18 Space Shuttle Integration

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Introduction

The function of the flight- and cargo-integration effort is to ensure that elements of the total payload complement for a flight are compatible in form, fit, and function, and that all associated flight-design parameters and crew activities are within Space Shuttle Program (SSP) capabilities. This effort includes assessments by flight- and ground-systems engineering, safety, and all elements of SSP operations. Figure 18.1 illustrates the SSP/payload thermal-integration process in flowchart form. The

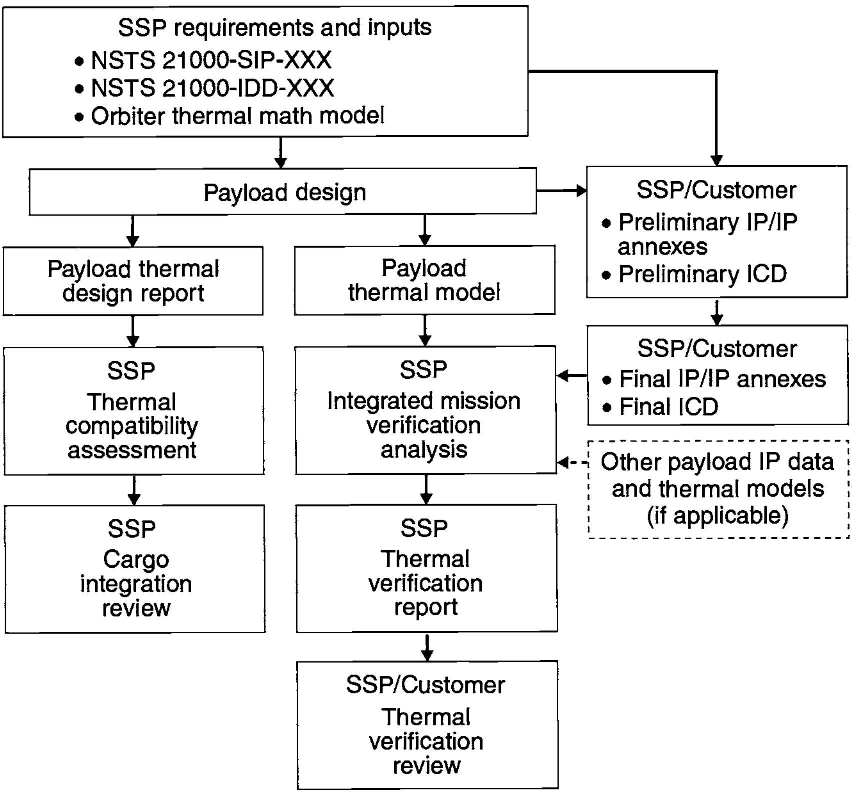

Fig. 18.1. SSP/payload thermal-integration process.

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**Microcosm Inc., El Segundo, California.

Cargo Integration Review (CIR) is the major cargo-related review of this assessment effort, and it occurs at the same time customer concurrence is obtained. A typical schedule of events leading to the CIR, subsequent reviews and, ultimately, flight is shown in Fig. 18.2.

The following assessments are required prior to formal reviews to ensure an adequate SSP understanding of the cargo and flight requirements and the ability to support such requirements.

- crew-activities assessment
- flight operations and support assessment
- payload operations control center/mission control center
- network assessment
- training assessment
- ground-operations assessment
- conceptual flight-profile assessment
- human use
- engineering-compatibility assessment
- interface-verification status
- safety assessment

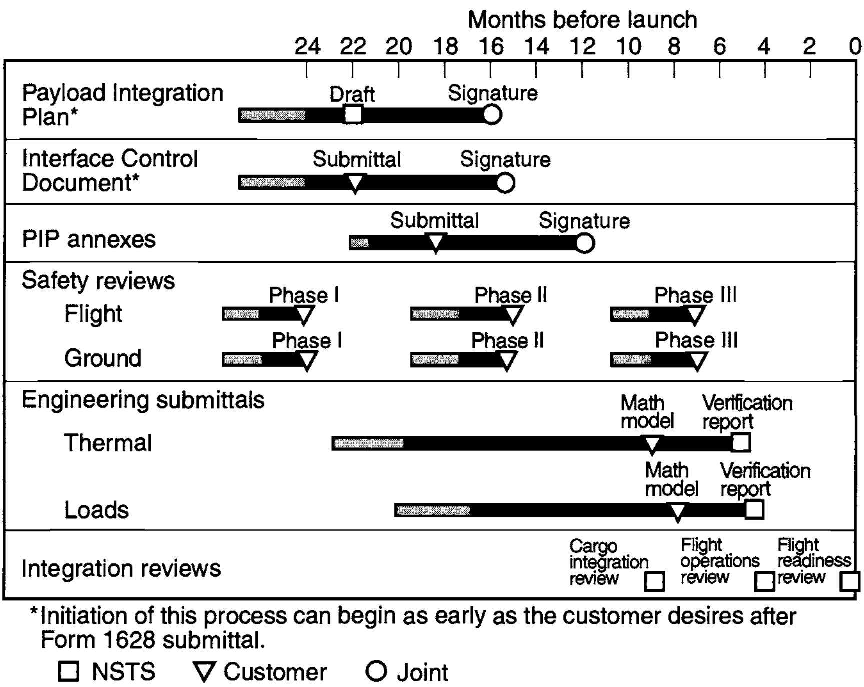


Fig. 18.2. SSP/payload integration timeline.

Most of these assessments do not require direct involvement of the payload thermal engineer; two that do, however, the engineering-compatibility assessment and the safety assessment, are examined in the sections that follow.

Engineering-Compatibility Assessment

One assessment that does require extensive support from the payload thermal engineer is the engineering-compatibility assessment. Its purpose is verification of the compatibility of the integrated SSP flight hardware, software, and engineering-flight products with current mission requirements, cargo requirements, and orbiter accommodations. This verification is accomplished by teams with specialization in thermal control, avionics, structures, electromagnetic compatibility, flight preparation, interface verification, reliability and certification, and cargo interfaces.

Because of the complexity of the space shuttle and its flight operations, much more documentation and analysis is required to control and verify the integration of payloads with the shuttle than with expendable launch vehicles. Figure 18.3 lists the standard STS (Space Transportation System) documents that describe the shuttle and its payload interfaces and ensure engineering compatibility between the shuttle and payloads. These documents are available in electronic form at the National Aeronautics and Space Administration/Johnson Space Center (NASA/JSC) and United Space Alliance (USA) Web sites.

The individual payload compatibility assessment begins with the process of developing the payload Integration Plan (IP), the payload-unique Interface-Control Documents (ICDs) and drawings, the Command and Data Annex (Annex 4), the Orbiter Crew Compartment Annex (Annex 6), and the Extravehicular Activity (EVA) Annex (Annex 11). The individual payloads' physical and functional requirements are integrated by NASA into an engineering data package.

The thermal portion of the compatibility assessment includes a comparison of both the active and passive thermal-control requirements of the payload with the shuttle and cargo thermal capabilities and requirements, as defined in the Shuttle Orbiter/Cargo Standard Interfaces, ICD 2-19001. This document contains the orbiter vehicle attitude hold-time constraints, orbiter deorbit and entry-preparation constraints, typical temperature ranges for the cargo-bay wall/liner, entry-air inlet conditions, typical prelaunch and postlanding environments, typical Remote Manipulator System (RMS) thermal interfaces, orbiter surface materials and their optical properties, and the vent/purge and active cooling systems capabilities and parameters. This data should be reviewed and checked against payload requirements to ensure that no payload requirement conflicts with the orbiter's capability.

Not only is the payload-to-orbiter compatibility determined, but also the compatibility of the payload with stated mission objectives must be assessed. This is a more complicated task, as the mission objectives and companion payload's requirements and limitations may not be well defined. However, once payload thermal compatibility with the orbiter and mission is determined, a compatibility statement must be signed by both the contractor/payload thermal representative and the NASA/USA thermal-engineering team leader. This is typically done at the CIR. Sample active and passive thermal-compatibility statements are shown in Figs. 18.4 and 18.5.

NSTS 07700 Volume XIV
Space Shuttle System Payload Accomodations

NSTS 21492 Payload Bay
Payload User's Guide

Safety
- 45 SPW HB S-100/KHB 1700.7
- NSTS 1700.7B
- NSTS 16879
- NSTS/ISS 13830C
- NSTS/ISS 18798
- NSTS 14046
- NSTS 22648

Shuttle/Payload
Standard Integration
Plans (SIPs)

*Annexes

NSTS 21000-SIP-ATT
Attached Payloads

NSTS 21000-SIP-DRP
Deployable/Retrivable
Payloads

NSTS 21000-SIP-GAS
Get Away Special
Payloads

NSTS 21000-SIP-MDK
Middeck Payloads

NSTS 21000-SIP-ISS
International Space
Station

Orbiter/Payload
Interfaces

ICD 2-19001:
Vol. XIV
Attachment 1 - Shuttle
Orbiter/Cargo
Standard Interfaces

NSTS 21000-IDD-SML
Small Payloads

NSTS 21000-IDD-ISS
International Space
Station

NSTS 21000-IDD-MDK
Middeck Payloads

Vol. XIV Appendixes:
System Description
and Design Data

Appendix 1
Contamination
Environment

Appendix 2
Thermal

Appendix 3
Electrical Power
and Avionics

Appendix 4
Structures and
Mechanics

Appendix 5
Ground Operations

Appendix 6
Mission Planning and
Flight Design

Appendix 7
Extravehicular
Activities

Appendix 8
Payload Deployment
and Retrieval System

Appendix 9
Intravehicular
Activities

Appendix 10
Integration Hardware

*Annexes
(Note: appropriate annexes are outlined in the individual SIPs)
- Annex 1 Payload Data Package
- Annex 2 Flight Planning
- SIP Table 8.1 Data Submittals
- Annex 4 Command and Data
- Annex 5 POCC
- Interface Control Annex
- Annex 7 Training
- Annex 8 Launch Site Support Plan
- Operations and maintenance requirements Specifications Document (OMRSD)
- Annex 11 Extravehicular Activities (EVA)

Fig. 18.3. STS documentation for shuttle/payload compatibility.

STS _________ CARGO INTEGRATION REVIEW
COMPATIBILITY STATEMENT

The NASA/USA Team Leader and the contractor/payload representative have assessed the compatibility of the integrating hardware and software design against the STS and cargo requirements in the

TR/Thermal Systems Engineering - Passive ______________________ as of ____________________
(system or other) (date)

The engineering assessments listed below, with the exception of (A) open items, and (B) open DNs/ECRs are found to be compatible.

☐ Verify compatibility of IH with cargo design

☐ Verify compatibility of IH with mission objectives

☐ Verify compatibility of IH with thermal constraints (max-min average temperatures, max-min entrapment temperatures, and predicted versus ICD temperatures)

☐ Status ICD TBDs, TBRs, and PIRNs

☐

☐

☐

(A) Open Items

(B) Open DNs/ECRs

______________________________________ ______________________________________
Contractor/Payload Representative Date NASA/USA Team Leader Date

Fig. 18.4. Passive thermal-control compatibility assessments.

STS __________ CARGO INTEGRATION REVIEW
COMPATIBILITY STATEMENT

The NASA/USA Team Leader and the contractor/payload representative have assessed the compatibility of the integrating hardware and software design against the STS and cargo requirements in the

TR/Thermal Active ______________________________ as of ______________
(system or other) (date)

The engineering assessments listed below, with the exception of (A) open items, and (B) open DNs/ECRs are found to be compatible.

- ☐ Verify compatibility of Orbiter active thermal systems with payload heat loads
- ☐ Verify compatibility of Orbiter gas supply system with payload requirements
- ☐
- ☐

(A) Open Items

(B) Open DNs/ECRs

______________________________ ______________________________
Contractor/Payload Representative Date NASA/USA Team Leader Date

Fig. 18.5. Active thermal-control compatibility assessments.

The orbiter has, in general, greater attitude-hold capability than most payloads require. Although some payload capabilities exceed its capability, payload attitude-hold requirements may not exceed those defined for the orbiter, to ensure that there are no orbiter temperature-limit violations and that the heat-rejection requirements imposed by the orbiter systems, crew, and payloads are met.

Incorporated into the design of payloads that share flights with other payloads and utilize the standard accommodations must be a minimum thermal capability common to all users of a particular flight. To ensure this mixed-cargo compatibility, NASA has defined a set of on-orbit orbiter attitude requirements with which (as a minimum) all payloads sharing a flight must be compatible. All mixed payloads must be able to continuously accommodate a selected attitude, i.e., one that can be maintained without interruption. For missions with beta angles less than 60 deg, the selected attitude is one with the orbiter payload bay continuously facing Earth (+ZLV). For missions with beta angles greater than 60 deg, the selected attitude is specified as the one with the orbiter x-axis perpendicular to the solar vector within 20 deg and rolling about the x-axis at a rate of two to five revolutions per hour. (This attitude is called passive thermal control, or PTC.) The continuous attitude will be maintained during orbiter crew sleep periods as well as long-duration coast periods such as those between deployment opportunities for deployable spacecraft. Short-term deviations from the continuous attitude are required for the deployment of deployable spacecraft. As a minimum, all mixed payloads must be able to accommodate 30 min of orbiter $+z$-axis directed toward the sun, as well as 90 min of $+z$-axis directed toward deep space. Thermal recovery from the short-term solar or deep-space attitudes will be made in the applicable continuous attitudes; i.e., +ZLV or PTC.

Payloads that may be manifested on International Space Station (ISS) assembly or servicing missions must be compatible with a 51.6-deg-inclination orbit and with an extended duration in the ISS docked attitude. The docked duration during these missions is typically 6 to 8 days, and these durations may become longer in the future. The orbiter's primary orientation while docked is a local vertical, local horizontal (LVLH) attitude with the orbiter tail pointed toward Earth and the orbiter bottom in the velocity vector (VV); that is, +XLV, –ZVV.

As the following sections indicate, many analyses must be completed to adequately assess the payload's compatibility with the orbiter, other payloads, and the mission environment. Results of these analyses are used by NASA/USA to aid nominal and contingency mission planning. Analysis results defining the payload's thermal capabilities and limitations are placed in the payload IP. (Fig. 18.6 shows a sample form used for tailoring the IP.) Because these thermal assessments require accurate temperature predictions, payload thermal models should be verified by comparing model predictions to thermal-balance-test or flight data. Discrepancies should be worked so that precise temperatures can be predicted. Temperature margins, if required by the payload program, should also be added to predicted temperatures used to establish thermal limits to allow for analysis uncertainties. Documentation identifying and explaining payload thermal limits and margins should be developed and provided to NASA/USA.

MICB CHANGE REQUEST/ DIRECTIVE NASA-Johnson Space Center	Page: Date: 9/12/89
Number P17559-38	CHANGE TITLE Thermal Environment

4.2.3.1. Thermal Environment - (cont):

IS:

The payload design and operation shall be compatible with the following attitude conditions. The Orbiter will normally be oriented in one of the attitudes contained in Table 4-1. The payload will be designed to allow deep-space excursions that Include a 35-min inertial measurement unit (IMU) alignment occurring approximately every 12 hr. The table specifies the payload constraints and recovery times for these excursions, so that repeat of the attitudes can be planned.

Table 4-1.-Attitude Requirement/Capabilities

Attitudes	Time Constraint	Nominal recovery attitude	Time	Preferred operational recovery attitude	Time
+ZLV	Continuous	N/A	N/A		
PTC	Continuous	N/A	N/A		
+Z Solar	30 min	+ZLV	TBD		
+Z Space	TBD	TBD	TBD		
-XLV*	TBD	+ZLV	TBD	TBD	TBD
-XLV**	TBD	+ZLV	TBD	TBD	TBD
-XLV***	TBD	+ZLV	TBD	TBD	TBD
±XSI	TBD	+ZLV	TBD	TBD	TBD
+YLV, XPOP***	TBD	+ZLV	TBD	TBD	TBD

* Nose down right wing velocity vector and rotated approximately 30°North of orbit plane.

** Nose down left wing in velocity vector and rotated approximately 30°South of orbit plane.

*** Nose down wing perpendicular to orbit plane and bay on RAM.

**** Wing down, nose perpendicular to orbit plane and bay on RAM.

2. Revise 1st sentence of 3rd para as follows:

WAS:

In the event of an anomaly, the STS will observe the attitude constraints of either Table 4-1a or Table 4-1b, as appropriate, to the extent possible.

IS:

In the event of an anomaly, the STS will observe the attitude constraints of Table 4-1 to the extent possible.

3. Add the following paragraph to the end of section:

The payload must be designed to be safe with any cargo bay flood light failed on. (Reference para. 6.1.6 of ICD2-19001 for floodlight characteristics.) If floodlight operation impacts mission success, operational constraints and appropriate safeguards will be negotiated between the NSTS and customer and will be documented in the Flight Operations Support Annex, Annex 3.

Fig. 18.6. Instructions for tailoring the IP. The IP contains analysis results that define the payload's thermal capabilities and limitations.

Safety Assessment

In addition to the design and engineering-compatibility considerations associated with completion of payload mission objectives, STS safety requires special attention from the payload thermal engineer. The customer is responsible for investigating the potential effects of unplanned events that may occur to ensure that no payload thermal-limit violations exist that could endanger the crew or compromise the flight during any mission phase. This assessment has two aspects: verifying that the payload thermal design meets the minimum capability requirements for contingency operations, and defining the payload's ultimate safety constraints.

Minimum Design Requirements for Contingency Operations

Payloads must be designed to be thermally compatible with an abort return to Earth during any mission phase. During powered ascent, abort can occur as either a return to launch site (RTLS) or an abort to an alternate landing site, such as a transatlantic one. On-orbit aborts can occur prior to or subsequent to payload-bay door opening. Prior to door opening, abort-once-around (AOA) presents the minimum orbit time, while the maximum time depends on the orbit inclination. (AOA is an abort condition in which the orbiter lands after making one complete orbit around Earth.) The payload-bay doors are normally opened 1 to 1.25 h after liftoff; however, customers must design for a maximum door-opening time of 3 h. If the doors are not opened by 3 h, an abort will be declared and landing will occur by liftoff plus 6.5 h for 28.5-deg-inclination missions, or liftoff plus 11.5 h for 57-deg-inclination missions. Following the 3-h abort time, special orbiter contingency operations may be required necessitating curtailment of standard payload services (e.g., power, cooling). Following payload-bay door opening, aborts can occur at any time; therefore, payloads must be compatible with an abort from the worst hot or cold condition that could be encountered for that particular mission.

Payloads must also be designed so that they do not present a hazard to the orbiter for flights ending at contingency landing sites (i.e., those where ground services such as payload-bay purge or active cooling are not available). Payloads using orbiter-provided heat-rejection provisions must be designed so that they do not present a hazard to the orbiter if heat-rejection capabilities are reduced or lost. Payloads using orbiter-provided electrical energy for thermal control must also not present a hazard in the event of loss of power.

Definition of Ultimate Payload Safety Constraints

Thermal data must be provided to NASA/USA to support contingency planning. Payload temperature limits affecting safety must be identified, and long-term off-nominal exposure to worst hot or cold mission environments must be analyzed to determine how long the payload can tolerate those conditions before the identified safety limits are reached. For deployable payloads, limitations associated with delay in the deployment sequence or restow of erectable spacecraft (if applicable), and delayed deployment must be identified and thermal recovery periods defined.

Additional contingencies may exist as a result of payload-unique characteristics, and these contingencies, as well as those noted above, must be defined and documented in the applicable IP or IP annex. Also, payload operational constraints associated with implementation of payload objectives should be established by conducting appropriate thermal analyses of the payload design.

Safety Assessment Activities

Safety assessments of the mission design and configuration for cargo are conducted in three activities.

- Payloads are assessed for compliance with requirements as specified in NSTS (National Space Transportation System) 1700.7B ("Safety Requirements for Payloads Using the NSTS").
- NSTS cargo-integration hardware is assessed for compliance with requirements as specified in NSTS 5300.4 ("Safety, Reliability, Maintainability, and Quality Provisions for the Space Shuttle Program").
- The plan for an Integrated Cargo Hazard Assessment (ICHA) is presented at the CIR for review and approval. A final report is presented to the Payload Safety Panel and to the Mission Integration Control Board (MICB), and is available prior to the Flight Readiness Review (FRR).

The status of these assessments is presented at the CIR. The final results of these assessments, along with the safety assessments of other NSTS elements, are used to develop an NSTS Mission Safety Assessment (MSA).

The Cargo Integration Review

The engineering-compatibility and safety work should be completed prior to the CIR. This review is a 4-day session held approximately 8.5 months prior to the subject flight. A CIR dry run (CIRD) of the briefings is completed one month prior to the CIR. A data package is then sent to the customer. The first two days of the CIR are devoted to team reviews of the engineering detailed in the package, and identification of discrepancies. The third day is a preboard review of all discrepancies, issues, and recommendations. This review includes Kennedy Space Center, orbiter, and payload-engineering members. The fourth day is a CIR board review of assessment summaries, unresolved discrepancies/issues, and recommendations. The board, chaired by the flight manager of the NSTS program, is responsible for the direction, conduct, and authorization of flight production. The following is a typical fourth-day agenda:

- Introduction
- Flight overview
- Flight planning
- Flight-design assessment
- Crew-activities overview and assessment
- Flight-operations support
- Ground data systems—Mission Control Center/Payload Operations Control Center (MCC/POCC) requirements/implementation
- Systems assessment
- Training
- Ground operations—payload processing
- Engineering-compatibility summary
- Safety (ground and flight)
- Summary/actions

Engineering-compatibility concerns and issues identified at the CIR should be worked and closed at subsequent status meetings, such as Mission Integrated Product Team (IPT) meetings and Payload Operation Working Group (POWG) meetings.

Orbiter Payload-Bay Thermal Environment

The thermal environment in the orbiter payload bay is considerably more diverse, and sometimes considerably more severe, than that on an expendable launch vehicle. The orbiter's tremendous attitude flexibility and multipayload manifesting have a downside for the thermal engineer in that they can expose the payload to a very wide range of environments, unless appropriate attitude restrictions are in place.

Payload-Bay Purge*

The payload-bay purge system supplies conditioned air or gaseous nitrogen (GN_2) to the payload bay during prelaunch operations with payload-bay doors closed, and it supplies conditioned air during the postlanding period at primary and alternate landing sites. The main function of the payload-bay purge system is to render the payload bay inert; the purge produces only limited thermal conditioning. Payloads that require close temperature control and/or large heat-rejection capacity may therefore benefit from the use of optional services, such as spigot cooling with purge gas or active cooling through the payload heat exchanger. The use of optional services, however, may increase the cost and complexity of the payload-integration process.

Purge air is normally provided to the payload bay after the payload-bay doors are closed, except during the following activities.

- mobile ground support equipment (GSE) facility/mobile GSE transfer
- towing of the orbiter
- orbiter mate/demate
- orbiter test- or purge-system line-replaceable-unit replacement or test
- GSE periodic maintenance at the Orbiter Processing Facility (OPF), Vertical Assembly Building (VAB), and pad

The purge gas that is used is conditioned air, except during cryogenic servicing of the orbiter power-reactant storage-and-distribution subsystem and during final launch countdown from just before external tank loading until launch (or through detanking, when necessary). During these periods, temperature-conditioned GN_2 is provided as the purge gas for inerting purposes. All gas used to purge the payload bay, whether air or GN_2, is filtered using high-efficiency particulate air (HEPA) filters (Class 5000). The resulting purge gas contains 15 or fewer parts per million of hydrocarbons based on methane equivalent.

The purge-gas inlet temperature can be set between 7 and 37°C at the pad, nominally controllable to within ±3°C. Under steady flow conditions, a tolerance of ±1.2°C with excursions to ±3°C for one hour over a period of 12 h is negotiable for temperature-sensitive payloads. The standard purge-gas inlet temperature is set

*The remainder of this chapter is derived from NSTS 07700, Volume XIV, Appendix 2, "System Description and Design Data—Thermal," courtesy of NASA.

at 18°C and can vary between 15 and 21°C. Payloads that require other than the standard purge temperature must negotiate a different purge temperature with any other payloads that are manifested on the same flight. Because the temperature control point is on the facility side (upstream of the orbiter T-0 umbilical), gas temperatures within the payload bay may vary from the set point, depending on ambient conditions. Orbiter payload-bay thermal analytical models (which will be discussed later) can predict purge-gas temperatures throughout the bay and account for the resultant influence on the payloads. Additional characteristics of the purge gas (including flow rates) are given in ICD 2-19001.

Payloads sharing a mission require special consideration of flow rate. The purge-gas flow enters the payload bay at the forward bulkhead location (X_0 576) and exits at the aft bulkhead (X_0 1307). Because of leakage through the payload-bay doors and flow to the lower midfuselage (the volume beneath the payload bay) through payload-bay vents, the local flow rate may be less than the inlet flow. Additionally, three spigots are available as an option to provide supplemental flow through special ducting to meet unique payload requirements. For analysis purposes, the supplemental spigot flow is introduced into the payload bay where it exits the using payload. Therefore, the local purge-flow rate may vary considerably for shared missions. Customers whose payloads share a flight must design for both the maximum and minimum flow rates specified in ICD 2-19001 because the location in the payload bay will be determined by NASA.

Payload-bay purge is normally provided at the planned primary and alternate landing sites, starting approximately 45 min after touchdown at the primary site and 90 min after touchdown at the alternate site. Payload-bay purge is provided within 72 h at any landing site. The payload-bay purge may not be used to satisfy payload safety requirements. Payload requirements for special postlanding services are negotiated with NASA and documented in the IP. Emergency-landing-site environmental conditions are documented in ICD 2-19001. Purge at ferry-flight stopover sites can be provided as an optional service.

Payload-Bay Wall Temperatures

During the prelaunch and ascent phases of the mission, when the payload-bay doors are closed, temperatures in the payload bay are relatively moderate. After the orbiter reaches orbit and the payload-bay doors are opened, however, temperatures can vary over a wide range, depending on flight attitudes and the payload/cargo configuration. Representative payload-bay wall temperature ranges for various mission phases are shown in Fig. 18.7. Actual temperatures are expected to fall within the ranges shown; they depend upon payload design, thermal characteristics, and flight conditions.

Significant solar entrapment may occur on orbit when direct solar radiation into the payload bay is present and the gap between the cargo and the payload-bay surface or adjacent payload is small. This phenomenon is illustrated in Fig. 18.8, which shows temperatures from an integrated thermal analysis of the Spacelab module and pallet cargo. Local temperatures can exceed the 93°C maximum reached if the payload bay is empty and can approach 162°C.

Another situation that can result in excessively high temperature is the "greenhouse effect" that can occur when a material that transmits solar energy (such as

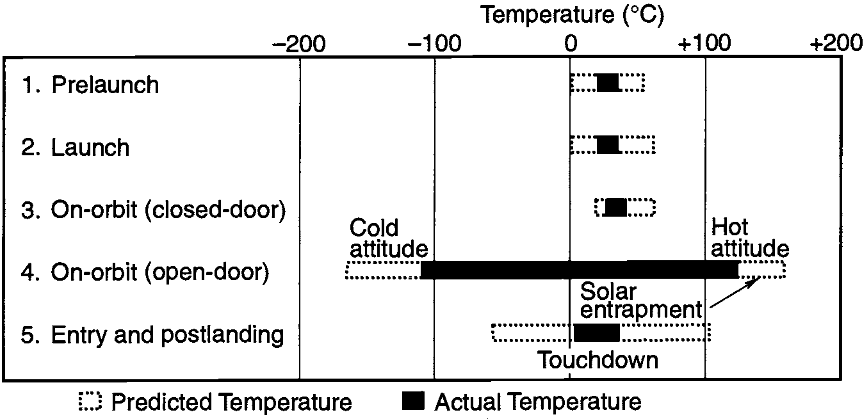


Fig. 18.7. Payload-bay wall temperatures.

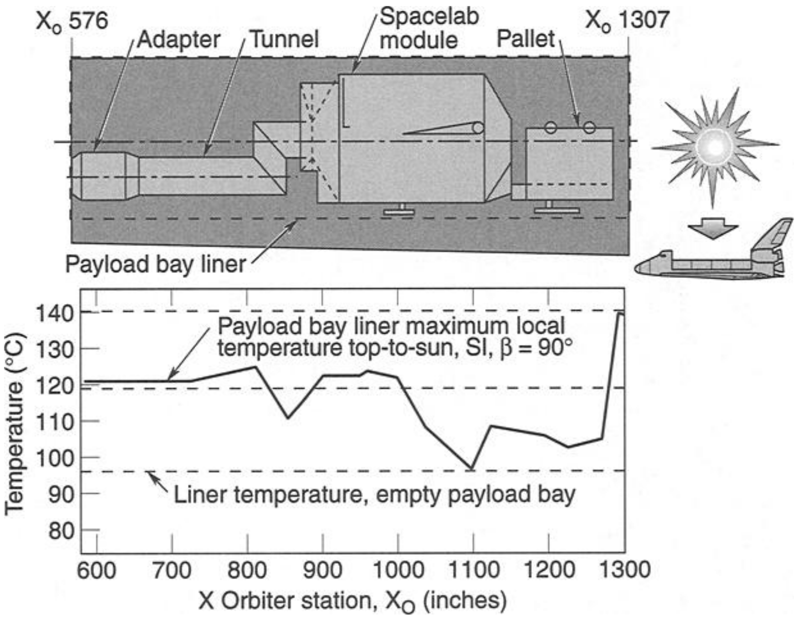


Fig. 18.8. Payload-bay liner temperature with solar entrapment.

Beta cloth) is used on the payload surface and is exposed to direct solar radiation. The portion of solar energy transmitted through the material becomes trapped under it, thereby creating relatively high temperatures on surfaces immediately below the material.

The payload-bay wall temperature ranges given in Fig. 18.7 can be used to estimate the thermal environment for use in initial payload thermal design. Table 18.1

Table 18.1. Steady-State Liner Temperature for Preliminary Design

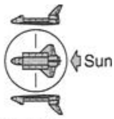
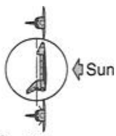
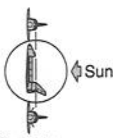
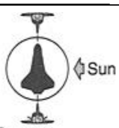
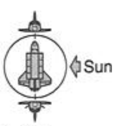
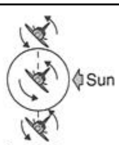
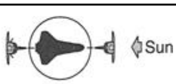
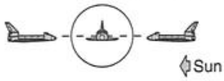
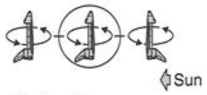
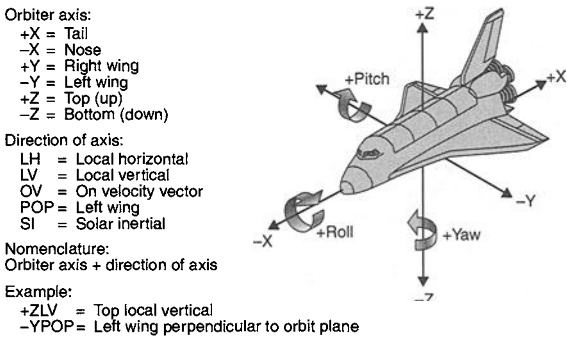
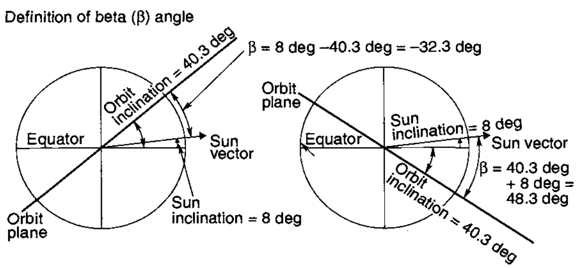
Case Description	Empty Payload Bay Liner Temperature (°C)		Cylindrical Payload Liner Temperature (°C)	
	Maximum	Minimum	Maximum	Minimum
 −ZLV, XPOP, $\beta = 90°$	−107	−131	−43	−87
 +ZLV, XPOP, $\beta = 90°$	−15	−23	−14	−32
 −YLV, −XOV, $\beta = 90°$	−70	−81	−7	−32
 +YLV, −XOV, $\beta = 90°$	94	57	162	101
 +ZLV, −XOV, $\beta = 90°$	−14	−23	41	−5
 −ZLV, −XOV, $\beta = 90°$	−102	−129	−18	−70
 PTC (4 rev/h), $\beta = 90°$	—	−9	—	24
	For this case, liner temperature is for information only; orbiter temperature limits are exceeded under steady state conditions			
 +ZLV, −XOV, $\beta = 0°$	4	−1	16	4

Table 18.1. Steady-State Liner Temperature for Preliminary Design—*Continued*

Case Description	Empty Payload Bay Liner Temperature (°C)		Cylindrical Payload Liner Temperature (°C)	
	Maximum	Minimum	Maximum	Minimum
 –XLV, +YOV, β = 0°	–18	–23	–11	–21
 PTC (4 rev/h), β = 0°	—	–15	—	16





(a) Maximum negative β angle condition for a given orbit plane (ascending/descending nodes perpendicular to the sun vector.)

b) Maximum positive β angle condition for a given orbit plane (ascending/descending nodes perpendicular to the sun vector.)

provides additional analytical predictions of steady-state liner temperatures for specific flight attitudes and beta angles when the payload-bay doors are open. The influence that a large payload has on payload-bay liner temperatures can be seen in the table data. Empty payload-bay liner temperatures can be used for the thermal design of payloads with diameters up to 230 cm if the payload centerline coincides with the longitudinal axis of the payload bay. For payload diameters between 230 and 305 cm, liner temperatures can be estimated by interpolating between the empty payload-bay temperature and the temperature of the bay when it contains a cylindrical payload.

During entry and postlanding phases, the thermal environment is influenced by the initial pre-entry condition, entry heating and subsequent heat conduction inward, ground purge (if any), and weather conditions at the landing site. Generally, the maximum temperature is reached after landing as a result of heat soakback through the orbiter structure and air entering the payload bay through the vent doors.

Orbiter Attitude-Hold Capabilities

The maximum time that the orbiter can remain in a given attitude has been established, based on analyses, tests, and actual flight experience. The attitude-hold times (documented in ICD 2-19001) vary from 5 to 160 h, depending on the beta angle and the payload-bay orientation. These attitude-hold times are representative of orbiter maximum capability and are applicable to most payload missions.

The orbiter pre-entry thermal-conditioning attitude and duration are established during the mission and are based upon real-time temperature measurements. The thermal-conditioning duration may range from 0 to 12 h. For normal entry, the pre-entry thermal-conditioning attitude and duration are selected to be compatible with both orbiter and payload operational or refurbishment temperature limits. If mutually compatible requirements cannot be established, pre-entry conditioning will be accomplished by PTC.

In the event of an anomaly, NASA will observe the payload operational attitude constraints to the extent possible. If these constraints must be violated, payload safety constraints will be observed. Payload flight-safety constraints and operational or refurbishment attitude-hold constraints are established by the customer and documented in the payload-unique IP and IP annexes.

Payload-Bay Floodlights

Payload surfaces or elements that may be located near one or more payload-bay floodlights should be analyzed to determine if the heat flux from floodlight operation could cause overheating. If a temperature violation could occur and a suitable redesign is not feasible or practical, a floodlight operational constraint should be specified in the payload-unique IP and analysis results supplied to NASA/USA for evaluation and planning. Because floodlights can fail on, the payload must also be designed so as not to present a safety hazard if that should occur. The payload should not, however, be designed to utilize payload-bay floodlights for thermal control.To conduct a floodlight analysis, the engineer should use the payload-bay floodlight locations and thermal characteristics given in ICD 2-19001. In special situations that require a more detailed analysis, NASA/USA can provide a floodlight thermal math model (TMM).

Reflected Solar Energy

Cargo elements that extend above the payload-bay door-hinge line or that are deployed transversely over the orbiter radiators may be exposed to reflected solar radiation from the orbiter radiators. The radiators have moderately specular reflective surfaces.

The magnitude of the local fluxes and thermal effect is a function of cargo location, orbiter orientation relative to the sun, and duration of the exposure. In most cases, except for solar inertial attitude, if solar radiation is reflected onto a payload in the bay, the exposure is a brief, nearly instantaneous one resulting from the continuously changing solar angle. For payloads located in the bay, these reflected solar loads can only occur when the forward radiators are deployed, as shown in Fig. 18.9. (Normally, the forward radiators are not deployed unless maximum heat rejection is required.) For payloads that deploy from the bay, reflections from either stowed or deployed radiators are possible, unless attitude restrictions are specified by the customer. Reflection of solar energy from the radiators during payload-bay door opening is precluded by opening the doors with the payload bay facing Earth (+ZLV).

NASA and other organizations have conducted analytical studies of the solar focusing phenomenon from orbiter radiator panels. Solar ray tracing (plotting the path of light rays as they are reflected off surfaces) for various solar angles and radiator-panel geometries has been developed. Figure 18.10 illustrates ray tracing for various solar angles for a deployed forward radiator.

Air Inlet During Orbiter Re-entry

The temperature and mass flow rate of the air entering the payload bay during entry, and the resulting bay pressure (given in ICD 2-19001), are the maximum or worst conditions that occur at or near the payload-bay vents (Fig. 18.11). Thermally sensitive payload surfaces that may be located near a vent should be analyzed to determine the impact of exposure to hot entry air after the vent doors are opened. As given in the ICD, the entry-air temperature declines rapidly from approximately 205°C at vent-door opening (low-density air) to 38°C approximately 60 sec later. As the distance from a vent increases, the effect of entry air on a payload surface decreases rapidly.

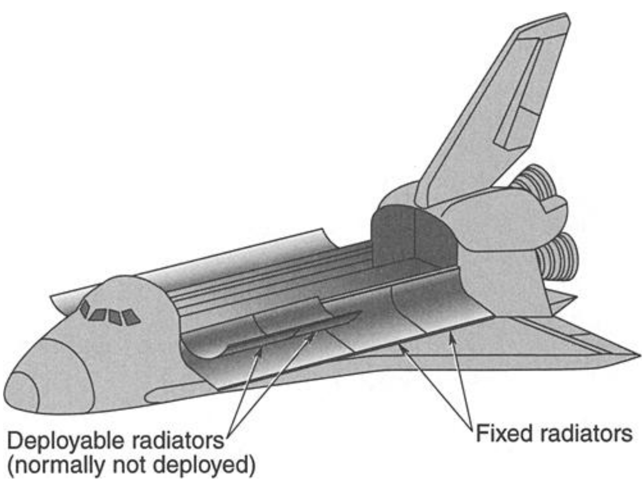


Fig. 18.9. Orbiter radiator configuration during on-orbit operations.

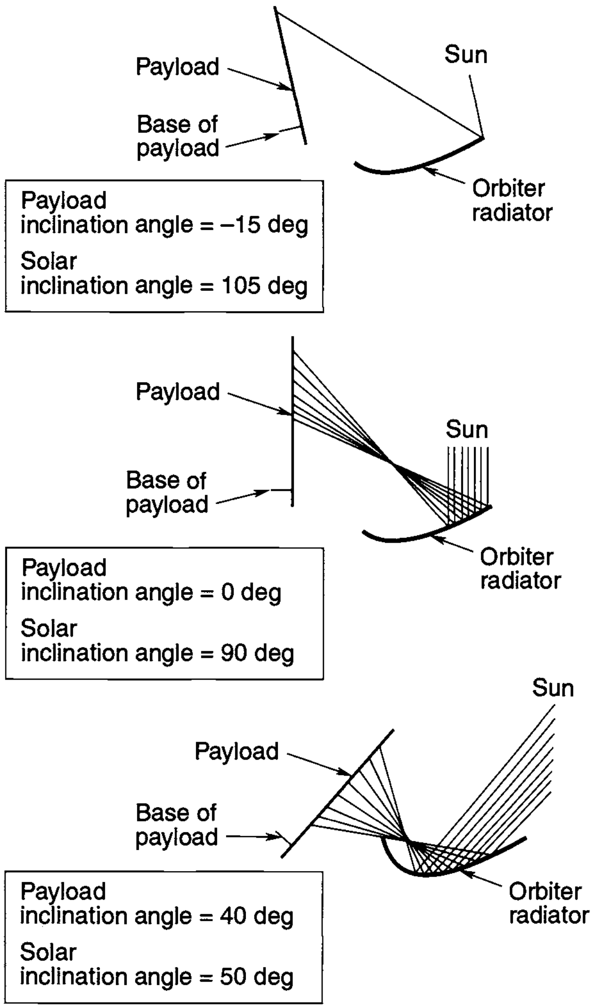


Fig. 18.10. Reflected solar-energy ray tracing from deployed orbiter radiator.

Normally, payload-bay vent doors are closed at the start of entry and do not open until after peak aerodynamic heating has occurred. However, customers must conduct thermal assessments to confirm that no safety hazards arise in either the payload or in its integration hardware if one or more vent doors fail in the open position and remain open during re-entry. The methodology for performing these assessments is presented in ICD 2-19001.

Integrated Thermal-Analysis Considerations

The payload thermal design and integration process must include an integrated payload/orbiter thermal analysis to ensure that the payload design meets expected

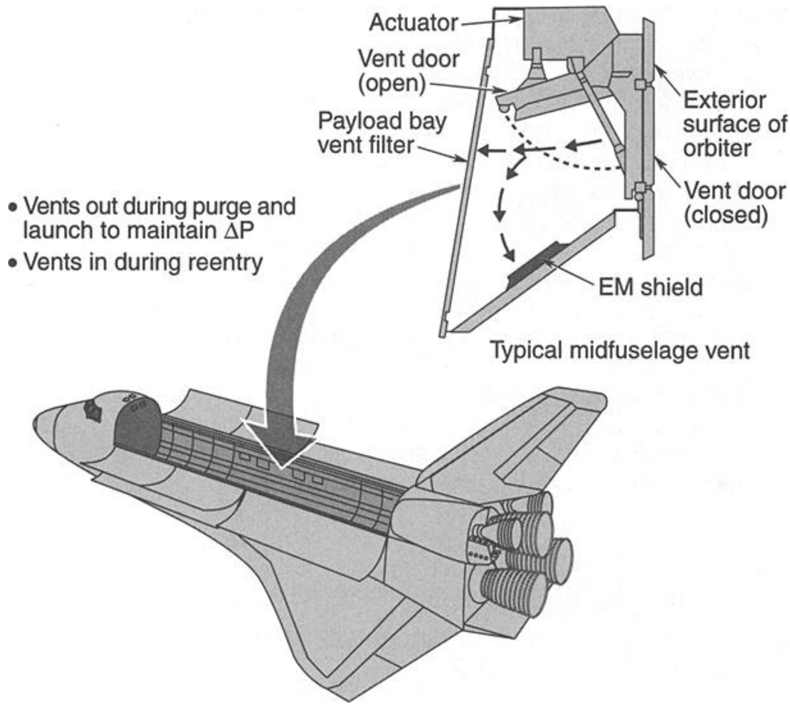


Fig. 18.11. Payload-bay vent ports.

mission objectives and to define payload-unique thermal requirements for inputs to the IP and ICD. Integrated thermal analysis can be an iterative process in which the initial effort is directed toward defining the payload thermal design and subsequent analyses, conducted after the payload design has matured, are directed toward establishing payload-unique requirements, particularly in orbit.

An integrated analysis may consist of several separate analyses, depending on the thermal interfaces involved with the particular payload. The following separate analyses should be performed:

- payload/orbiter analysis for payloads and Airborne Support Equipment (ASE) located in the payload bay
- payload-bay floodlight analysis for payloads in the payload bay (including failed-on floodlight analyses)
- failed payload-bay vent-door analysis
- heat-rejection analysis for payloads utilizing the payload heat exchanger
- heat-rejection analysis for payloads utilizing the spigot system
- ferry-flight analysis for payloads and ASE located in the payload bay, middeck, or aft flight deck
- payload/grapple fixture/end effector analysis for payloads utilizing the remote manipulator system (RMS). Grapple fixture thermal data are given in System Description and Design Data—Payload Deployment and Retrieval System, NSTS 07700, Volume XIV, Appendix 8.

The integrated thermal analysis for a payload and ASE, in the payload bay or deployed from the payload bay, is relatively complex. The process requires use of suitable payload and orbiter math models, development of relatively large integrated math models (with several hundred to thousands of nodes), and use of computer programs capable of analyzing them.

A flowchart of the integrated analysis task is presented in Fig. 18.12. Analysis cases should consist of the worst hot, worst cold, and design or nominal conditions. Design timelines for these conditions must be defined. The orbiter thermal and geometric math models to be used in the integrated analysis are available from NASA, as are the industry-standard thermal-analysis codes SINDA and TRASYS (see Chapter 15).

Generally, integrated TMMs (ITMMs) and analysis cases are tailored specifically for the payload, its mission conditions, and the objective of the analysis. For example, if the integrated analysis is performed primarily in support of payload thermal design, a detailed payload thermal model would be used in conjunction with the simplest models to represent the orbiter and adjoining payloads in the payload bay. These and other considerations that minimize the cost of integrated thermal analysis are discussed in subsequent sections.

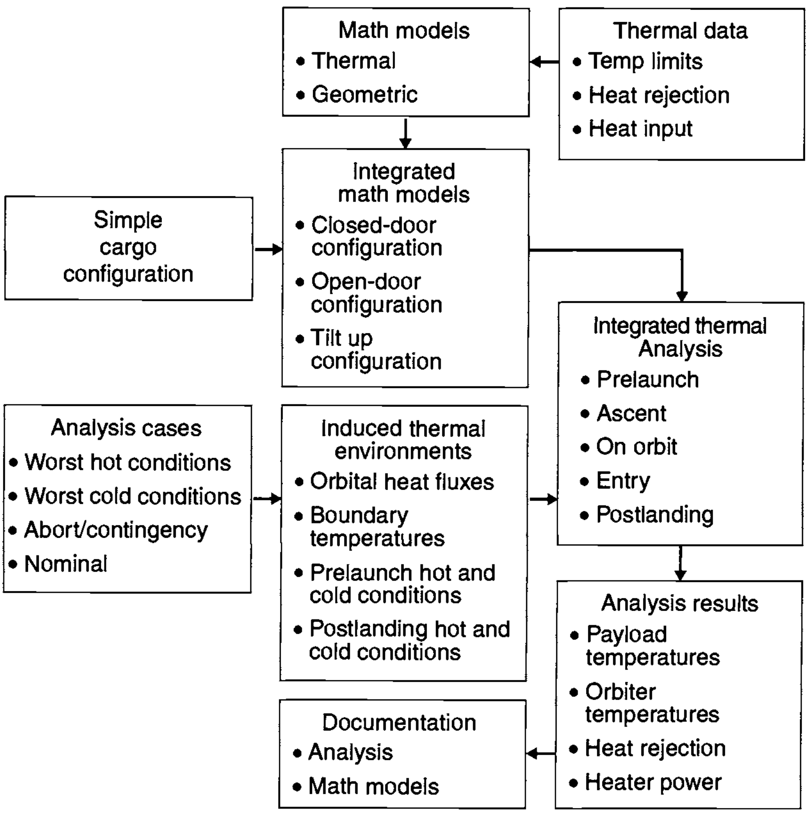


Fig. 18.12. Payload/orbiter integrated thermal-analysis flow diagram.

On-Orbit Attitudes and Constraints

The orbiter's attitude/duration constraints are identified in ICD 2-19001. Similar constraints for the payload must be determined by integrated analysis and documented in the payload-unique ICD. Worst hot and cold mission attitudes must be considered along with planned operational and nonoperational attitudes for all payloads. The standard worst hot and cold mission attitudes, +ZSI (bay toward the sun, inertial) and +XSI (tail toward the sun, inertial), are most often treated as limited-duration excursions from the nominal flight attitudes. Generally, the shortest time required to exceed the operating and nonoperating temperature limits of critical payload components in these worst-case attitudes is used to define constraints for the payload-unique ICD. Of course, if these constraints violate orbiter operational requirements, the needs of the orbiter prevail.

Some attitudes may be hotter or colder than the standard "worst" cases. These are the +X sun orbital rate (tail to sun, one revolution per orbit about the x-axis), which keeps the payload bay always facing deep space with little or no view toward Earth, or other specific attitudes that may represent extreme conditions resulting from special circumstances such as shadowing or reflection of sunlight, and unusual payload geometry or physical properties.In addition, the orbit beta angle influences the thermal severity of these and other attitudes. Identifying the true worst-case attitudes for a particular payload can require some analysis on the part of the thermal engineer.

In addition to the time required to exceed a temperature limit, the time to recover from a limiting temperature to a nominal condition (e.g., to +ZLV, payload bay facing Earth) is also of interest. This time establishes the waiting period before commencing another hot or cold attitude excursion. Depending on whether a hot or cold extreme has been reached, the recovery attitude is generally +ZLV, PTC, +XSI, or +ZSI. The designation PTC (passive thermal control) is assumed for analysis purposes to be rotation of the orbiter about its x-axis at two to five revolutions per hour with the x-axis within 20 deg of perpendicular to the sun vector. This type of rotation is sometimes called the barbecue mode.

The orbiter attitudes referred to above are depicted in Fig. 18.13. Note that other orbiter orientations could also satisfy these attitude designations. The direction of at least one other orbiter axis is needed to uniquely define the attitudes shown.

Prelaunch, Ascent, Entry, and Postlanding Mission Phases

These mission phases are of particular interest for AOA and contingency-landing-site conditions, and for cryogenic and high-heat-generating payload components, for which thermal compatibility with the closed-door orbiter must be determined. Launch and landing sites, time of year, time of day, and orbiter payload bay, purge-gas parameters and availability are variables that must be considered. Environmental and orbiter parameters required for analysis of these mission phases can be found in ICD 2-19001.

Analysis Approach

A typical approach to integrated thermal analysis is shown in Tables 18.2 and 18.3 for hot and cold cases, respectively. Figures 18.14 and 18.15 show sample hot- and

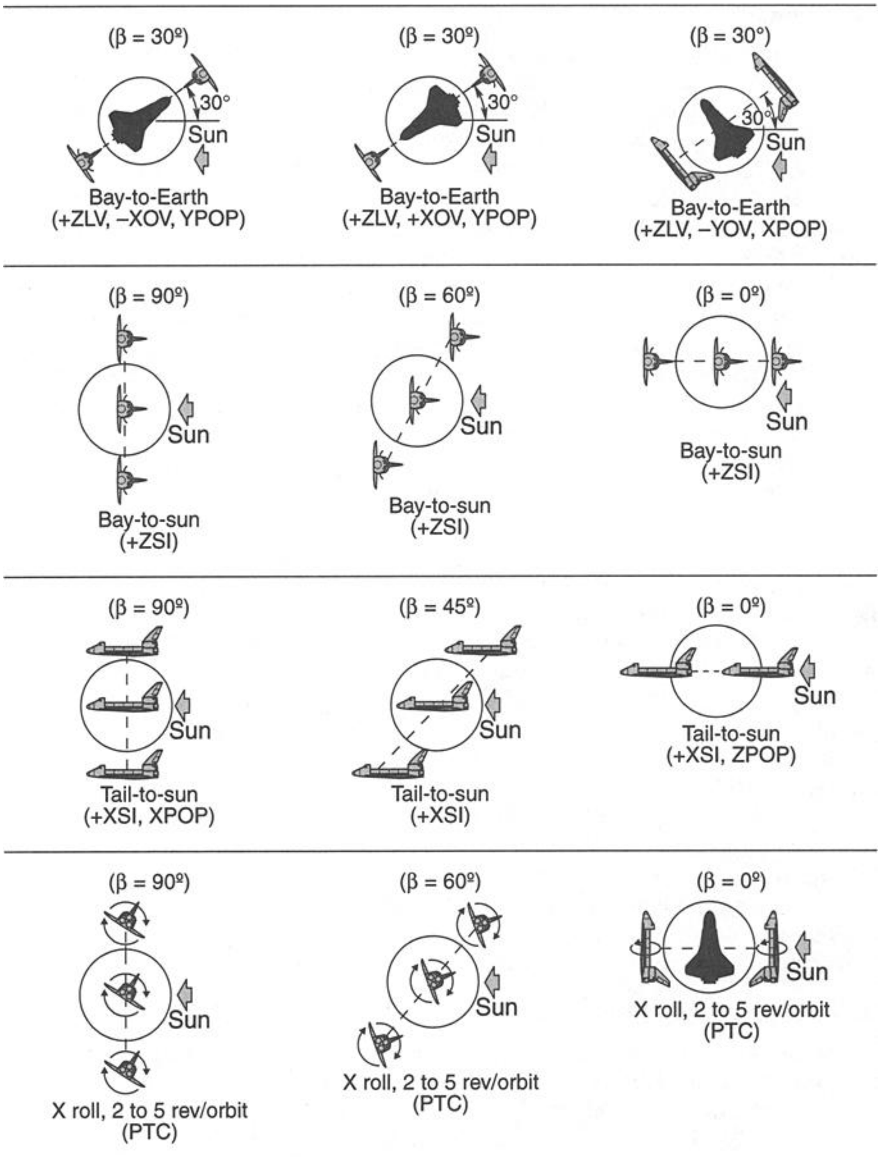


Fig. 18.13. Some standard orbiter attitudes.

Table 18.2. Typical Integrated Thermal Analysis Approach (Cold Case)

Analysis Task	Notes
Perform cold excursion/recovery analysis to satisfy IP TBDs	• Both SV/ASE and ASE alone (if required) • Use cold-biased mission timeline and environments to generate initial conditions
Perform cold entry/postlanding analysis to determine allowable exposure time to cold postlanding environment	• Both SV/ASE and ASE alone (if required) • Use coldest point in timeline for initial conditions • Assume no purge at landing site and continue analysis until cyclic steady state is reached • Cold safety limits eventually will be exceeded • Ground power or warm purge air is required • Establish length of time prior to power/warm air need

Table 18.3. Typical Integrated Thermal Analysis Approach (Hot Case)

Analysis Task	Notes
Perform hot excursion/recovery analysis to satisfy IP TBDs	• Both space vehicle (SV)/ASE and ASE alone • Use hot-biased mission timeline and environments to generate initial conditions
Perform hot entry/postlanding analysis to determine temperature rise for each component	• Both SV/ASE and ASE alone (if required) • Use hottest point in timeline for initial conditions • Assume no purge at landing site and continue analysis until all temperatures begin decreasing
Determine allowable excursion times prior to entry	• Both SV/ASE and ASE alone (if required) • Use temperature changes generated from excursion temperature curves to determine allowable times • Determine minimum allowable time for each excursion attitude
Run entry/postlanding to verify minimum allowable times	
Refurbishment limits can be similarly established	

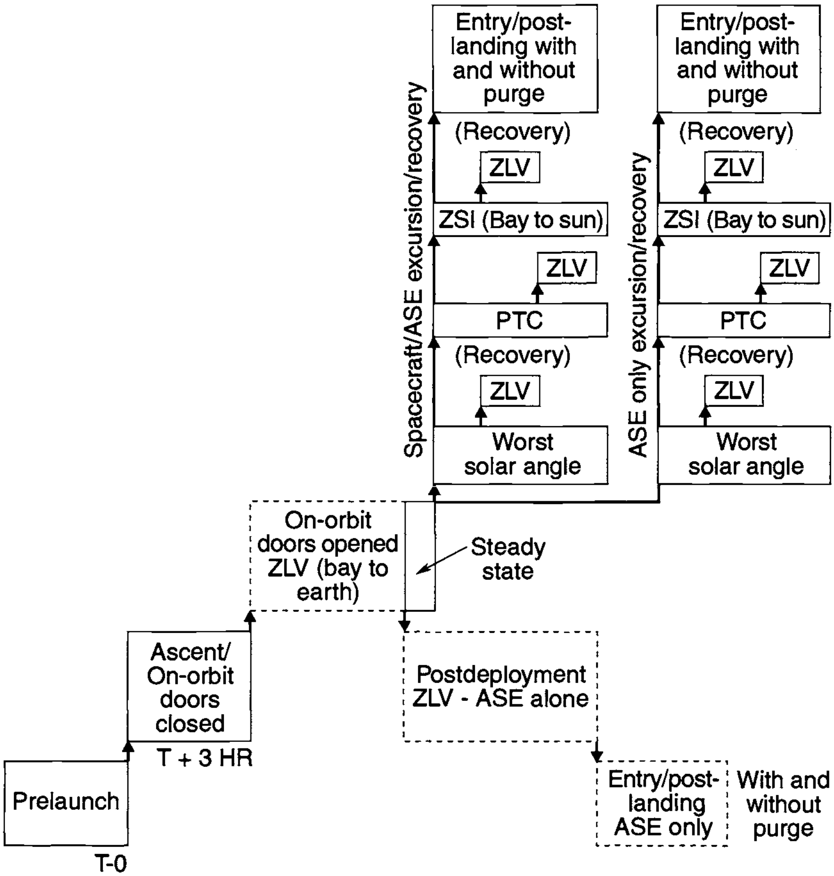


Fig. 18.14. Typical hot-case thermal design timeline.

cold-case timelines, and Figs. 18.16 and 18.17 illustrate temperature plots that can be used to determine on-orbit attitude hold and recovery times, attitude hold times prior to entry, times to reach entry/postlanding temperature extremes, and refurbishment times. Sample actual analysis timelines used for determining attitude thermal constraints and verifying mission thermal compatibility of a specific payload are presented in Fig. 18.18 for the hot condition, Fig. 18.19 for the cold condition, and Fig. 18.20 for the ASE-only configuration.

Payload TMMs

Among the first details a thermal analyst considers in preparing a payload TMM are those associated with its eventual inclusion in an orbiter TMM. An analysis with the resulting ITMM is required to confirm thermal compatibility of the payload with the orbiter and with its mission environment.

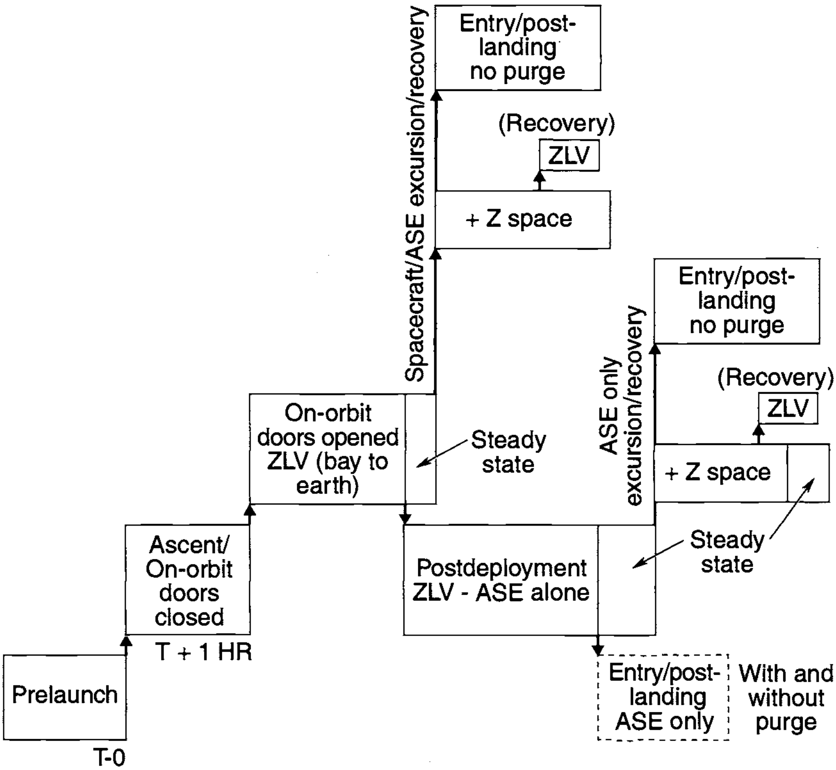


Fig. 18.15. Typical cold-case thermal design timeline.

Specific payload TMM criteria and guidelines have been established (Criteria/ Guidelines for Payload Thermal Math Models for Integration Analysis, JSC 14686) to assist the thermal analyst in TMM preparation. These criteria and guidelines ensure consistency of the TMM and supporting data, and adequacy of the TMM for economic and reliable analysis and compatibility with NASA standard services. Among these requirements are payload TMM size restrictions (i.e., number of nodes, conductors, external surfaces), minimum allowable stable-calculation time interval, payload/orbiter interface considerations, and adequate documentation.

A complementary payload geometric math model (GMM) is required for each TMM for combining with an orbiter GMM to produce an integrated GMM (IGMM) for use in calculating radiation interchange factors and orbital heat rates for external surfaces. Payload math-model documentation should be referenced in the payload-unique ICD.

Orbiter TMMs

Several orbiter-midsection/payload-bay TMMs are available for integrated thermal analyses and are authorized in the appropriate IDD or ICD. In Table 18.4 these are listed in order of decreasing detail, and major differences are noted.

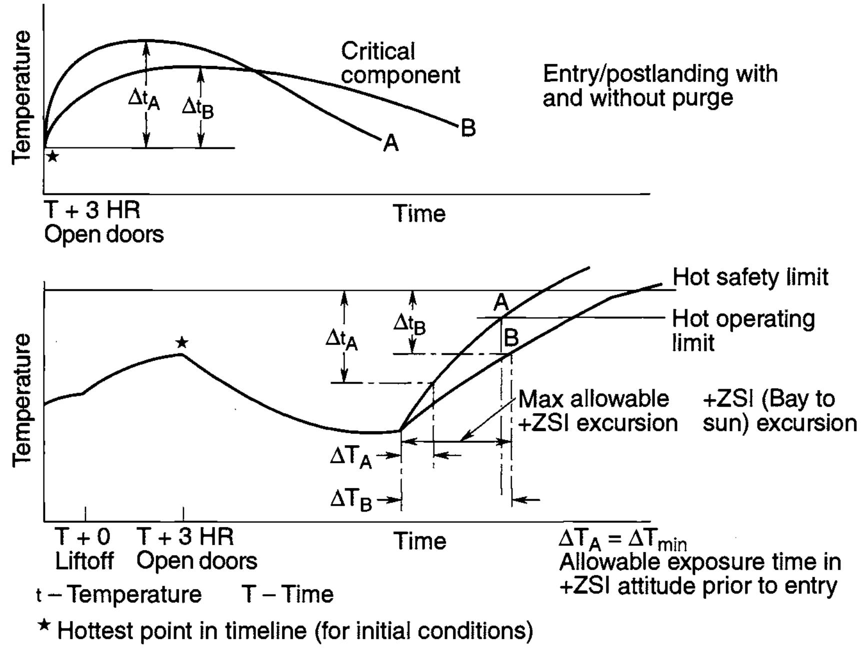


Fig. 18.16. Hot-case temperature profiles for determining safety and operating limits.

Table 18.4. Available Orbiter TMMs

Orbiter TMM Nodes	Modeling of Payload-Bay Liner and Outward through Orbiter	Wire Trays, Frames, and Aft Fuselage	External Orbiter Heat Loads and Radiation Interchange	References
390	Detailed	Included	Directly applied	ES3-76-1, ES3-77-3
136	Less detailed	May be added	Directly applied	ES3-76-7, ES3-77-1

Each orbiter TMM is constructed in a manner that allows for renodalization of its payload-bay liner and wire-tray nodes (or zones) to provide additional and/or better distribution of nodes to attain the desired degree of accuracy for both the liner/wire trays and an included payload TMM. Renodalization of the payload-bay liner should be considered when the sun's rays may shine directly into the payload bay parallel to the orbiter z-axis. (This process is discussed in more detail later.) The TMM references also describe how to add the optional payload-retention fittings and Remote Manipulator System (RMS).

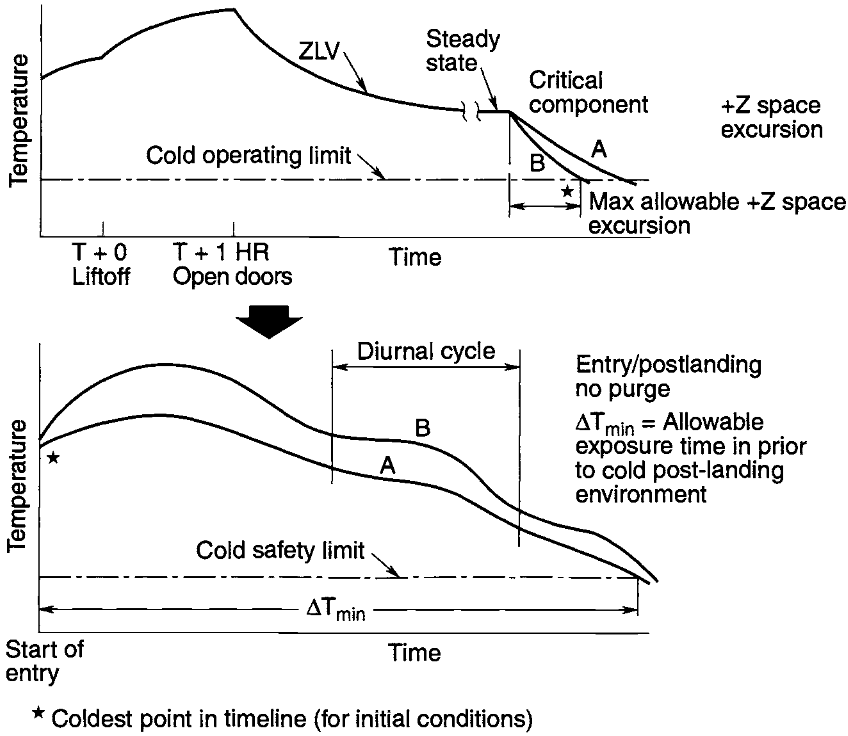


Fig. 18.17. Cold-case temperature profiles for determining safety and operating limits.

Input data for constant and diurnal prelaunch and postlanding environments, consisting of ambient air and surrounding boundary temperatures and solar heat rates for different conditions at the eastern test range (ETR), are included in the closed-door TMM documents, "390 Node" Atmospheric Orbiter Midsection/Payload Bay Thermal Math Model Description, ES3-77-3, ES3-76-7, and ES3-77-1.

Although simpler orbiter models may suffice for most applications, one should understand the capabilities and limitations of ES3-76-7 and ES3-77-1 before using them.

ITMMs

To keep analysis cost down, the size (number of nodes) of the ITMMs should be as small as practical and governed by the required accuracy of the results. Thus the ITMMs or models used primarily in support of payload design consist of a detailed payload TMM and the simplest orbiter-interface math model. The objective is to obtain accurate thermal results for the payload.

As the payload design matures, payload math models are finalized with emphasis on obtaining accurate temperatures at the payload and orbiter interfaces, so a more detailed orbiter-interface math model is needed, particularly in the payload bay.

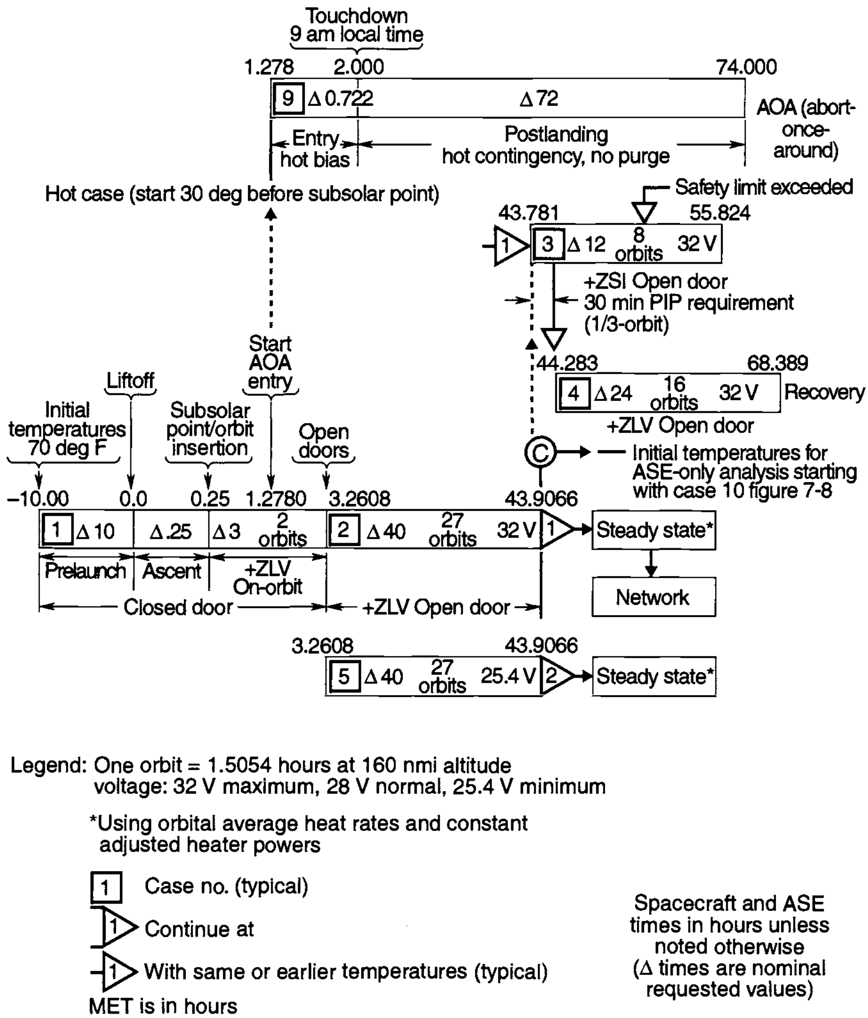


Fig. 18.18. Sample hot-case timeline for a specific payload.

To keep the overall integrated-model size within reasonable range and cost to run, the size of the payload math model may be reduced. The number of surface nodes has the maximum effect on the computer run time.

Generally, payload math-model simplification should aim to reduce the number of nodes "buried" within the payload or its components, because those nodes will have a small effect on the payload surfaces that constitute the interface with the orbiter. For example, a payload component that is covered with high-performance insulation could be represented by a single "lumped" node rather than several nodes, unless this element or component is sensitive to surface temperature or has

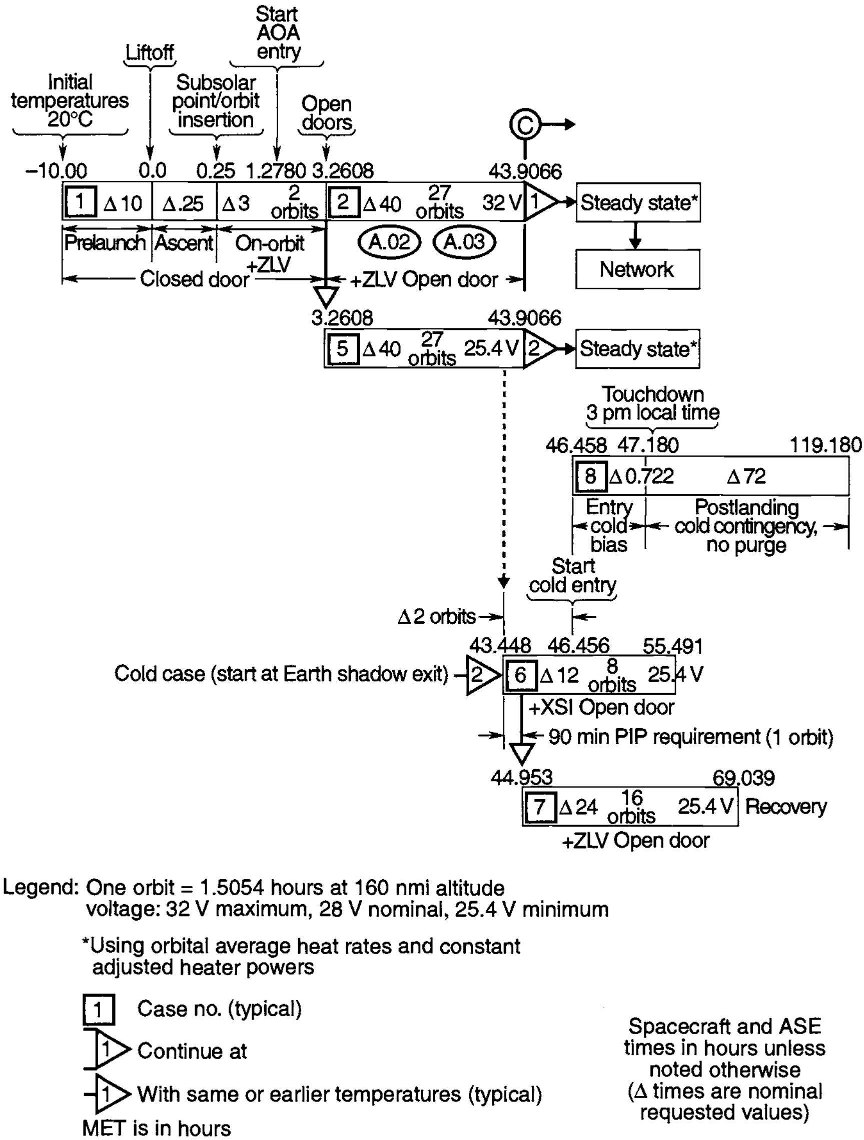


Fig. 18.19. Sample cold-case timeline for a specific payload.

a relatively strong influence on the surface temperature. The simplified payload TMM should be checked by comparing the temperature results with those derived from the detailed or original model to ensure that the payload surface temperatures, i.e., the interface temperatures, are in agreement.

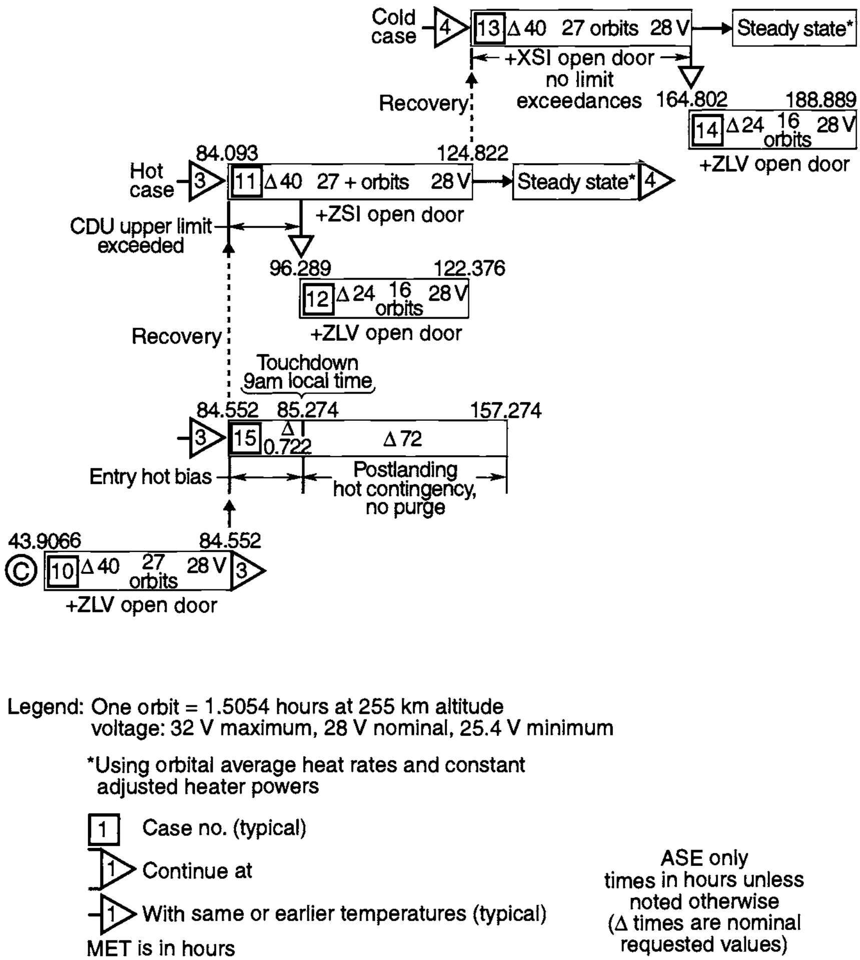


Fig. 18.20. Sample timeline for ASE only.

Node and Conductor Identification Numbers

When adding a payload TMM to an orbiter TMM, do not assign duplicate node and conductor identification numbers. The preferred method is to use 5-digit node numbers greater than 20,000 and 6-digit conductor numbers when a payload TMM is first constructed. The payload GMM node or surface numbers should be treated similarly.

Convective Heat Transfer

When convection simulation is required, the orbiter TMM external surface convection code, which is built into the 390-node closed-door TMM (ES3-77-3), may be readily adapted to apply to the payload TMM external surfaces by making the associated payload conductors adhere to the format and placement in the model of orbiter TMM convection conductors. Convection effects should be included in conductors across single-layer insulation blankets and multilayer insulation (MLI). For best results, these conductors should vary with pressure and temperature for ascent and entry mission phases. ES3-77-3 contains additional information regarding convection.

Other Effects

As noted, solar entrapment can present special problems. In a +ZSI (bay-to-sun inertial) attitude, the sun's rays are parallel to the orbiter z-axis. In this attitude, direct or reflected solar energy may make orbiter payload-bay bulkhead and payload surfaces significantly hotter than anticipated in local areas where the view factor to space is small. This solar entrapment can occur on payload surfaces that face the payload-bay liner and have no direct view of the sun. If a few relatively large payload-bay liner nodes are used in the analyses, this effect may not be discernible, especially if the payload shadow outline crosses a liner node. Therefore, to provide the needed accuracy, the payload-bay liner in the vicinity of the payload should be renodalized to more accurately simulate the trapping of local energy and the resulting temperatures.

Other nearby payloads can also cause solar entrapment by reducing the view factor to space. In determining payload-attitude thermal constraints, modeling this adjacent payload with a simulated blocking surface may suffice. For example, a large-diameter, insulated, adjacent payload can be simulated by employing two zero-capacitance back-to-back disks (or geometric shapes representing the projection of the adjacent payload on the orbiter y-z plane) located at the end of the adjacent payload nearest the payload of interest. A mission-verification integrated analysis, on the other hand, may require detailed modeling of both (all) payloads.

Middeck Payload Accommodations

Accommodations for payloads located in the orbiter middeck are provided by use of either standard orbiter lockers or adapter plates mounted to standard locker attachment provisions. Shuttle/Payload Interface Definition Document for Middeck Accommodations, NSTS 21000-IDD-MDK, specifies the standard thermal interfaces for middeck payloads. Standard middeck payloads are passively cooled; i.e., no active liquid or air cooling is provided as a standard service, although active cooling can be provided as a optional service. Payloads that generate waste heat and cannot reject it to the cabin air (using a fan or similar means) are limited to a continuous heat load of 60 W. Cooling requirements above this level must be negotiated with NASA. Figure 18.21 shows an overview of the middeck area and stowage locker locations. Figures 18.22 and 18.23 show an experiment apparatus container (EAC) payload and available mounting locations, while Fig. 18.24 depicts a fan-cooled payload. Inlet and outlet filtration are recommended if fans are used.

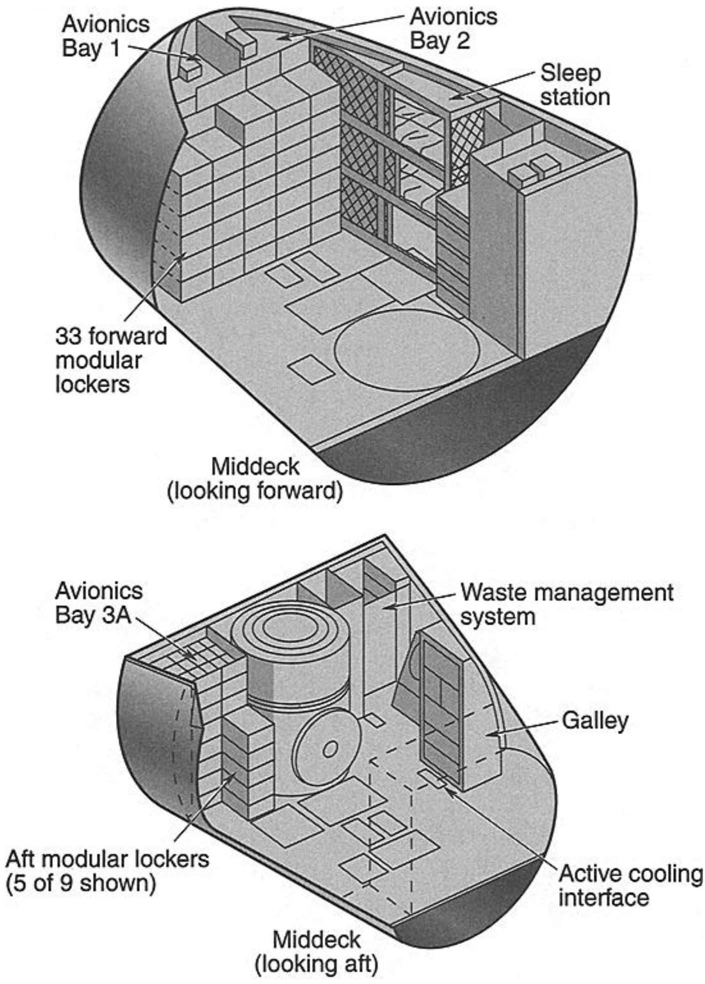


Fig. 18.21. Middeck stowage lockers

Maximum Temperature Limit

Middeck payloads should be designed so that external surface temperatures do not exceed 48°C. If the payload design incorporates a fan for enhanced heat rejection, the air outlet temperature should not exceed 48°C.

Middeck Environment

Heat generated by the payload is primarily rejected to the middeck air by means of convection resulting from the air movement in the middeck, or by enhanced forced-air convection from the use of an internal fan. During a nominal mission without any planned EVA, the cabin air temperature and pressure are at approximately 25°C and 10.1 N/cm^2. For missions with planned EVA, the cabin pressure

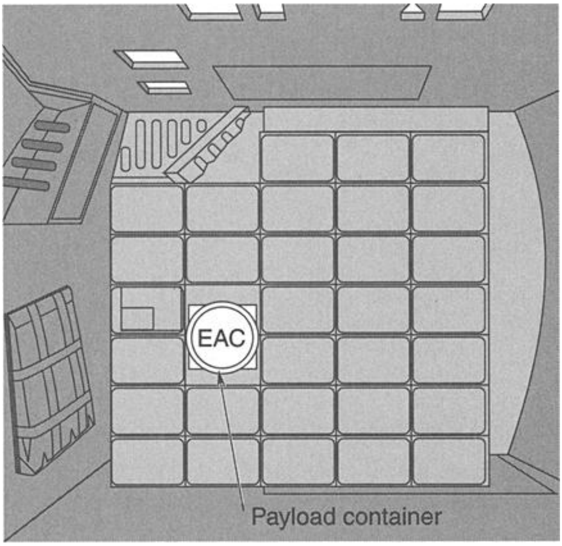


Fig. 18.22. Experiment apparatus container payload.

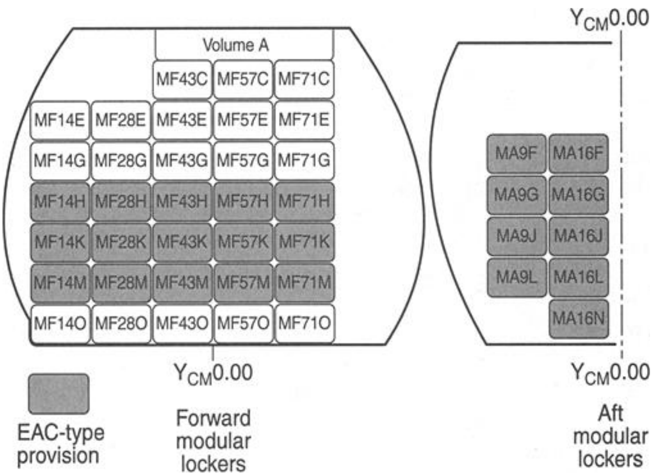


Fig. 18.23. Middeck locker locations for EAC-type provisions.

is normally reduced to 7.0 N/cm^2 during the EVA and EVA prebreathe periods. In both cases, the heat-removal capability is low because air flow in the middeck locker area is minimal. The natural heat-convection coefficient is normally low, approximately 1.4 W/m^{2}C for 10.1 N/cm^2 cabin pressure and 0.97 W/m^{2}C for a

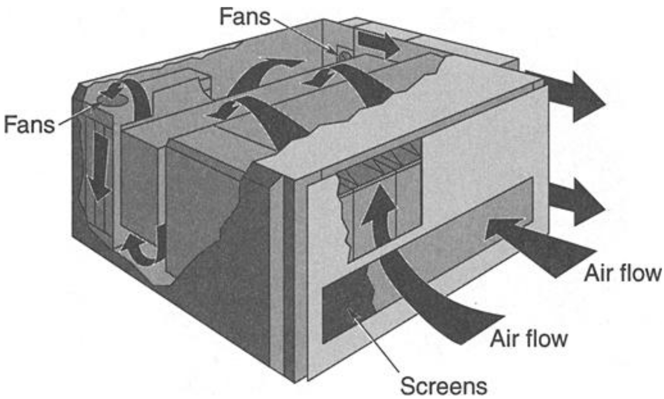


Fig. 18.24. Typical payload with internal fans.

7.0 N/cm^2 cabin. Additional heat generated by the payload is rejected by conduction and radiation to the adjacent structure, such as the avionics closeout panels and surrounding lockers. The maximum structure temperature is 48°C, as defined in NSTS 21000-IDD-MDK. However, it is normally lower, approximately 26 to 33°C, provided no heat generation is in the adjacent locker.

Thermal Analysis of Middeck Lockers

NASA performed a parametric study of middeck lockers for various heat loads, payload locations, and single and multiple lockers. Air temperature of 26°C in the cabin and avionics bays 1, 2, and 3 was assumed. The following general observations could be made:

- No single 60-W source will cause any exposed surface of any locker to exceed the 48°C limit.
- Within the range of heat sources of 30 to 60 W, the temperature increase in the surrounding lockers is proportional to the source power. For example, if 60 W heats an area to 32°C (6°C above cabin), then a 30-W source will heat the same area to 29°C (3°C above cabin).

Thermal-Analysis Requirements

Each payload should be analyzed by the payload designer to ensure that adequate cooling is provided. The analysis must consider the worst-case environment (defined in NSTS 21000-IDD-MDK). Where warranted, NASA/USA performs an integrated analysis based on a specific flight manifest. The manifest may include a combination of certain middeck payloads, not necessarily one single payload. The purpose of the integrated analysis is to determine if any external surfaces of the lockers or the payload containers exceed the touch temperature limit of 48°C and to ensure that adjacent lockers and equipment do not exceed temperature limits.

Ferry-Flight Accommodations

Usually when a shuttle flight ends at Edwards Air Force Base (EAFB) in California, the payload (cargo) remains aboard the orbiter, which is flown or ferried on the shuttle carrier aircraft (SCA) from EAFB to the launch site in Florida. Payloads and ASE should be designed to be compatible with ferry-flight thermal environments.

During ferry-flight operations, payloads within the payload bay are exposed to ambient conditions that are not controlled or monitored. Payloads normally are not powered, heated, or cooled. Customers should specify any unique requirements in the IP, Annex 8, and the Operations and Maintenance Requirements and Specifications Document (OMRSD).

Flight Phase Thermal Environment

The maximum duration of any ferry-flight segment is limited to approximately 4 h, during which time the payload-bay environment is not controlled. According to measurements recorded during several ferry flights, the temperature in the payload bay could range from about 1 to 30°C. Although the payload-bay thermal environment is not controlled during ferry flight, the payload temperature range may be biased at takeoff, as an optional service, within a reasonable range by conditioned air supplied to the orbiter payload bay via the orbiter purge system while the orbiter and SCA are on the ground.

Ground Phase Thermal Environment

The interval on the ground at selected Air Force bases or NASA facilities varies from a few hours to 24 or more hours, and the payload-bay temperature may vary from about –12 to about +52°C as the result of diurnal and seasonal variations. During stops en route, conditioned air can be made available to the payload in the payload bay. If a payload requires conditioned air, the requirement must be specified in the IP, Annex 8, and in the OMRSD. The specific temperature range and flow rate are negotiated with NASA. When determining conditioned-air requirements, the customer should consider possible payload and payload-bay temperatures at touchdown, minimum duration of the ground service available between flights, and the influence of the ground environment and the payload-bay surface temperatures.

Payloads with Active Cooling Systems

For payloads that utilize water cooling, the water must be prevented from freezing in the cooling system during the ferry flight by employing a ground purge to precondition the payload bay before flight and at stopover sites. To prevent freezing for middeck payloads, NASA provides electrical power to the orbiter coolant pump so warm coolant can be circulated during the flight and during intervals on the ground.

Optional Services

NASA provides payload customers optional services that may significantly increase the cost and complexity of the thermal-integration process.

Active Liquid Cooling

Active liquid cooling is available to payloads located in either the payload bay or middeck. Cooling is accomplished by the payload heat exchanger, a component of the orbiter active thermal-control system (ATCS). The payload heat load, together with loads from the various orbiter heat sources, are absorbed into the orbiter ATCS Freon-21 coolant loop as shown in Fig. 18.25. The ATCS, in turn, rejects the heat to one of the following sinks:

- GSE heat exchanger (during prelaunch and approximately 45 min after landing)
- flash evaporator (during ascent and deorbit)
- radiator supplemented by flash evaporator (on orbit)
- radiators and ammonia boiler operation (during descent and postlanding)

The payload heat exchanger has two passages available to payloads. One is normally provided to payloads in the middeck, and the other is provided to payloads in the payload bay. However, both passages can be made available to payloads in the payload bay. The supply temperature to the payload is a function of actual heat-exchanger performance and should be based upon the effectiveness curves defined in ICD 2-19001. Dual use of the payload heat exchanger will reduce performance, and the supply temperature will be determined by NASA/USA. The cooling capacity available at the payload heat exchanger varies as a function of mission phase. Cooling during the prelaunch, ascent, descent, and postlanding phases is limited to 1525 W. The on-orbit capacity is 8500 W after the payload-bay doors are opened. For checkout purposes, the 8500-W capacity is available for limited time periods during prelaunch; however, this availability requires special negotiation with NASA/USA, and the capacity is not available during the final hours of countdown. In addition, the cooling capacity for middeck payloads is limited to an amount that is not greater than the electrical power available to middeck payloads and that will not cause the cabin temperature limit to be exceeded during any mission phase.

The customer provides a pump package with an accumulator and controls coolant flow rate and pressure (123 N/cm^2 maximum) on the payload side of the heat exchanger. In addition, the customer is responsible for freeze protection, filtration, and instrumentation. Freon 114 or water may be used in the payload bay; however, Freon 114 is recommended to avoid potential freezing problems. The required coolant for middeck payloads is water, which is not expected to have freezing problems as long as at least two orbiter fuel cells are operating at a total of 11 kW. Water coolant is also required for habitable modules in the payload bay.

Although lines are insulated, stagnant sections of water lines may require heaters when water is used as a coolant for payloads in the payload bay. Failure modes that preclude proper water flow rates can cause water to freeze. When water is used as a coolant, a minimum flow rate of 4.6 kg/h is required during all on-orbit periods to prevent freezing. Water-line freezing can cause payload heat-exchanger over pressurization and present a catastrophic hazard to the orbiter if both orbiter Freon loops are lost.

In addition to having a maximum operating pressure of 123 N/cm^2, the payload must also withstand 123 N/cm^2 on the payload side of the heat exchanger if a leak develops in the heat exchanger between the payload side and the orbiter side.

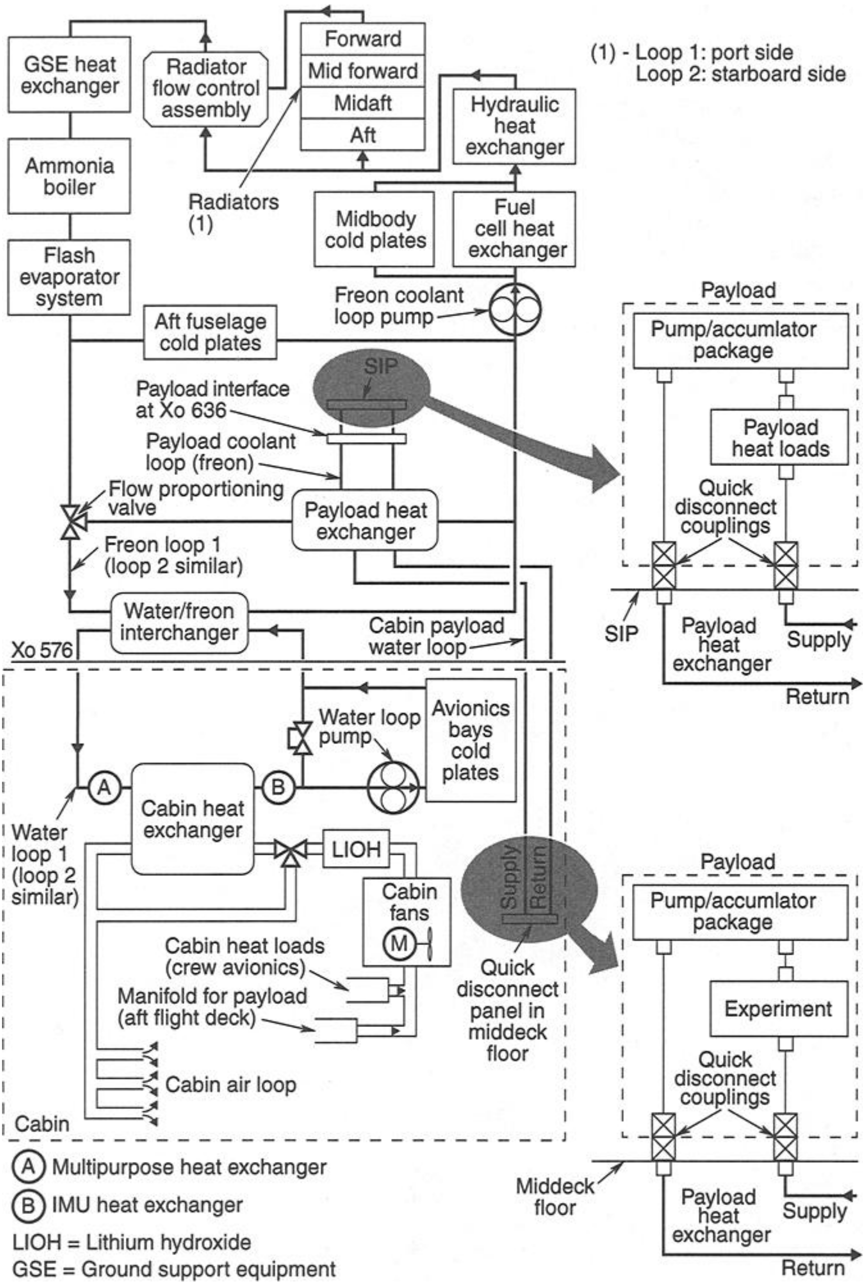


Fig. 18.25. Simplified orbiter active cooling system.

Payload Active Cooling Kit (PACK)

For a payload located in the payload bay, a PACK (Fig. 18.26) provides a connection to the orbiter ATCS. The plumbing interconnecting the PACK and the payload is furnished by the customer. The PACK interface is located on a standard interface panel on the port side of the orbiter at a longitudinal position specified in the payload-unique ICD. The PACK installation is designed for a wet mate (quick disconnect) interface and accommodates either horizontal installation of payloads in the Orbiter Processing Facility (OPF) or vertical installation at the launchpad. The quick disconnects are furnished by NASA/USA.

PACK Leakage Rates

For payload system analyses, the PACK leakage rates in Table 18.5 are used. The ground condition assumes an internal pressure of 41 N/cm^2 and an external pressure of 10.1 N/cm^2. The on-orbit condition assumes an internal pressure of 69.0 N/cm^2 and a vacuum outside the lines.

Cabin Middeck Payloads

The interface for liquid cooling in the middeck is via NASA-furnished quick disconnects located on the middeck floor as shown in Fig. 18.27. The system is designed for wet mate installation. The coolant plumbing located in the cabin

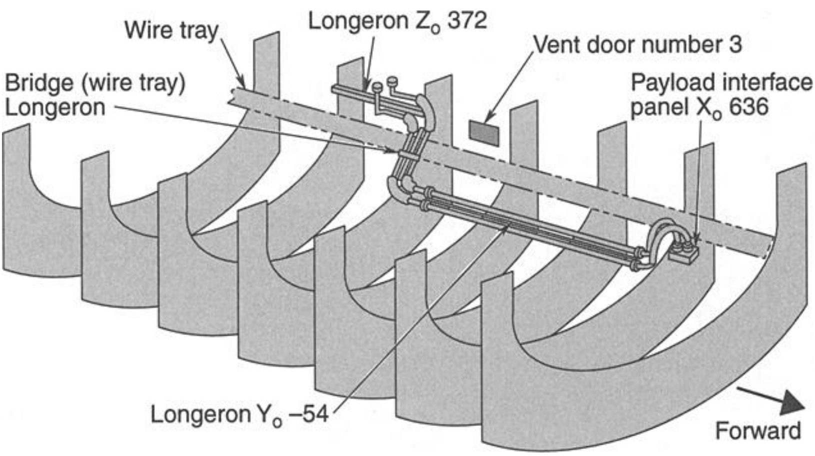


Fig. 18.26. Typical PACK installation.

Table 18.5. PACK Leakage Rates

	Ground (cm^3/h)	On-Orbit (cm^3/h)
Water	0.1	0.2
Freon 114	0.2	0.5

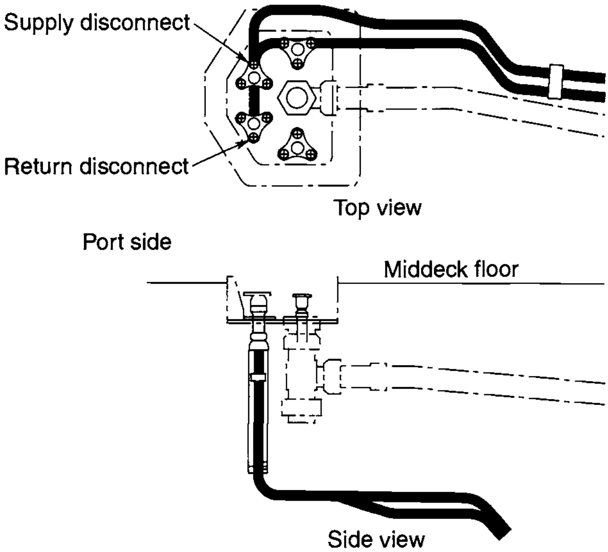


Fig. 18.27. Payload interface with the water loop in the orbiter middeck.

must be appropriately insulated to preclude condensation. Also, if the payload uses an air-to-water heat exchanger, the coolant water-temperature inlet should be controlled so that water does not condense at the heat exchanger. Maximum cabin dew point is defined in Shuttle/Payload Interface Definition Document for Middeck Payload Accommodations, NSTS 21000-IDD-MDK.

Prelaunch/Postlanding Spigot Cooling

Three gas-cooling spigots are available to supplement the standard payload-bay purge during prelaunch operations and the postlanding period at primary and alternate landing sites. If spigots are used, NASA designs and fabricates the ducting and support fixtures from the negotiated payload interface to one or more spigots, as required. The nominal flow of 22 kg/min is available from each spigot if all three spigots are utilized. If only one of them is used, the maximum flow rate is 45 kg/min for it. Since the spigot system is part of the payload-bay purge system, the conditioned gas is the same as the purge supply. Therefore, system designers must negotiate gas conditions and flow rates needed for compatibility with other payloads that are manifested for the flight.

Aft-Flight-Deck Air Cooling

Orbiter air ducting can provide air cooling for electronics boxes compatible with cooling by forced convection. Cabin air, at 35°C maximum, is drawn into the box and exits (via an orifice and interface duct) into the orbiter manifold duct. The orifice and interface duct are provided by NASA/USA. The combined pressure drop for the avionics box, the orifice, and the interface ducting is limited to 2.54 cm of water at the design air flow of 0.185 kg/h/W. Therefore, the payload-unique ICD must define the pressure-drop allocation for the payload. After the completion of avionics-box pressure-drop testing (provided by the customer), the orifice is sized so that the total pressure drop is 2.54 cm of water. The payload-unique ICD is then updated, if necessary, to define the maximum pressure drop for the payload, as well as the other unique parameters (heat load, air-flow requirement, and geometric and connection interface definition).

Payload Station and Mission Station Support (10.1 N/cm^2 Cabin Pressure)

The orbiter can provide for the removal of a combined total of 725 W average from both stations during on-orbit operations. For prelaunch, ascent, descent, and postlanding, the air cooling is limited to 350 W. The above values include up to 100 W of cooling for aft-flight-deck payload equipment consuming small quantities of power (10 W each) by direct radiation or convection to the cabin. Specific forced-air cooling is not provided for these low-power boxes.

Total air flow available to the aft-flight-deck stations is approximately 135 kg/h but depends on the flow distribution requirement between the payload and mission stations as defined in the IDD. Air-cooled avionics air flow is provided at a rate of 0.185 kg/h/W of heat load, and therefore, cooling design is based on an air-temperature increase of 19°C across each avionics box.

Physical Location and Ducting Installation

Payload areas in the aft flight deck are shown in Fig. 18.28. Only compartments at L10, L11, L12, and R11 are dedicated for air-cooled payloads. Figure 18.29 depicts isometric views of the orbiter manifold duct at both the payload and mission stations. The available area for duct routing and connection accessibility is very limited because of wiring, connectors, and secondary structure, so NASA/USA provides interface ducting (between the manifold and avionics box) and installs the required orifice previously discussed.

Operation at Reduced Cabin Pressure

All air-cooled equipment may be subjected to reduced air flow because of the reduction of cabin pressure from 10.1 to 7.0 N/cm^2. The 7.0 N/cm^2 condition is implemented to accommodate on-orbit pre-EVA (prebreathe) operations, and it could last the entire on-orbit duration for some missions. The resulting air flow equals the 10.1 N/cm^2 air flow times the pressure ratio of the reduced cabin pressure (7.0 N/cm^2) to the normal cabin pressure (10.1 N/cm^2). The maximum air-inlet temperature for this condition is 27°C.

Another mode of reduced cabin pressure is the 5.5 N/cm^2 contingency mode. This mode, which occurs in the event of a puncture in the pressure walls of the cabin, is considered an abort mode. All payload equipment is powered off for this cabin condition so that maximum heat rejection is available for orbiter use.

Middeck Ducted Air Cooling

The ducted air-cooling interface is defined in NSTS 21000-IDD-MDK for middeck locker payloads that require active cooling. Each locker payload must provide its own circulation fan to draw air from the avionics-bay volume and dump hot (return) air into the orbiter return air duct. The avionics-bay volume (supply) air temperature is nominally 27°C, except during ascent, entry, and certain mission

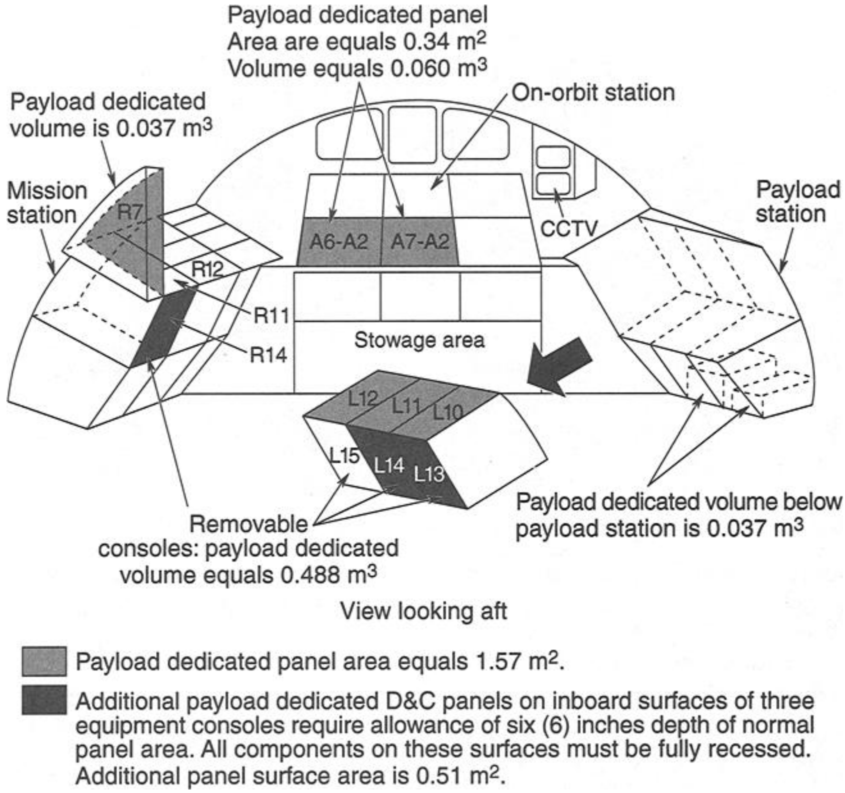


Fig. 18.28. Shuttle orbiter aft flight deck.

phases. The supply air for these mission phases is 29°C nominally with possible 10-min spikes up to 35°C. The services are available in avionics bays 1, 2, and 3A. The locker locations with the cooling interface in each bay are also identified in NSTS 21000-IDD-MDK. Each location has a dedicated air-cooling flow rate of either 51 or 102 liters/minute.

Middeck Accommodations Rack (MAR) Cooling

The MAR is designed to permit integration of small payloads and experiments into the middeck and supplement the middeck lockers. The payloads that use it must meet the requirements specified in NSTS 21000-IDD-MDK or those negotiated through the IP process. The amount of heat that can be dissipated into the cabin environment or into the orbiter coolant loop is limited to values dependent upon specific mission capabilities. The maximum heat loads that a payload is permitted to dissipate into the cabin atmosphere are specified in NSTS 21000-IDD-MDK or negotiated through the IP process.

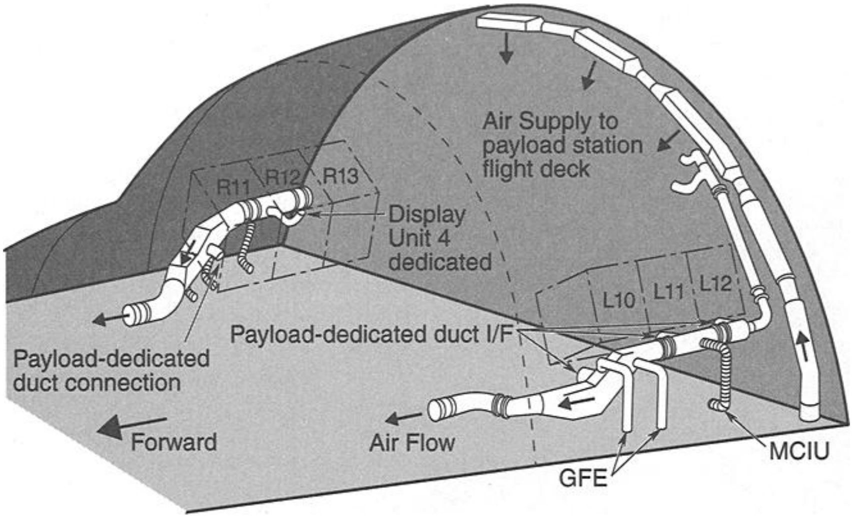


Fig. 18.29. Aft-flight-deck air-duct interface locations.

Thermal control for payloads or experiments installed in the MAR is obtained through one of the following methods, which must be approved through the IP negotiation with NASA:

- **Passive thermal control:** All payload-generated heat is conducted or radiated to the MAR structure for reradiation to the middeck cabin environment. Convective circulation of cabin air past the MAR dissipates the heat. A thermal-closeout panel is not installed when this method of thermal control is used.
- **Active thermal control:** A thermal-control module called the MAR cooling module, utilizing a water-to-air heat exchanger, is designed to dissipate heat loads of up to 1000 W of payload-generated heat with 28°C coolant temperature change. An integral fan and system of ducting create a closed system that circulates payload-heated air through the heat exchanger and back past the payload components. A payload-supplied thermal-closeout panel is installed when this method of thermal control is used.
- **Water-circulating pumps only:** The MAR cooling module is fabricated so that the circulating pumps and accumulator can be used alone. This is to accommodate users wanting water circulation through cold plates or a water jacket for thermal control. Using this system, a payload can get more than 1000 W of cooling if the orbiter payload cooling loop has enough reserve to allow it.
- **Payload-unique module:** When dictated by design of a payload or experiment, a payload-unique thermal-control module can be installed in the MAR for direct connection to the orbiter heat-exchange loop. All coolant lines and cold surfaces need insulation to prevent or minimize condensation. Installation of the thermal-closeout panel is optional when this method of thermal control is used.