heat loads from thermal shields should not result in structural damage of magnet components or overheating of coils above 50°C.

In order to ensure reasonable design conservatism, the following values of magnet and VV surface emissivity shall be used in the design:

1. for magnets at room temperature and above 0.4
2. for magnets at normal operation conditions 1.0
3. for vacuum vessel 0.3

The emissivity value of 0.4 used for surfaces above room temperature is a typical value used for stainless steel surfaces where no surface treatment is applied to give a low emissivity. The emissivity value of 1 corresponds to cold surfaces being covered with a cryo-deposited layer of non-permanent gas.

12.2.2 Space Occupancy

The thermal shield system shall have a minimal impact on the machine radial build. The space envelope for the VVTS shall not exceed the values specified in Table 12.2-1 including panels, tubes, joints, and other components. Bumper and stopper elements, which project beyond the VVTS surfaces, are used to limit mutual displacements by providing local contact with adjacent tokamak structures during accident/fault events thereby preventing damage to reflective surfaces, and their associated cooling pipes and joints. Such projecting elements must also be kept within space allocations. The VVTS design and fabrication shall meet the requirements for fabrication and assembly dimensional tolerances as specified in section 12.2.9 of this chapter.

The open gap between the VVTS and each of its surrounding components shall be large enough to preclude exceeding the damage limits specified in Table 12.2-6 during machine assembly, commissioning, component cooling and heating, normal and off-normal operation conditions, and accident and fault events (see Table 12.2-1).

Table 12.2-1 Maximum Space Envelope for the Vacuum Vessel Thermal Shield

VVTS part	Space envelope, mm
Inboard part	99
Outboard part	118
Top/bottom parts	108
Ports	111

12.2.3 Vacuum

- An adequate pumping conductance for the TF coil case/TS, VV/TS and cryostat/TS interspaces shall be provided. The maximum pressure within the interspaces between the thermal shields and adjacent components shall not exceed 5×10^{-3} Pa at a pressure of 1×10^{-4} Pa within the free cryostat volume.
- The design and construction of the thermal shields shall be consistent with providing a high quality vacuum. In particular, the requirements specified in the ITER vacuum design handbook shall be complied with. The maximum allowable test leak rate from the cooling tubes shall be 10^{-10} Pam^3/s per weld for both the hot and cold leak tests (see section 12.2.11).
- All thermal shields shall be bakeable at a temperature above 110°C during a TS baking/cryostat pumping period.
- The thermal shields shall have provisions for active cooling where necessary. Pressurised He gas from the main cryogenic plant shall be used.
- In order to provide high reliability of the thermal shield system the helium cooling pipes shall have 100% redundancy and each pipe loop shall have isolation valves at the cold valve boxes so that the leaking pipe can be localised by successive evacuation of the cooling pipe loops. Each cooling pipe loop shall be capable of evacuation in order to implement this leak localisation procedure.

- It should be noted that the apparent emissivity of the thermal shield reflective surfaces will increase beyond the design value in the event that they cryo-condense excessive amounts of non-permanent gases present within the cryostat vacuum envelope (H_2O, CO_2, heavy hydrocarbons etc.). This apparent emissivity degradation occurs on account of the relatively high thermal radiation adsorptance of such cryo-deposits at infra-red wavelengths. Water ice is the worst specie in this context and fractional μm deposit thickness increases the apparent emissivity beyond the design range. It is essential that both the thermal shields, and all in-cryostat components, be designed such that their surface outgassing, prior to thermal shield cooldown, can be reduced to a level that will not endanger the thermal shield emissivity during cooldown and operation.
- In order to minimise the likelihood of leaks into cryostat vacuum from the helium coolant pipes, the longest practical lengths of individual pipes shall be used, while keeping the overall coolant path as short as possible, so as to minimise the number of inter-pipe welds. For the same reason, the cooling pipe thickness and support shall be such that stresses are moderate and fatigue margins adequate.

12.2.4 Structural

The thermal shield shall be designed in compliance with codes and standards given in section 12.3.

The thermal shield shall withstand the following loads and load combinations as specified in Table 12.2-2:

1 Combination of internal coolant pressure and external pressure in the cryostat including water and cryogenic fluid leakage at 4.5K and 80K:

Normal operation:

Internal coolant pressure	1.8 MPa
External pressure (in the cryostat)	$< 1\text{x}10^{-3}$ Pa

Off-normal:

External pressure (in the cryostat) (cat. IV)	0.2 MPa

Maintenance and tests:

Internal pressure in the cooling tube (hot and cold tests)	2.25 MPa
External pressure (cryostat pressure test)	0.2 MPa
External pressure (during hot and cold test)	$< 1\text{x}10^{-2}$ Pa

2 Global and local electromagnetic loads induced in the thermal shields:

Normal and off-normal operation:
Vertical displacement events (VDE)
Central plasma disruption (CPD)
Toroidal field coil fast discharge (TF FD)
Poloidal field coil fast discharge (PF FD)

These loads must be reacted either internally without damage to the thermal shield components, or by the shield gravity supports, with stress levels in the elastic range, and without contact with neighbouring components.

3 Gravity loads (self-weight):
These loads result in deflections that, when added to the tolerances of thermal shield manufacture and assembly, define the minimum TS space envelope. These deflections shall be small compared to the fabrication tolerances and the minimum clearance between the thermal shields and adjacent components, and no more that about 2 mm for the VVTS, and 5 mm for the CTS, TTS and STS.

4 Displacements imposed by other tokamak components:
Loads resulting from displacements of other components, as applied through the TS support structures (namely, TF coils, VV port connection ducts, and cryostat).

5 Test loads:
Forces applied during tests, assembly, commissioning maintenance and disassembly of TS parts.

6 Seismic loads on thermal shields:
The rationale for the seismic design of the thermal shields is that under the loading conditions resulting from a SL-2 seismic event, no VVTS damage shall be sustained requiring repair of any VVTS part needing disassembly of the VV and TF coils to repair it. In a analagous way, the other thermal shields are the same seismic class as the cryostat, and many of the in-cryostat components, so that these components, and/or the cryostat feedthroughs of the thermal shield coolant pipes, do not have to be disassembled to make repairs. It should be noted that momentary contact between neighbouring tokamak components and thermal shield bumper structures is acceptable, indeed this is their design function.

7 Thermally induced loads:
The thermal shields will be subject to thermally induced loads consistent with the temperature states defined in section 12.2.5. All thermal shields shall be able to expand without excessive stress, and clearances shall be sufficient for the maximum design thermal deflections. The thermal shield support structure shall be designed to withstand the temperature states described in section 12.2.5 of this document. Total loss of helium cooling in the thermal shield system is an extremely unlikely event, on account of the design requirement for full redundancy of cooling channels. The most adverse temperature state for the VVTS is that resulting from a combination of VV loss of (forced) flow event (LOFE) and VV ICE II , with consequent VV temperature increase up to 250°C. Accidental water, helium and air ingress into the cryostat result in significant thermal convection and produce adverse temperature conditions in all thermal shields. The stresses resulting from all the load and combination conditions compiled in Table 12.2-2 shall be compatible with the allowables permitted by the design codes specified in section 12.3 of this document.

8 Fatigue loads:
Sufficient margin in fatigue lifetime for components under all loads and combinations thereof should be provided in accordance with the design codes specified in section 12.3.

The load cases and combinations for the thermal shields are shown in Table 12.2-2 using the methodology presented in the LSC annex of DRG1. As elaborated in section 12.2.8, the seismic classifications of the thermal shields are assigned on grounds of safety function and investment protection, the former being tightly prescribed in the PSR and the GSSR (an annex to DRG1), and the latter a cost-effectiveness issue and hence not so stringently prescribed. For the VVTS, the design approach shall be that it shall not suffer enough damage, as a consequence of some event, that would require removal of a VV sector to repair it, if the event does not require removal of a VV sector anyway. Thus, the VVTS has to withstand the same most adverse loading cases and combinations as the VV, without needing repairs that would necessitate removal of a VV/TF coils sector, and this requirement is reflected in Table 12.2-2. The approach for the other thermal shields is that they shall be designed such that failures do not damage the cryostat confinement boundary, as elaborated in section 12.2.8. This approach is reflected in Table 12.2-2.

Table 12.2-2 Design Load Combination, Number of Cycles and their Categories for Thermal Shields

Thermal Regime	Load Category	Pressure	Seismic	Plasma	Magnet	Number of cycles
Test	I					-
Operation	I					40,000
Operation	I			VDE I		150
Operation	I			Disr. I		3,000
Operation	I			Disr. I	F. Disch	50
Operation	I			VDE I	F. Disch	50
VV, TS baking, magnets at RT	I					100
TS cooldown/warm-up	I					100
VV baking, magnets at 4K	I					200
Operation	II	ICE II		Disr. I		15
Operation	II	ICE II		Disr. II		15
Operation	II	ICE II		VDE II		15
Operation	II		SL-1	VDE I		1
Operation	II		SL-1	Disr. I		1
VV, TS baking, magnets at RT	II		SL-1			1
VV baking, magnets at 4K	II		SL-1			1
Operation	III	ICE III		VDE II		1
Operation	III	ICE III		Disr. II		1
Operation	III			Disr. II	F. Disch	1
Operation	III		SL-1	VDE II	F. Disch	1
Operation	III		SL-1	Disr. II	F. Disch	1
Operation	III	ICE III		VDE III		1
Cryostat air ingress, magnets VV at op.	III					1
Cryostat air ingress, VV baking, magnets at 4K	III					1
Cryostat air ingress, VV, VVTS baking, magnets at RT	III					1
Operation	IV	ICE IV		Disr. I		1
Operation	IV	ICE IV		VDE III		1
Operation	IV	ICE IV		VDE III		1
Cryostat water ingress, magnets, VV at operation	IV					1

Table 12.2-2 Design Load Combination, Number of Cycles and their Categories for Thermal Shields (cont'd)

Thermal Regime	Load Category	Pressure	Seismic	Plasma	Magnet	Number of cycles
Cryostat water ingress, magnets at 4K, VV baking.	IV					1
Cryostat water ingress, magnets at RT, VV, VVTS baking.	IV					1
TS LOFE, magnets, VV at operation	IV					1
TS LOFE , VV baking, magnets at 4K	IV					1
Cryostat air ingress, magnets, VV at operation	IV		SL-1			1
Cryostat air ingress, VV baking, magnets at 4K	IV		SL-1			1
Operation	IV	VV LOFE + ICE II		VDE II		1
Operation	IV	VV LOFE + ICE II		Disr. II		1
Operation	IV		SL-2	VDE I		1
Operation	IV		SL-2	Disr. I		1
VV, TS baking, magnets at RT	IV		SL-2			1
VV baking, magnets at 4K	IV		SL-2			1

12.2.5 Thermal-hydraulic

The coolant for normal operation is pressurised He gas with an 80K minimum inlet temperature. It is compatible with the nuclear and high vacuum external environments, being non-activatable and gaseous at 4K. The same coolant shall be used for heating during thermal shield baking.

Operating pressure and pressure drops shall be compatible with the cryoplant warm compressors, as follows:

Inlet pressure	1.8 MPa
Maximum overall pressure drop for the TS cooling system outside cryoplant	0.1 MPa

The thermal shield and thermal anchors must be designed to remove the heat due to:

1. Thermal radiation and conduction through the VV support from the VV, with VV surface emissivity ε ≈ 0.3
   - normal operation condition 120°C
   - VV baking 200°C
   - VV LOFE + ICE II 250°C
2. Radiation and conduction through the TS supports from the cryostat at room temperature
3. Radiation and conduction through the TS supports from the VV manifolds
   - normal operation condition at 120°C
   - VV baking at 200°C
4. Radiation and conduction through the TS supports from the blanket manifolds
   - normal operation condition at 150°C
   - VV baking at 250°C
5. Nuclear heating 200 W/m^3

The temperature difference between inlet and outlet of coolant shall be within:

normal operation condition	20°C
VV baking and TS baking	50°C
Cooldown/warm-up	50°C
VV LOFE + ICE II	70°C

The cooldown and warm-up regime should be consistent with the corresponding magnet procedure. It is foreseen that advance cooldown of magnets, with a temperature difference of 30 to 50°C between TS and magnets, will be performed. The thermal shield baking shall be compatible with the VV baking.

Table 12.2-3 Design Temperature Conditions for the Thermal Shields (Centigrade)

Temperature regime	**Load Category**	**VV**	**TFC**	**Cryostat**	**VVTS**	**CTS/STS**	**TTS**
Test at factory	I	-	-	-	RT, 150, -193	RT	RT
Normal							
Construction/maintenance/off state	I	20	20	20	20	20	20
Operation	I	120	-269	20	-193…-120	-193…-153	-193…-140
VV ICE II, TF coil at 4K	II	160	-269	20	-193… –100	-193…-143	-193…-100
VV, TS baking, TFC at RT	I	200	20-50	20-50	110…145	100…150	110…150
VV baking, TF coil at 4K	I	200	-269	20	-193… –60	-193…-143	-193…-90
Abnormal							
VV LOFE + ICE II, TF coil at 4K	III	250	-269…	20	-193… 5	-193…-50	-193…-50
Cryostat air ingress/water ingress/TS LOFE, TF coil at 4K, VV in operation	III/IV/IV	120	-269	20	-193…50	-193…20	-193…50
Cryostat air ingress/water ingress/TS LOFE, VV baking, TF coil at 4K	III/IV/IV	200	-269	20	-193…120	-193…20	-193…120
Cryostat air ingress/water ingress TS, VV baking, TF coil at RT	III/IV/IV	200	20	20	110-170	20-150	110-170
Coil helium leak, VV&TS in operation	IV	120	-269	-68.20	-193…50	-193…20	-193…50
Coil helium leak, VV baking, TS in operation	IV	200	-269	-68.20	-193..120	-193…120	-193…120

12.2.6 Electromagnetic

The TS shall have the requisite number of electrical breaks to reduce induced currents to a level that avoids complication of the TS design from the electromagnetic loading standpoint. The TS structures shall withstand all electromagnetic loads as specified in section 12.2.4. The electrical resistance of the thermal shield shall be large enough so as not to perturb the poloidal shield system. Ferromagnetic materials shall not be used.

12.2.7 Chemical

The thermal shield insulation material shall be chemically inert with respect to the operating environment. Surface coatings shall be resistant to oxidation.

12.2.8 Seismic

All thermal shields shall be designed to meet the seismic design criteria defined in the LSD Annex of DRG1, section 5.1. Thermal shield seismic classifications are assigned on two bases, safety and investment protection. In the safety context, the thermal shields are not safety importance class components and therefore from this standpoint, require no seismic classification. The GSSR (vol. IX) specifies that if the response of a first component to a given event jeopardises the function of a second component which is required for safety, then the first component requires to be seismically qualified to the same level as the second component (same seismic classification). Thus, the seismic classification of all the thermal shields shall be at least the same as the cryostat, so that damage of thermal shield cooling pipe feedthroughs does not endanger the cryostat confinement boundary. Conversely, the VVTS, although being non-safety relevant and hence with no seismic classification from a safety standpoint (PSR), has an investment protection context. It shall not suffer enough damage, as a consequence of some event, that would require removal of a VV sector to repair it, if the event does not require removal of a VV sector anyway. Thus, the VVTS shall have the same seismic classification as the VV, to preclude the need to repair the VVTS, following a seismic event not adversely affecting the VV function. In a similar way, the VVTS shall not need repair requiring disassembly of a VV sector, following a combination of VV LOFE with ICE-II, since none of these events require removal of a VV sector. Moreover, the VVTS should keep its thermal-physical properties in specified limits (section 12.2.1) after SL-2 in order to provide normal operation of the machine.

The consequence requirements of the thermal shield components in response to a SL-2 earthquake are shown in Table 12.2.4.

Table 12.2-4 Seismic Consequence Requirements of Thermal Shields in Response to a SL-2 Earthquake

Components	Rationale
VVTS	No damage requiring VVTS disassembly for VVTS repair, including damage due to movement, deformation or arcing resulting from a SL-2 seismic event
Other thermal shields	All thermal shield components constituting part of the cryostat confinement barrier shall meet the requirements of the PSR for a SL-2 earthquake.

In terms of consequences, a key issue is the mutual motion of the TF coils and VV and resulting potential crushing of the VVTS between these massive neighbouring components, or electrical contact between tokamak components, with resulting arcing hazard for the VVTS. The main design concept is to avoid TF coil/VV structural damages up to seismic event SL-1. However, it is reasonable to avoid serious damage of the thermal shields during at SL-2 event also. Bumper and, or stopper structures shall be provided for all thermal shields as a precaution against local damages and electrical contact. For the VVTS in particular, these bumpers and, or stopper structures may be partially sacrificial elements, in that they may suffer significant damage during mutual motion of VV and TF coils. Table 12.2-5 shows how the damage limits relate to the loading conditions for the thermal shields, while Table 12.2-6 defines the damage limit for each loading condition.

Table 12.2-5 Thermal Shield Damage Limits for Loading Conditions

Operation Loading Category I	Likely Loading Category II	Unlikely Loading Category III	Extremely Unlikely Loading Category IV	Testing
Normal	Upset	Emergency	Faulted (Emergency for VVTS)	Normal

Table 12.2-6 Thermal Shield Damage Limits

Damage Limits	Damage Limits to Thermal shield component level
Normal/Upset	The components must withstand this loading without significant damage requiring inspection or repair.
Emergency	Deformations in areas of structural discontinuity and large deformation of sacrificial bumper and stopper elements without having to remove components for repair.
Faulted	Gross damage to sacrificial elements, large deformation of component without consequent loss of dimensional stability, and without damage requiring immediate repair. Deformation of thermal shield should not lead to the damage of other components.

12.2.9 Manufacturing

The VVTS must be fabricated to very tight tolerances in order to fit into the narrow gaps provided between neighbouring components. The sum of fabrication, installation and positioning tolerances shall not exceed the allowable total tolerance bands specified in Table 12.2-7, in order that the VVTS fits into the space envelope values shown in Table 12.2-1, while maintaining adequate operational clearances. The achievement of tight tolerances for the VVTS flanged joints is crucial for the function and assembly of the joints.

Table 12.2-7 Fabrication and Assembly/Positioning Tolerances for VVTS

Item	Tolerances (mm)
Fabrication tolerances for 10° sections	
Horizontal for inboard part	± 10
Horizontal for outboard part	± 15
Vertical for top and bottom part	± 10
Vertical and horizontal tolerances for joint flanges	± 2
Assembly tolerances	
Vertical and horizontal directions	± 2.5
Positioning tolerances and spring-back effect	
Vertical and horizontal directions	± 2
Fabrication tolerances for ports	± 6
Assembly tolerances for port	± 2
Positioning tolerances and spring-back effect for ports	± 2

The gaps between CTS and TTS panels and adjacent components are also very narrow. Therefore, the reference tolerance for the CTS and TTS panel dimensions shall be ± 5 mm and the overall reference tolerance band ± 10 mm.

It is expected that bolted joints shall be used for joining thermal shields segments, since the application of silver reflective coatings to the panel surfaces precludes the subsequent use of welding. The cooling tubes shall be welded with welds on alternating sides to avoid cantilever effects.

12.2.10 Construction and Assembly

The VVTS sectors shall be fully constructed in the factory. Full poloidal 40° sectors shall be pre-assembled using templates to emulate the ideal neighbouring VVTS sectors and facilitate achievement of the tolerance requirements. The 40° sector shall then be dismantled into two outboard 20° half sectors, an inboard rigid support frames, packed and shipped from the factory. The serial production of the full poloidal 40° sectors shall be performed with a precision commensurate with the requirements of Table 12.2-7.

The fabrication and all other activities undertaken on all thermal shields at the supplier's shop shall comply with the requirements of the ITER vacuum design handbook, particularly the requirements on clean room practice. The on-site assembly activities shall be integrated with the overall machine assembly schedule.

12.2.11 Testing

All tubes welded to the panels, tube joints and manifolds shall be helium pressure and leak tested at the factory at 80K and 150°C. The magnitude and direction of the pressure differential and stress state shall be the same or higher than experienced during operation. The maximum allowable test leak rate from the cooling tubes shall be 10^{-10} Pam^3/s per weld for both the hot and cold leak tests. All insulated joints shall be tested for integrity and strength of the electrical. The insulated joint electrical testing, during assembly, shall be designed to minimise any re-work resulting from a test failure. All grounding resistors used shall be within 20% of specified values. All plated surfaces shall be visually inspected and distributed emissivity measurements shall be made using a calibrated bolometer.

12.2.12 Instrumentation and Control

Each separate coolant manifold shall have remotely indicating inlet and outlet helium temperature and mass flow measurements to enable flow rate balancing during commissioning and to obtain a heat balance during operation. Each separate cooling manifold shall have remote operated control and isolation valves, located in the thermal shield cold valve boxes.

12.2.13 Materials

The thermal shield materials and surface finishing shall be compatible with the requirements of the ITER vacuum design handbook. The materials shall be also selected considering cost, performance and manufacturing.

The material for all TS panels and supports shall be polished non-magnetic austenitic stainless steels with low emissivity coatings. Copper may be used to augment thermal conduction. Non-metallics may be used for electrical insulation and low heat loss structural components (subject to compatibility with the requirements of the ITER vacuum design handbook). These materials shall be demonstrated to be compatible with the nuclear environment at the shield.

The use of ferromagnetic materials is prohibited.

Principal materials used in the thermal shields shall be:

- the main material used for the thermal shields and ancillaries is stainless steel type 304L as allowed in ASME section VIII, division 2.
- For the inboard VVTS support, Inconel rods, nuts and bushes are used.
- The outboard support structure is made of stainless steel type 304L or 316 LN.
- The CTS and TTS panel supports are made from Ti-6A1-4V alloy.
- The insulators are from fiberglass plastic and polyamide insulation. Plasma sprayed $A1_2O_3$ coatings are used at the gravity support and on the lateral faces of the VVTS flange joints for electrical insulation.
- The reflective surfaces of the thermal shields are coated with a nominal thickness of 5 μm of silver.
- Some parts of labyrinth joints between thermal shields require blackening of the surface by ceramic coating.

12.2.14 Electrical

The gravity support of the VVTS as well as the VVTS itself shall be electrically isolated from the toroidal field coils and remain so even during disruptions, seismic and other dynamic events. The VVTS shall be electrically segmented both toroidally and poloidally in order do not to prejudice the effectiveness of the poloidal field system. For the same reason the CTS and TTS shall be more electrically resistive than the cryostat. Electrical contact between the VVTS and the VV as well as between the VVTS and other thermal shields shall be precluded.

12.2.15 Nuclear

The VVTS and TTS are located in a region of strong neutron and gamma radiation. The CTS is less affected but even here the nuclear radiation must be considered. It constrains the materials choices, particularly in view of the very high reliability required. Prudent conservatism is in order, and therefore materials in all thermal shields shall be capable of withstanding a lifetime neutron fluence (E > 0.1 MeV) of 5×10^{17} n/cm^2, together with a gamma dose of 10 MGy.

12.2.16 Grounding

It is essential that the vacuum vessel thermal shields shall be grounded against charge buildup, using resistors if necessary, and be electrically insulated from the toroidal field coils, especially under dynamic loading when momentary structural contact is possible. The cryostat and transition thermal shields shall be electrically grounded using their respective structural connections.

12.2.17 Decommissioning

The thermal shields shall be decommissioned in accordance with the requirements for irradiated stainless steel.

12.2.18 Operation and Maintenance

The thermal shields are permanent components of the machine (remote handling (RH) class 3). A VVTS sector shall be capable of being replaced integrally with a VV/TF coil sector without damage to adjacent shield sectors. VVTS splice plate joints shall be capable of re-assembly. The CTS and TTS panels shall be capable of being replaced as individual panels with minimum RH.

The CTS and TTS shall provide penetrations and access ports for in-cryostat access on the same alignment as the corresponding cryostat penetrations and connecting ducts.

The thermal shield around the VV supports and the machine support thermal shield (STS) require provision for periodic inspection of the supports.

No surveillance requirement, except ice-detection, is foreseen. However, the design must allow for in-situ leak testing. All manifolds, which are the most likely source of leaks, must be accessible for repair or replacement.

As noted in section 12.2.3, the emissivity of the thermal shields could be degraded by cryo-deposits of residual gases, particularly water, to the point where the 80K heat load is beyond the design maximum. To avoid this, the cryostat and all internal components shall be de-gassed to such a level that subsequent outgassing results in a cryodeposition rate that does not endanger the thermal shield emissivity over the duration for which the magnets remain cold. An optimised programme of pumping and venting with warm boil-off nitrogen, and baking cycles shall implement this de-gassing.

12.2.19 Quality Assurance (QA)

Because of the inaccessibility of the VVTS, and the difficulty with access to other thermal shields, they must be conservatively designed as permanent components, with reliability high enough to render a failure extremely unlikely. Ample safety factors are required, and pipe manifolds and joints, the probable location of failures, must be accessible for repair. Furthermore, the low emissivity surfaces must remain that way over the life of the plant even in the event of an air or hot/cold steam intrusion into the cryostat volume. To facilitate achievement of the requisite level of reliability, the design, material procurement, fabrication and testing shall be subject to a QA programme at a level concomitant with the high reliability requirement.

12.3 Codes and Standards

The thermal shield system design shall be performed in accordance with the design criteria described in the structural design criteria (an annex of DRG1).

- ASME pressure vessel code section VIII division 2
- ASME pressure vessel code section VIII-NC for cat. III and IV loading
- ASME B31.3 for piping.

The use of the codes is limited to the evaluation of stress and fatigue limits. Code values of the allowable stresses, such as Sm, are used for 304, 304L stainless steels. However, because the code does not specify allowable stresses below about -30°C, adjustments are made to the allowables (where appropriate) by scaling published material properties data yield and fatigue strengths.