SPIRE

DESIGN REQUIREMENTS FOR THE SPIRE SHUTTER SUBSYSTEM

Ref: SPIRE-USK-NOT-000826

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1 SCOPE OF THIS DOCUMENT

This document specifies the performance requirements and design constraints to be placed on the SPIRE shutter.

The rationale for the inclusion of a shutter in SPIRE is presented in §4, and a concept for the shutter subsystem is described in §5. The requirements which follow in §6 are based on this concept. The design constraints in §7 are to ensure compatibility with the SPIRE instrument.

The requirements presented herein are applicable to the proto-flight model of the instrument. Other deliverable models may not be subject to all of the requirements.

2 REFERENCES

2.1 Governing documents

The documents in table 1 contain requirements to which the shutter must conform. Current issue numbers and dates are given. Revisions of these documents may appear during the course of the project and will become binding when agreed to by CSA and USK.

Table 1: Governing documents.

	Title	Document No.	Date
GD-1	FIRST/Planck Instrument Interface Document Part A	SCI-PT-IIDA-04624 Current issue 1/1	20 Dec 2000
GD-2	FIRST/Planck Instrument Interface Document Part B 'SPIRE'	SCI-PT-IIDB/SPIRE-02124 Current issue 1/0	01 Sep 2000
GD-3	Instrument Requirements Document	SPIRE-RAL-PRJ-000034 Current issue 1.0	23 Nov 2000
GD-4	SPIRE Systems Budgets	SPIRE-ATC-PRJ-000450 Current Issue 2.0	12 Apr 2001
GD-5	ICD Structure - Mechanical I/F	SPIRE-MSS-PRJ-000617 Current Issue 1.0	Apr 2001
GD-6	SPIRE Harness Definition	SPIRE-RAL-PRJ-000608 Current Issue 0.4	10 Aug 2001

2.2 Applicable Documents

The documents in table 2 are to be considered as if they had been included in the text of this document. Current issue numbers and dates are given. Revisions of these documents may appear during the course of the project and will become binding when agreed to by CSA and USK.

Table 2: Applicable documents.

	Title	Document No.	Date
AD-1	SPIRE Shutter Usage Forecast	SPIRE-USK-NOT-000827 Current Issue 1.0	27 Aug 2001

2.3 Reference documents

These documents provide useful information, but do not contain any shutter requirements:

Table 3: Reference documents.

	Title	Document No.	Date
RD-1	Scientific Requirements Document	SPIRE-UCF-PRJ-000064 Current Issue 3.0	21 Nov 2000
RD-2	SPIRE Design Description	SPIRE-RAL-PRJ-000620 Current Issue 0.1	12 Apr 2001
RD-3	Instrument Qualification Requirements Document	SPIRE-RAL-PRJ-000592 Current Issue 1.1	29 Mar 2001
RD-4	Instrument AIV Plan	SPIRE-RAL-PRJ-000410 Current Issue 2.1	29 Mar 2001
RD-5	SPIRE Sensitivity Models	SPIRE-QMW-NOT-000642	6 Apr 2001

3 ABBREVIATIONS

AD	Applicable Document
BOL	Beginning of Life
CSA	Canadian Space Agency
ESA	European Space Agency
FPU	Focal Plane Unit
GD	Governing Document
RAL	Rutherford Appleton Laboratory
RD	Reference Document
SPIRE	Spectral and Photometric Imaging Receiver
TBD	To Be Determined
USK	University of Saskatchewan

4 RATIONALE FOR THE SHUTTER

In the Herschel flight configuration, the background flux on the SPIRE detectors will be dominated by thermal emission from the telescope. The telescope is defined in GD-1. The relevant thermophysical parameters are:

- temperature: 80±10K
- BOL emissivity: 0.04

The temperature range is large since the telescope will be passively cooled; the actual temperature will not be known until equilibrium is achieved in orbit. The emissivity is also uncertain due to recent changes in telescope supplier and design, and could be as low as 0.02. Several representative telescope emission spectra are shown in figure 1, along with the five SPIRE filter bands. As a result of the uncertainties in emissivity and temperature, the telescope emission intensity is itself uncertain by roughly plus or minus a factor of two.

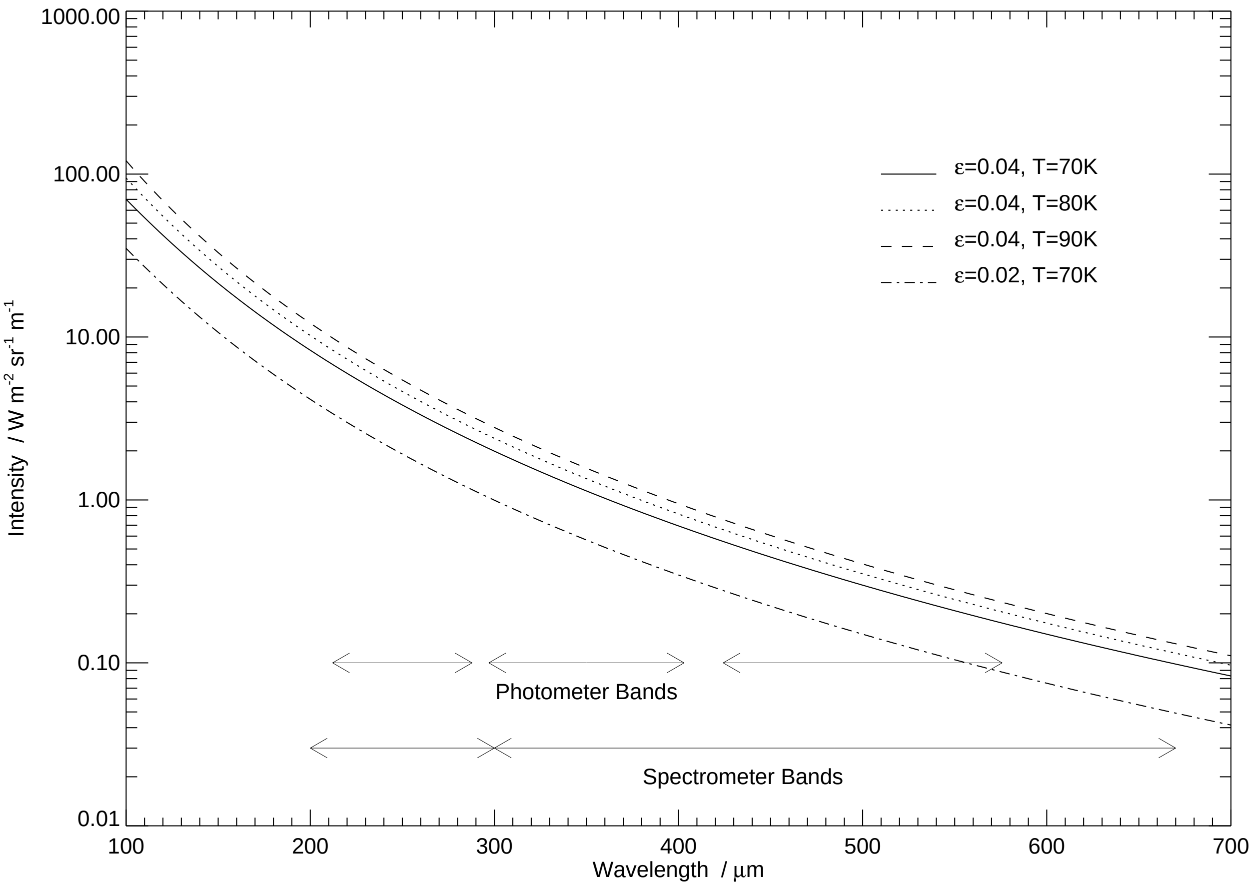

Figure 1: **Telescope Thermal Emission Spectra.** Spectra are shown for different values of telescope emissivity and temperature. The five SPIRE filter bands are also indicated.

During the period between spacecraft integration and launch, this background must be simulated so that the instrument can be operated and tested under flight-representative conditions. In order to provide a vacuum environment in which the instruments can be cooled to their operating temperature, however, the lid of the spacecraft cryostat will be closed during this phase. The situation is depicted in figure 2. This lid will not be actively cooled and will therefore be at an elevated temperature. If the lid temperature and emissivity are sufficiently high, the photon flux will be high enough to saturate the detectors, making instrument tests impossible.

In order to accommodate this situation, a shutter is required in the instrument. It will be placed into the fore-optics of the instrument such that it will be the first optical element encountered by the input beam. The shutter thus has two functions:

1. to reject the high flux from the cryostat lid; and
2. to simulate the background flux from the Herschel telescope.

Each of these is discussed in more detail in the following sections.

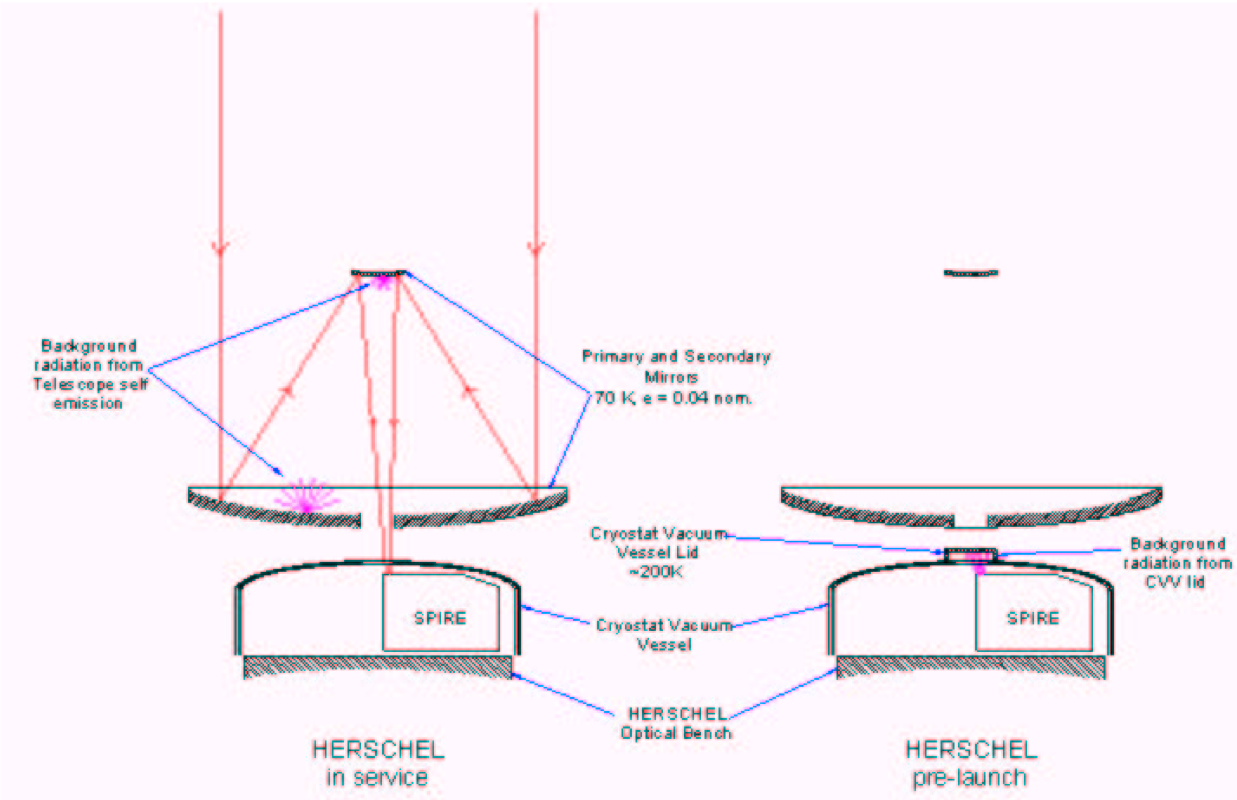

Figure 2: **Cryostat Lid.** In orbit, the lid will be open and the background flux will be dominated by thermal emission from the telescope; in spacecraft tests, the lid will be closed and the background flux is potentially high enough to saturate the detectors.

4.1 Rejection of lid flux

The emissive properties of the cryostat lid are currently undefined. The emissivity could be anywhere from 0.02 to 1; there are arguments in favour of both extremes. The temperature will not be controlled and will be determined by the thermal environment; it could be anywhere from 4K to room temperature. The worst case corresponds to unit emissivity and a temperature of 300K: this would produce an emission intensity two orders of magnitude higher than in orbit. Provision of the Herschel cryostat is an ESA responsibility; the timescale for these decisions to be made is unknown.

In order to simulate flight conditions, the flux from the cryostat lid must be rejected. Given the uncertainty in the lid properties, the shutter should be designed to be as independent of the lid as possible. This argues in favour of a reflective finish on the side of the vane which faces the cryostat lid.

4.2 Simulation of flight-representative flux

Once the spacecraft is in orbit, the cryostat lid will be opened and the telescope will provide the dominant background flux. There is therefore no need for the shutter after launch. The shutter therefore has an unusual configuration: it is a flight item since it will be incorporated into the optical system of the instrument, but it need not be flight-capable.

The critical quantity which must be simulated is the power absorbed by the detectors ('loading'), since this parameter determines the responsivity. Using a simple model based on the optical design of the instrument (App. 1), the power loading by the telescope can be calculated for any assumed values of telescope emissivity and temperature. The result of this calculation is shown in figure 3 for an assumed emissivity of 0.04.

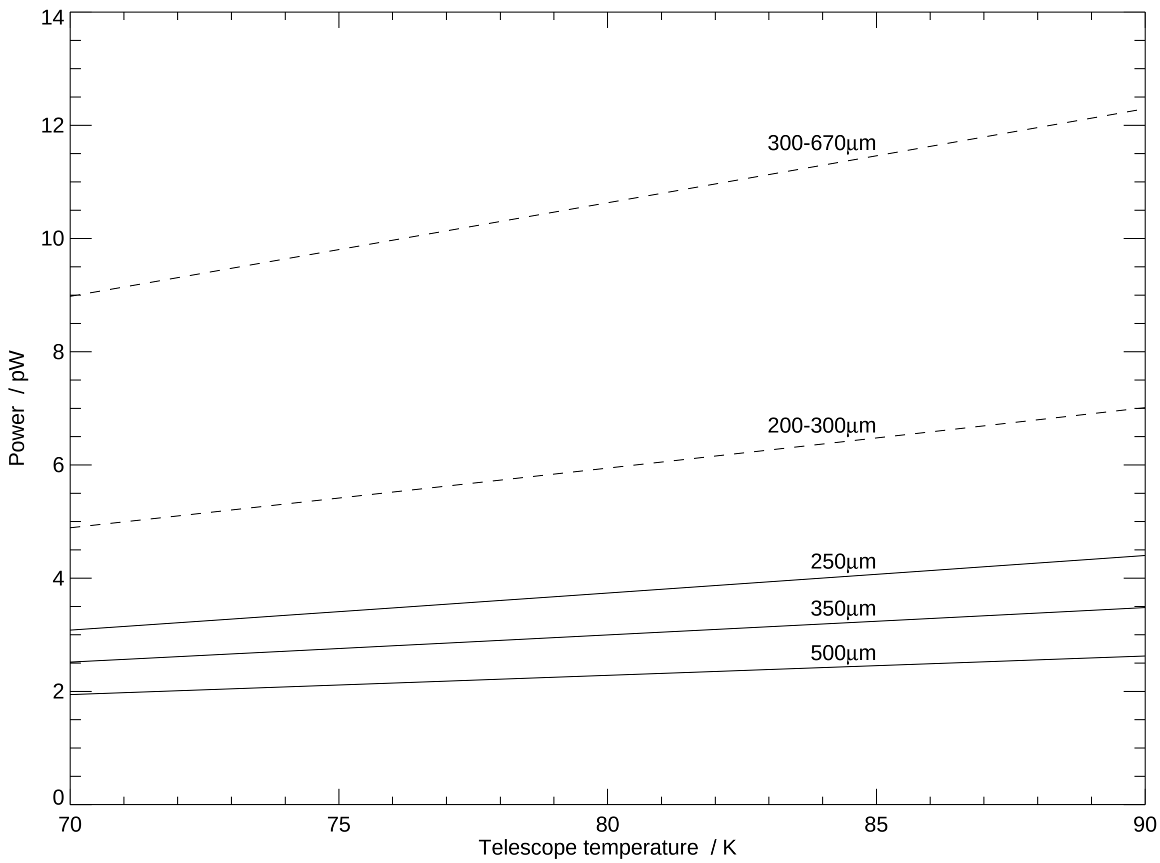

Figure 3: **Power loading by telescope.** The assumed telescope emissivity is 0.04 and the telescope temperature range is 70-90K.

The range of power loading to be simulated by the shutter is thus different for each of the five channels. Grouping the photometer channels together, and including a margin of a factor of 2 to allow for the uncertainty in the telescope parameters, the power loading to be produced by the shutter in each channel is:

Table 4: Power loading to be produced by the shutter.

Channel	Power Loading /pW
Photometer	1 - 9
Spectrometer short	2.5 - 14
Spectrometer long	4.5 - 25

In generating this range of absorbed powers, there are two degrees of freedom in the shutter design: emissivity and temperature. Using the same model, the power loading by the shutter can be calculated for any combination of these two parameters. Two examples of this calculation are shown in figures 4 and 5. For each channel, the required temperature range is shown as a function of emissivity in figure 6. This plot clearly demonstrates the tradeoff between these two parameters. Finally, in order to cover all SPIRE channels with one shutter, the shutter parameters must span the extremes of the ranges calculated for each channel. The range to be covered is shown in figure 7.

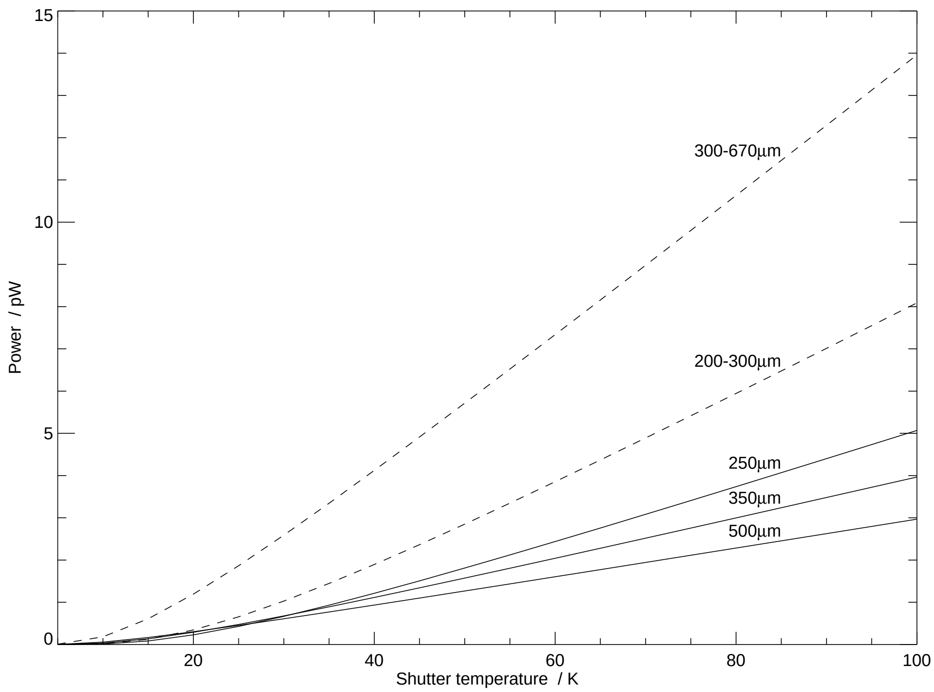

Figure 4: **Power loading by shutter.** The assumed shutter emissivity is 0.04. In order to cover the range of required power, temperatures in excess of 100K are required.

Whilst any emissivity can in principle be selected for the shutter so long as the corresponding temperature range is made available, selection of a high emissivity for the shutter vane offers several advantages:

- insensitivity of the required temperature range to the actual emissivity value;
- the thermal stabilisation time is much shorter for temperatures closer to the ambient instrument temperature;
- the thermal gradient across the flex-harness to the shutter vane is much smaller; and
- a high-emissivity material is to be selected by ESA as a standard coating for the Herschel project as a whole.

Note that provision of a known irradiance for absolute photometric calibration of the instrument is not the purpose of the shutter. SPIRE will be calibrated on the ground using laboratory sources, and in orbit using standard astronomical sources.

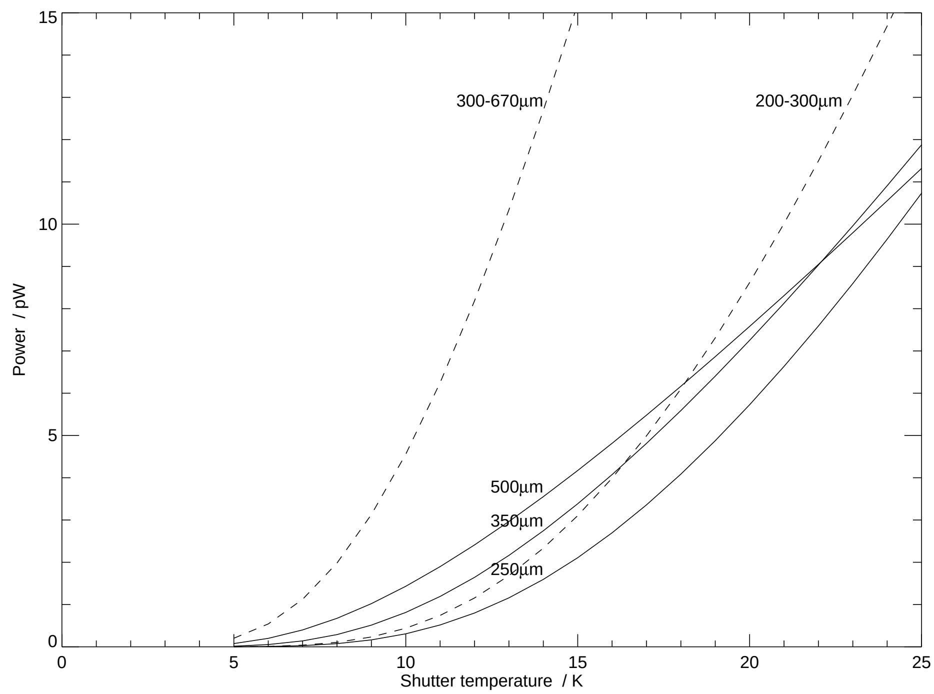

Figure 5: **Power loading by shutter.** The assumed shutter emissivity is 1. The range of required powers can be obtained for temperatures less then 25K.

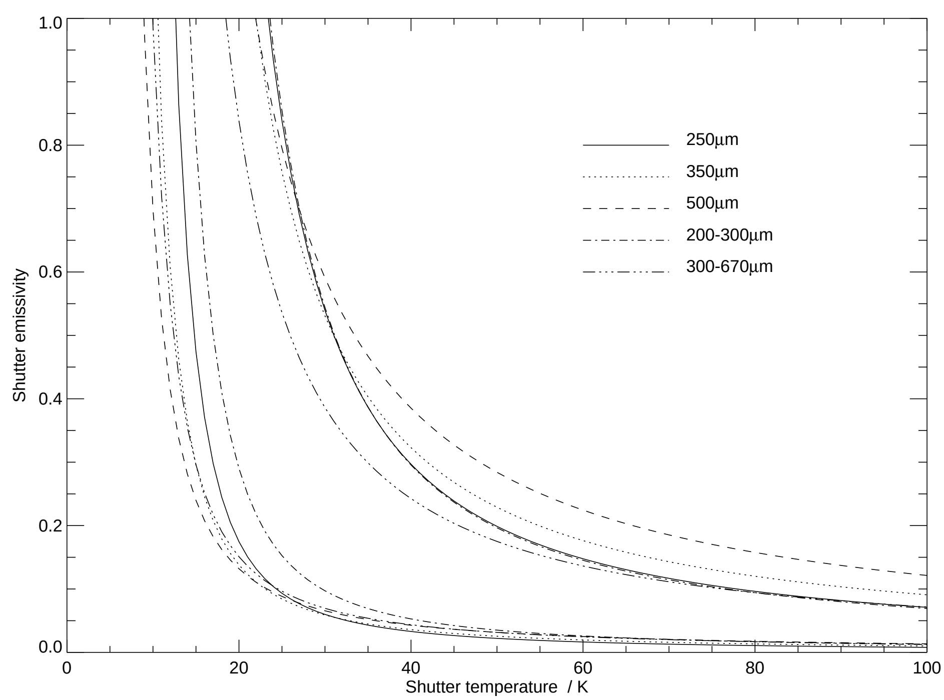

Figure 6: **Shutter parameters.** The two curves for each channel represent the minimum and maximum shutter temperatures to produce the required range of power loading for any given value of shutter emissivity.

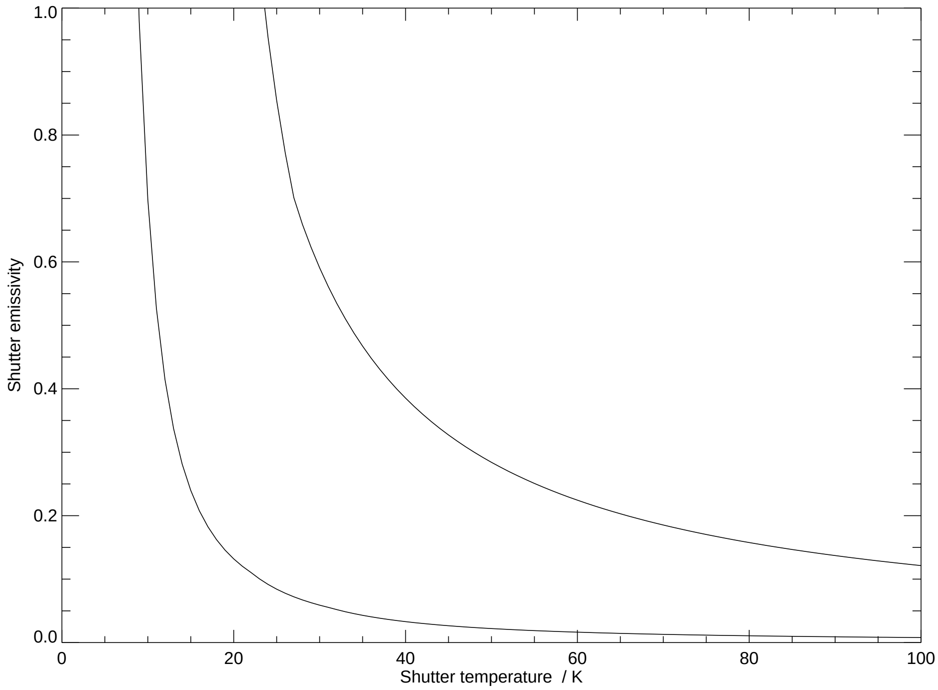

Figure 7: **Shutter parameters.** The two curves represent the minimum and maximum shutter temperatures to produce the required range of power loading for any given value of shutter emissivity.

5 SHUTTER CONCEPT

On the basis of the preceding discussion, a shutter concept has been developed. The shutter subsystem will consist of an actuator and a vane, as described below:

1. The subsystem will be located on the top cover of the instrument such that the vane can physically block the SPIRE entrance aperture.
2. The actuator will be at instrument temperature ($\sim$4K) and its function is to move the vane into and out of the beam on command.
3. The vane must prevent the flux from the cryostat lid from entering the instrument. The side of the vane which faces the lid will be reflective so that most of the energy is reflected away from the instrument.
4. The side of the vane which faces the instrument optics will be emissive and its temperature will be controllable over the range specified in section 4.

We therefore anticipate that the vane will consist of two separate plates, as shown in figure 8. The instrument side of the vane will incorporate a heater and thermometry for temperature control. Since the vane is a moving part, electrical connections to the heater and thermometers at cryogenic temperatures will require careful design. The subsystem concept also includes:

- a housekeeping thermometer for the actuator;
- a vane position sensor;
- a means of electrical connection to the Herschel cryoharness.

The shutter represents a potential single-point failure in the instrument. Although the shutter will not be used in flight, it is nevertheless critical that the shutter not fail with the vane in the beam. This criticality

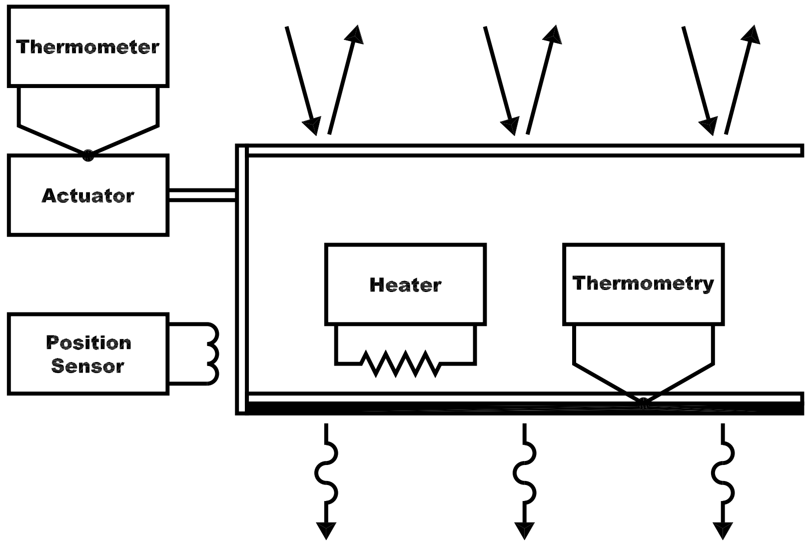

Figure 8: **Shutter Concept.** The shutter subsystem will consist of an actuator, a double vane, a vane heater, a vane position sensor, and thermometers.

applies to ground spacecraft-level tests as well as the flight phase. Once SPIRE has been integrated into the spacecraft and cooled, it is a lengthy and expensive operation to warm up the entire spacecraft and de-integrate the instrument. The subsystem must therefore be designed on the assumption that physical access to the instrument will not be possible after spacecraft integration. Reliability engineering and failure analysis will accordingly be key aspects of the design.

SPIRE is a large and complex instrument containing many subsystems which are being provided by different institutes. This has two immediate implications:

1. the shutter will have interfaces with several of the other subsystems (section 7.3); and
2. many design issues pertaining to the shutter are common to other subsystems and will be addressed at system level rather than subsystem level. A simple example of this is the choice of electrical connector for the subsystem harness.

Since the shutter is for ground use only, a laboratory-standard control system is required. The functions of the control system will be:

- to actuate the vane on command;
- to monitor the vane position;
- to monitor the actuator temperature; and
- to control and monitor the vane temperature.

The shutter control system should be capable of independent operation, but must also interface with the SPIRE test facility such that the shutter can be driven from the SPIRE instrument command console. This document specifies requirements for the shutter subsystem hardware only.

6 DESIGN REQUIREMENTS

Consideration of the shutter functions, as discussed in the previous two sections, leads to the following requirements:

Table 5: Design requirements.

Requirement ID	**R-01**
Description	Rejection of direct flux
Value	The shutter vane must physically prevent thermal radiation from the Herschel cryostat lid from directly entering the instrument.
Comment	This requirement applies only to thermal radiation which is directly incident on the shutter vane from the Herschel cryostat environment. This requirement applies only when the vane is in the beam.
Requirement ID	**R-02**
Description	Rejection of indirect flux
Value	The seal of the shutter vane shall be designed so as to reduce stray light entering the instrument to an acceptable level.
Comment	The meaning of 'acceptable level' shall be determined by iterative modelling using the SPIRE stray light model at RAL. This requirement applies only when the vane is in the beam.
Requirement ID	**R-03**
Description	Vane emissivity
Value	The emissivity of the instrument side of the vane at SPIRE wavelengths shall be greater than 0.9.
Comment	High emissivity is required in order to keep the required vane temperature as low as possible. The project-approved 'black' is therefore recommended.
Requirement ID	**R-04**
Description	Vane emissivity accuracy
Value	The average emissivity of the instrument side of the vane at SPIRE wavelengths shall be determined to an accuracy of ±2%.
Comment	The power loading depends linearly on vane emissivity (App. 1). An emissivity accuracy of ±2% implies a power loading accuracy of ±2%. This is significantly smaller than the absolute photometric accuracy of the instrument.
Requirement ID	**R-05**
Description	Vane emissivity uniformity
Value	The emissivity of the instrument side of the vane at SPIRE wavelengths shall be uniform to within 2% (rms).
Comment	Since the vane is not in a SPIRE focal plane, it will not be imaged onto the detector arrays. Variations in emissivity across the area of the vane will be averaged out. The uniformity of the vane emissivity is therefore not critical.
Requirement ID	**R-06**
Description	Vane temperature
Value	The temperature of the instrument side of the vane shall be controllable over the range 9-25 K.
Comment	This temperature range is derived from figure 7. Ability to operate at 7K would be advantageous but is not required. This requirement applies only when the shutter is being used at instrument temperature.
Requirement ID	**R-07**
Description	Vane temperature control
Value	There shall be at least 16 set points over the temperature range specified in R-06.
Comment	This allows for the provision of different power loadings to different channels.

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Requirement ID	**R-08**
Description	Vane temperature accuracy
Value	The temperature of the instrument side of the vane shall be monitored. The average temperature of the emitting surface must be known to an accuracy of ±0.1 K.
Comment	This requirement applies only when the shutter is being used at instrument temperature. This temperature accuracy corresponds to a power loading accuracy of ±2% for the nominal power loading and ±5% at the minimum temperature.
Requirement ID	**R-09**
Description	Vane temperature uniformity
Value	The temperature of the instrument side of the vane shall be uniform to within 0.1K (rms).
Comment	This requirement applies only when the shutter is being used at instrument temperature. Since the vane is not in a SPIRE focal plane, it will not be imaged onto the detector arrays. Variations in temperature across the area of the vane will be averaged out. The uniformity of the vane temperature is therefore not critical.
Requirement ID	**R-10**
Description	Vane temperature repeatability
Value	The average temperature of the instrument side of the vane shall be repeatable to within ±0.040K.
Comment	This requirement applies only when the shutter is being used at instrument temperature. It corresponds to a power loading repeatability of ±2% at the minimum temperature and ±0.8% for nominal power loading.

7 DESIGN CONSTRAINTS

The shutter design is constrained by a number of issues since it is a subsystem of a larger instrument.

7.1 Reliability

The life cycle of the shutter is schematically depicted in figure 9. The estimated usage of the shutter is defined in the Shutter Usage Forecast (AD-1). In summary:

- Following delivery to RAL, the shutter subsystem will be used in the SPIRE-level test phase for functional tests and to establish a datum for the Herschel-level tests which follow. This test phase is described in RD-4.
- Following delivery of SPIRE to ESA, the shutter subsystem will be used to test the SPIRE instrument under flight-representative conditions. This test phase is described in GD-1.
- After launch, the shutter will not be used.

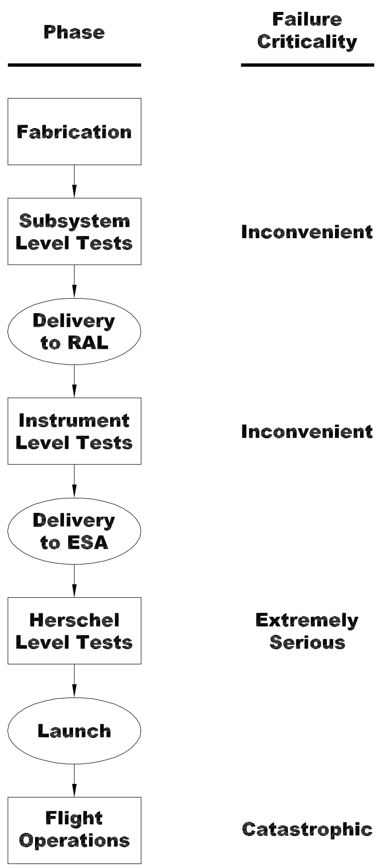

Figure 9: **Shutter Life Cycle .**

Because the shutter represents a potentially catastrophic single-point failure, it must be designed to ensure that it cannot fail with the vane in the beam. The criticality varies according to the program phase at which the failure occurs:

- A failure with the vane in the beam after launch is catastrophic since the entire SPIRE instrument would be lost.
- A failure during the Herschel-level test phase is extremely serious. Once the spacecraft has been integrated and cooled, it is a very costly and time-consuming procedure to warm up the spacecraft, de-integrate the instrument, and repair or replace the shutter. The shutter should therefore be designed on the assumption that access will not be possible after integration of SPIRE into the spacecraft.
- A failure during the subsystem-level or SPIRE-level test phases is inconvenient.

These considerations lead to the following requirement:

Table 6: Reliability requirement.

Requirement ID	**R-11**
Description	Reliability
Value	The shutter shall be designed to a reliability requirement of 0.9999.
Comment	The reliability constraint is driven by (a) criticality of the failure mode, and (b) lack of access after spacecraft integration. The requirement applies only to the shutter subsystem and not the cryoharness or the shutter EGSE.

7.2 Resources

The SPIRE system resources are maintained in GD-4. Several budgets in that document are not applicable since the shutter will not be used in flight.

Because the shutter subsystem will physically fly, its mass must conform to the mass budget of the instrument. This leads to the following requirement:

Table 7: Resource requirement - mass.

Requirement ID	**R-12**
Description	Mass
Value	The mass of the subsystem must conform to the allocation in GD-4.
Comment	The working version of the mass budget is currently contained in a spreadsheet. GD-4 will be updated at some point to bring it into agreement with the spreadsheet. The mass allocation for the shutter in the spreadsheet is 592g including contingency.

Thermal dissipation in the SPIRE FPU is under very strict constraints because of its effect on the cryogen boiloff rate. Ultimately, this dictates the total amount of observing time to be obtained with Herschel. Because the shutter will not operate in flight, however, it is independent of this constraint. The limitation on the shutter thermal dissipation is dictated by the thermal response of the instrument itself.

Table 8: Resource requirements - thermal.

Requirement ID	**R-13**
Description	FPU thermal dissipation
Value	The temperature of the instrument structure in the vicinity of the shutter shall rise by no more than 2 K after 30 minutes when the shutter subsystem is energised.
Comment	These values are a best estimate. The thermal response of the instrument to power dissipation in the shutter subsystem will be determined using the thermal model of the instrument at RAL.

7.3 Interfaces

The shutter subsystem has two interfaces with the rest of the SPIRE instrument: a mechanical/thermal interface to the instrument structure, and an electrical interface to the spacecraft cryoharness. These interfaces are defined in GD-5 and GD-6.

Table 9: Interface requirements.

Requirement ID	**R-14**
Description	Structure interface
Value	The subsystem design shall conform to the structure interface specification in GD-5.
Comment	This document should be regarded as negotiable as the design proceeds.
Requirement ID	**R-15**
Description	Harness interface
Value	The subsystem design shall conform to the harness interface specification in GD-6.
Comment	This document should be regarded as negotiable as the design proceeds.

7.4 Operations

Consideration of the operational plan for the shutter and its test phase leads to the following requirements:

Table 10: Operation requirements.

Requirement ID	**R-16**
Description	Operating temperature
Value	The shutter mechanism (actuator and vane position sensor) shall be capable of operation at instrument temperature and at room temperature. The vane heater and all thermometry need only function at instrument temperature.
Comment	Operation at instrument temperature is a *sine qua non*. This requirement ensures that the mechanism can be functionally tested at room temperature before it is cooled.
Requirement ID	**R-17**
Description	Operating orientation
Value	The shutter shall be capable of operation in any orientation.
Comment	The SPIRE instrument will be placed in various orientations during the various test phases (AD-1). Operational problems can be avoided if the shutter can operate in any orientation.

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Requirement ID	**R-18**
Description	Transition time
Value	The time required to move the vane into the beam on command shall be less than the thermal stabilisation time (R-19).
Comment	This requirement ensures that actuating the mechanism will not constrain the flow of the instrument test procedures.

Requirement ID	**R-19**
Description	Thermal stabilisation time
Value	The time required to increase the vane temperature by 5K, assuming that the vane is initially at its minimum (unpowered) temperature, shall be less than 10 minutes.
Comment	The number is essentially arbitrary. This requirement ensures that heating the vane will not constrain the flow of the instrument test procedures.

Appendix 1: SPIRE Power Loading Calculations

The following equations are adopted without explanation from a sensitivity model of the instrument (RD-5).

1. Photometer Channels.

$$P_T = \eta_1\eta_2\eta_3\epsilon_T \int_{\lambda_1}^{\lambda_2} \lambda^2 B(\lambda, T_T)\, d\lambda$$

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5 \left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]}$$

$$\lambda_1 = \lambda_c \left(1 - \frac{1}{2R}\right)$$

$$\lambda_2 = \lambda_c \left(1 + \frac{1}{2R}\right)$$

where:

Symbol	Meaning	Value
η_1	instrument optical efficiency	0.3
η_2	cold stop efficiency	0.8
η_3	feedhorn efficiency	0.7
ϵ_T	telescope emissivity	0.04
λ_c	centre wavelength	250,350,500 μm
R	resolving power	3.3
T_T	telescope temperature	80 K

2. Spectrometer Channels.

$$P = P_{TE11} + P_{TM01} + P_{TE21} + P_{TE01}$$

$$P_m = \eta_1\eta_2\eta_3\eta_4\epsilon_T \int_{\lambda_1}^{\lambda_2} \lambda^2 B(\lambda, T_T)\, d\lambda$$

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5 \left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]}$$

where:

Symbol	Meaning	Value
η_1	instrument optical efficiency	0.147
η_2	cold stop efficiency	0.8
η_3	feedhorn efficiency	0.7
ϵ_T	telescope emissivity	0.04
T_T	telescope temperature	80 K

and

Symbol	Meaning	Value	
		Short	Long
λ_1	lower wavelength	200 μm	299 μm

and

Mode	η_4		λ_2 / μm	
	Short	Long	Short	Long
TE11	1.0	1.0	299	667
TM01	0.5	0.5	237	513
TE21	0.0	0.5		404
TE01	0.0	0.5		322