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METHODOLOGY FOR MODELLING OF CRYOCOOLERS FOR SYSTEM LEVEL MISSION ANALYSIS

EXECUTIVE SUMMARY

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1 Introduction.

A number of cryocoolers are being considered for use in European science and Earth observing missions. Future spacecraft will increasingly use cryocoolers to improve performance of their payloads, whether it is for science, Earth observation, or telecommunication and small spacecraft may also need to make use of the technologies. For system level studies, it is necessary to quickly and easily assess the impact of these coolers on the overall thermal budget of a spacecraft. This requires the new capability of simulating in a simplified yet representative manner the interaction of a cooler mathematical model with the overall thermal mathematical model of the spacecraft and instruments. No such models currently exist in an accessible form for mission level designers so for each mission it has been necessary to create these models to perform even basic analyses. There does not even exist an established methodology for how to approach this problem. Whilst it is clear that detailed cooler models are needed for final optimisation of thermal design, it is the purpose and innovation of this programme of work to explore how to create basic models for system level studies.

The objective of this activity is to understand how to develop components to carry out system level thermal analyses of spacecraft that use cryocoolers and to identify the most promising methodologies. Potential methodologies have been identified and preliminary prototypes created in order to assess the methods and algorithms identified. Preliminary verification has been carried out in order to verify that they run without error, in a reasonable time and produce realistic results. It is important to ensure that implementing a cooler mathematical model in an overall system level model does not lead to unacceptable CPU times. The limitations of the implementation must also be clear to the user. Recommendations are given for areas to be investigated in future activities.

2 Definitions, Abbreviations and Acronyms

ADR	Adiabatic Demagnetisation Refrigerator
COP	Coefficient Of Performance
CSIM	Cryogenic Systems Integration Model
ESA	European Space Agency
ESATAN	ESA Thermal Analysis Network Software
ESARAD	ESA Radiative Analysis Software
FHTS	Fluid Heat Transport System
GUI	Graphical User Interface
IR	Infra Red
JT	Joule-Thomson
Pelt	Peltier
P/L	Payload
RAL	Rutherford Appleton Laboratory
VB	Visual Basic

3 Literature Survey

Library databases, journals, project proposals, progress reports and conference proceedings related to cryocoolers and associated topics were searched for information. Many papers were found on the stand-alone modelling of specific cooler types, but few detailing system level modelling of cryocoolers in space. While this modelling will undoubtedly have been carried out it is not widely reported in the available literature. In an attempt to fill gaps, personal contacts were made with project scientists and engineers whose knowledge of certain missions proved extremely useful. Manufacturers' data sheets were also a useful source of information.

The Cryogenics Systems Integration Model (CSIM) developed by The Aerospace Corporation is particularly relevant to this study. It is an interactive PC Windows based tool for the simulation and analysis of spacecraft cryogenic systems. It was developed to estimate the mass and power of a system with a mechanical refrigerator given a set of requirements. The choice of coolers is limited to Peltier, Pulse Tube and Stirling. Joule-Thomson coolers cannot be used. For each cooler, performance curves must be entered into a database. CSIM covers a wider area than that required for this contract and includes hardware such as thermal straps, switches and heat pipes. It employs a variety of modelling methods including design algorithms, subroutines and databases. A graphical interface is used for input, design information and system output, with C++ as the underlying programming language. Unfortunately it has not been possible to get hold of a copy, though the Aerospace Corporation's Software Release Committee is currently processing a request. The product has not previously been distributed outside the US.

NASA AMES have developed the online ARCOPTR (Ames Research Centre Orifice Pulse Tube Refrigerator) Pulse Tube model to model the behaviour of orifice and inertance coolers. Detailed design data is required as an input. The Cryogenics Group of the Sensors and Instrumentation Branch at NASA AMES have also set up an online database giving comparative tables and bibliographies of Pulse Tubes. Melcor and Harvard Thermal have produced the 'TAS-PCB' Printed Circuit Board Thermal Analysis software allowing users to select a Melcor product from a component library, which is then added to a system level model.

4 Investigation of Methodologies

In order to ensure an appropriate methodology is adopted, system and thermal engineers were consulted to obtain an understanding of the tools typically needed for system level analysis involving cryocoolers and the level of detailed interaction necessary. Five types of cooler were assessed and typical specifications based on current available technology, given in Table 4-1, were used as a starting point to frame the approach adopted:

	Single-stage Stirling	**Two-stage Stirling**	**Pulse Tube**	**JT**	**Peltier**
Base temp	50K	14K	55K	4K	240K
Cold tip temp	80K	20K	80K	4K	250K
Precooling stage temp	300K	150K	300K	20K	290K
Heatlift	1.0W	0.2W	1.2W	0.014W	1W
Input Power	44W	100W	40W	70W	2W

Table 4-1: Typical Cryocooler Performance Parameters

4.1 Requirements and Constraints

The most relevant requirements and constraints are summarised below:

- Models must be widely available to the thermal systems engineering community. ESARAD/ESATAN is ESA standard and the packages well known within the community.

- A significant constraint on development is a lack of data. Commercial manufacturers supply data sheets but the data presented is often difficult to apply to the thermal system being analysed. Also, many of these coolers are based on relatively new technology and have not been widely used for space applications, leading to a lack of data.

- When modelling interface temperatures, it should be clear which side of the interface is relevant, as there may be a significant temperature difference between the two sides.

- It is essential that the speed of execution and memory requirements are such that implementation of a cooler model does not lead to unacceptable CPU times. Any thermodynamic computation is likely to slow down the run-time of the models.

- It is essential the system is robust and handles errors in a well-defined manner. Routines must be in place to ensure input parameters and calculations are valid. The routines must show the nature of the error in a helpful way.

- Documentation must be available to describe the operation and implementation of the models. Training required must be minimal and if possible operation must be largely intuitive for anyone familiar with thermal modelling methods.

- Models must be fully tested and the test programme documented. Tests must show the models function for a number of scenarios and that they accurately predict performance.

- In the future it is likely that the cooler library will be extended to include different types of coolers. The development process must be clearly documented to allow this.

- The level of accuracy must be considered in the context of functional and non-functional requirements. It must not be so high as to impose undue constraints on the required detail in a system model. Sufficient representation of boundary stages is required but the level of detail there may be minimal. A table such as the following may be useful.

Data item	**Cooler type**				
	Single-Stage Stirling	**Two-Stage Stirling**	**Pulse Tube**	**JT**	**Peltier**
Cold head temp	±2K	±1K	±2K	±0.1K	±1K
Heat lift	±0.1W	±0.05W	±0.1W	±1mW	±0.1W
Input power	±3W	±3W	±3W	±3W	±0.5W

Table 4-2: Suggested Format for Specifying Model Accuracy Requirements

The following items have been identified as those being the most important to understand the capabilities of the cooler, the resources consumed and the impact on other spacecraft budgets:

Essential data required by user

- Final operating temperatures of the cryocooler
- Cryocooler heatlift
- Cryocooler dissipated power at precooler stages and warm end components
- Input power needed by the cooler system
- Non-operational heat loads

Desirable data required by user

- Thermal links between cooler and spacecraft
- Heat lift at non-nominal temperatures
- Dependence on the heat rejection temperature and the stability of this level

4.2 Specific Software Packages

The requirements and constraints identified have been used to identify feasible options for a software package or language with which to develop cooler models. The relative merits of the various options identified as suitable for more detailed analysis are summarised below.

Method	Advantages	Disadvantages
ESARAD /ESATAN	• Standard ESA thermal engineering tool • Familiar to thermal engineers • Provides submodel functionality • Flexible format - $ELEMENT • Can handle large models • Suitable for whole project life cycle	• No diagrammatic representation
SINDA, IDEAS/TMG etc	• In built thermal solvers • Flexible format	• Not standard ESA tool • Expensive
Thermo-hydraulic solver	• Additional functionality over pure thermal solvers	• Expensive • Not widely used by thermal engineers • Longer processing time
VB within Excel/Access	• Widely available • Diagrammatic representation possible • Underlying databases available	• Requires user to interface data within system model • Compatibility with Unix
VB + ThermXL	• Easy interface • In built thermal solvers • Low cost	• Not widely used
GUI	• Easy user interface if well designed • Diagrammatic representation possible	• Inflexible format • User must include data in system model
Web browser interface	• Easy user interface if well designed • Widely available • Easy to update • Diagrammatic representation possible • Low cost	• User must include data in system model • Maintenance of web server • Reliant on network

Table 4-3: Summary of Advantages and Disadvantages

The emphasis of the study is system modelling rather than cooler selection and as such models should enable the user to analyse whether a cooler works or doesn't work for a particular application. There already exist packages that assist with cooler selection. For example, Melcor's Aztec helps the user choose a Peltier product to suit their needs. These packages are extremely useful but don't provide a unified approach to cooler selection and system modelling. The user must enter extracted data into their own system model to assess the cooler's impact. Packages such as ESATAN or ThermXL offer an advantage in that the cooler models are integrated with a system level model. A 'pure' thermal formulation such as ESATAN will have advantages over thermo-hydraulic solvers. Thermal solvers are well understood by thermal engineers and are likely to be faster and more reliable. ESATAN is the most common tool used and it is a tool fully supported by ESA. For this reason, it has been selected as the focus for prototype development. Conversion utilities are available for translation to other thermal packages, although these tools are not always robust.

5 Model Descriptions

5.1 Stirling Cooler Model Description

For the purposes of modelling the cooler the real performance can be derived from measured data, as thermodynamic calculations are too computationally intense. In any event, subtle differences that arise between cooler builds would still need to be implemented.

A typical single stage system comprises of a pre-regulator (if required), drive electronics, a compressor, displacer body, cold end and cold end interface. The pre-regulator and electronics can be considered as separate coupled objects. The other items are linked. The compressor and displacer bodies are linked with a Copper (or Stainless Steel) pipe. The displacer body is connected to the cold end via the cold finger. This must be taken this into account for non-operating conditions. The cold end is connected to the cold end interface by a thermal link. Harnesses to the cold end are not included as only thermometry is required which is considered to be an instrument issue.

Cooling power is calculated in two steps; first input power from compressor stroke and then cooling power from input power. Input power follows a quadratic law as a function of stroke with coefficients evaluated at various temperatures from measured data. Cooler performance changes as the heat sink temperature is varied with cold tip temperature increasing with heat sink temperature. A thermal link connects the cold finger to the item to be cooled. The contact conductances for the electronics are calculated in the same manner as for any electronics box.

5.1.1 Extension of model to two-stage Stirling coolers

Two-stage cooler cooling power is typically expressed as a two-dimensional load map graph with cooling power of each stage varied according to the temperature of that stage. Several methods of modelling two-stage coolers have been tested at RAL. For example:

- Distinct arrays of data for each stage heat lift
- Two-dimensional arrays of data that combine the relative heat load on the two stages
- Polynomials that model heat lift over the entire temperature range
- Subroutines comprising logical expressions to identify an approximate temperature range, followed by polynomials derived to model performance in that range

While some methods produce reasonable results it has been found that the models are not robust and numerical instabilities can occur. This is particularly true for non-nominal conditions and occurs because the heat load and temperature for the two stages are connected. Multiple steady-state results are possible from a single starting point and thus the results are dependent on control constants and solution routines used by the solver. It has been the experience of the author that a more robust way of modelling the performance of a two-stage cooler is to hold each stage at a boundary temperature, calculate the heat lift required and compare this with load maps. After discussions with cooler manufacturers, no other suitable method was suggested without resorting to detailed thermo-dynamic modelling. For this reason it is suggested that two-stage coolers are not investigated further using the identified methodology in this study. A system using arrays of performance data that can be interpreted by the user is likely to be more robust.

5.2 Pulse Tube Cooler Model Description

As with the Stirling cooler, the real performance can be derived from measured data as thermodynamic calculation would be too computationally intense and subtle differences arising between cooler builds would still need to be implemented.

Of the four main types suitable for space applications, classified as basic, orifice, double inlet and thermo-acoustic, we are concerned with the single stage orifice type. The components are very similar to those for a Stirling cooler; in particular the compressor, electronics and pre-regulator can be considered identical. The displacer is replaced by a pulse tube/regenerator stack combination. There are several different forms that this may take and we are interested in the in-line and u-shaped configurations. The compressor and pulse tube bodies are mounted to the spacecraft structure at their respective warm end interface flanges. The transfer line links the compressor and the pulse tube bodies. For a u-shape architecture, the warm ends of the pulse tube and regenerator are connected to the mounting interface. These thin wall tubes are a low conductive link to the cold end and contribute to the parasitic loads. For the in-line configuration only the regenerator is connected to the warm interface. In general the parasitic load for Pulse Tubes is larger than for Stirling coolers. These losses must be taken into account for non-operational cases.

The cooling power can be calculated from the input power in the same manner as described for the Stirling cooler. Although there will be less variation between Pulse Tubes of the same design, it is possible to tailor the design to suit a particular application. It is therefore clear that each cooler should be characterised individually. Performance is usually characterised in terms of operating parameters such as compressor stroke, frequency and heat rejection temperature. Input power follows a quadratic law as a function of stroke with coefficients evaluated at each temperature from measured data. For a given input power, the cooling power of the cooler decreases, or correspondingly for a given heat load, the cold end temperature increases, as the heat rejection interface temperature is increased.

5.3 4K Joule-Thomson Cooler Model Description

Stand-alone Joule-Thomson systems can achieve temperatures of 65K, but with a precooler they can go as low as ~4K. A RAL Helium based cooler with mechanical compressors and a base temperature of ~4K has been selected for the Planck mission and this type is discussed here. The main components of such a system are as follows:

- Two compressors to provide high and low pressure gas
- Ancillary plumbing including a getter and filter to ensure gas purity
- Cold temperature plumbing including heat exchangers and filters
- 4K cold end liquid reservoir
- Harness to cold end – heaters are required for gas purification
- Electronics unit to control drive, housekeeping data and getter

Precooling to ~20K is required and this must be represented in the system level model. It can be achieved active or passive cooling methods. Performance depends on compressor pressure, mass flow rate, heat exchanger geometry and mechanical configuration. At the warm end, requirements on electronic components mean the electronics unit will have to lie within a temperature range of approximately 0°C to 40°C.

Thermo-dynamic modelling is computationally intense and thus it is proposed that the adopted approach involves taking available performance data and deriving parametric equations to simulate that performance. Input power is high compared to other cooling cycles. Efficiencies as high as 85% can be achieved at the power amplifiers, but the effective efficiency is lower because power used for gas cleansing and telemetry must be taken into account. Precooling loads from the heat exchangers can be represented as a function of precooling stage and compressor temperatures, derived from theoretical modelled values and measured data. For a fixed compressor pressure and coldhead temperature cooling power can be modelled as a function of the temperature of the 20K precooling stage. Coldhead temperature is a function of the pressure supplied by the compressors. Fluctuations will also be induced by temperature changes in the precooling stage. A linear dependence is valid for small temperature changes. It should be noted that this type of fluctuation is dependent on the intrinsic characteristics of a particular system and thus is considered outside the scope of this study. For non-operational cases, parasitic loads will be due to conductance from the pipes and cryoharness.

5.4 Peltier Cooler Model Description

The Peltier Effect is defined as the resulting change in temperature at the junction of two dissimilar metals produced when an electric current flows through it. Practical Peltier modules exploit the effect to act as small coolers and are particularly useful when moderate cooling is required. Modules can be connected in parallel to provide additional cooling.

Modules consist of semi-conductors connected by a metallic conductor and sandwiched between two ceramic plates. When a voltage is applied, heat from the cold side is absorbed and rejected at the warm side. Reversing the voltage polarity will cause the reverse effect, heating the previously cooled face. They are therefore suitable for use in precise temperature control applications, providing control to better than ±0.1°C. They are typically used for local cooling applications when only small changes in temperature are required and are widely available commercially, 'off the shelf'. Multi-stage modules are available but efficiency is reduced when large temperature gradients are required.

The power at a junction is directly proportional to the current, I, flowing across it and the time for which it flows. The module's Peltier coefficient depends upon the temperature and material of the junction but is independent of the temperature of the other junction. The effect can also be described in terms of the Seebeck coefficient of the module, which is equal to the Peltier coefficient, divided by the absolute temperature. This is a more usual means of definition for commercially available Peltier modules. On a practical level, performance depends on the temperatures of the two sides, semiconductor type, supply voltage and current and any power dissipated on the cold side.

The heat removed from the cold side is the difference between the Peltier cooling effect and the Joule heating effect (I^2R heating), plus heat conducted from the hot to the cold side. The material properties of a module can be approximated by a constant or modelled as temperature dependent. Manufacturers data sheets often give temperature dependent equations for these properties based on a polynomial with specified coefficients for particular modules. It would be possible to define a database of coefficients for library modules or to apply a correction factor to a standard equation.

6 ESATAN Implementation

The submodel functionality of ESATAN, in which a top-level model can contain several submodels, will be familiar to most users. Definition can be either 'explicit' or 'implicit'. When giving an explicit definition the user manually defines a submodel within the main model file, whereas implicit definition involves including a previously defined model, as would be the case here. Implicitly defined models can either be non-preprocessed or preprocessed. For non-preprocessed models a definition is called from the user's file base, using the $ELEMENT keyword, and is used as a template. Actual values are then substituted for standard variables within the template. Preprocessed submodels are included using the $EXTERNAL, $REPEAT or $VIRTUAL keyword. The user can make then changes to the model through edit commands.

Using preprocessed models means the user cannot see the source code. This is an advantage in that proprietary data and equations can be used, but also means the user does not have good visibility of what is included. There is also an issue of cross-platform compatibility. For this reason, the implementation method selected makes use of the non-preprocessed $ELEMENTS functionality. FHTS is an extension to ESATAN that enables thermo-hydraulic solution of fluid networks. Users may already be familiar with an $ELEMENTS library of fluid-loop components included with FHTS which could be extended to cooler models within ESATAN.

Once a cooler model has been included within a system level model it is necessary to define the interfaces between the two. Coolers can easily be coupled to the system model by defining couplings within the $CONDUCTORS block of the main model. Node numbers are not restricted as they are always preceded by the relevant submodel name. Entities (such as areas and capacities) within the cooler submodel can also be referenced using standard syntax. The $SUBSTITUTIONS block is used to create substitutions of literal text strings within the element submodel. In this way a generic model can be written for each cooler type and the user can vary specific variables such as input power.

System-level prototype models have been produced with the aim of establishing a practical methodology for further development. Variable input data, required conductive links and calculated outputs are given. During future development it would be possible to make additional variables available for substitution.

7 Verification

Simple system level models have been created in order to conduct basic functional testing of prototypes. When integrated, all of the prototypes successfully ran without causing ESATAN error messages. They produced the correct type of output, that is, the calculated output variables were all of the right form (real numbers) and of the correct order of magnitude. Execution time for a simple system model was of the order of 1 second and larger models showed no significant increase.

In-flight data, lab tested data and manufacturers modelling software have been used to conduct further validation for selected cases. For all cases the models were shown to produce realistic results with reasonable accuracy. No high accuracy requirements have been placed on the verification at this time, as these are prototypes designed to verify the methodology only. However, 25% is a typical margin given for preliminary system level analyses and all prototypes had errors well within these bounds. It should be noted that the models were created and verified using specific coolers in order to verify the modelling methodology. There is no guarantee that the results will be correctly represent cooler performance in all circumstances. If the models are further developed then it will be necessary to extend the models to model a wider range of coolers.

It is clear that full testing is necessary when models are further developed but this preliminary testing has shown the validity of the methodology selected. Examples are given below:

- Validation against a wider range of measured data
- More in-depth runtime checks
- Testing of incorrect input parameter types
- Testing of out of range input parameters

8 Summary and Recommendations

This report has summarised the findings of study to investigate potential methodologies for developing cryocooler model components that can be used by system thermal engineers to carry out system level thermal analyses. No such models currently exist in an accessible form for mission level designers and for each mission it has been necessary to create these models. Below are a summary and recommendations for the future developments.

Literature review: Few published papers were found on the system level modelling of cryocoolers in space. Although this modelling has undoubtedly carried out it is not widely reported in the available literature. Many references were found concerning modelling of individual coolers

Existing software: There currently exist many packages that can be used when selecting coolers for space missions. However, the emphasis of this study is on system modelling rather than merely selection. The CSIM software created by the Aerospace Corporation may be an interesting tool for system analysis. Although it has not been possible to obtain a copy a request is under review.

Suggested methodology: It is recommended that coolers be represented as mathematical objects to be included within nodal network system level models. Internal thermodynamic calculations are computationally intense and the level of detail produced is not necessary for this type of system level analysis.

Multi-stage cooling: It is recommended that multi-stage coolers, and in particular two-stage Stirling coolers, are not included as part of this methodology. The thermo-dynamics of the heat lift balance between the two stages is complex and temperature dependent. This can lead to numerical instabilities within a system level model and multiple solutions are possible for a given set of initial conditions. Inclusion of a simple model for system analysis could easily lead to incorrect and misleading results. It is suggested that comparison of heat lift requirements from a system model with cooler heat lift load maps is likely to be more reliable.

Suggested implementation: Use of the $ELEMENTS functionality within ESATAN is suggested as the preferred implementation. ESATAN is ESA's standard thermal modelling tool and is well understood by thermal engineers. There already exists a library of standard model elements that can be used as submodel templates. Extension of this library to include coolers would be relatively simple and would provide a valuable tool for system level modelling. When using this method it is important that the method of integration for the cooler models is made clear, in particular for coolers requiring precooling.

Peltier elements: Alstom are developing their own version of a Peltier model. The model is developed as an element within ESATAN and is currently at the development stage.

Extension of cooler library: Only generic cooler models have been created but the methodology could be extended to include many specific examples of cooler types. It is also recommended that other types of cooler such as 3He Sorption and Dilution refrigerators be considered for inclusion, though the thermodynamics may be too complex. Open cycle coolers could also be included.

Further testing: Currently only prototypes have been developed and it is recommended that more detailed models are created and thoroughly tested to ensure the models are robust and will only allow their use in the correct operational environment.