

CRANFIELD UNIVERSITY

Joseph Palmer

Design Concepts for Cryogenic Cooling Systems for All-Electric Thrust Aircraft Propulsion Systems

School of Aerospace, Transport, and Manufacturing

Doctor of Philosophy Thesis

Academic Year 2015-2016

Supervisors: Dr. Essam Shehab and Dr. Ip-Shing Fan

January 2016

CRANFIELD UNIVERSITY

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING

Doctor of Philosophy Thesis

2015-2016

Joseph Palmer

Design Concepts for Cryogenic Cooling Systems for All-Electric Thrust Aircraft Propulsion Systems

Supervisors: Dr. Essam Shehab and Dr. Ip-Shing Fan

January 2016

This thesis is submitted in fulfilment of the requirements for the degree of Doctor of
Philosophy

© Cranfield University 2016. All rights reserved. No part of this publication may be
reproduced without the written permission of the copyright owner.

Abstract

The aim of this thesis is to investigate concepts and possibilities for cryogenic cooling systems within future superconducting all-electric thrust aircraft (AETA) electrical networks. The research comprises of a combination of qualitative and quantitative analysis, following the systems engineering process where possible. The thesis presents a modified version of the Rolls-Royce systems engineering process suitable for early stage conceptual design that was used to enable decision-making analysis of conceptual cryogenic systems. The research has led to a robust choice of cryocooler, a toolset capable of design space analysis, and determination of where future research efforts should be concentrated for eventual successful implementation.

The thesis begins by gathering information from literature about the various topics of expertise in this project, and then taking a systems engineering approach to design using the Rolls-Royce process as a guide. The most likely concept for cryocooling was identified through qualitative analysis as the reverse-Brayton cycle through function means analysis. A set of numerical models for superconducting machines and cables were developed to examine the interrelationships that exist within a basic superconducting electrical network. Two cryocooler models were generated; a single-stage and a two-stage reverse-Brayton cryocooler.

It was found that the single stage option could only be used for the MgB_2 liquid hydrogen-cooled concept. The two-stage design was deemed feasible for the MgB_2 liquid methane-cooled concept and for the BSCCO liquid methane and air cooled concepts. Furthermore, it was found that after overall temperature configuration, the compressor and turbine polytropic efficiencies were the most critical technologies to develop.

The key contributions to knowledge include a set of design assessment tools that can rapidly assess the feasibility of high-level cryocooler concepts. The development of the world's first fully superconducting and cryogenic support system models that can be used to determine future research direction are also a key contributions. The key industrial benefit to the sponsor, Rolls-Royce plc, is a clear indication of which concepts are feasible for cryogenic cooling systems, along with a toolset that

advances the companies capability in this research area. This will prove valuable in proposed future projects, most crucially as distributed propulsion technology matures and the need for superconducting components grows. Furthermore, identification of the compressor and turbine as the most critical technologies to develop highlights that Rolls-Royce's expertise could be used to commercial advantage if high-power cryogenics are ever required.

Keywords: Distributed Propulsion, Cryogenics, Superconductors, Systems Engineering

Acknowledgements

The author would like to first and foremost formally thank the institutions and organisations that have given me the opportunity to further my studies and to work on such an interesting, novel, and challenging area of engineering. I would like to thank Cranfield University, Rolls-Royce, Airbus Group Innovations, and the Engineering and Physical Sciences Research Council for funding and support over the last four years.

I would also like to formally thank my academic supervisor, Dr. Essam Shehab, without whom this research would not have been possible. Your continuing guidance and support has allowed me to flourish as a developing researcher. I would also like to thank my industrial supervisor, Mark Husband, for his continuing advice and support. Again, without your help, this thesis would not have been possible. Both of you have endured my persistent requests for advice for years, and for that alone, you deserve recognition beyond that which I can bestow! I would like to thank Mark Halliwell at Rolls-Royce for his advice and support during the course of the research also, and for enabling me to work with the prestigious company Rolls-Royce, whom I've wished to work with for all of my adult life.

I want to send a thank you to all of the staff at Cranfield University including Dr. Ip-Shing Fan, Dr. Craig Lawson, Dr. Kim Blackburn, Prof. Peter Malkin, Prof. Riti Singh, Prof. Pericles Pilidis, and to anyone I have missed out. I would also like to thank my colleagues and fellow students at Cranfield University for making my time both memorable and enjoyable whilst studying. You have all been fantastic sources of support and guidance, and I have enjoyed working with you immensely.

I would like to thank all of the staff within the departments of Rolls-Royce, notably the staff in the SRC including Paul Miller, John Cullen, Lorenzo Raffaelli, Dimitris Triantafyllidis, Andrew Rolt, and Rory Stieger. I also want to thank everyone in EPACS, notably Kevin Daffey and Chris Bright. I wish to also thank Airbus Group Innovations for their support during modelling work, with a special thanks to Fred Berg and Graham Dodd. Without support from these industrial partners, this research could not have reached the conclusions it generated, so thanks to you all.

I would also like to thank my friends and family, particularly my dad, John Palmer, and my sister, Lucy Palmer, and my many other friends and family who have been there for me. Without your continuing advice, support, shoulders to cry/lean/pound on, I don't think I could have gotten through this era of my life. Through blood, sweat, and many, many tears, this thesis has only been possible through continuing support from you all, so from the bottom of my heart, thank you all.

I wish to sincerely and regrettably acknowledge those who have left us during the course of my study. First and foremost, I wish to thank my mum, Tina Palmer, who sadly passed away during the course of this research. Despite never getting to see me graduate for a second time or finish this research, her shining example of resilience in the face of extreme adversity constantly motivates me, and she has been and continues to be my source of light through the toughest times I've ever encountered. The incredible courage she showed during her fight against cancer and unwavering love and support for me throughout my life will be with me until the day I die. I'll love you always, and you'll always be deeply missed, but never forgotten.

I also would like to thank both of my Grandfathers, Brian 'Ernie' Norris, and Fred Palmer, who also sadly both passed away during the course of this study. Both were inspirations from a generation that lived through an era in history with hardships and challenges worse than I can possibly imagine. I shall toast you both during my graduation and successes in life, and continue to remember your influence. Thank you both.

My final thought, is that this period of study and research has changed me for the better. I believe doing this PhD has made me a better person, researcher, and engineer, and through long nights of coffee, frustration, and keyboard abuse, I've somehow made it through mostly intact. So, thanks again to all who made it possible.

Contents

Abstract	i
Acknowledgements	iii
List of Figures	ix
List of Tables	xvi
List of Acronyms	xvii
List of Publications	xx
Journal Papers	xx
Conference Papers	xx
Chapter 1. Introduction	1
1.1. Project Motivation and Background	1
1.2. Problem Definition	7
1.3. Research Aim and Objectives	10
1.4. Research Scope	11
1.5. Industrial Sponsor Overview: Rolls-Royce plc	13
1.6. Thesis Structure	14
Chapter 2. Literature Review	17
2.1. Introduction	17
2.2. Aircraft	20
2.3. Superconductors	24
2.4. Electrical Components	30
2.5. Cryogenics	37
2.5.1. Thermodynamic Cycles and Techniques	37
2.5.2. Cryocoolers and Fluid Transfer	45
2.5.2.2. Pulse Tube Cryocoolers	48
2.5.2.3. Stirling Engine Cryocoolers	49
2.5.3. Fluid Transfer Cooling	50
2.6. Cryogenics	50
2.6.1. Liquid Hydrogen	50
2.6.2. Liquid Methane	52
2.7. Support Systems and Cryogenic Architecture	53
2.7.1. Thermal Shielding	53
2.7.2. Operational Procedures	55

2.8. Research Gap Analysis.....	57
2.9. Summary.....	57
Chapter 3. Research Methodology	59
3.1. Introduction	59
3.2. Adopted Research Methodology	59
Chapter 4. Stakeholder and Requirements Analysis.....	68
4.1. Introduction	68
4.2. Stakeholder Identification and Selection	69
4.3. Key Stakeholder Interviews and Requirements Capture	74
4.4. Key Requirement and Requirement Type Identification	82
4.5. Discussion.....	87
Chapter 5. Functional Requirements Modelling, and Analysis	90
5.1. Introduction	90
5.2. Functional Requirement Capture	91
5.3. Mission Profile and Modes of Operation	92
5.4. Functional Modelling	94
5.5. Functional Model Analysis	99
5.6. Functional Analysis Discussion	112
Chapter 6. Systems Engineering Process Adaptation and Concept Selection..	114
6.1. Introduction	114
6.2. Rolls-Royce Systems Engineering Process Overview	114
6.3. Rolls-Royce Systems Process Limits and Adaptation.....	118
6.4. Concept Selection Overview	123
6.5. Function Means Analysis	123
6.5.1. FMA Solutions	125
6.5.2. Solution Elimination Rationale and Final FMA.....	132
6.6. Completed FMA and Concept Selection	142
6.7. Discussion.....	145
Chapter 7. Superconducting Network Modelling	148
7.1. Introduction	148
7.2. Superconducting Machines.....	151
7.2.1. Machine Topology	151
7.2.2. Input and Output Parameters and Relationships	156

7.2.3.	Machine Dimension and Mass Estimation	157
7.2.4.	Final Machine Model Overview.....	161
7.3.	Superconducting Cables	165
7.3.1.	Superconducting Cable Topology.....	165
7.3.2.	Superconducting Cable Model Overview.....	167
7.4.	Power Electronics	170
7.5.	Discussion.....	171
Chapter 8.	Cryogenic Cooling System Modelling.....	176
8.1.	Introduction	176
8.2.	Reverse-Brayton Cycle Cryocoolers	176
8.2.1.	Overview.....	177
8.2.2.	Assumptions.....	180
8.2.3.	Single Stage	182
8.2.4.	Double Stage.....	184
8.2.5.	Other Configurations	187
8.3.	Modelling.....	189
8.3.1.	Modelling Method and Mass Estimation	189
8.3.2.	Single Stage	194
8.3.3.	Double Stage.....	201
8.4.	Discussion.....	213
Chapter 9.	Modelling Results Analysis.....	215
9.1.	Introduction	215
9.2.	Cryogenic Cooling System Observations.....	215
9.2.1.	Single Stage Model	215
9.2.2.	Two-Stage Model	225
9.2.3.	Concept Comparison.....	232
9.2.4.	Model Limitations.....	236
9.3.	System Level Interactions and Sensitivities	237
9.4.	Discussion.....	244
Chapter 10.	Discussion and Conclusions.....	247
10.1.	Introduction	247
10.2.	Methodology and Systems Process.....	247
10.3.	Concept Selection and Modelling.....	250

10.4.	Discussion of Results, Analysis, and Concepts	254
10.5.	Fulfilment of Research Objectives	255
10.6.	Contribution to Knowledge	257
10.7.	Overall Conclusions	258
10.8.	Recommendations for Future Work	259
	References	262
	Appendix A	272
	Appendix B	286

List of Figures

Figure 1-1 - ‘S’ Curve graph of aircraft engine development (Parker, 2013)	2
Figure 1-2 - NASA’s N3-X Blended Wing Body (BWB) airframe concept (Armstrong <i>et al</i> , 2012)	3
Figure 1-3 – Distributed propulsion schematic	4
Figure 1-4 – Boundary layer ingestion (BLI) schematic.....	5
Figure 1-5 – Copper and superconducting cable examples, both with a 12,500 A current rating (CERN, 2015).....	6
Figure 2-1 – Literature review topic scope including major sub-topics (Acronyms described in list of acronyms).....	17
Figure 2-2 – Literature review strategy shown in order of capture	18
Figure 2-3 – NASA’s N3-X BWB concept electrical schematic showing propulsion system configuration (Armstrong <i>et al</i> , 2012).....	20
Figure 2-4 – Boeing and Cranfield Aerospace’s X-48B test aircraft (NASA, 2010) ..	22
Figure 2-5 – DEAP concept schematic overview showing location of the BLI intake (note the number of fans shown is not representative of the likely true number) (Wright <i>et al</i> , 2015).....	23
Figure 2-6 – Examples of equal current carrying capacity cables; conventional in the background, with superconducting in the foreground (CERN, 2006)	24
Figure 2-7 – Meissner effect on a superconducting sphere; left, $T > T_c$; right, $T < T_c$	25
Figure 2-8 – Meissner effect of a HTS material (Warwick, 2000)	26
Figure 2-9 – Comparison of wires and strips with equal penetration depths, λ_L , and with equal areas, A	27
Figure 2-10 – Molecular structure of MgB_2	28
Figure 2-11 – YBCO molecular structure and physical appearance.....	29
Figure 2-12 – BSCCO molecular structure and physical appearance	30
Figure 2-13 – Eddy currents shown in a superconducting inductor (Masson and Luongo, 2005)	31
Figure 2-14 – Superconducting material phase diagram showing the critical parameter relationships for a superconducting material.....	32
Figure 2-15 – Example of a BSCCO-wound rotor superconducting machine, with cooled copper stator (Gamble <i>et al</i> , 2006)	33

Figure 2-16 – Siemens 36.5 MW superconducting motor for marine propulsion	34
Figure 2-17 – Graph showing Paschens law; breakdown voltage results in arcing from the conductor (McAllister and Crichton, 1987)	36
Figure 2-18 – An example of a cross-section of a superconducting cable (SupTech, 2013)	36
Figure 2-19 – Adiabatic Reverse Brayton cycle and T-s graph (Boles, 1998)	38
Figure 2-20 – Stirling cycle schematic and P-V graph (Bole, 1998)	39
Figure 2-21 – Vapour-Compression cycle as used in air conditioning systems (Rodway, 2009)	40
Figure 2-22 – Schematic and T-s diagram of the Hampson-Linde liquefaction cycle (Bole, 1998)	43
Figure 2-23 – Dilution refrigeration practical example for the Planck satellite (Collaudin and Passvogel, 1999)	44
Figure 2-24 – Graph showing the optimum temperature ranges for some types of cryocooler (Jha, 2006)	46
Figure 2-25 – GM cooler schematic of operation phases (Boles, 1998)	47
Figure 2-26 – Pulse tube cryocooler schematic (Radebaugh, 2000)	48
Figure 2-27 – Solar array with Stirling cryocooler in Spain (Schlaich Bergermann, 2006)	50
Figure 2-28 – Temperature-Resistance graph of MgB_2 showing LH_2 range in red (Nagamatsu <i>et al</i> , 2001)	51
Figure 2-29 – Aerogel samples; the left picture is a 2.5 kg brick supported by a 2 g slice of Aerogel; the right picture is a flower being shielded from a naked blowtorch flame (NASA, 2004)	54
Figure 2-30 – Schematic diagram of multi-layered insulation (Keller <i>et al</i> , 1994)	55
Figure 3-1 – Project Phases 1-3	61
Figure 3-2 – Project phases 4-6	62
Figure 4-1 – Stakeholder map	70
Figure 4-2 – Stakeholder exclusion map with rationale for stakeholder exclusion or inclusion for further study	71
Figure 4-3 – Initial set of requirements tree diagram	75
Figure 4-4 – SRC electrical team leader requirements tree and key requirement selections	76

Figure 4-5 – SRC electrical team member requirements tree and key requirement selections	77
Figure 4-6 – SRC aerospace team member requirements tree and key requirement selections	78
Figure 4-7 – SRC senior aerospace team member requirements tree and key requirement selections	79
Figure 4-8 – EPACS team member requirements tree and key requirements selections	80
Figure 4-9 – Head of EPACS requirements tree and key requirement selections....	81
Figure 4-10 – Final set of consolidated requirements with key requirements.....	82
Figure 4-11 – Final set of requirements with requirement type labels and exclusion rationale	85
Figure 5-1 – Functional Requirements Brainstorm Results	91
Figure 5-2 – Basic mission profile of the Boeing 777-200LR showing altitude on the vertical axis in feet.....	92
Figure 5-3 – Modes of Operation of the Cryogenic Cooling System	93
Figure 5-4 – Modes of operation with associated mission segments	94
Figure 5-5 – Higher Tier Functional Flow Diagram.....	95
Figure 5-6 – Lower Tier Functional Flow Diagram	98
Figure 5-7 – QFD House of Quality for Maintain Temperature at Load Mode	111
Figure 6-1 – Overall Rolls-Royce Systems Engineering Process.....	115
Figure 6-2 – Table showing the cost factors of fixing errors at various project stages (UK Systems Eng Council, 2009)	117
Figure 6-3 – Standard (left) and modified (right) Rolls-Royce systems engineering processes.....	119
Figure 6-4 – Customer excitement and satisfaction diagram	121
Figure 6-5 – Example of FMA	124
Figure 6-6 – FMA diagram showing all conceivable means of achieving the functions generated	126
Figure 6-7 – DREd solution rationale for ‘detect cooling demands’ function	134
Figure 6-8 – DREd concept rationale for detect quench function	135
Figure 6-9 – DREd concept rationale for exchange heat function	136
Figure 6-10 – DREd concept rationale for insulate components function.....	137
Figure 6-11 – DREd concept rationale for maintain temperature/pressure function.....	138

Figure 6-12 – DREd concept rationale for monitor cryogen levels function.....	139
Figure 6-13 – DREd concept rationale for transport/pump cryogen function.....	140
Figure 6-14 – DREd concept rationale for store cryogen function.....	141
Figure 6-15 – Final FMA diagram showing eliminated solution (red wording, crossed), accepted viable solutions (Dark green) and plausible solutions (light green)	144
Figure 7-1 – Example schematic power flow networks for AC/AC (Top) and AC/DC/AC (Bottom)	148
Figure 7-2 – Model validation strategy	149
Figure 7-3 – The major parts of a superconducting machine (Wright <i>et al</i> , 2015)..	153
Figure 7-4 – Survey of conventional machines for active length to active outer diameter ratios against volumes.....	159
Figure 7-5 – The relationship and curve fit for stator and rotor diameters of known conventional and partially superconducting machines	160
Figure 7-6 – Graph showing the machine model generated variation in machine mass with machine power and machine rpm	162
Figure 7-7 – Superconducting machine model overview in Matlab Simulink.....	164
Figure 7-8 – Typical cross-section cutaway view of both conventional (top) and superconducting (bottom) 3-phase AC cable examples (Nexans, 2012).....	166
Figure 7-9 – Superconducting cable model overview.....	169
Figure 7-10 – The relationships between different cable current (A) values and frequencies (Hz) on the cable losses	172
Figure 7-11 – The variation in generator-to-cable system mass against machine speed for assumptions outlined in Tables B-1 and B-2 in Appendix B	173
Figure 8-1 – The difference between Brayton and reverse-Brayton cycles for both temperature-entropy (T-S) and pressure-volume (P-V) graphs (note: both cases shown are adiabatic for comparison purposes).....	178
Figure 8-2 – A reverse-Brayton cycle refrigerator showing components and relative thermodynamic process points 1-4 as shown in Figure 8-1	179
Figure 8-3 – A single-stage simple RBC and its associated T-S diagram	182
Figure 8-4 – A single-stage recuperated RBC and its associated T-S diagram	183
Figure 8-5 – A single-stage intercooled RBC and its associated T-S diagram.....	184
Figure 8-6 – A two-stage RBC with its associated T-S diagram.....	185
Figure 8-7 – A two-stage recuperated RBC design.....	186

Figure 8-8 – Single-stage recuperated RBC with J-T expansion valve and its associated T-S diagram	187
Figure 8-9 – Two-stage, multiple b-stage RBC design	188
Figure 8-10 – Specific mass curve for space Brayton turbo-alternators	192
Figure 8-11 – Relationship between cryocooler specific mass and Log_{10} of cryocooler input power for known RBC cryocooler examples	192
Figure 8-12 – Curve fit for all known reverse-Brayton cryocoolers with generated equation shown	193
Figure 8-13 – Single-stage RBC cryocooler with input-output flow shown by thick black arrows	194
Figure 8-14 – Cold heat exchanger model block and table of inputs, transfer functions, and outputs	195
Figure 8-15 – Turbine model block and table of inputs, transfer functions, and outputs	196
Figure 8-16 – HSHX model block and table showing inputs, transfer functions, and outputs	197
Figure 8-17 – Compressor model block and tables showing inputs, transfer functions, and outputs	198
Figure 8-18 – Motor, mass estimation, and input power model blocks with table showing inputs, transfer functions and outputs	199
Figure 8-19 – Full-model over view of the single stage RBC Simulink model	200
Figure 8-20 – Two-stage RBC showing parametric flow direction with black arrows	201
Figure 8-21 – Cold stage cold heat exchanger model block and table showing block inputs, transfer functions, and outputs.....	202
Figure 8-22 – Stage-to-stage temperature share model block and transfer function equation	203
Figure 8-23 – Cold stage turbine model block and table showing inputs, transfer functions, and outputs	204
Figure 8-24 – Intermediate heat exchanger model block and table showing inputs, transfer functions, and outputs	206
Figure 8-25 – Cold stage compressor model block and table showing inputs, transfer functions, and outputs	207

Figure 8-26 – Warm stage turbine model block and table showing inputs, transfer functions, and outputs	208
Figure 8-27 – Warm stage heat sink heat exchanger model block with table showing inputs, transfer functions, and outputs.....	209
Figure 8-28 – Warm and cold model blocks for the two-stage RBC model	210
Figure 8-29 – Warm stage compressor model block and table showing inputs, transfer functions, and outputs	211
Figure 8-30 – Two-stage RBC model overview showing all components of the model, inputs, parametric flow, and outputs.....	212
Figure 9-1 – Required input powers for a single stage cryocooler	217
Figure 9-2 – Cryocooler mass for a single stage cryocooler	218
Figure 9-3 – Required compressor pressure ratio for a single stage cryocooler with 1, 2, and 3 stage compressor regions shown between ratios 0 and 30.....	219
Figure 9-4 – Cryocooler overall efficiency for a single stage cryocooler.....	220
Figure 9-5 – The percentage of ideal efficiency achieved for a single stage cryocooler.....	220
Figure 9-6 – The target specific masses for a single stage cryocooler.....	221
Figure 9-7 – Required input power for heat sink and target cold temperatures for single stage cryocoolers.....	223
Figure 9-8 – Required pressure ratio for single stage cryocooled concepts at different heat sink and target cold temperatures	224
Figure 9-9 – The target specific masses of the heat sink and cold target temperature concepts for the single stage cryocoolers.	224
Figure 9-10 – Required input power for two-stage cryocooler.....	225
Figure 9-11 –The masses of a two-stage cryocooler	226
Figure 9-12 – Required compressor pressure ratios of a two-stage cryocooler	227
Figure 9-13 – The overall efficiency of two-stage cryocoolers.....	227
Figure 9-14 – Percentage of ideal efficiency achieved by a two-stage cryocooler .	228
Figure 9-15 – The variation in target specific mass of a two-stage cryocooler	229
Figure 9-16 – The required input power for two-stage cryocooler at different heat sink and cold target temperatures	230
Figure 9-17 – The two-staged average required compressor pressure ratios for two-stage cryocooler at different heat sink and cold target temperatures	230

Figure 9-18 – Target specific masses for two-stage cryocoolers for various heat sink and cold target temperatures	231
Figure 9-19 – Surface plots showing the required input power for both single stage (left) and two-stage (right) cryocooler designs	232
Figure 9-20 – Surface plots showing the cryocooler mass for both the single stage (left) and two-stage (right) cryocooler designs	233
Figure 9-21 – Surface plots showing the required pressure ratios for both the single stage (left) and two-stage (right) cryocoolers designs	233
Figure 9-22 – Surface plots showing the overall efficiency for both the single stage (left) and two-stage (right) cryocooler designs	234
Figure 9-23 – Surface plots showing the percentage of ideal efficiency achieved for both single stage (left) and two-stage (right) cryocooler designs	235
Figure 9-24 – Surface plots showing the target specific masses for both the single stage (left) and two-stage (right) cryocooler designs.....	235
Figure 9-25 – Sensitivity graph showing percentage mass variation against percentage input variation	238
Figure 9-26 – Sensitivity graph showing the cable mass sensitivity with input variables.....	242
Figure 9-27 – Sensitivity graph showing the variation in cable loss to input parameters	243
Figure 9-28 – Projected future development of reverse-Brayton cryocoolers (1990-2050)	245

List of Tables

Table 3-1– Phase 1 and 2 detailed breakdown of tasks.....	63
Table 3-2 – Phase 3 detailed breakdown of tasks.....	64
Table 3-3 – Phase 4 detailed breakdown of tasks.....	64
Table 3-4 – Phase 5 detailed breakdown of tasks.....	65
Table 3-5 – Phase 6 detailed breakdown of tasks.....	66
Table 5-1 – Flow Sensitivity Matrix for the Maintain Temperature at Load Mode...	101
Table 5-2 – FMEA for the Maintain Temperature at Load Mode	107
Table 7-1 – Superconducting machine loss types, mechanisms, suggested percentage share, and relevance to cryogenics.....	155
Table 7-2 – Superconducting machine model inputs, outputs, and transfer functions	157
Table 8-1 – All known reverse-Brayton cryocoolers with masses given (Breedlove, Magari and Miller, 2008, Chow <i>et al</i> , 2007, Crespi, 2012, Davis and Abhyankar, 2004, Swift, 1993, Swift <i>et al</i> , 1999, Zagarola <i>et al</i> , 2009)	192
Table 9-1 – Machine mass sensitivity to outputs.....	238
Table 9-2 – Table showing the machine loss sensitivities to changes in input parameters.....	239
Table 9-3 – Table showing the machine frequency sensitivities to changes in put parameters.....	240
Table 9-4 – Mass percentage variability with varied input parameters.....	241
Table 9-5 – Cable loss sensitivity to percentage variations in input parameters	242
Table 9-6 – Feasibility of cryocooler concepts at different temperature configurations	246
Table B-1 – Superconducting machine model assumptions table.....	286
Table B-2 – Superconducting cable model assumptions table.....	287

List of Acronyms

^3He – Helium-3

AC – Alternating Current

AETA – All Electrical Thrust Aircraft

ATC – Air Traffic Control

BLI – Boundary Layer Ingestion

BSCCO – Bismuth Strontium Calcium Copper Oxide

BWB – Blended Wing Body

CAA – Civil Aviation Authority

CERN - Conseil Européen pour la Recherche Nucléaire

CO_2 – Carbon Dioxide

COP – Coefficient of Performance

DC – Direct Current

DEAP – Distributed Electrical Aerospace Propulsion

DREd – Design Rationale Editor

EPACS – Electrical Power and Control Systems

EPSRC – Engineering and Physical Sciences Research Council

FAA – Federal Aviation Administration

FCL – Fault Current Limiters

FFD – Functional Flow Diagram

FMA – Function Means Analysis

FMEA – Failure Modes and Effects Analysis

FR – Functional Requirement

GM – Gifford McMahon

GT – Gas Turbine

HL – Hampson-Linde

HoQ – House of Quality

HP – High Pressure

HSHX – Heat Sink Heat Exchanger

HTS – High Temperature Superconductor

HX – Heat Exchanger

IC – Internal Combustion

ICMR – International Conference for Manufacturing Research

IET – Institute of Engineering and Technology
IHX – Intermediate Heat Exchanger
IP – Intellectual Property
ISABE – International Symposium on Air-Breathing Engines
ISO – International Organization for Standards
J-T or JT – Joule-Thompson
LCH₄ – Liquid Methane
LH₂ – Liquid Hydrogen
LHC – Large Hadron Collider
LHe₂ – Liquid Helium
LN₂ – Liquid Nitrogen
LNe₂ – Liquid Neon
LP – Low Pressure
LTS – Low Temperature Superconductor
MC – Magneto-caloric
MEA – More Electric Aircraft
MgB₂ – Magnesium Diboride
MLI – Multi-Layered Insulation
MRI – Magnetic Resonance Imaging
MTAL – Maintain Temperature at Load
NASA – National Aeronautics and Space Administration
NFPR – Non-Functional Performance Requirement
NFSR – Non-Functional Systems Requirement
NO_x – Nitrous Oxides
OR – Operational Requirement
PE – Power Electronics
PT – Pulse Tube
QFD – Quality Function Deployment
RBC – Reverse-Brayton Cycle
RPM – Revolutions per Minute
RPN – Risk Priority Number
RTD – Resistance Temperature Detectors
SA – Sensitivity Analysis

SC – Superconducting
SE – Stirling Engine
SN₂ – Solid Nitrogen
SRC – Strategic Research Centre
SS – Stainless Steel
STS ET – Space Transportation System External Tank
TRV – Torque per Rotor Volume
TSB – Technology Strategy Board
USAF – United States Air Force
UTC – University Technology Centre
VC – Vapour Compression
YBCO – Yttrium Barium Copper Oxide

List of Publications

Journal Papers

Palmer, J., and Shehab, E., (2016) “Modelling of Cryogenic Cooling System Design Concepts for Superconducting Aircraft Propulsion”, IET Electrical Systems in Transportation Journal, In Press

Berg, F., Palmer, J., Miller, P., Husband, M., and Dodds, G., (2015), “HTS Electrical System for a Distributed Propulsion Aircraft”, IEEE Trans. Applied Superconductivity, 2015, 25 (3), doi: 10.1109/TASC.2014.2384731

Conference Papers

Palmer, J., Shehab, E., and Husband, M., (2012), “Cryogenic Systems Study for Turbo-electric Distributed Propulsion Aircraft Solution”, More Electric Aircraft Conference on 20th November 2012, Bordeaux, France

Palmer, J., Shehab, E., and Husband, M., (2013), “Development of a Cryogenic Cooling System Model for Aerospace Propulsion”, Proceedings of the 21st International Symposium for Air-Breathing Engines, September 9-13, Busan, South Korea, paper no. ISABE-2013-1206

Palmer, J., Shehab, E., Fan., I. S., and Husband, M., (2013), “Quality Function Deployment and Sensitivity Analysis of Requirements of Future Aircraft Propulsion Cryogenic Cooling Systems”, Proceedings of the 11th International Conference of Manufacturing Research, September 16-20, Cranfield University, UK, doi: 10.13140/2.1.2264.7042

Palmer, J., Pagonis, M., and Malkin, P., (2015), “Configuration Options for High-Power, Low Weight Aerospace Superconducting Distributed Propulsion Cryocoolers”, Proceedings of the 22nd International Symposium for Air-Breathing Engines, October 25-30, Phoenix AZ, USA, Paper No. ISABE-2015-20203

Berg, F., Palmer, J., Bertola, L., Miller, P., and Dodds, G., (2015), “Cryogenic System Options for a Superconducting Aircraft Propulsion System”, Proceedings of the Cryogenic Engineering Conference (CEC) 2015, June 28th-July 2nd, Tucson AZ, USA, doi:10.1088/1757-899X/101/1/012085

Chapter 1. Introduction

1.1. Project Motivation and Background

The work described in this research thesis was carried out as part of a Rolls-Royce Industrial sponsor project involving a full-time placement at Rolls-Royce's Strategic Research Centre within their Electrical Systems and Measurement team. The work focusses on providing strategic system design to their aerospace sector.

Aviation is expected to grow at 4.7% per year (ATI, 2013). This growth is highly dependent on the control of operating costs. Two key factors in controlling this operating cost include fuel cost and future stringent emissions targets in order to minimise the impact of the growth (ACARE, 2011). It is perceived in the industry that current aircraft traditional tube-and-wing, turbofan-driven configurations, having been developed for more than 60 years, are beginning to see limited opportunities to achieve the step-change benefits required to achieve the latest targets. Rolls-Royce, in collaboration with airframers, is investigating future potential new aircraft with integrated propulsion systems in order to address these concerns. These new concepts involve the integration of new aircraft configurations and novel propulsion systems necessitating a new collaborative systems design engineering approach between airframers and propulsion system providers. Both the US and European aerospace sector are focussing on a more-electric solutions, involving the use of superconducting electrical technologies with their associated cryocooling systems. This work describes the method and delivery of design concepts in cryocooler solutions to support this collaborative work.

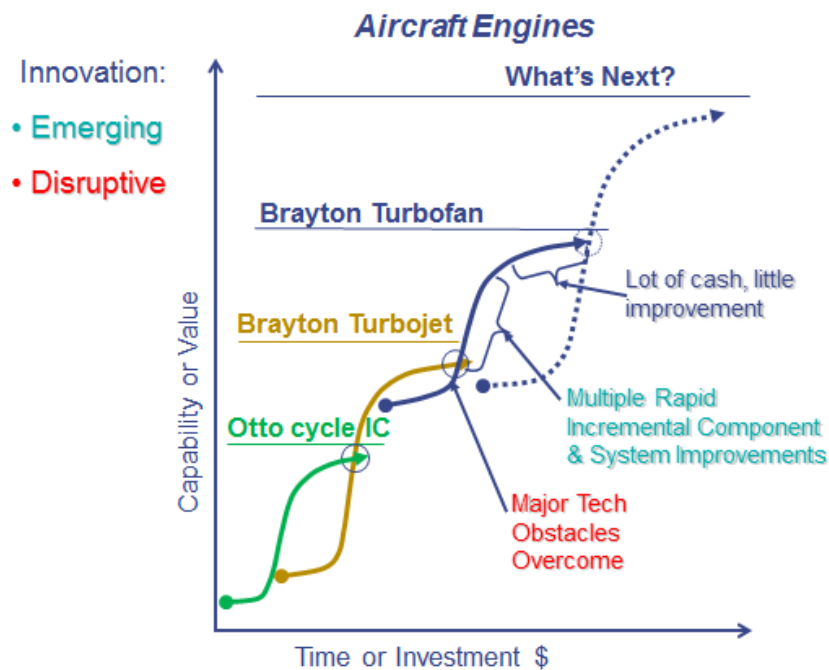


Figure 1-1 - 'S' Curve graph of aircraft engine development (Parker, 2013)

Figure 1-1 shows an 'S-curve' representation of the historical manner in which new aircraft revolutionary propulsion technology has been adopted. Typically a new propulsion method is discovered long before it begins to make financial sense; hence development initially is slow and costly. Early jet engines were conceived during the 1930's through efforts led by the UK and Germany, however realisation of practicable use was not realised until over a decade later (Rolls-Royce, 1986). The current gas-turbine solution employs Brayton turbofan technology which has been around for almost 50 years. Given this development period it is now perceived that ongoing development is now becoming more costly and delivering diminishing returns. The aviation industry is approaching the point on the S-curve whereby new methods of propulsion are being considered. This need is further compounded with air traffic set to double between 2010 and 2025 and with fuel supplies worldwide dwindling in availability (ACARE, 2011), there is an ever-increasing urgency with which these new technologies must be developed if aviation is to be environmentally sustainable.

Airframe designers and engine manufacturers are now working within their strategic centres to address these challenges through collaborative working relationships. Integration between airframe and propulsion systems such that overall benefits can be achieved is driving innovation, rather than the modular evolutionary improvement

methodology used at present. Systems engineering methods can highlight which systems aboard aircraft are closely linked with others, such that overall efficiency gains can be made where previously no known link existed. By investigating links between various systems, relationships can be established between incremental improvements of a modular nature, combining them to assess the overall benefits of a given system configuration. Systems engineering provides a clear, repeatable, reliable methodology of assessing complex problems such as the one presented in this thesis.



Figure 1-2 - NASA's N3-X Blended Wing Body (BWB) airframe concept (Armstrong *et al*, 2012)

For example, Blended wing body (BWB) airframes, shown in Figure 1-2, is one collaborative option considered as a major leap forward in terms of aerodynamics and integrated systems by industry leaders, with NASA, Airbus, and Boeing all beginning to investigate this promising airframe configuration. The primary benefits associated with BWB aircraft are perceived as:

- Reduction or elimination of parasitic drag on the fuselage and wing roots
- Increase in the lift-to-drag ratio
- Larger storage space within the aircraft for additional payload and systems
- Lower overall empty weight due to reduction in required wing box reinforcements
- Integrated propulsion systems

New propulsion configurations are also being considered as part of the integration of systems, to allow many previously undiscovered advantages to take place. With the current Brayton cycle the key efficiency challenges are thermal and propulsive efficiency. Thermal efficiency is approaching its theoretical maximum and would require new materials to deliver any reasonable levels of improvement. The main focus, in terms of efficiency improvement, focusses on propulsive efficiency that is largely achieved by increasing the bypass ratio. However, fan sizes are reaching practical limits imposed by the configuration of the aircraft. Traditional engine placements on pylons below the wing mean that the wing-to-ground clearance becomes a critical consideration when trying to increase the fan size (Gohardani, Doulgeris, and Singh, 2011). Fan blade material technology is also becoming a key area of research due to ever larger fan size requirements, pushing the limits of what is physically possible with current titanium and composite designs. Despite considerable development efforts in these areas, designers are seeking to explore other ways of increasing the bypass ratio. One of the most promising concepts for increasing the engine bypass ratio is to use distributed propulsion, whereby one gas turbine drives multiple fans or propellers leading to an increased swept area.

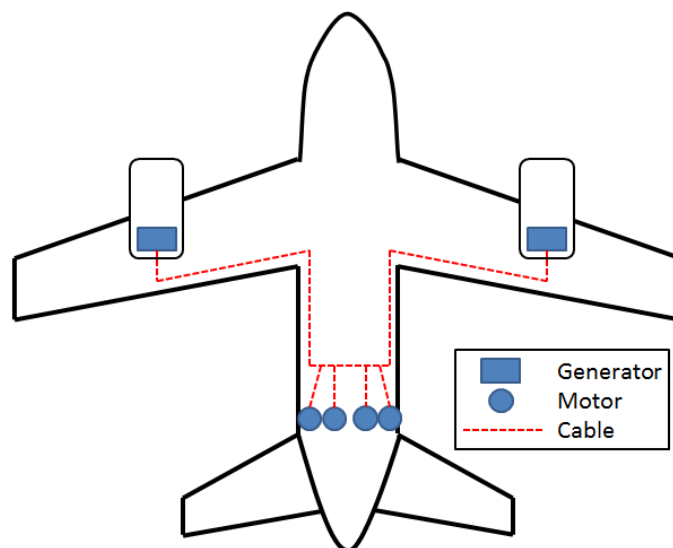


Figure 1-3 – Distributed propulsion schematic

Distributed propulsion (Figure 1-3) is not a new concept; many previous designers have highlighted this as a way of increasing the efficiency of aircraft (Kim, 2011). Present day iterations however are looking at ducted fan distributed propulsion placed at aerodynamically strategic locations around the airframe, where additional

benefits such as wake re-energising and boundary layer ingestion (BLI) can be realised (Figure 1-4).

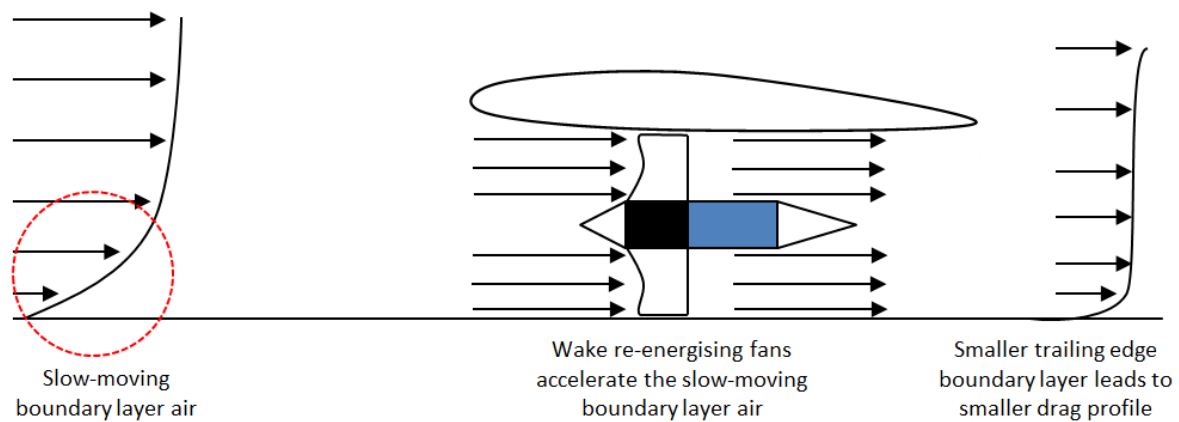


Figure 1-4 – Boundary layer ingestion (BLI) schematic

While there are different methods of distributing propulsion, including mechanical and pneumatic, to coincide with developments in more electric transportation (cars, trains and ships), electrically distributed propulsion is being considered in detail due to a number of perceived advantages. The advantages include:

- Freedom of propulsor placement
- High energy transmission efficiency
- Ability to separate thermal and propulsive efficiencies for the propulsion system
- Greater control
- Potential to utilise technologies being developed in the other transportation applications

The key caveat to using electrically distributed propulsion however is that to achieve favourable power densities that enable overall benefit over present day technology, machines and networks may have to utilise superconductivity.

Superconductivity is the phenomena exhibited by certain materials of the ability to carry current in DC with zero electrical resistance. Extremely high power densities can be achieved through use of superconducting components (Figure 1-5), with even very small conductors able to transport large currents with very little loss. Superconductivity is used in many industries ranging from MRI scanning to particle

acceleration and fusion research, mostly due to their ability to sustain high magnetic fields. Superconducting components for machines such as rotors have been developed in the past (Gamble *et al*, 2011), however to-date there are no fully superconducting electrical machines or comparable networks that exist. Therefore there are numerous electrical challenges that need addressing before any benefits can be accurately predicted. Superconductivity however is not without its own caveats; superconducting materials that currently exist require extremely low temperature environments in order to function normally, typically in the cryogenic temperature range (Ekin, 2006).

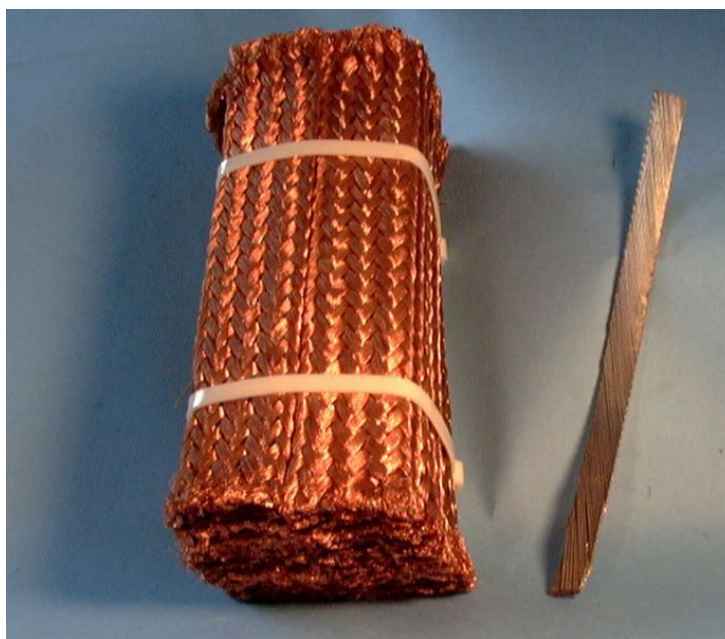


Figure 1-5 – Copper and superconducting cable examples, both with a 12,500 A current rating (CERN, 2015)

Cryogenic cooling systems are widespread throughout numerous industries. It is however when applying cryogenic cooling to aerospace problems that the commonly associated issues with cryogenics of weight and efficiency adds significant complexity to any study. Coupled with the high power requirements, the cryogenic cooling system required at present day technology performance will add significant weight to any superconducting propulsion concept, offsetting benefits gained through their use. This project aim is to formulate a design process for high-power aerospace cryogenic systems, through taking the systems engineering approach, identifying the

optimum choice of thermodynamic cycle and configuration based on a combination of qualitative and quantitative research methods.

1.2. Problem Definition

Part of successfully performing research of such a conceptual nature is to accurately define the problem. The best way to do this is to explore the challenges implying the complexity in the system, identifying areas that require significant improvement and assessing whether those areas can be suitably addressed within the bounds of this project.

Cryogenics is a well-established and understood field of science; however the application of cryogenics to the specific problem of high power superconducting networks is new. Superconducting machines are still only in their infancy in terms of practical use with some partially superconducting machines already in development (Masson and Luongo, 2005). At the time of writing however there has never been a fully superconducting machine demonstrated in practical form. This statement is particularly relevant when considering the cryogenic cooling system, because it means that the magnitude of thermal losses in any future superconducting network is not fully understood. In addition, cryogenic cooling requires a large amount of input power. This cannot be circumvented; the coefficient of performance of a cryogenic cooling system is given by:

$$COP = \frac{T_c}{T_h - T_c} \quad (1)$$

Where the hot (T_h) and cold (T_c) temperatures are the desired cooling point and rejection temperatures in Kelvin respectively. When considering that the COP is the ideal performance, as the cold temperature approaches 0 K, the COP dramatically decreases; hence cryogenic cooling systems are inherently inefficient as the desired temperature reduces. Typical actual efficiencies when cooling to 4 K from 300 K rejection are below 1%, with a maximum theoretical efficiency of only 1.3% given by equation (1) at these temperatures. When considering the coefficient of performance for a cryocooler (COP), the low temperatures necessary for superconductivity mean that considerably more power than is absorbed in the cryostat must be put in to the system. When fixing the rejection temperature and cold power in a cryogenic system, the required input power with respect to temperature follows a rough inverse-square

curve as given in equation (1). This non-linear relationship begins to describe how small changes within the cryogenic system input parameters could potentially have significant impacts on key output parameters, in this case the required input power and mass of the system. There will be a number of design trade-offs within the study also, meaning that there is likely to be an optimum scenario for any given concept or set of parameters.

The first major design trade-off challenge arises out of the previous optimum scenario statement when considering the performance of superconductors. A superconducting materials' current-carrying capability depends on three parameters; current density, magnetic field density, and temperature. For example if the temperature for a given superconductor is lowered, the current density and magnetic density parameters improve leading to improved electrical system performance. Decreasing the temperature however means that the cryogenic cooling system will have to work exponentially harder as described by equation (1). This effect can be observed in N3-X study where the potential cryogenic plant weight is between 25-34% of the total propulsion system weight depending on whether Bismuth Strontium Calcium Copper Oxide (BSCCO) or Magnesium Diboride (MgB_2) superconducting materials are used respectively (Brown, 2011). From a design perspective this means that the performance of the superconducting network will vary inversely to the performance of the cryogenic system. This presents the opportunity for an optimum design between the superconducting network and cryogenic system, whereby the design is determined effectively by the temperature input parameters.

The second major trade-off between the systems is the weight, whereby a larger superconducting network will result in a larger cryogenic system by definition, therefore requiring more fuel over any given mission. However, the efficiency of both the superconducting network and the cryogenic system is proportional to the size; hence the additional fuel required for the additional equipment may be offset by the efficiency gains made by increasing the network size. Currently it is unknown how much superconducting machines efficiency may increase with size, however cryogenic systems are better understood. Larger machines are more efficient than smaller machines in conventional electrical networks, and larger cryogenic systems result in an overall better efficiency. The key to understanding this will be to determine whether the increase in efficiency in fuel burn terms surpasses the

additional fuel burn required for the heavier system. This will lead to one of two key outcomes; the system will either benefit from being larger or smaller overall in terms of propulsive power. This trade-off will heavily affect future concept configurations, as a key question to be answered will be whether to use the electrical system as a support to the turbofan or as the primary source of propulsion.

There are also trade-offs that exist within the cryogenic cooling system itself. Of particular significance is the trade-off between different rejection temperatures. Since the system is likely to have losses in the kilowatt to sub-megawatt range, the medium through which heat is dispersed is crucial to success. An example of this could be the trade-off to using liquid open-loop heat sinks, or gaseous open-loop heat sinks. There are advantages and qualities that are present in both, however for any given concept, this could change. This further illustrates the need to understand the system and to have an adaptive model that can be applied in each scenario to understand the impact certain design choices will make. Furthermore, there are many different methods of achieving cryogenic temperatures. The options must be assessed according to their most critical parameters and qualities, leading to the more complex challenge of requirements. The systems engineering process was followed in order to understand the system in greater detail.

Given the complexity of the system, the problem can thus be defined as follows:

- The superconducting network is as of yet unknown; therefore the likely size and power of the cryogenic system is a resultant compound unknown. This lack of knowledge must be mitigated using expert opinion and qualitative analysis backed up by numerical modelling of the known aspects. The validation steps taken must be rigorous and numerous to ensure information is not missing or misunderstood.
- The cryogenic cooling system is unknown; the system relies upon knowing the requirements, hence requirements must be accurately captured and complete. A complete set of requirements from all involved stakeholders should ensure that any design process is valid, with a clear and repeatable process followed.
- Design options for the cryogenic cooling system are known, but in terms of suitability are unknown; each concept for cooling must be assessed in terms

of their overall suitability to the system, therefore a database of ideas must be generated in order to understand which options are available and which options are unfeasible when considering the problem from an aerospace design perspective.

- Rapid iteration design capability does not yet exist; numerical modelling must provide the capability to assess different parameters and aircraft configurations in terms of impact on the overall aircraft system, its weight, and its overall viability when considering the aircraft constraints such as available power.
- The critical components within the cryogenic cooling system are not yet known; numerical modelling again will also play a key role in determining this, however before this can be completed, a concept must be selected. Different concepts are modelled fundamentally differently; hence a baseline concept idea must be outlined before this can take place.

Each of these challenges is addressed to varying degrees throughout this project in order to gain a meaningful understanding of how the cryogenic cooling system concept must perform and how it must interact with the supported systems and aircraft. At the end of each chapter in this project, a brief discussion will refer back to these challenges, and will examine whether part or all of any of these have been met and to what extent. The final conclusion will also refer back to this section to assess whether or not these challenges still exist. If they do exist, how can they be answered in the future work, and if not, then speculation is offered as to what other challenges have been uncovered during the course of the project.

1.3. Research Aim and Objectives

The overall aim of this project is:

“To investigate concepts and possibilities for cooling systems within future all-electric thrust aircraft (AETA) systems”

The five key objectives within the research are as follows:

- Capture and structure knowledge on current cryogenic cooling systems and evaluate standard industry practice.

- Establish requirements for the design of the AETA electrical systems and the cooling subsystem.
- Identify the functions to be satisfied by the AETA cooling systems and represent relationships among the different subsystems of the AETA systems that are directly linked to the cooling system.
- Generate options regarding the cryogenic cooling system and assess and validate them through the use of models.
- Consider future technology enablers and how they may impact the models and outcomes of the project.

1.4. Research Scope

The scope of this project must ensure that adequate coverage of the objectives is ensured without being too broad or narrow. Limitation is crucial with such a multidisciplinary project because of the high tendency to follow a tangential route when looking at different technologies. The limited availability of knowledge, particularly regarding superconducting components, means temptation to explore these areas is high. The scope however must limit the field of research to suit the objectives and overall aim such that realistic goals that still challenge the researcher and push the boundaries of scientific knowledge are realised.

It is easier in this case to define what is out of scope for the research. Within the scope is a multidisciplinary investigation into the system level intricacies of a complex conceptual aircraft propulsion system. However, by defining accurately what is out of scope, the project is then not bound by the in-scope definition; rather it is constrained to what is off limits, allowing exploration of non-out-scope topics not covered by the more restrictive in-scope.

The out of scope topics for this project are as follows, with a brief explanation given to what each statement entails:

- Investigation into the aircraft types other than commercial

This essentially means looking at other types of aircraft such as military, business jets, or unmanned systems is out of the project scope. The reasons for this are that each type of aircraft will have its own set of requirements, and thus the process during this project would have to be repeated in order to find the optimum system for

a given application. Since the process is not known it is best to develop the process for the most pressing application, which is commercial airliners, whether the purpose is for freight or passengers. Once the process is perfected and streamlined, it can then be applied to other concepts more rapidly, with models already in place to predict the possible benefits available for each type of aircraft.

- Aircraft system design aspects outside of the cooling system and electrical network

Systems such as the gas turbine used to drive the generators, the cabin environmental control system, or auxiliary power units, will be ignored in the study. The reason for this is that whilst there are likely to be synergies for exploitation, the overall aim of this project is essentially to understand firstly whether cryogenics for superconducting electrical propulsion can be light and efficient enough to provide an overall benefit, and secondly what that system would look like in terms of concept and configuration. Since the primary driver of both weight and efficiency will ultimately be the loss within the electrical system, the other aircraft level subsystems can be ignored at this stage as this project is looking at feasibility as the critical factor.

- Aerodynamic design aspects

Aerodynamic design is integral to the success of BWB, BLI, and potentially a myriad of other advantages so far not conceived, however these are complex issues that require detailed investigation. Aerodynamics forms the basis of other concurrent studies undertaken by other researchers/institutions; hence it will not be necessary to include them in this project.

- The impact of using LH_2 on systems outside of the cryogenic cooling system, although design impact and challenges to implementation are addressed

Liquid hydrogen (LH_2) is a favourable coolant due to its temperature, high latent and specific heat capacities, and energy content, which coupled with its flammability, make it an excellent fuel. LH_2 will be discussed in part of this project purely for investigation on whether it could be used in conjunction with cryocoolers but detailed investigation into whether it can be used alone without cryocoolers is out of scope for this project. The reasons for this include super-system level considerations, such as

whether a hydrogen economy can be sustained and the practical challenges of storing hydrogen. These issues will be discussed briefly; however no further analysis will be given with respect to modelling hydrogen-specific systems.

1.5. Industrial Sponsor Overview: Rolls-Royce plc

Rolls-Royce plc is an internationally renowned brand in power systems, most notably in the aero engine market. With a market share of 50% in wide-body aircraft engines, Rolls-Royce is a global leader in aviation propulsion (Rolls-Royce, 2016). A long and prestigious history precedes it; previous aircraft that flew using Rolls-Royce engines include the Spitfire, Lancaster, Concorde, Harrier Jump Jet, Boeing 747, and more. Many iconic aircraft have flown using Rolls-Royce engines, and as the current producer of the world's most efficient aircraft engine (at the time of writing), the Trent XWB, its future is all but secured (Rolls-Royce, 2016).

Rolls-Royce also produces a number of non-aviation power systems products. The UK nuclear deterrent fleet of submarines are all powered by the Rolls-Royce Pressure Water Reactor (PWR). The PWR 3 has also been selected to power the UK Trident replacement submarines, set to take over nuclear deterrent responsibilities when the current Vanguard-class fleet is retired. Rolls-Royce also produces both land and sea power systems, with the MT-30 engine, derived from the Trent aero engines, being one of the most successful ship power system products in Rolls-Royces history.

Despite the strong position and global brand of Rolls-Royce, technology is ever changing. In order to maintain global dominance of the power system market, Rolls-Royce must look to the future. This project shows that Rolls-Royce is willing to look into the distant future, where uncertainty is high and the technology is highly immature. Rolls-Royce has a history of doing so, and often it has paid dividends to do so. Rolls-Royce has always been ahead of the technology curve, and its aim with research projects such as this thesis is to continue the trend and to develop the skills and tools to compete in the hostile world of aviation.

1.6. Thesis Structure

The structure of this thesis will follow a loose chronological format whereby the chapters are arranged in the order the work was undertaken, with the objectives given priority in each chapter.

Chapter 2 shows the structure of the thesis and the research methodology taken, with tables showing how each process is completed.

Chapter 3 provides a comprehensive literature survey of all of the related and relevant subject areas within the project. The subject areas will be aircraft concepts, superconductivity, and cryogenics. Each subject will have sub-categories within each area, for example, aircraft concepts will include distributed propulsion, BWB aircraft, and BLI.

Chapter 4 focuses on stakeholder identification and requirement capture. This chapter begins the project by finding out firstly who holds a major stake at this conceptual stage, what their individual requirements are, and then interviewing those stakeholders in order to find out which requirements they deem most important. The outcome of the chapter is a completed set of requirements, knowledge of who holds the largest stake in the project, and their views on which requirements overall should be given highest priority.

Chapter 5 follows on from Chapter 4 by isolating the functional requirements of the cryogenic cooling system from the main set of requirements and completing these through functional modelling. The overall functional model is generated providing the systems with which it must interact, and then the internal cryogenic model is generated, showing how each input or output parameter is managed. The model is then tested for sensitivity once it is validated by experts, using three system engineering methods; sensitivity matrix, failure modes and effects analysis (FMEA), and the house of quality (HoQ). The outcome for chapter 4 is a greater understanding of the system and a qualitative assessment of which functions are most critical, along with identification of which events are more likely to adversely affect the cryogenic cooling system during operation.

Chapter 6 presents a systems engineering optimisation proposal, with a detailed explanation of where the Rolls-Royce process breaks down and how optimisation

using numerical modelling can prevent the project from stagnation. Once the adapted process is defined, concepts are explored within the cryogenic cooling system options using function means analysis (FMA), where each way of achieving a function is listed and qualitatively assessed. This allows the selection of a few possibilities that appear feasible for future testing, and for the first parts of a cryogenic concept to be chosen. The first key design choices are made within this chapter.

Chapter 7 is where the first numerical assessment takes place to better understand the superconducting electrical network. Close collaboration with experts and other researchers is used to develop the first known design tools of superconducting electrical machines, which are used to assess the likely magnitude of required cooling power for the cryogenic system. Models built within this chapter allow the project to begin quantitative assessment of concepts, providing the ability to rapidly iterate concepts by modifying the assumptions and parameters that are most likely to affect the system.

Chapter 8 outlines the modelling process used for the cryogenic cooling system, once the parameters from chapter 6 are fully understood. By this chapter the overall cryogenic concept is chosen as the Reverse-Brayton cycle, and the modelling centres around two key concepts for this; single and two-stage designs. The chapter describes the models in detail, with the models allowing rapid iteration of certain aircraft-level design choice impacts.

Chapter 9 presents the results of the modelling for chapters 7 and 8, culminating in a detailed design space understanding that highlights where the biggest design configuration gains can be made. The chapter also shows at which point individual concepts of design choices fail or succeed based on the numerical results, and considers the FMA results from chapter 6 to see if any of these concepts can realistically be achieved with present day technology. Critical components are able to be identified within this chapter, with the most critical for given parameters explained in detail. Finally within chapter 9 potential design mitigations are offered for concept optimisation, with some recommendations given in the discussion section as to how performance improvements could be made in the future.

Chapter 10 will present the conclusions and findings of the project, and provide detailed discussion of the strengths and weaknesses of the project in retrospect. The final conclusions on viability, feasibility, and commercial potential are discussed with respect to cryogenics, with a prediction outlined for the future based on these conclusions. Future work recommendations will also be provided, highlighting based on the results of the thesis where future efforts should be concentrated.

The references section will show sources used, and the appendix will include any incidental information on the models used and the data generated, principally expert questionnaires and model assumptions not used in the main text but deemed relevant nonetheless.

Chapter 2. Literature Review

2.1. Introduction

Cryogenic cooling systems for superconducting electrical aerospace propulsion networks are at the very first concept stage in terms of development. This means that at the time of writing this thesis, there are no specifically targeted previous papers on the issue of cryogenics for this application. Therefore in order to have a thorough survey of technology that could be relevant to the project, it is necessary to outline the areas of technological interest. Given the complexity of this project and the many facets of knowledge that will have to be incorporated, the literature search is not straightforward. While it is necessary to cover all topics associated with this project, it is also necessary to limit the reach of the literature review to avoid out-scope study. The first task is to identify the literature review scope, which includes all of the topics and sub-topics to be analysed. As the project evolved with time, certain subject areas were deemed moot whilst others were introduced. This continuous evolution of the knowledge areas required further highlights the projects complexity, particularly concerning the cryogenics aspects of the project.

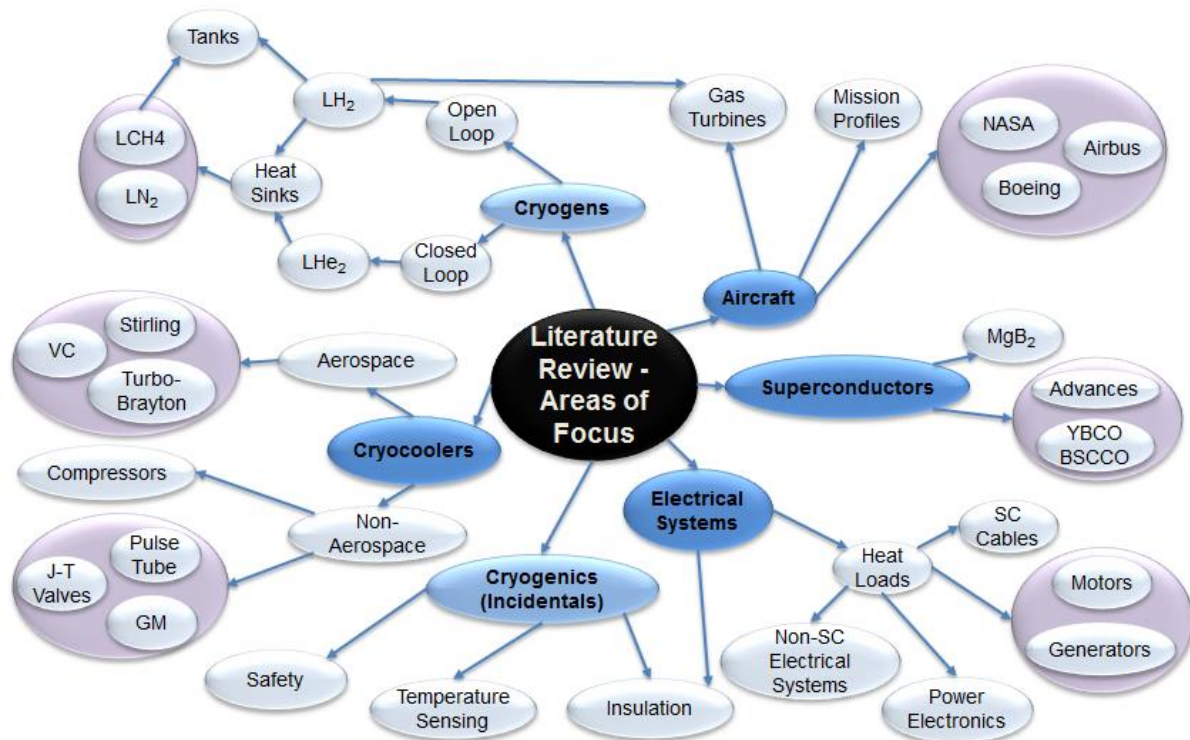


Figure 2-1 – Literature review topic scope including major sub-topics (Acronyms described in list of acronyms)

Figure 2-1 shows the relationships and categories of the topics covered within the literature review however the structure of the search is not represented. Since the complexity of this project is high, it is necessary to develop a strategy for knowledge capture in order to understand better the knowledge areas that must be covered.

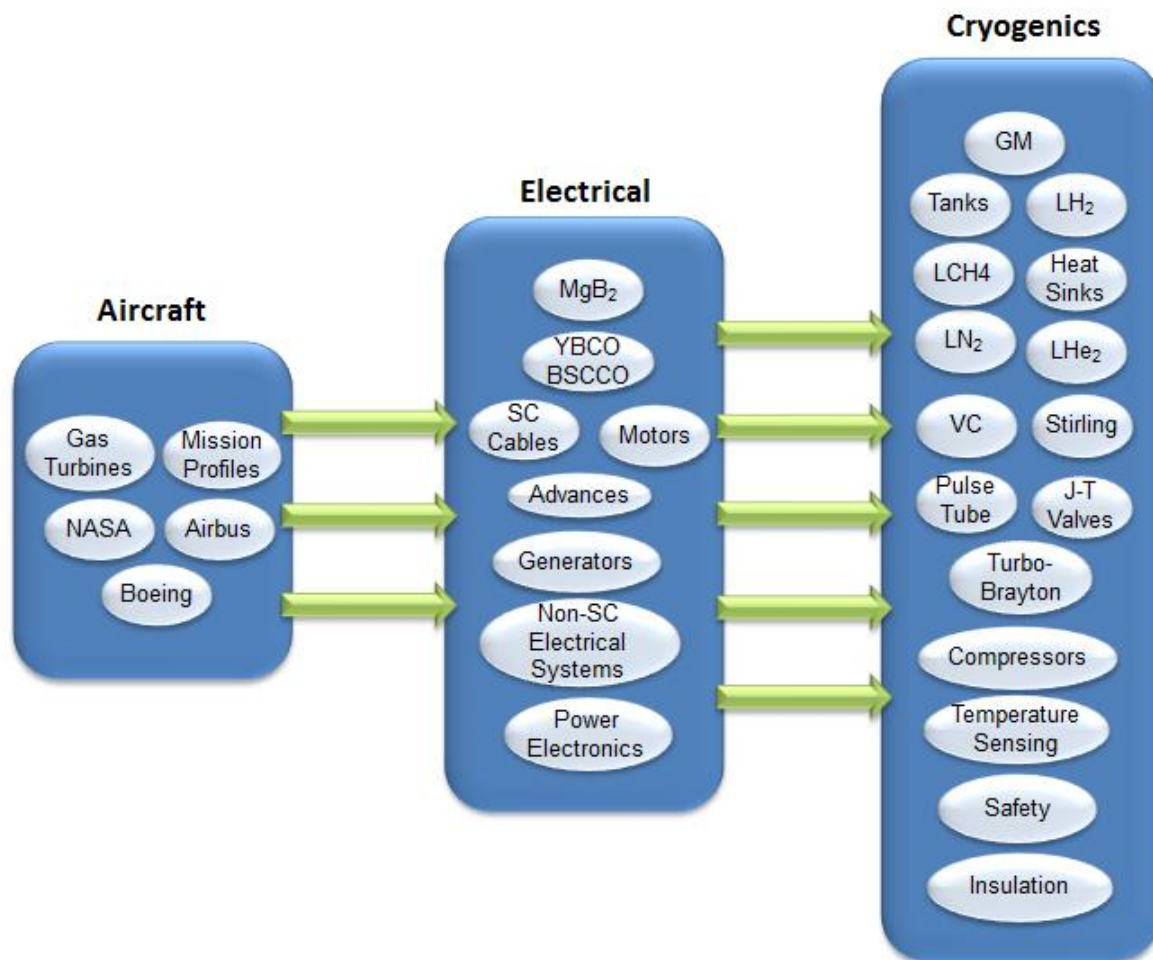


Figure 2-2 – Literature review strategy shown in order of capture

Figure 2-2 shows the methodological order in which topics were researched, starting with the super-system (aircraft), supported system (electrical and superconductor), and finally the cryogenic cooling system. The rationale behind capturing knowledge in these areas in this order largely stems from the understanding of each system. Since the cryogenic cooling system is a support system to the superconducting electrical network, which in turn is a support system for the aircraft, each system must be understood before the design process can begin. Conversely, the number of topics and associated depth of knowledge increases as each key topic progresses, leading to the conical structure shown in Figure 2-2. For each literature review

section, the topics will be covered briefly with the relevance to the project discussed. Some topics shown in Figure 2-2 are not presented during this section. Reasons for exclusion include low relevance, technological crossovers or technological similarities to already covered topics, and basic knowledge that is not the state-of-the-art in terms of knowledge capture. Some areas of knowledge shown in Figure 2-2 are covered during latter stages of the project, particularly Chapter 6 where concepts are qualitatively eliminated. As previously stated, to keep the literature review at a sensible length, some topics are omitted until they are required, where they are described at a later date.

2.2. Aircraft

The aircraft that utilise distributed propulsion are varied from traditional tube-and-wing configurations to more novel BWB airframes. This section presents a brief summary of the known concepts that are being considered. Aircraft are necessary to consider for this project because of the implications surrounding the configuration of aircraft affecting the cryogenic system design, such as type of fuel used and assumed power levels of the superconducting system.

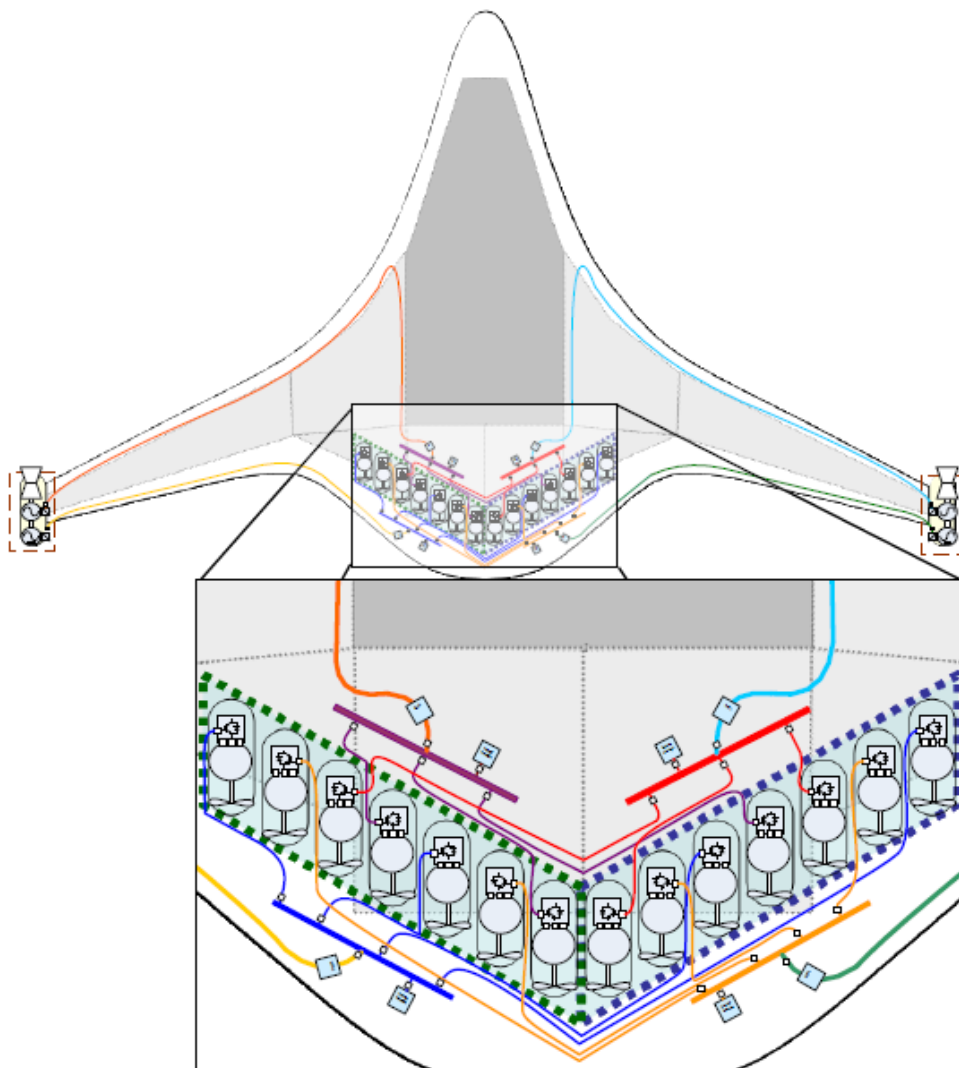


Figure 2-3 – NASA's N3-X BWB concept electrical schematic showing propulsion system configuration (Armstrong *et al*, 2012)

The first such notable concept is the N3-X, a BWB airframe design using turbo-electrically driven BLI distributed propulsion (Felder *et al*, 2011). The N3-X concept in summary includes two wing-tip mounted gas turbines that drive four

superconducting generators, which drive fourteen superconducting ducted-fan motor propulsors mounted on the trailing edge of the body (Figure 2-3). From an electrical perspective, the N3-X project is investigating two types of superconducting material that require different cooling conditions to function. The first is Magnesium Diboride (MgB_2), superconductor with a critical temperature (T_c) of 39 K (Nagamatsu *et al*, 2001). The second is Bismuth Strontium Calcium Copper Oxide (BSCCO), which describes a family of superconductors. The type of BSCCO that is assumed for the N3-X project has a T_c of 110 K (Ekin, 2006). The aircraft assumes a fully superconducting network with a total installed maximum propulsion power rating of approximately 80 MW (Felder *et al*, 2011). Predicted generator-to-propulsor losses for the N3-X are as low as 0.03% for the concept with fully-superconducting electrical machines and DC distribution. With these improvements the estimated reduction in fuel burn for the concept is 72% for the LH_2 cooled MgB_2 version and 70% for the BSCCO version when compared to the baseline aircraft, a Boeing 777-200LR (Felder *et al*, 2011).

Use of a cryocooler for the N3-X is restricted to the BSCCO concept, due to the exponential rise in required cryocooling power as temperature decreases. The primary assumption behind this is that the cryocooler will exchange heat with the ambient air, using air flow as the heat sink in order to remove loss inside the cryostat. Both of these types of superconducting material will be discussed in terms of suitability in more detail during this literature review.

NASA's N3-X is the only study at present that incorporates the novel BWB airframe design, BLI, and the distributed propulsion concept. Boeing have also looked at BWB designs for their aircraft, however as of yet they are not incorporating distributed propulsion or BLI within the same design. The Boeing X-48 series of testing aircraft has undergone three iterations, the X-48, X-48B, and the X-48C (Croft, 2010), working with Cranfield Aerospace based at Cranfield University.

The original X-48 was intended to be a small-scale testing model in order to assess the aerodynamic performance of the BWB shape. The propulsion configuration was three small turbojet engines on the top leading edge of the body. The similar X-48B was slightly larger, with a slightly different aerodynamic shape, intended to assess

the performance of the aircraft during stable flight and for ground mission profile phases (Figure 2-4).



Figure 2-4 – Boeing and Cranfield Aerospace's X-48B test aircraft (NASA, 2010)

The X-48C was originally planned to be much larger, however testing on the modified X-48B was deemed sufficient. This has led to further studies between NASA and Boeing on BWB designs, assuming the incorporation of ideas from the N3-X concept and X-48 programs (NASA, 2010). Since this aircraft is not assuming electrical propulsion configurations, the X-48 aircraft is provided as reference only, serving to highlight the fact that both competing major airframe manufacturers (Airbus and Boeing) are considering radical airframe designs.

Airbus is working closely with Rolls-Royce and Cranfield University on the Innovate UK (formerly the Technology Strategy Board) funded project DEAP (Distributed Electrical Aerospace Propulsion) (Wright *et al*, 2015). The concept began in 2012 with the primary aim to investigate the feasibility of using electrically driven propulsion for commercial aviation. The key difference between the NASA N3-X study and DEAP is the airframe; DEAP assumes a more traditional tube-and-wing configuration. The reason for this decision to use tube-and-wing for the study is to assess a like-for-like propulsion system comparison, such that the real benefits can be assessed without over-complicating the design. Should a benefit over the baseline comparison be realised, the technological area providing the benefit can be much more easily identified. There is a caveat however; BWB or other novel types of airframe could produce a compound benefit when the purported benefits of BLI are

included, hence the result from the DEAP study may not be the optimum solution overall. DEAP is critical to understanding of the capacity of electrical propulsion to produce benefits over traditional turbofan technology through design space mapping and concept feasibility studies.

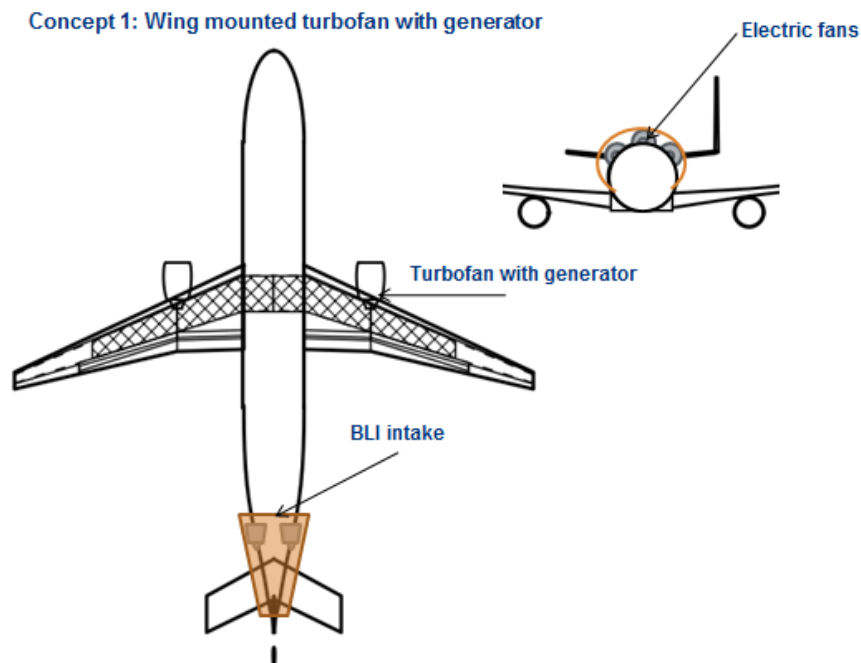


Figure 2-5 – DEAP concept schematic overview showing location of the BLI intake
(note the number of fans shown is not representative of the likely true number)
(Wright *et al*, 2015)

The general propulsion configuration of the DEAP aircraft is to use BLI on the rear fuselage instead of over the wings to reduce parasitic drag (Figure 2-5), with two conventional turbofans supplying a portion of the thrust. The portion of thrust supplied by the turbofan or electrical system is another variable. As of yet there is no fixed number of generators or motors, as this is another variable that is being investigated by the study. By placing the electric fans on the fuselage, the fuselage drag profile can be reduced, making the overall drag profile of the aircraft smaller. This potentially yields benefits from making the overall propulsion system smaller, to allowing better cruise propulsion system operation point optimisation. The DEAP aircraft is the baseline example to which the models for this project are created for and are tested against. The key system-level assumptions that affect the cryogenic cooling system are:

- Use of fully superconducting network, despite no fixed configuration
- Use of MgB_2 as the default superconductor
- Minimum redundancy level within the cryogenic system of at least 2

Further assumptions are needed for numerical analysis of both the superconducting and cryogenic cooling systems, and are explained during Chapters 7 and 8.

2.3. Superconductors

Superconductivity is a property of certain elements and compounds whereby electrical resistance suddenly drops to zero at a specific temperature. The temperature at which each respective material or compound exhibits this phenomenon is called the critical temperature, T_c . The strange quantum effect was discovered in 1911 by Heike Kamerlingh Onnes, a Dutch physicist, by cooling mercury down to 4.2K (Shi, 1995). Superconductivity has many strange properties regarding magnetism and conductivity, which make them useful for certain applications in the fields of medicine, transportation, power transmission, and electronics.



Figure 2-6 – Examples of equal current carrying capacity cables; conventional in the background, with superconducting in the foreground (CERN, 2006)

Figure 2-6 shows the equivalent current carrying capacity of two types of transmission cable, the smaller type is the same type of superconducting tape used in the Large Hadron Collider (LHC) at CERN Laboratories in Switzerland. The

notable size difference illustrates the huge potential superconductors have regarding power density for components such as generators and motors.

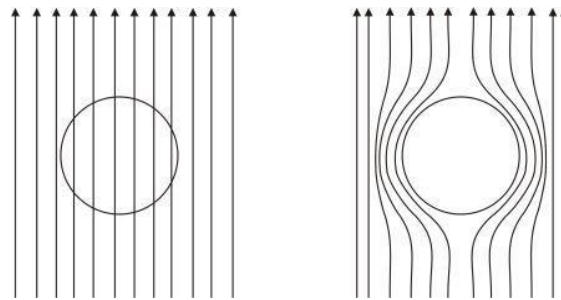


Figure 2-7 – Meissner effect on a superconducting sphere; left, $T > T_c$; right, $T < T_c$

In 1933, Walther Meissner and Robert Ochsenfeld discovered what is known as the ‘Meissner Effect’ whereby as a superconductors temperature reaches its respective T_c , any magnetic field applied to the material is expelled (Figure 2-7). When a superconductor reaches its T_c , an electric current begins to autonomously circulate within the material creating its own electric field that opposes any induced field outside of the material. This works to effectively repel magnetic fields applied to it, making the material simply levitate above the conventional magnet (Meissner and Ochsenfeld, 1933).

This effect was characterized by images of levitating cylinders of superconducting materials. The effect also states that by effectively parting the magnetic flux lines (Figure 2-7), it is able to hold its position above a magnet in both the vertical axis (y) and the x - z plane. A good analogy to use with this effect is to imagine a superconducting maglev train model, and to position it above a magnetic track. Due to a superconductors’ ability to hold its position within flux lines, the model, when given forward momentum, will cruise around the track at the same height above it, and will not lean to the side or fall off of the track at the corners (Figure 2-8). The effect will allow you to alter the height of the model physically, the position of which will then remain fixed until disturbed once more, or the temperature of the superconducting material rises above its T_c .

Since the first discovery of superconductors, progress has been made in establishing which materials exhibit this property. Advances in materials science and crystal structure analysis have meant that there are now many types of practical and

theoretically predicted superconductors. The reason for ongoing research is to ultimately reach a point where superconductors can operate with a T_c at or above that of room temperature, effectively eliminating the need for cryogenic cooling systems. The discovery of a material or compound with these properties has yet to be made, however many superconductors have been discovered with varying critical temperature values.



Figure 2-8 – Meissner effect of a HTS material (Warwick, 2000)

Superconductors currently fall into four main overlapping categories, low temperature superconductors (LTS), high temperature superconductors (HTS), and Type I and Type II superconductors. The definition of a HTS material is given to be a material where $T_c > 30\text{K}$ (Shi, 1995). These HTS materials are an important discovery, as their cooling power requirements will be significantly less than LTS materials. Type I and Type II superconductors are defined by their magnetic properties, whereby Type I materials completely eject any outside magnetic field, and Type II have a magnetic penetration depth or London penetration depth, λ_L (London and London, 1934). Type II superconductors are largely HTS however there are a few LTS examples. Type II superconductors are essential within aerospace applications, due to the earlier explained magnetic field ejection. For electrical machines such as generators and motors to work, magnetic flux lines must be passed through and cut, generating current through the material. If the material is a Type I superconductor the magnetic flux is completely repelled, creating no useful current in generators and repelling any induced magnetism in motors.

Project DEAP has specified that Magnesium Diboride (MgB_2) is to be used as the superconducting material for their generators and electric motors. This means that the machines have a fixed target temperature range dictated by the T_c of MgB_2 at 39K (Nagamatsu *et al*, 2001). The reasons for this choice are that as Type II superconductors suffer from alternating current (AC) losses when moved through a magnetic field (due to their London penetration depth), it is beneficial to find materials that both exhibit superconductivity and have easy to manipulate physical structures. Rectangular strips (As is the typical geometry for most ceramic HTS such as YBCO) geometrically have a small cross sectional area when penetration depths are accounted for (Figure 2-9). This can be largely avoided however by manufacturing circular cross-sectional wires instead of strips, twisted together like traditional cables minimising the AC losses (Prestemon *et al*, 2007). The rationale behind this can easily be confirmed using a simple calculation to check whether two samples of the same cross sectional area.

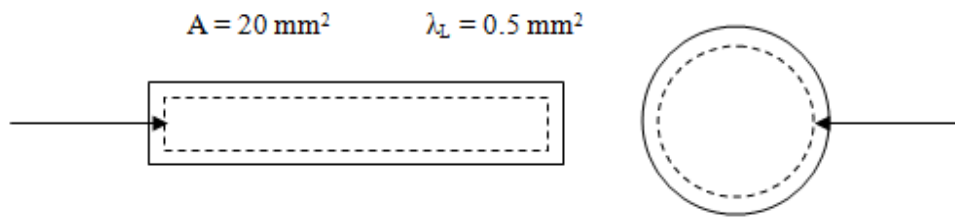


Figure 2-9 – Comparison of wires and strips with equal penetration depths, λ_L , and with equal areas, A

Figure 2-9 shows two cross sections, one rectangular (strip) and one circular (wire). The total area of both is set to be 20 mm^2 . The dotted line shows a magnetic penetration depth of 0.5 mm from the outside wall. If the area within the dotted line is larger, the wire will be able to carry more current free from interference, and therefore higher magnetic fields will result. The following calculation shows how the cross sectional area varies in a non-linear fashion with these two shapes when the same material (and therefore same London penetration depth) is applied. The suffix r denotes the rectangular cross section shown in Figure 2-9, while the suffix c demotes the circular cross section. The suffixes o and i denote outer area (total) and inner area (dotted line area) respectively.

$$A_{r_o} = A_{c_o}$$

$$A_{r_o} = L \times W \qquad A_{c_o} = \pi r^2$$

$$\therefore LW = \pi r^2$$

For a penetration depth p :

$$A_{r_i} = (L - 2p)(W - 2p)$$

$$A_{c_i} = \pi(r - p)^2$$

Substituting values for p , W , L , and r :

$$\text{let: } p = 0.5; \quad L = 10; \quad W = 2; \quad r = 2.523$$

$$A_{r_i} = 9 \text{ mm}^2$$

$$A_{c_i} = 17.725 \text{ mm}^2$$

As indicated by this simple check, the choice of MgB_2 due to its ability to be drawn into wires is an important one, as nearly double the current can be passed through a circular cross section than with a rectangular one. This yields greater magnetic fields overall, with the ability to resist AC losses due to the uniform nature of the penetration depth. The manufacturability of MgB_2 is also a much simpler process due to its comparatively less complex molecular structure, shown in Figure 2-10.

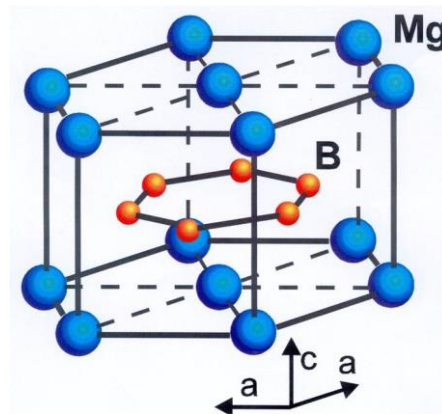


Figure 2-10 – Molecular structure of MgB_2

Despite the information available on MgB_2 , there is limited information on the many other types of superconductor listed in online resources and books, due to their technological infancy and variability in terms of practical synthesis. The motivation

behind looking at different superconductors is to theorise what impact the choice of superconductor might have, even if only briefly, on future cooling system designs. Looking at future technology and hypothesising the cooling requirements, or at least generating a rule-of-thumb for certain relationships, will allow faster analysis and design when technology does become available, ensuring the user does not waste time on problems that have already been solved. In this paper however, it is worthwhile to look at the current alternatives to MgB_2 , to establish why they are being ignored along with some general information about their properties. The effect on the required operation temperature of superconductors will heavily impact the results of the cryogenic cooling system both in terms of power and weight. Knowing the basic thermal properties of other types of superconductor for use within models developed may influence the outcome of the project future goals, since the likely power required would decrease drastically.

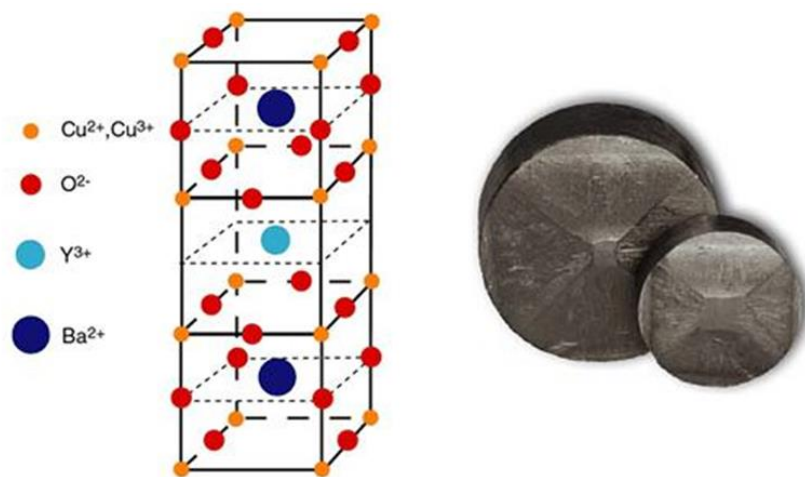


Figure 2-11 – YBCO molecular structure and physical appearance

The first type to be examined is the YBCO family, or Yttrium Barium Copper Oxide superconducting family. This material was first discovered to be superconducting in 1987, and was the first to be demonstrated with a $T_c > 77$ K, the boiling point of Nitrogen (Wu *et al*, 1987). The material comprises of layers of atoms, bonded together to form a stack with an Yttrium atom in the centre of the stack (Figure 2-11). The physical properties of YBCO, largely its brittleness, restrict the material in its application within superconducting machines. Despite the very favourable T_c and lightweight structure, the material cannot be easily manipulated due to its complex

molecular structure, meaning it cannot be drawn into wires, and cannot be wound once formed due to its brittleness (Holland and Stacy, 1988). This limits the material significantly, and despite becoming a superconductor at a much higher temperature than MgB_2 , it is these physical properties that mean YBCO currently is not a viable option for consideration. However if manufacturing technologies can produce either a flexible version, or can produce a variant that can be manipulated more easily, then YBCO could potentially make cryogenics for this application much more feasible.

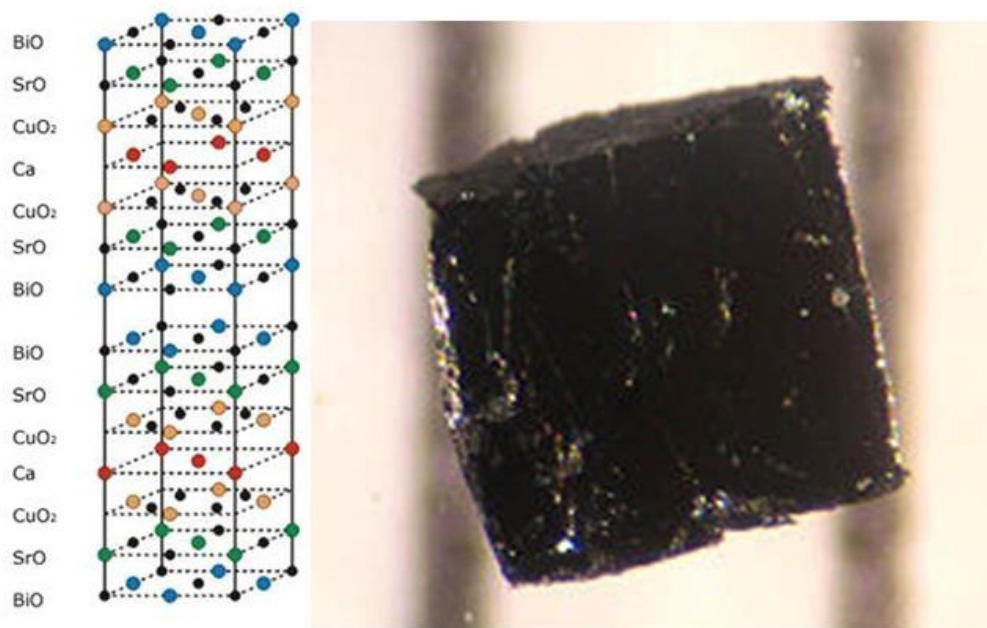


Figure 2-12 – BSCCO molecular structure and physical appearance

Aside from YBCO, BSCCO, or Bismuth Strontium Calcium Copper Oxide is the other common alternative in HTS. It has a T_c of between 95 K and 108 K, depending on the molecular structure, making it one of the highest known T_c superconductors (Van der Laan et al, 2008), (Figure 2-12). Unfortunately much like YBCO, BSCCO is brittle and difficult to manipulate physically, making it an unappealing prospect for implementation. The potential benefits with these two HTS materials are huge; however it is worth noting that machines of this type have been built, and are explained in the next section.

2.4. Electrical Components

An essential part of determining the efficiency and required size of the cryogenic system will be to determine the dimensions and required heating capacity of the

proposed design. As specified in the previous section, the superconducting parts of these components will be made of MgB_2 , so as to minimise AC losses. The superconducting electrical network configuration will have a significant impact on how cryogenic cooling system will be designed, particularly when concerning the practical aspects of keeping electrical machines at the desired temperature.

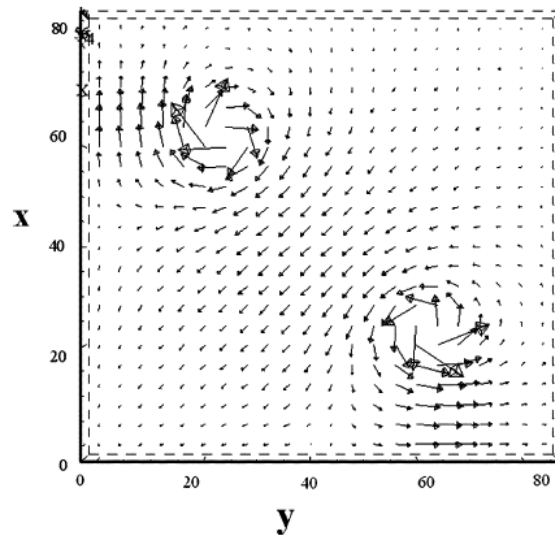


Figure 2-13 – Eddy currents shown in a superconducting inductor (Masson and Luongo, 2005)

It will be highly likely that both the stator and rotor will be superconducting, as it will provide the most efficient electrical system, with minimal losses. In the past, the United States Air Force (USAF) has shown interest in superconducting motors and generators, as early as 1977, in which scientists speak of both superconducting stator and rotor windings (Oberly, 1977). The paper states that at certain speeds, the motors can be subject to strong eddy currents (Figure 2-13) and can quench the superconductors, meaning that in the superconducting coils sudden heating can occur in localised areas, effectively raising the temperature of the material past their T_c . This effect then in turn causes Ohmic heating due to the sudden resistance incurred; meaning the material (or at least the quenched local area) must be then allowed to cool down before resuming normal operation. These Eddy currents are unfortunately unavoidable due to the high strength of magnetic field that will be essential to operation. Their effects however can be minimised though having a safe current and magnetic field limit that does not surpass any of the critical values shown in the superconducting phase diagram in Figure 2-14.

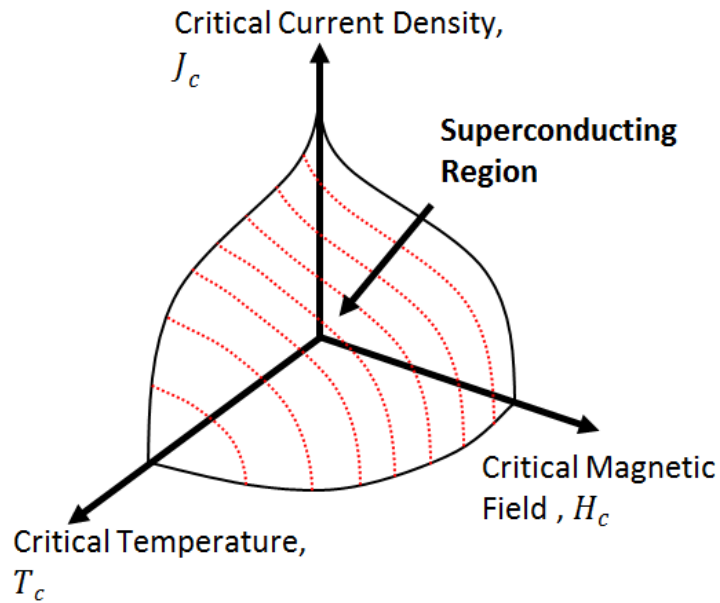


Figure 2-14 – Superconducting material phase diagram showing the critical parameter relationships for a superconducting material

Once a material is cooled below its superconducting inversion temperature, its performance as a superconductor is dependent on three critical parameters; temperature, magnetic field, and current density (Buckel and Kleiner, 2004). If a superconductor is cooled far beyond its critical temperature, the permissible magnetic field or current density in the conductor is increased, resulting in better electrical performance. This however relies upon available cooling power; there is certainly a trade-off decision between electrical and thermodynamic performance. If the current in any given portion of the superconductor surpasses the critical density limit, or similarly if the magnetic field at any given point is sufficiently high, a quench can occur. This is complicated by potential minute variations in the superconducting material temperature, which in turn varies the criticality properties. Accurate temperature control will be essential to practical operation that is free from unreasonable limits to safety margins for the critical parameters. This trade-off is crucial in estimating the losses within electrical machines, particularly when considering the speed and torque of machines. A machines speed will largely dictate the level of losses encountered in the form of AC losses, whilst torque is a crucial consideration when considering the current in the machine. These relationships are explored in more detail within Chapter 7.

The issue presented by quenching may be an early indication of the likely operating parameters that may have to be established. If quenching occurs during operation, the motor may need to be shut down completely and allowed to cool back to its superconducting state should the rate of cooling be insufficient. If cooling is not allowed to happen, the likely outcome will be that the material (which would at that point suddenly have a resistive value) could continue to heat through the likely very large current flowing, possibly leading to catastrophic failure. This potential failure mode will need addressing during the modelling phase to ensure the final solution is robust enough to cope without significant loss either to system operation time or functionality.

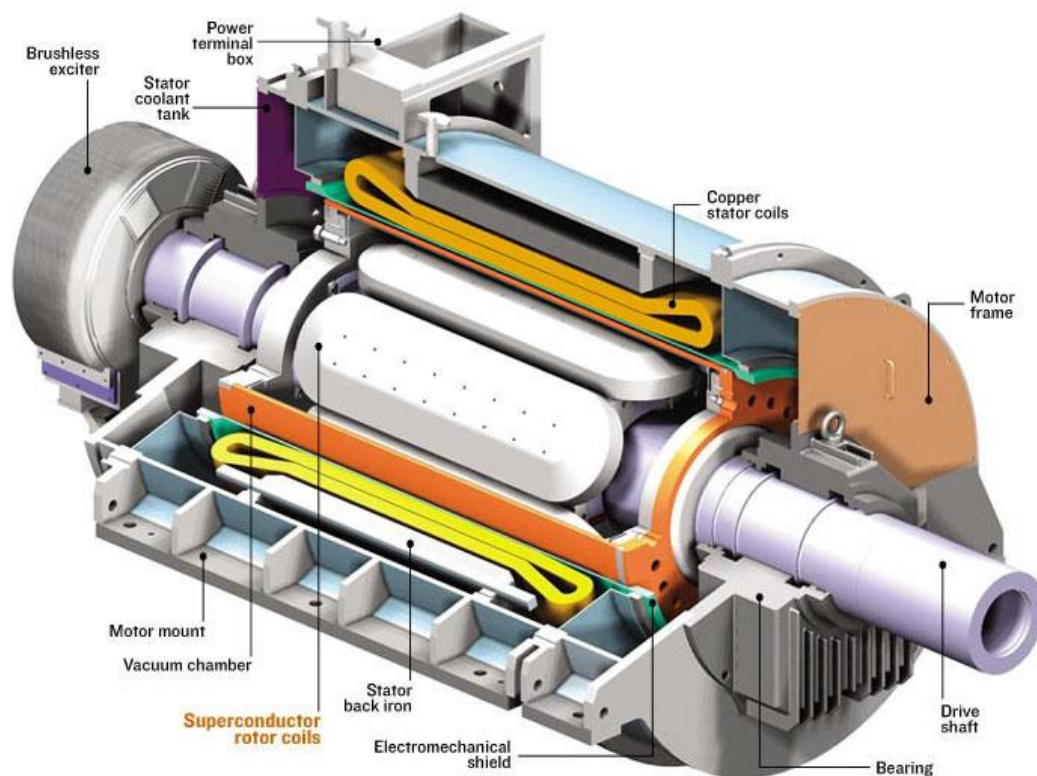


Figure 2-15 – Example of a BSCCO-wound rotor superconducting machine, with cooled copper stator (Gamble *et al*, 2006)

There are numerous examples of superconducting electrical machines with either a superconducting rotor or stator. There are however at the time of writing no known examples of a fully superconducting electrical machine, due to the complexity associated with them. A short analysis of current partially superconducting machines highlights the relatively new introduction of MgB_2 into the public eye as a superconducting material. Figure 2-15 shows a cutaway diagram of a hypothetical

partially superconducting machine, with the rotor only being superconducting. The stator in this example is cooled copper, taking advantage of the increase in current-carrying capability of copper when cooled. The machine itself is sealed within a cryostat, which keeps the machine windings cooled.

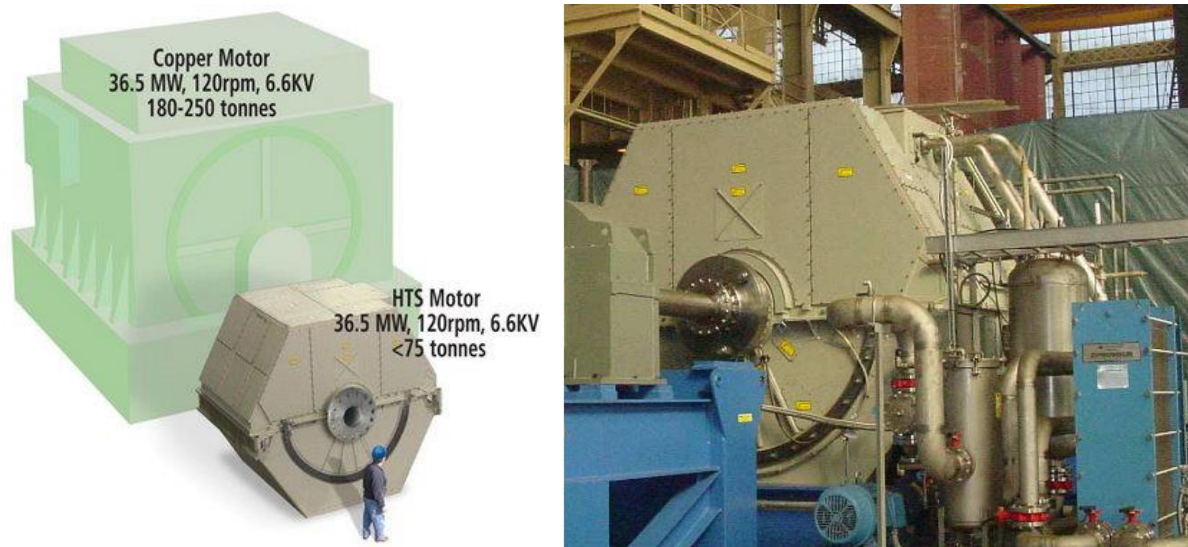


Figure 2-16 – Siemens 36.5 MW superconducting motor for marine propulsion

Siemens are currently developing a 36.5 MW superconducting motor for naval propulsion pictured in Figure 2-16, using BSCCO windings on the rotor (Gamble *et al*, 2011), while Kyoto University in Japan have constructed a proof-of-concept MgB_2 rotor winding cage example (Nakamura *et al*, 2011) with the first known machine to implement a liquid cooling system. Both machines pay heavy attention to the design of the motor, however the cryogenic plant is neglected almost entirely, leading to inevitable space and weight problems on the potential aerospace applications of such technology. Since the key advantage to superconducting machines is the current density available, by definition superconductivity will increase the force exerted in the windings, making them attractive in high-torque applications where the size of the machine may be an issue. Torque and rpm will be discussed with regards to their relevance within Chapter 6 of this thesis.

While there are numerous examples of partially superconducting machines, researchers are reluctant to state how these machines are cooled. Since superconducting machine technology is so novel and complex, most research projects are likely concerned only with the machine itself while support systems is

commonly a secondary consideration. Through their choice not to investigate the cryogenic plant, it can be confidently postulated that aerospace application of these particular examples of superconducting machine in their current state is out of the question. Some previous work however has highlighted that there will be a need to study both superconducting networks alongside cryogenic cooling systems. Luongo *et al*, 2008, examines the overall viability of HTS within aerospace propulsion applications. Within this study, the first indication of integration of both cooling systems and superconducting networks is given, with useful target values in terms of efficiency and specific mass given. Further scrutiny of this paper is given within Chapter 8 when investigating the cryogenic cooling system in more detail, particularly when considering the outcomes of the models generated.

Superconducting cables are capable of delivering many times the current of traditional copper or aluminium cables with far superior efficiencies (Figure 2-18). DC distribution losses are typically assumed to be zero, whilst AC superconducting cables typically experience losses of less than 0.001% (Oomen, 2000). Typical uses at present for superconducting cables are applications where losses must be avoided or where high power and high current or low voltage distribution, particularly over large distances is a priority. One example of large-scale use of superconducting cables is the LHC at CERN on the French-Swiss border, where the large main LHC ring requires high current power distribution for the many superconducting magnets (CERN, 2011). In the future it is thought that the short distances of cabling between power station generators and step-up transformers is an ideal candidate for superconducting technology because of the potential large losses before the voltage is increased. Ohmic losses for these applications can be high at peak power outputs; hence if even a single percentage point can be gained on 500 MW of power, this translates to an efficiency power saving of 5 MW.

The application of superconducting cables to aerospace use is relatively novel and new. Aerospace applications have previously not required such efficient power distribution because electrical power levels have typically been too low to realise advantages over the additional complexity required for cooling. With the advent of aircraft producing over 1 MW of electrical power, as in the example of the Boeing 787, the desire for ever more efficient and lightweight power distribution is increasing (Malkin and Pagonis, 2015). Furthermore, aerospace electrical designers must

overcome the design challenge of electrical voltage vs electrical current distribution. Using traditional conductors, the increasing electrical power levels on aircraft mean that either current or voltage must be increased. Increasing the current results in larger, heavier conductors, whereas increasing the voltage increases the chance of dielectric breakdown due to the Paschen's law (Figure 2-17).

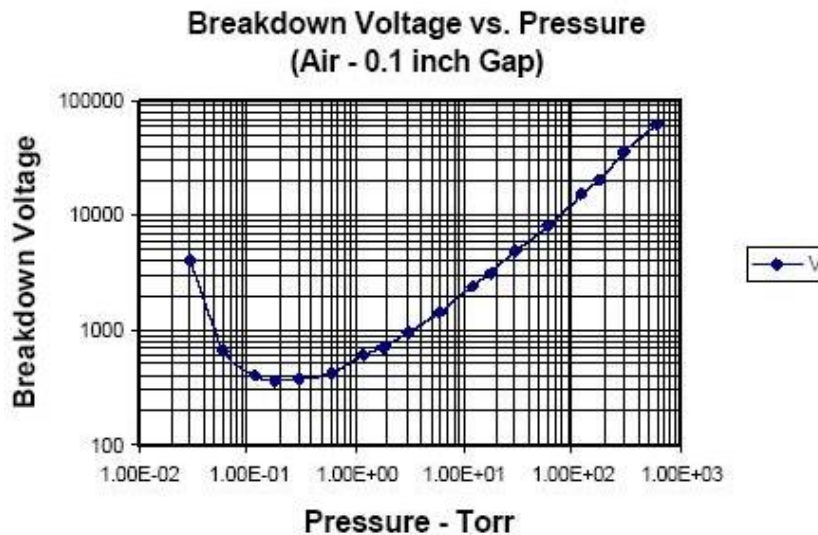


Figure 2-17 – Graph showing Paschens law; breakdown voltage results in arcing from the conductor (McAllister and Crichton, 1987)

Typical HTS Cable Configuration

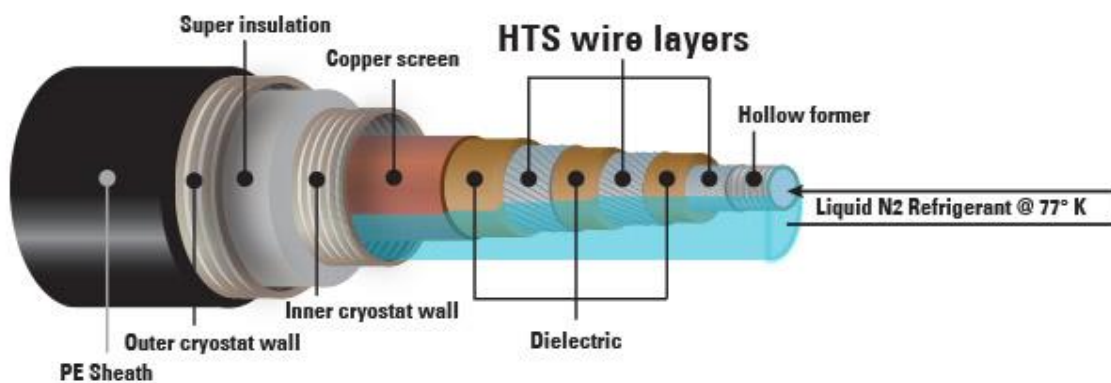


Figure 2-18 – An example of a cross-section of a superconducting cable (SupTech, 2013)

Through using superconducting cables, the voltage level can be kept low for non-superconducting components, and the current can be increased without loss or significant increase in mass. The caveat to this is cooling, as with all other superconducting components.

2.5. Cryogenics

Cryogenics by definition is the science behind low temperature measurements, specifically below 77K (Ekin, 2006) which is approximately the point at which nitrogen becomes a liquid. At these temperatures materials behave differently, for example certain metals (mild steel, aluminium, titanium) suddenly exhibit properties not previously seen, such as becoming brittle and easily fractured, while others retain toughness or contract as the temperature drops. Knowledge of current cryogenic cooling systems will be crucial to success of this project, as all of the potential options must be explored. This will include examining current practices for cryocoolers and the theoretical principles behind each of them, to determine whether cryogenics for aerospace propulsion applications can be commercially feasible.

2.5.1. Thermodynamic Cycles and Techniques

To fully investigate the possibilities regarding cooling options, this project must look at each cooling method from a fundamental perspective, allowing a systems approach to selection of potential candidate cycles. Some are unsuitable due to their temperature limitations, while others are simply impractical from a physical perspective. Gathering knowledge on cycles will be important for selection purposes during the latter stages of the project. There are five cycles known that are applicable to cryogenic refrigeration, however there are a number of methods and techniques that cannot be classified as cycles that must be examined, such as liquefaction processes and throttling valves.

2.5.1.1. Reverse Brayton Cycle

The reverse Brayton cycle, also known as the Bell-Coleman cycle is a method of turbo-driven expansion whereby a fluid is first compressed, then allowed to expand through an expansion nozzle or turbine and pass through the target cold space or object. It works in the opposite way to a Brayton cycle, where the main objective is to extract work from the shaft. The reverse Brayton requires mechanical input from the shaft, which then does work on the fluid in a closed loop to separate the heat into different parts of the cycle. The hot heat exchanger then takes the heat away to be ejected, while the cold side heat exchanger cools the required space. Figure 2-19

shows the process in schematic terms along with its temperature-entropy diagram, illustrating the cycle and in which parts of the system heat is removed.

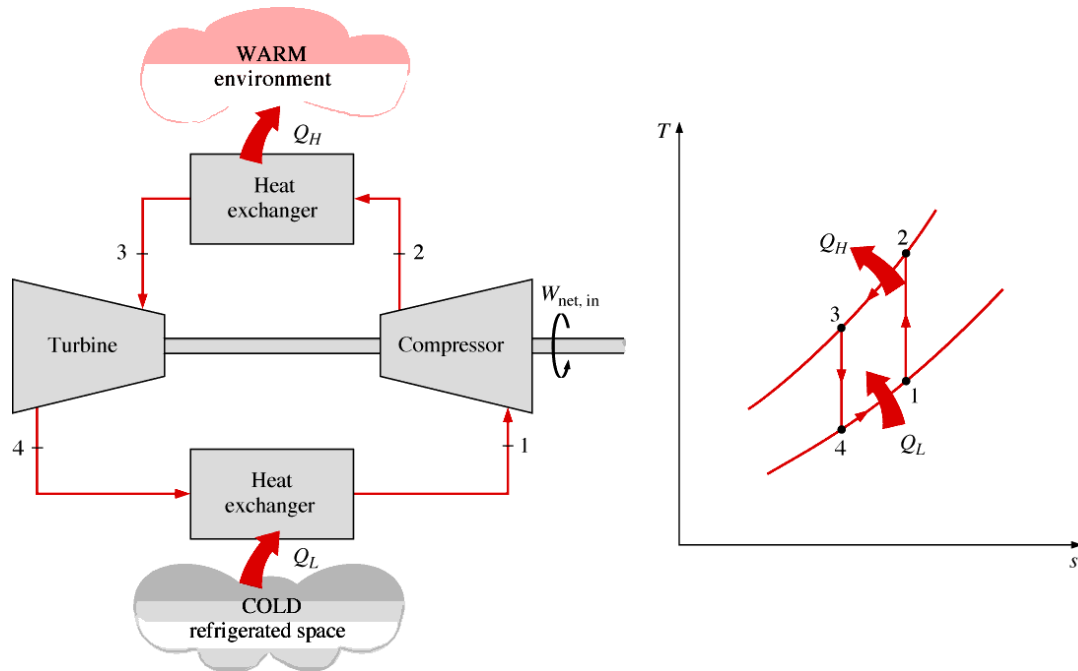


Figure 2-19 – Adiabatic Reverse Brayton cycle and T-s graph (Boles, 1998)

The reverse Brayton could potentially offer a viable solution as it can cool rapidly due to high mass flow rates. They are also highly reliable, with previous examples of reverse-Brayton cryocoolers surpassing 50,000 hours of maintenance free operation (Zagarola *et al*, 2009). The shaft could potentially be linked to the shaft inside current GT engine designs, achieving a compact synergy between the two processes. There is evidence to support this type of application; a patent granted in 2008 (Andres, 2008) showed that the idea had already been theorised, however as the idea is so new, no known examples of an internally housed, GT reverse Brayton cryocooler are available for comparison.

2.5.1.2. Stirling Cycle

The Stirling cycle was invented in 1816 by Reverend Dr. Robert Stirling, as a reversible way of producing work from heat or vice-versa (Walker, 1980). The Stirling engine works with a closed fluid, two pistons, and a rotating crank, connected to both pistons with an offset in timing.

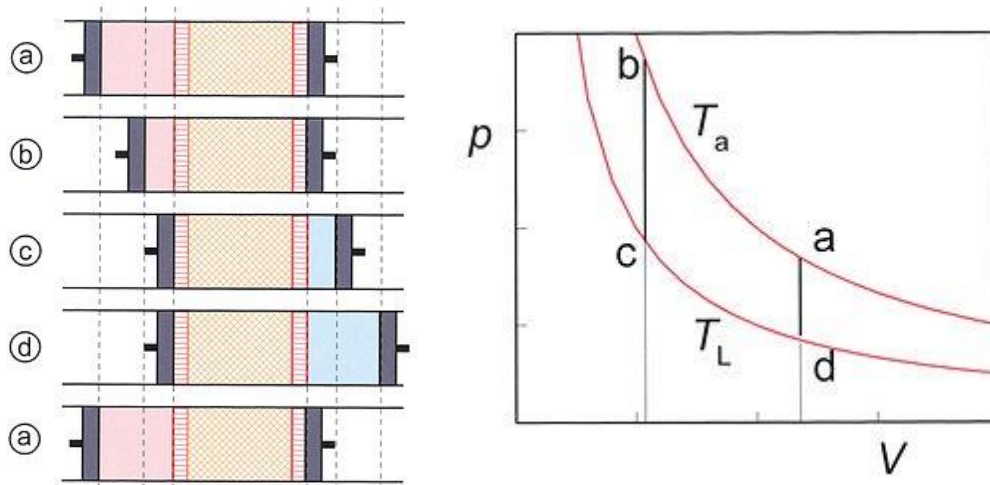


Figure 2-20 – Stirling cycle schematic and P-V graph (Bole, 1998)

Figure 2-20 shows the basic principle behind the Stirling cycle from start to finish. The parts of the machine can clearly be seen in the schematic, with the pistons either side of the tube, the hot head (left) and cold head (right) shown in red, and the regenerative matrix in the middle shown in orange.

- At point A the hot piston begins to compress the fluid, creating heat while the cold piston remains stationary.
- Then at B the fluid reaches its maximum pressure, and the hot head ejects the heat outside the system.
- At C the cold piston begins to retract, allowing the fluid to expand, thus absorbing heat from the cold head surroundings.
- Finally at D the cold piston has expanded to its limit, and both pistons then move in unison to the starting point of A.

The regenerator matrix is there to store thermal energy (or debt) while the fluid is expanded or compressed. This ensures the separation of hot and cold fluid at either end. The Stirling engine is currently in use within many different applications, with one of the most recent in solar power stations in Spain, where heat from solar arrays heat the fluid which creates mechanical work for generators. The cycle could potentially be used for this application, although the effective temperature range of between 60 and 80 K may restrict it for the purposes of use with MgB_2 machinery (Jha, 2006).

2.5.1.3. Vapour-Compression Cycle

The vapour-compression (VC) cycle is a common means of removing heat from a desired area through phase change from vapour to liquid and back again. The main components of a VC refrigerator are compressor, condenser, expansion valve, and evaporator. The evaporator is essentially a heat exchanger, whereby an outside fluid (usually ambient air) is used to evaporate the closed circuit fluid and cool the desired space.

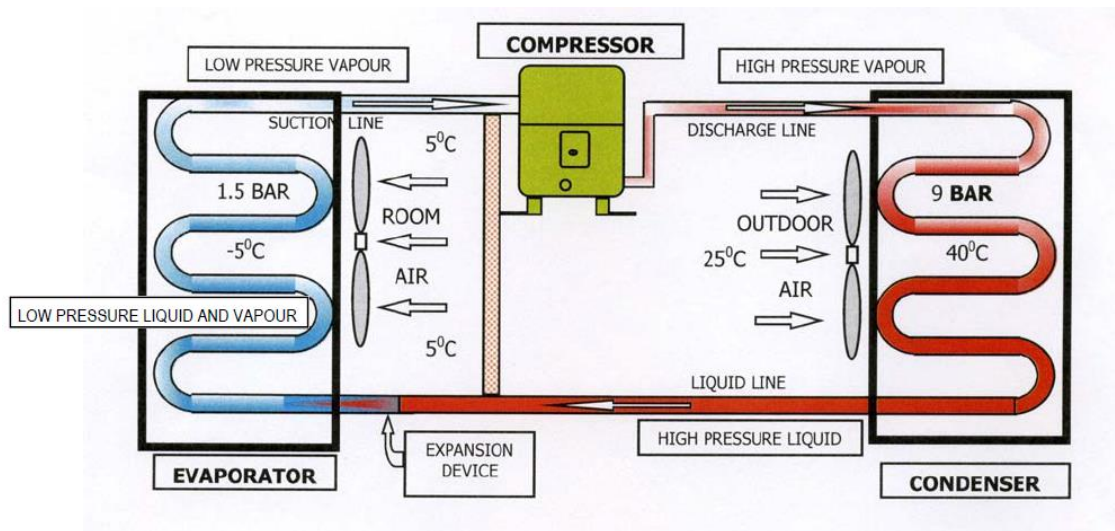


Figure 2-21 – Vapour-Compression cycle as used in air conditioning systems
(Rodway, 2009)

Figure 2-21 shows the VC cycle and its components; however it is worth noting that the diagram only shows single stage refrigeration, whereas typical applications use multi-stage systems.

The cycle begins with a closed loop refrigerant, typically fluids with boiling points close to the desired temperature range, although other considerations such as safety and environment may affect the choice. The fluid starts as a vapour and is then compressed via the compressor, heating the fluid. The fluid then passes through a condenser, which is essentially a heat exchanger where the compression heat is removed and the fluid cools to liquid state. The fluid is then expanded through an expansion valve, which is usually a throttle valve, losing heat further, but partially vaporising. The cold vapour-liquid mix then passes into a vaporiser located in the desired cold space, vaporising the liquid while absorbing the heat from the cold

space. In multi-stage designs, the fluid may pass through more compression and expansion stages, achieving lower temperatures than with single stage designs.

The VC cycle on initial analysis appears to be unsuitable for cryogenic applications, as the ΔT from ambient to operational temperature is likely to be too large; however it may be beneficial to combine one or more cycles for a more efficient overall system, and the use of such a cycle for perhaps initial refrigeration of systems not able to initiate from ambient conditions must be considered.

2.5.1.4. Carnot Cycle

The Carnot cycle is essentially a basic principle used to determine ideal performances of thermodynamic systems, so that it can be compared to real systems for a calculation of efficiency. It was conceived in 1824 by Nicolas L. S. Carnot (Carnot, 1878), and has ever since been used to determine the ideal operating principles for all types of heat engines. The related equations are as follows (Brake and Wiegerinck, 2002):

$$\eta_{Carnot} = \frac{COP_{cooler}}{COP_{Carnot}} \quad COP_{cooler} = \frac{Q_c}{P_{in}} \quad COP_{Carnot} = \frac{T_c}{T_h - T_c}$$

Where:

- η_{Carnot} = Carnot Efficiency
- COP_{cooler} = Coefficient of performance for the cooler
- COP_{Carnot} = Coefficient of performance (Carnot)
- Q_c = Cold heat power supplied
- P_{in} = Power supplied into the system
- T_c = Cold head temperature
- T_h = Ambient temperature (heat rejection temperature)

With these equations it is possible to perform overall simple-terms analysis, and compare efficiency of predicted performance with other coolers, allowing a simple evaluation of effectiveness. To assess the required mechanical work for the compressor, the following equation is used (Bumby, 1983):

$$W = \frac{T_2 - T_1}{T_1} Q$$

Where:

- W = energy input from compressor (W)
- T_1 = Desired temperature (K)
- T_2 = Ambient temperature (K)
- Q = Amount of heat removed from the cold space at temperature T_1 (W)

This allows estimates of the required power for compression of a fluid, which is essential in any thermodynamic heat pump cycle. All of these techniques (including component-specific equations) will be applied at a later date during quantitative analysis phases, to build a database of values from tried and tested machines. This will create a benchmark for improvements, and will act as a good representation of project performance.

2.5.1.5. Siemens Cycle

The Siemens cycle is similar in principle to the Stirling cycle, with the main difference being that the cooling of the hot compressed fluid is achieved by passing it through a recuperative heat exchanger in a continuous loop rather than a regenerative reciprocating heat exchanger. Due to its similarity to the Stirling engine, the Siemens cycle can be quickly described to save time reiterating the same points. It does however have importance when describing Joule-Thompson valves in the next section.

2.5.1.6. Joule-Thompson Valves

This type of valve is essentially a convergent-divergent choke nozzle that forces the molecules of vapour or gas to do internal work on each other before expanding the fluid, cooling it in the process (Jha, 2006). The simplicity of the device means it has no moving parts, which is extremely advantageous due to the extremely low temperatures in its usual application. Moving parts tend to fatigue and wear faster under cryogenic temperatures (Ekin, 2006) due to the lack of lubricant, and so this type of valve is preferable to having multiple, progressively colder stages in a cycle. Usually in a low temperature cryocooler, the J-T valve is the final stage in the cooling process. Joule-Thompson expansion is often used where liquefaction is the target, since the small amount of work required and lack of moving parts means the

reliability is high. J-T valves are often used in series with fluid cycles such as the Siemens cycle.

2.5.1.7. Hampson-Linde Cycle

The Hampson-Linde (HL) cycle is a combination of the Siemens cycle and JT valve specifically for liquefaction of gases. The method was patented in 1895 by W. Hampson and C. Von Linde (Jha, 2006), with the difference to the Siemens cycle of having the JT valve where the cold expansion piston would normally be.

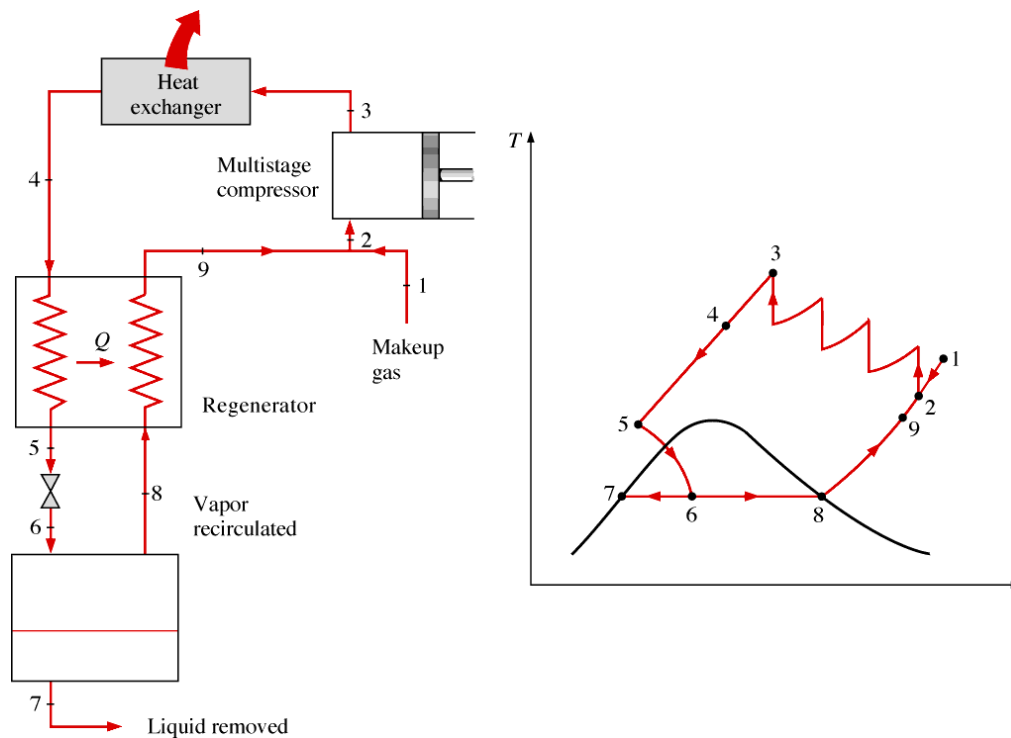


Figure 2-22 – Schematic and T-s diagram of the Hampson-Linde liquefaction cycle (Bole, 1998)

Figure 2-22 shows a schematic diagram of the HL cycle, with the key components shown on the adjacent temperature-entropy graph. The cycle is the most common used for liquefaction of gases, with numerous applications in use throughout the world. Understanding this cycle will be important because of the likelihood of the need for re-liquefaction of boil-off gases in a proposed system, and knowing whether or not a system is capable of returning all boil-off products to liquid state. Analysis of the HL cycle will take place at a later stage in the project, as part of the quantitative assessment.

2.5.1.8. Low Temperature Cryogenics

While cryogenics focuses on low temperature physics in general, it is worth noting the specialised branch of cryogenics, which deals with temperatures in the single Kelvin range or less. The methods to achieve such low temperatures are somewhat novel and exotic, however knowing their applications and limitations will help to either include or disregard them when the concept selection is underway. The two main methods for achieving such low temperatures are the Dilution Refrigerator, and the Magneto-Caloric effect.

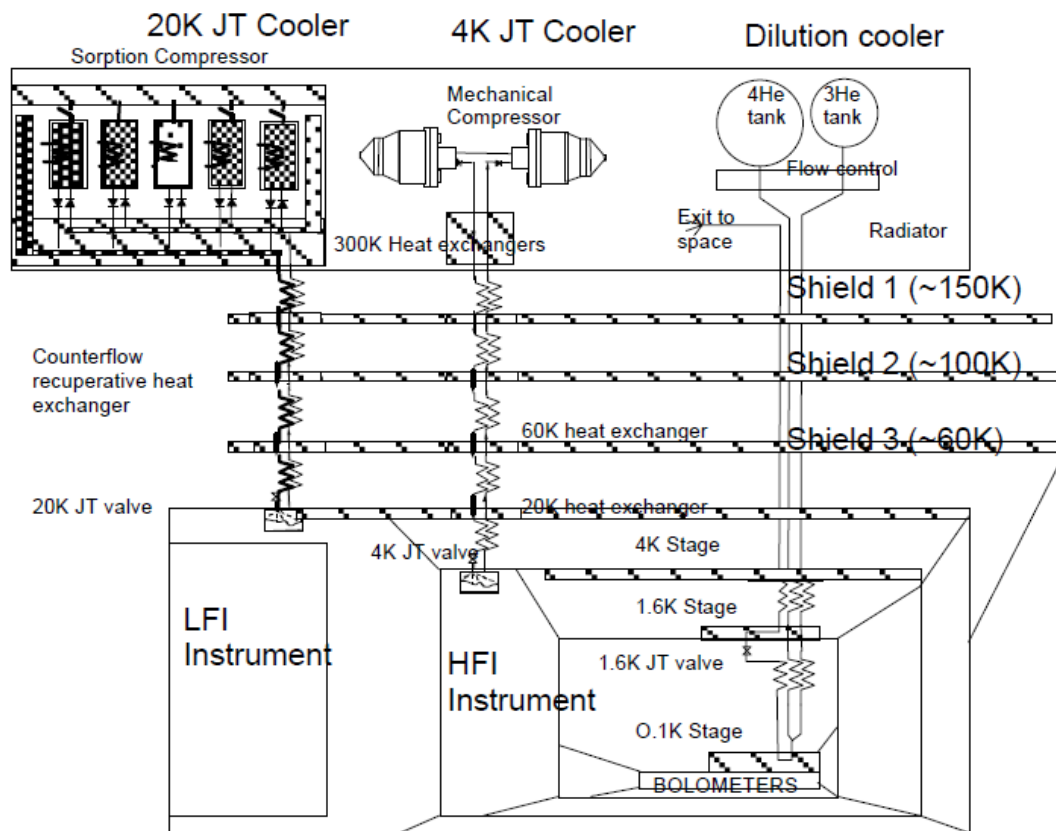


Figure 2-23 – Dilution refrigeration practical example for the Planck satellite
(Collaudin and Passvogel, 1999)

Dilution refrigeration (Figure 2-23) is used only for very low temperature physics, where coolers are typically used for achieving temperatures below 1 K (Radebaugh, 2009). The method uses liquid Nitrogen (LN_2) and Helium (^4He) to cool a closed loop system of Helium (^3He) through various stages of heat exchangers. The use of ^3He however is controversial, the reasons for which will be explained in the cryogenics

section. The method at this stage is not a viable option, due to its reliance on different cryogenics and possible effects on weight as a result.

The Magneto-Caloric (MC) effect is a cooling method whereby a strong electromagnetic field is applied to the solid ferromagnetic mass inside a cooler (typically Gadolinium) (Gomez *et al*, 2012). The material experiences heating whilst inside the magnetic field, giving off heat through adiabatic magnetization. The material then is cooled with fluid (^4He), losing enthalpy. The magnet is then switched off (adiabatic demagnetisation), and the material cools. The system then is allowed to return to thermal equilibrium, whereby it can begin again. This type of cooler could prove useful, due to the high magnetic field available with superconducting electrical machines, and one day a possible synergy between the SC electrical machines and coolers could be achieved. MC cooler efficiency is high at around 50%, and with a 5 Tesla magnetic field, can generate up to 600 W of cooling power. This however is at a significant weight penalty due to the mass of the ferromagnetic material and superconducting systems. It will be worthwhile researching despite this possible weight penalty, and cannot be discounted at this stage.

2.5.2. Cryocoolers and Fluid Transfer

Cryocoolers will be one of the key areas of focus within this project, due to the implications of each possible design and the impact that choice of cooler will have on the efficiency of the overall system. To make sure the correct decision is being made, and that the choice is not made under bias on current technology or ideas, every possible variable will be scrutinised from the basic cycles that dictate their operation, to the physical manufacture of the machines, in an attempt to understand the areas that could either be improved upon or completely re-assessed. The literature search will eventually be turned into first stage concept designs and system configuration, which will in turn be validated through cryogenics industry experts.

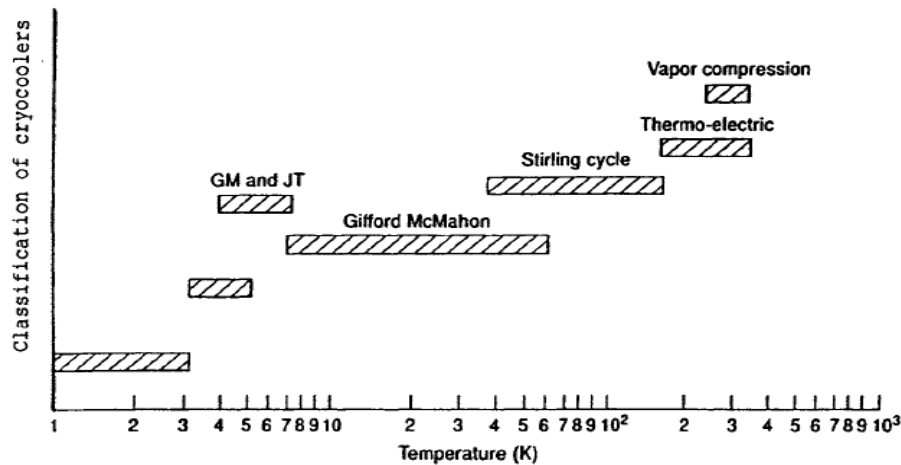


Figure 2-24 – Graph showing the optimum temperature ranges for some types of cryocooler (Jha, 2006)

There are a number of different types of cryocooler, with all types having a theoretical limit to their operative temperature ranges. Figure 2-24 shows the current perceived effective temperature ranges for some types of cryocooler, with the temperature ranges shown on a logarithmic scale for visual proportionality. Rolls-Royce have already specified that MgB_2 is to be used for the large part of superconducting materials, hence the temperature range to be considered should include LH_2 as a fuel, and be below the T_c of MgB_2 . However the effective range of other cryogens should also be considered, allowing full analysis of cryocoolers with a range encompassed by $\sim 15\text{K}$ to 77K using different cryogens. Figure 2-24 shows most of the types of cryocooler that will be of possible interest to the project, with a few missing compared to this literature search. The main missing elements in the graph are the Pulse tube cooler, a relatively new type of cryocooler with no moving parts at the cold head, and the reverse-Brayton cycle. As the project is trying to determine the feasibility of using these types to cool various cryogens, extensive work on each cryostats properties and workings must be undertaken, to ensure the proposed design is capable of efficiently utilising the respective cryogen.

Three main cryocooler will be investigated for use, due to the availability of data from various companies that manufacture the coolers. These are Gifford-McMahon (GM), Pulse tube (PT), and Stirling engines (SE). Other types such as the reverse-Brayton cycle cryocooler do exist, however it will be difficult to compare them within this report due to their custom design nature. Another method of cooling explained within

this section will be fluid transfer, which although relies upon coolers to maintain temperature, has potential applications in its own right.

2.5.2.1. Gifford-McMahon Coolers

The GM cooler uses the Ericsson cycle, which has not been included in the thermodynamic cycle's section due to its close relationship with the Stirling cycle. The only difference between the GM and SE cycle is that the coolers hot piston or displacer provides the work for the machine, where the Stirling uses the crank shaft (Ekin, 2006). The GM cooler is used throughout industry as a benchmark for cryocoolers, and is the most common type due to its availability and reliability. It can also be combined with JT valves to cool further, and as with most other cryocooler, practical examples can have multiple stages. Multiple stages help cool samples or machines from ambient, with first stages generating between 77 and 40 Kelvin, and the second stage typically ranging from 20 to 4.2 Kelvin. This makes the cooler ideal for the desired temperature range of MgB_2 .

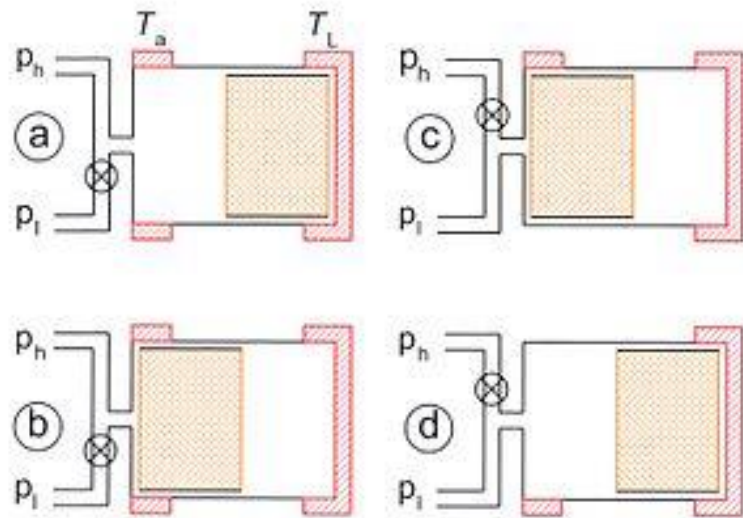


Figure 2-25 – GM cooler schematic of operation phases (Boles, 1998)

Figure 2-25 shows the simple schematic arrangement for a typical single stage GM cooler. In phase A, the high pressure valve is open and the regenerative piston begins to move to the ambient heat exchanger shown in red on the left, compressing the fluid and forcing the fluid through the piston. Phase B then shows the piston fully extended into the ambient exchanger, whilst the fluid is at maximum pressure. Phase C then shows the valve switch to low pressure, causing the fluid to expand and

absorb heat, which then in turn causes the regenerator to move to the right once more, completing the cycle. Typical frequencies of this cycle are fixed at 50-60 Hz, relating to the electrical supply available in most areas. A major disadvantage of the GM cooler is the requirement for a separate compressor. These are often large and bulky, and are likely to detract significantly from any advantages gained.

2.5.2.2. Pulse Tube Cryocoolers

Pulse tube cryocoolers are a relatively new type of cooler, popularised by its low vibration operation and zero moving cold-head parts. They essentially work using the Stirling cycle principle, with the cooler acting as the expander only while fluid is pulsed through the device.

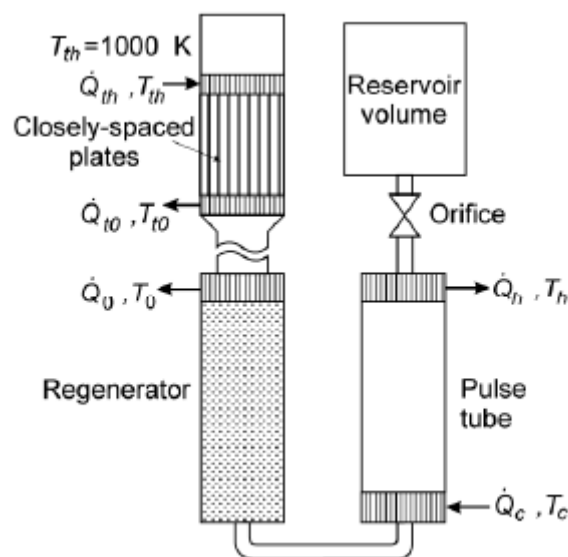


Figure 2-26 – Pulse tube cryocooler schematic (Radebaugh, 2000)

Figure 2-26 shows the schematic of the pulse tube, with the compressor piston to the left in black, hot and cold heads shown in red, and the regenerator material shown as crosshatched between the hot and cold heads. There is also an orifice to resist flow into the buffer, which is essentially a closed reservoir of the fluid. The cooling phases are not illustrated on the diagram; however they follow the same four phase pattern as with most cycles:

- Phase A – The piston moves to the right, creating high pressure and raising the temperature of the fluid, as it passes through the hot head and regenerator material.
- Phase B – The fluid loses its heat in the regenerator, which then passes through into the cold head, then compressing through the second hot head and through the orifice, losing further heat.
- Phase C – The piston then moves to the left, pulling the fluid back through the regenerator, with the fluid expanding and absorbing heat at the cold head.
- Phase D – The fluid passes through the regenerator, gaining its heat back and dispersing it through the first hot head, ready to be repeated back to phase A.

The Pulse tube has advantages with maintenance and lifespan, as it operates with no moving parts at the cold head (Radebaugh, 2000). They can typically achieve the same temperature ranges as GM coolers, and similarly have multiple stages. However due to the technology's low maturity, coolers are limited in size, and can be bulky and heavy. As with GM coolers, pulse tubes also require external compression equipment, which are typically bulky and heavy.

2.5.2.3. Stirling Engine Cryocoolers

As the Stirling cycle has been explained in detail previously, it is not required to reiterate its operational characteristics. They are in use throughout the world, and as previously mentioned, currently are favoured for solar power arrays around the world (Figure 2-27). They however cannot on their own reach the same temperatures as GM or PT coolers, and may be subject to combination of other coolers, should the Stirling engine present any major benefits.

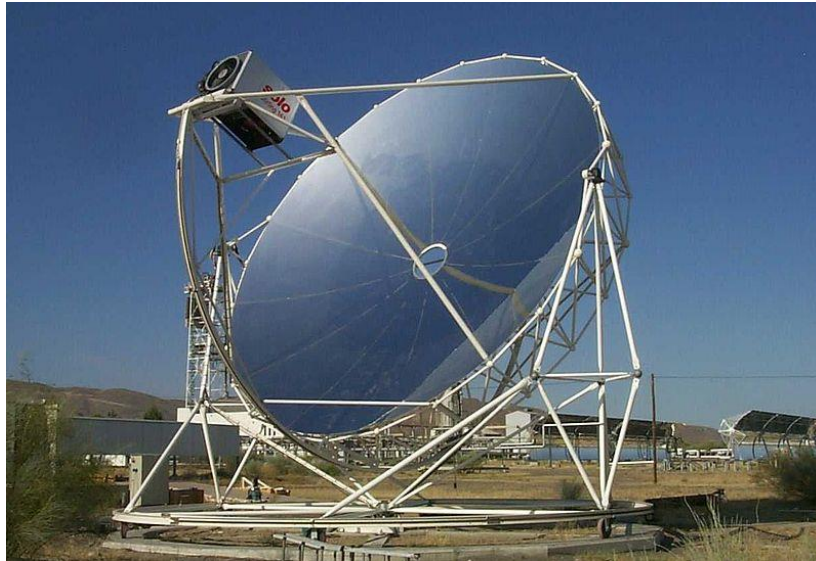


Figure 2-27 – Solar array with Stirling cryocooler in Spain (Schlaich Bergermann, 2006)

2.5.3. Fluid Transfer Cooling

Although cryocoolers are the preferred method for generating low temperatures, transfer of cold fluid through components exists as a major option. Having a liquid cryogen storage stabilised by cryocoolers and then pumped around a network of transfer lines to major components has numerous potential benefits. The key potential advantage of using the fluid is the option of choosing a combustible fluid which can be used to fuel or supplement the fuel of the aircraft. Using either liquid hydrogen (LH_2), liquid Methane (LCH_4) would exploit this synergy, with both fuels having high energy density and desirable ambient liquid temperatures.

2.6. Cryogenics

The choice of cryogen will be essential with regards to the temperature range and choice of cooling method. The cryogen or heat sink medium used will decide the other main temperature constraint around which the system must be designed. For the purpose of research, two cryogenics are being considered at this stage, LH_2 and LCH_4 .

2.6.1. Liquid Hydrogen

LH_2 as previously mentioned was initially of interest due to its high specific heat capacity, and potential use as a fuel supplement in the GT. LH_2 is a viable choice as

cryogen for cooling MgB_2 as its temperature range of 14.01K-20.28K (Ekin, 2006) falls neatly within the T_c area of MgB_2 (Figure 2-28).

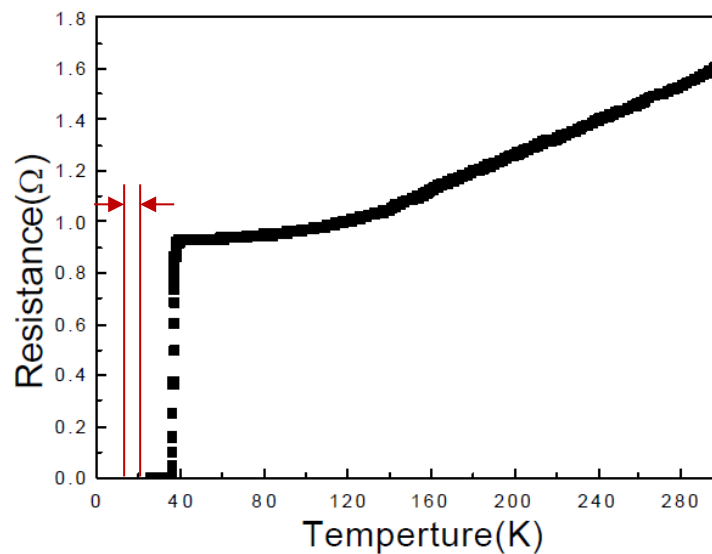


Figure 2-28 – Temperature-Resistance graph of MgB_2 showing LH_2 range in red (Nagamatsu *et al*, 2001)

The state of LH_2 can be controlled by pressure, so using higher pressure systems, LH_2 can be achieved at temperatures above its condensation temperature at only 1atm. The idea behind using LH_2 as a gas turbine supplement as well as a coolant can yield many advantages, such as higher fuel efficiency, lower fuel consumption, and cheaper overall operating costs due to certain overseas applications within the military (Johnson, 2012, Appendix A).

The use of LH_2 presents a number of problems, primarily to do with the system itself which will be required to be open loop, rather than closed loop. The reason this presents a problem is that for current cryogenic systems the expulsion of cryogen is not essential or necessary and would be seen as a disaster; this type of system however would require the LH_2 to pass through the cooling system and then be burnt in steady-stream fashion in the GT. Any mismatch in the mass flow rates between required cooling and required fuel flow presents design challenges, and further recuperative cryogen heating is likely to be required. In the scenario that more fluid is needed for fuel, advantages of compressor cooling on the gas turbine could be realised. If cooling demands are greater than fuel flow demands, then the warmed LH_2 could be fed back into a reservoir system, adding mass and complexity.

It will be a challenge in itself simply to keep the system under the required pressure and temperature in large enough quantities for commercial applications. The European Cryoplane project notes that only cylindrical or spherical storage tanks would be suitable (Faab, 2001), however during an interview with an expert in cryogenics, the expert confirmed that this was not the case, and that LH₂ storage does have a degree of freedom regarding geometry (Harrison, 2012, Appendix A). If a solution can be reached to this problem, then this may well be the initial progression to the first truly continuous open-loop cryogenics system used in aircraft applications. As the use of LH₂ as a cryogen is relatively new and the idea for its use as a double function coolant and fuel supplement is all but unheard of, there are no released articles concerning those topics apart from NASA's space shuttle main engines, which are also cooled by hydrogen before it is burnt in similar synergistic style (Kacynski and Hoffman, 1994).

There are similarities to both systems, and the study of the space shuttles main engine nozzles provides a working example to analyse, identifying whether any of that technology is useful for this research project. This study could yield benefits from trying to understand how their storage tanks function also, and in attempting to establish if the method of pumping could be limited to a slow trickle of LH₂ rather than the extreme quantities that are burnt per second during main engine burn.

Despite the lack of data available on LH₂ in aviation applications, hydrogen fuelled aircraft are not a new concept. During the 1950's, 1960's, and 1970's, U.S. hydrogen production grew to commercial scale, to fuel their space program. Lockheed Aeronautical Systems engineers worked on behalf of NASA and the USAF to produce viable design ideas for possible hydrogen fuelled aircraft (Brewer, 1991). The results were convincing, and while at the time hydrogen technology and demand for alternatives was minimal, today's problems with emissions and fuel costs/availability cement the need for such research. The results of the research will be a key part of this reports interest in LH₂ and will feature heavily during analysis stages.

2.6.2. Liquid Methane

Liquid methane (LCH₄) essentially is an alternative to LH₂, whereby it can double up in function as a cryogen and fuel supplement for aircraft. The temperature range for

LCH₄ in liquid state at ambient pressure is between 90.72 K and 111.7 K (Ekin, 2006). For the purposes of analysis during this paper, the upper limit will be taken in numerical analysis to give the worst-case scenario and avoid overt optimism. This temperature range is outside of the required temperature for operation of MgB₂ as a superconductor, and due to this, initially would be discounted. It also further adds to the problem of emissions, and essentially is still an un-renewable fuel that emits vast quantities of CO₂ and NO_x gases. It is worth investigating from an analysis perspective however, to ascertain whether using LH₂ with liquid methane could yield any benefits over standard jet fuel. The theory will be simple to test also, without the need for expensive test rigs and specialist or customised equipment.

2.7. Support Systems and Cryogenic Architecture

In addition to the core components, it will be important to examine what is required to control and operate cryogenic systems in order to understand the likely implications of their integration within aerospace applications. For example, when considering the weight of a cryogenic system, cryocoolers will require thermal shielding, sensory equipment, vacuum pumps, and more. This section of the literature review looks at familiarising the project to the additional requirements, with the aim of summarising current technology. The cryogenic architecture will also be mentioned as a statement of possibility, meaning initial theories on the most effective network arrangements should fluid transfer be the most appealing solution.

2.7.1. Thermal Shielding

Due to the extremely low temperatures required for operation, thermal shielding of superconducting components will need to be as effective as possible, to minimise the amount of heat leaking in. The most commonly used method to date is to have an evacuated space between the cold and ambient parts. This is achieved by pumping all of the air out of the space. This has two effects; firstly heat transfer by means of convection and conduction are eliminated and minimised respectively, and secondly and moisture or air that could freeze and decrease insulation properties is removed. For a high quality vacuum to be achieved, current systems use turbo-molecular pumps (Ekin, 2006) which can reduce the pressure within a system to around 10^{-5} - 10^{-8} Torr, or around 1.32×10^{-3} - 1.32×10^{-6} Pascals.



Figure 2-29 – Aerogel samples; the left picture is a 2.5 kg brick supported by a 2 g slice of Aerogel; the right picture is a flower being shielded from a naked blowtorch flame (NASA, 2004)

Thermal shielding cannot fully eliminate heat absorption however, as the pipes and various components must have at least minimal contact. Current cryogenic systems use small, thin strips of stainless steel (Ekin, 2006) to support the vacuum jacket whilst at the same time minimising heat loss, however it may be beneficial to explore other types of material for this purpose. One such material that may be ideal for this is silica Aerogel, a very light, very low thermal conductivity porous material developed for space applications (Figure 2-29).

The silica-based material is classed as ceramic, although the material does not shatter as easily as traditional ceramics. Aerogel is unique in its properties, with the lightest example of the material weighing around 2 mg per cm^3 (Fesmire and Augustynomicz, 2005). This makes it almost as light as air (1.2 mg per cm^3). The material also exhibits a very high porosity at up to 99%, allowing either fluid or vacuum permeation, further increasing its versatility. Furthermore, its thermal conductivity is very low, with some types exhibiting around 0.001 W/m-K. No other material exhibits the same combined properties as Aerogel, with only multi-layered insulation (MLI) surpassing its performance in terms of thermal insulation. It will be worth investigating Aerogel in terms of weight and effectiveness, as it could potentially be highly viable as an insulator.

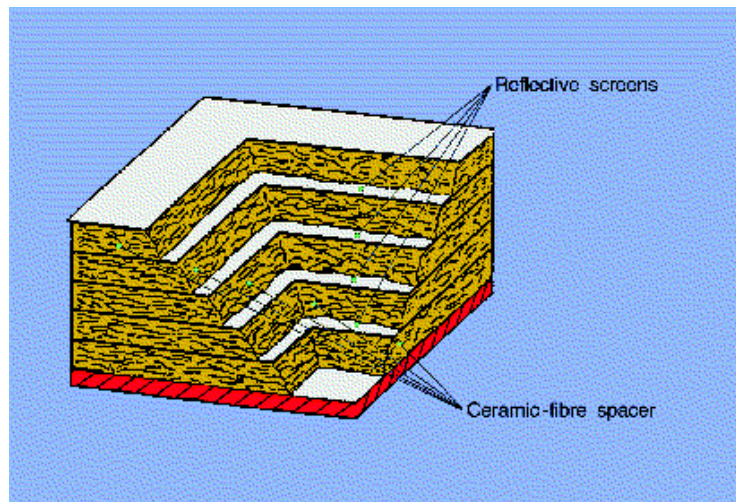


Figure 2-30 – Schematic diagram of multi-layered insulation (Keller *et al*, 1994)

MLI is another typical cryogenic insulator, used throughout the space industry as instrument shielding against the harsh thermal environment of space. MLI consists of alternating layers of reflective and insulating sheets of material, typically high-reflective aluminium foil and Mylar or fibre spacer respectively (Figure 2-30). By alternating reflective and insulating layers, MLI eliminates radiative, conductive, and convective heat transfer components. This makes the material highly effective, with lowest heat transfer coefficients of 0.073 mW/m-K , making MLI the best thermally insulating shielding known (Johnson, 2010).

Seals for the rotor of superconducting machines are a major design challenge. Due to the rotors need to spin at potentially high speeds, cryogenic fluid or cooling must be able to access a rotating medium, through fluid cooling or otherwise. This means rotating seals will have to be selected, which could include cryogenic bearings or graphite lubricated standard bearings. This problem however is outside of the scope of the project, as it is part of the detailed design of a concept, rather than the high level analysis undertaken. Despite this, it is worth noting the challenge in such components, in case the knowledge is relevant at any stage.

2.7.2. Operational Procedures

Cryogenics technology has very specific operational requirements, due to the potentially hazardous nature of some cryogens and cooler limits and specifications. Start and shut down procedures must be considered, otherwise designs in the theoretical sense may be unachievable in the practical sense. To understand real

world systems, a practical tour of Manchester University's electrical UTC was attended in February 2012, UK. The example shown was a double-stage GM cooler with He₂ compressor, manufactured by CryoMech (Smith, 2012, Appendix A). The operational procedures for the systems were as follows:

- “Turn on vacuum pump, ensuring the pressure is at the desired level (10^{-3} mbar for this system)”
- “Our LN₂ transfer medium into cryostat (this is to lower the temperature to 77 K, saving time waiting for the cryocooler to reach operational temperature).”
- “Turn on the compressor/cryocooler and seal the cryostat.”
- “Wait for temperature to reach the desired level.”

These procedures are common practices throughout the cryogenics industry, with some small differences such as methods of pre-cooling, whether the cold space is a cryostat or superconducting machine, and the cryogen used. Shut down procedures must also be adhered to; ensuring equipment lifespan is at its maximum. The shutdown procedures are:

- “Using the temperature controller, step the temperature down gradually, for example if the sample is at 20 K, step the sample first to 40 K, then to 60K, then when the temperature reaches the boiling point of LN₂, turn off the compressor/cryocooler. This gradual rise in temperature is preferable to sharp sudden rises due to thermal expansion allowances and the risk of material fracture (Ekin, 2006).”
- “Once the temperature rise above 77 K, the cryostat lid can be opened, and the nitrogen can be allowed to boil off. As nitrogen can asphyxiate, care must be taken when working in enclosed spaces to ventilate the area.”
- “Finally the vacuum can be switched off once the temperature reaches ambient.”

These procedures highlight a possible problem regarding the design of 20 K machines, which is pre-cooling of superconducting components. It may be beneficial to use a separate system to first pre-cool, and then use the primary cryogen/method for the operation of the machines. It is likely that for large-scale aviation, turn-around times for aircraft may present a significant technical challenge, particularly at

locations where maintaining cryogenic temperatures will be energy intensive such as in desert climates.

2.8. Research Gap Analysis

Cryogenics in aerospace systems is already scarce in terms of prior literature. The research gap widens when considering the application of high-powered propulsion cryogenics, hence the research gap is extremely large and easy to identify. For example:

- There are no high-powered (>5 kW cooling power) aerospace cryocoolers currently in existence.
- There are no superconducting electrical machines yet available in the form of fully superconducting motors or generators.
- To the best of public knowledge, there are no size and weight estimation tools for either superconducting components or networks or cryogenic cooling systems.
- There are no processes available that can readily tackle the problem of sizing an unknown system that exists to cool another unknown system for an as-yet undefined concept aircraft.
- There is no definitive and repeatable process to find a cryogenic cooling system design solution to the problem of superconducting electrical aerospace propulsion.

There are many more areas of potential investigation that can be discussed; however these gaps appear to be both the largest and most pertinent to the academic and scientific field.

2.9. Summary

In summary for this chapter, it has been highlighted that there are numerous different topics involved in this thesis. The term multidisciplinary can be justified in the case of this research, since the incorporation of electrical engineering, aerospace engineering, thermodynamics and superconductivity along with systems engineering shows a highly varied subject matter. Although the project is about a conclusion

within cryogenics, the research touches on a number of firsts, particularly during the systems engineering and modelling phases of the project.

Chapter 3. Research Methodology

3.1. Introduction

The research methodology can be effectively summarised as an adapted systems engineering process that incorporates numerical modelling to bridge gaps in knowledge. The traditional systems engineering process describes a robust method for solving complex problems by initially performing stakeholder analysis and requirements capture. By doing so, the problem can be much more effectively defined before solutions are suggested, making the likelihood of missing information or poorly defined requirements substantially lower. This project is however highly conceptual in nature; most traditional system engineering projects have all of the information or research available on concepts, and thus the process can be followed without modification. This project faces many unknowns in terms of technology, the supporting systems, and the overall concept; hence the system engineering process must deviate away from purely qualitative assessment and incorporate numerical analysis and modelling. By including numerical modelling, concepts can be investigated for the first time, effectively filling in any gaps in known research and allowing the process to continue. A more detailed breakdown of the optimisation of the systems engineering process is given in Chapter 6.

3.2. Adopted Research Methodology

This research methodology section aims to give a high-level view of each research phase. The phases themselves have undergone a number of iterations throughout the project, with the final structure presented in Figures 3-1 and 3-2. In Figure 3-1 the first three project phases can be seen, showing the initial requirements capture and the functional modelling stage. The reason this stage is so comparatively large is that both the literature review and requirements capture phases were significant in size. The literature review encompassed dozens of topics, and the requirements capture and functional definition was complex because of the number of remaining unknowns. Furthermore, the requirements capture and functional definition phase of this project was vital to its success. The number of unknown qualities and quantities means that if the requirements capture phase is treated hastily, the proceeding quality and decision robustness of the project will diminish. Figure 3-2 shows the second part of the thesis where the functional modelling leads to numerical

modelling and a re-evaluation of the overall system engineering process. Some milestones are also marked, such as the submission of final Rolls-Royce technical report and various conference and journal paper deadlines. These are to indicate the increasing maturity of the project as time progresses, along with highlighting the academic and industrial differences in reporting strategy. The steps taken in Figure 3-1 are explained in more detail in Tables 3-1 and 3-2, with steps taken during Figure 3-2 explained in more detail in Tables 3-3, 3-4 and 3-5.

Figure 3-1 shows the qualitative approach taken initially during the research. The rationale behind applying a qualitative approach early on is driven by the need to reduce the number of variables. Cryogenic cooling systems for high power aerospace applications are considered a radical application of technology, with no examples or present requirements for comparison. Due to this, the research methodology had to adopt a fluid and generic approach to remove the variables through broad technological study. Furthermore, the research validation had to be robust and regular for the same reasons. Expert validation is critical, particularly during the transition between qualitative and quantitative analyses. Figure 3-2 shows the step-by-step validation when modelling takes place, ensuring the assumptions and methodologies are all consistent with current scientific understanding. By using expert opinion, recognised toolsets, company collaboration and peer review, the variables during numerical modelling were reduced or mitigated sufficiently. Further validation also took place in cross-company studies with Airbus and NASA, with the combined approach resulting in a low risk of error or anomaly.

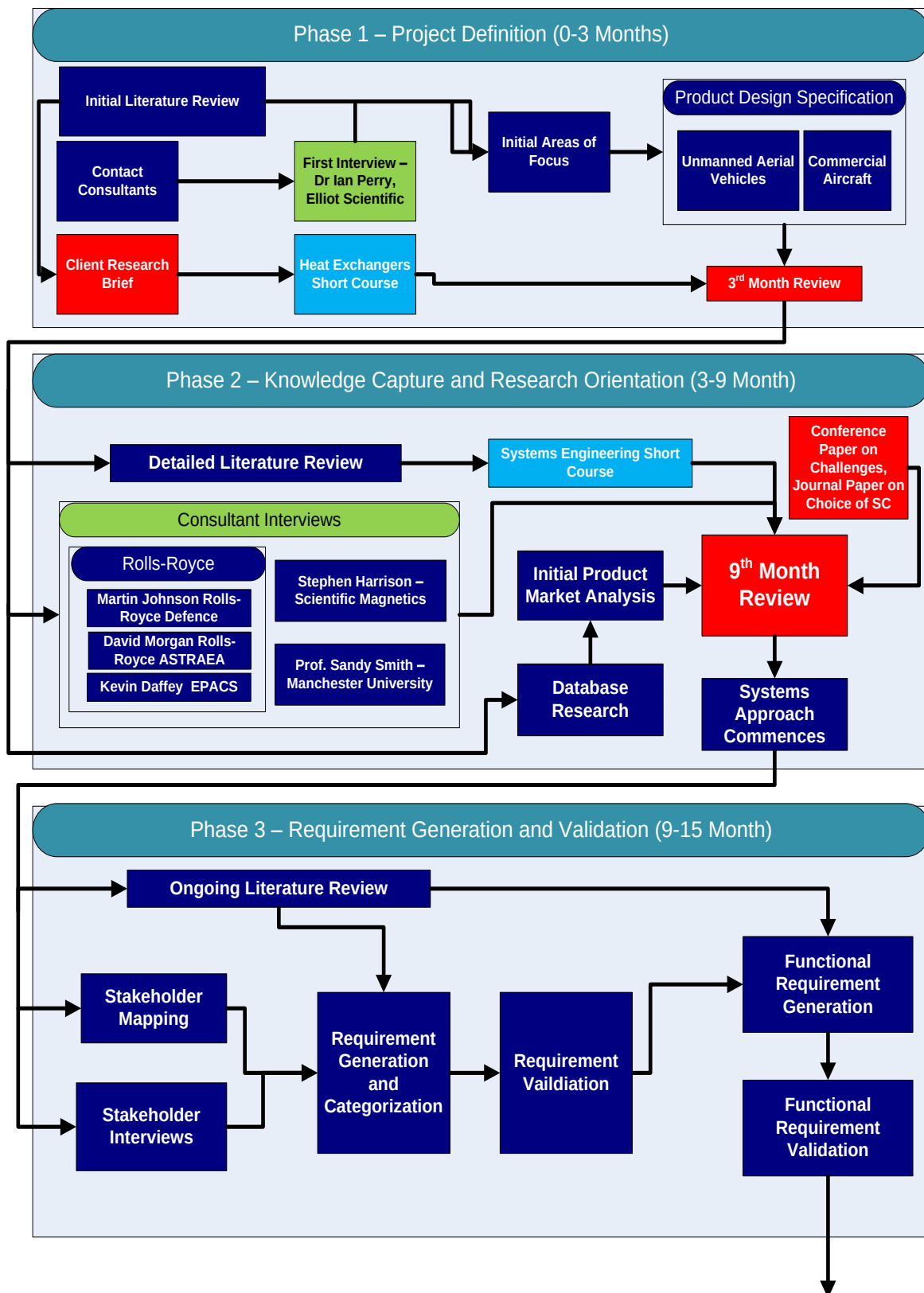


Figure 3-1 – Project Phases 1-3

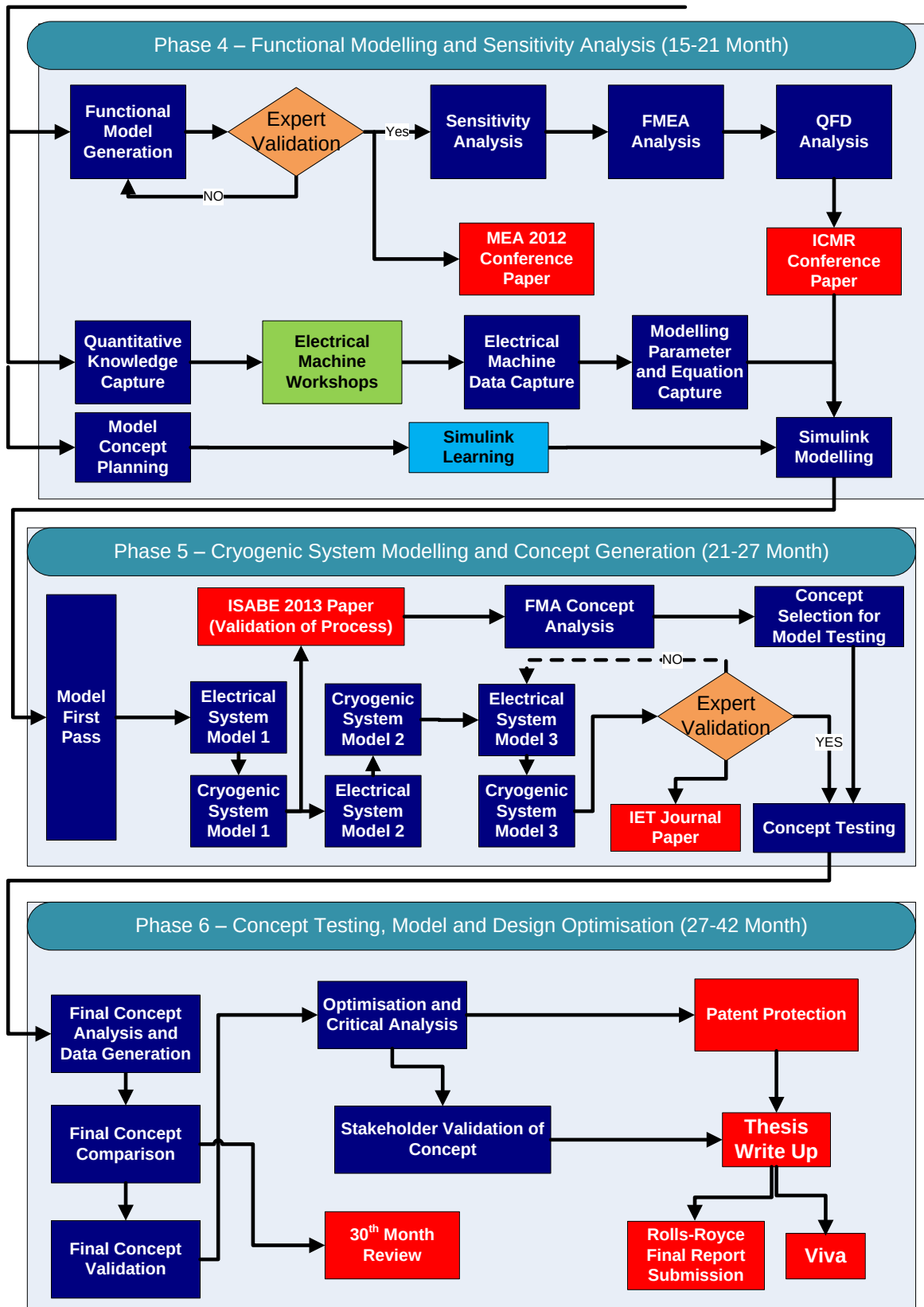


Figure 3-2 – Project phases 4-6

Table 3-1– Phase 1 and 2 detailed breakdown of tasks

Activity	Tools and Methods	Rationale	Outcome
Phase 1 – Project Definition			
Initial Literature Review	Reading journal and conference papers, past scientific community approved presentations, and related books.	Capture basic knowledge on the principles behind the key topics to do with electric flight and superconducting technology	Understanding of fundamental subject areas relevant to the design aspects of systems later in the research.
Initial Areas of Focus	Gathering data on the high level aspects of the project. Internet searches, sponsor documents and academic resources.	To understand initial direction and to secure the relevant knowledge areas for analysis during the project. This is performed closely with the literature review.	Better scope definition, objective planning, and understanding of the required individual high level aspects required for research within the project.
Contact consultants	Contact the relevant recommended consultants with arrangements made for future meetings/interviews.	To enable future liaison with the consultants, and to show general interest in their respective research areas.	Acknowledgement of interest to the consultants, such that they are aware of my presence and intentions in research.
Product Design Specification	Produce requirements for the individual applications concerning commercial designs using gathered knowledge about typical operating conditions.	Form a basic framework of understanding for the individual needs of each applications cooling system, which allows expansion.	Knowledge of the theoretical types of suitable systems known, and can also be used as a rudimentary validation tool at a later date.
Phase 2 – Knowledge Capture and Research Orientation			
Consultant Interviews	Visits to the various departments available for comment with a stake in the project. Construction of questionnaires with targeted questions relating to each consultants expertise	To establish and validate direction of the project before further progression, and to understand the main barriers to the research in the project.	Validation of initial project direction, understanding of stakeholder and industry professional requirements, and information on various aspects of the project.
Detailed Literature Review	Continue to read journal and conference papers on relevant topics, begin to catalogue all relevant aspects; use of internet searches, books, journals, conferences, presentations, expert contact.	To gain knowledge on specific areas of cryogenics, including cryocooler, thermodynamic processes, cryogen data, and superconducting machinery.	Detailed understanding of modern cryogenics, superconducting machinery, and theoretical low-temperature thermodynamics.
Database Research	Collection of manufacturer's data on all commercially available products related to the project. Data from companies collected extensively.	To build a picture of typical performance characteristics and to understand the state of currently available cryogenic technology.	Large sample of the types of coolers available, with many different parameter values gained for comparison later during the project.
Product Market Analysis	Database analysis with respect to fundamental parameters such as weight, efficiency, and power.	To gain initial techniques for analysis, making further analysis simpler and less time consuming.	Familiarisation of the benchmark standards for current types of available components.
System Design Knowledge Capture	Attend systems engineering course in Derby, work with EPACS at Rolls-Royce Derby.	To gain knowledge of the tools and methods of selecting complex problem concepts and to gain skills in analysis, selection process and requirement generation.	Understanding of the next steps after the literature search has been completed, relating to the concept design phase.

Table 3-2 – Phase 3 detailed breakdown of tasks

Activity	Tools and Methods	Rationale	Outcome
Phase 3 – Requirements Generation and Validation			
Stakeholder Mapping and Interviews	Group brainstorming, stakeholder meetings, Design Rationale Editor (DREd)	To gain detailed understanding of whom the stakeholders are within the project and their influence.	Knowledge of who influences the project, knowledge of which stakeholders are critical to understanding system requirements.
Ongoing Literature Review	Continue to read journal and conference papers on relevant topics, books, and any other resource deemed useful to the project.	To ensure any new or overlooked information is not ignored.	Complete knowledge capture with low risk of lack of current information.
Requirement Generation and Categorization	DREd, brainstorming, group sessions with key stakeholders, tree diagrams.	To understand the generic overall requirements of the cryogenic cooling system and what it must do to meet stakeholder expectations.	A large set of ungrouped requirements.
Requirement Validation	Stakeholder interviews, with later revisit of requirements once numerical modelling has been completed.	To gain approval on the requirements generated, and to identify any missing or needless requirements, including any modifications to existing requirements.	A stakeholder verified set of generic requirements for the system along with stakeholder preferred areas of interest.
Functional Requirement Generation	DREd, brainstorming.	To group together all of the functional requirements. This will also highlight other types of requirements already generated, such as performance requirements and non-functional requirements.	A large set of proposed functional requirements, understanding of which functional requirements are missing.
Functional Requirement Validation	Stakeholder interviews, comparison with numerical modelling outcomes later during the project.	To validate the general set of functional requirements perceived by the stakeholders before modelling and analysis.	A set of validated requirements to take to the next stage of modelling and analysis.

Table 3-3 – Phase 4 detailed breakdown of tasks

Activity	Tools and Methods	Rationale	Outcome
Phase 4 – Functional Modelling and Sensitivity Analysis			
Functional Model Generation	Functional flow diagrams, modes of operation, missions profiles, DREd.	To understand how the system interacts with other systems, how the system processes the inputs and outputs, and to assess which mode of operation is most critical according to mission segments.	Understanding how the system interacts with other systems, how it processes inputs, and which mode of operation is most critical.
Expert Validation	Using the previously mentioned expert opinions as to whether any critical analysis is missing, if so, what? If not, move to the next task.	Making sure the functional model is complete is critical to the proceeding tasks to ensure validity of the analysis techniques outcomes.	A validated, modified functional model free from error for testing.

Sensitivity Analysis	Sensitivity Matrix, DRED.	To understand which part of the cooling system is most sensitive to input variation, and to highlight the areas of high sensitivity within the system.	Confirmation of the most sensitive functions within the cooling system, knowledge of how the system will behave during input variation.
FMEA Analysis	FMEA spreadsheet. Systematically go through each function in the functional flow diagram and assess how they could fail and how likely and severe it potentially would be. Mitigation suggestions.	To understand the risks and impacts of potential failures of any given function prior to concept selection. This enables early warning of how a system may fail based on function, and can decide design choices early on.	Possible design choices made, understanding of possible failure modes, and deeper understanding of the risks associated with cryogenic cooling systems.
QFD Analysis	QFD spreadsheet, listing original requirements with functional model parameters to understand whether the proposed model meets the expected requirements.	To validate the approach and model against the original overarching requirements, as a final validation step before full system modelling and concept generation.	A validated system model that can be developed further, that meets all original requirements.
Concept Model Planning	Brainstorming on how to approach modelling the system from a quantitative viewpoint.	To ensure a plan of action is implemented due to the complexity of the model and the likely topics where out-scope knowledge is required.	A general plan of attack, whereby any unknown aspect of the modelling process is identified and mitigated.
Quantitative Knowledge Capture	Textbooks, internet resources, journals.	A low-level knowledge capture on all parts of the system to be included, to a basic level such that subsequent workshops and data can be understood properly.	A basic understanding of electrical machines, cables, power electronics, and power networks.
Electrical Machine Workshops	Workshops with the SRC electrical team, where sets of questions are asked and discussed as to the primary focus of the thermal loading.	To understand how to calculate thermal loads within electrical components, loss mechanisms, sizing rules and relationships.	A more detailed understanding of the electrical system and its components, the losses and loss mechanisms, and the rules and relationships surrounding them, including how they vary with power.
Electrical Machine Data Capture	Internet resources, companies and manufacturers, internal databases. Collecting mass data on various types of electrical machine	So that rules can be generated based on efficiency for thermal loss estimation on the model first pass.	A comprehensive database that can be analysed to provide accurate estimations of efficiencies and other parameters within the project.
Modelling Parameter and Equation Capture	Textbooks and expert advice. General gathering of theoretical and mathematical relationships and parameters.	To enable effective modelling capability within Simulink.	Enhanced understanding of electrical machines and networks.
Simulink Learning and Modelling	Using Simulink and Matlab, reading tutorials and related textbooks, using internet resources and basic modelling examples.	To learn how to use the modelling software Simulink effectively.	Knowledge of Simulink, gained experience of modelling thermal systems.

Table 3-4 – Phase 5 detailed breakdown of tasks

Activity	Tools and Methods	Rationale	Outcome
Phase 5 – Cryogenic System Modelling and Concept Generation			
Model First Pass	Simulink Modelling, input of parameters by compiling rules and relationships associated with electrical machines and cryogenics.	To allow the initial understanding of the effects of the electrical system on the cryogenics and the impact it will have on efficiency affecting factors.	Knowledge on how the basic electrical system affects the cryogenic system.
Electrical System Model 1, 2, and 3	Simulink models of increasing fidelity and complexity representing the electrical network and components.	To understand the efficiencies and loss mechanisms within the system and how they are spread within the network.	A high fidelity model of the electrical system and a detailed knowledge of the how the electrical network is likely to perform.
Cryogenic System Model 1,2, and 3	Simulink models of increasing fidelity and complexity representing the electrical network dependant cryogenic cooling system.	To gain knowledge on how the cryogenic system performs with increasing electrical network complexity, and how the system must perform from a quantitative perspective.	Knowledge of the quantitative requirements of the cryogenic cooling system and a model able to cope with increasing complexities within the electrical network.
Expert Validation	Meetings with experts, presentations, and peer reviewed articles.	to confirm the thermodynamic and electrical aspects of the models are accurate and valid and any new numerical methods are suitable.	A validated set of models or feedback on how to improve the models based on expert advice.
FMA Concept Analysis	Pooling of concept ideas and options by assessing the ideas from basic quantitative analysis using FMA.	To enable a smaller selection of concepts to be further assessed, and to eliminate outlandish or unlikely concepts before further scrutiny.	A selection of possible concepts and configurations that can be further assessed and modelled.
Concept Selection	Final selection of the cooling concepts for scrutiny by the model and qualitative analysis using the systems approach.	To generate a number for concepts ready for testing using the model, and to observe their behaviour when placed under different modes of operation.	A small selection of plausible concepts that can be modelled numerically.
Concept Testing	Assessment of the final group of concepts using Simulink and detailed qualitative analysis.	To understand how the specific concepts will perform within the model, and whether there are any clear out runners or obvious choices.	Knowledge on which concepts are viable to the already validated system model.

Table 3-5 – Phase 6 detailed breakdown of tasks

Activity	Tools and Methods	Rationale	Outcome
Phase 6 – Concept Testing, Model and Design Optimisation			
Final Concept Analysis and Data Generation	Testing of the models using assumptions based on expert advice.	To generate a large set of data from which design choices can be made.	Generation of a design map that can be used to determine the best concept based on assumptions.
Final Concept Comparison	Final quantitative and qualitative analysis is collated and discussed, with analysis of viability through the system process compared to original requirements.	To highlight the concepts most viable for future concepts, and to identify the parameter limits to each concept.	Knowledge of the wider impacts of the chosen concept on the system and the systems outside the aircraft, and which concepts should be chosen for a given case.

Final Concept Validation	Expert interviews and stakeholder meetings.	To gain insight into how the concept will perform and gain opinions as to the viability of the concepts based on their reactions to the analysis.	Insight into the viability of the concept, and whether any optimisation would be needed to enable the concept to progress.
Optimisation and Critical Analysis	Generation of ideas that may mitigate any problems encountered, along with novel solutions and component design concepts.	To understand whether there are any novel design solutions that may provide any additional advantages or competitive benefits within the cryogenics concept.	Possible intellectual property, an optimised final concept and understanding of the future mitigations to any issues with implementation of the concept.
Stakeholder Validation of Concept	Stakeholder meetings and discussions, expert interviews and discussions.	Final concept validation to ensure the process was fully comprehensive and to assess the success of the overall concept choice and whether it is likely to be implemented.	Valuable insight into the processes flaws and successes, with good indication whether the concept is viable for future implementation or whether it requires modification of any kind.
Thesis Write-Up and Viva	Write-up of all data gathered and defence of the thesis.	This is the required final element in fulfilment of a PhD.	Final acceptance of academic merits and criticism of research for publication.
Final Sponsor Report Submission and Presentation	Report to Rolls-Royce plc on the project, its outcomes, suggested further research, and recommendations based on the thesis to the feasibility of technological integration.	Required as part of the sponsorship agreement for the PhD, and to inform the sponsor of the findings and any other important aspects.	Final approval for publication release, possible future employment prospects.

Chapter 4. Stakeholder and Requirements Analysis

4.1. Introduction

The complexity of the cryogenic cooling system and the number of interrelationships between parameters requires a high-level systems engineering approach, whereby the problem is clearly defined before a solution can be found. Using a systems approach to design ensures a clear and repeatable methodology is adopted, making validation of design choices less prone to error and much simpler to validate. The chapter begins by simple use of brainstorming in order to gain knowledge of all of the potential stakeholders involved in this project. Once all stakeholders have been collated, each one is assessed in terms of their criticality at the current concept phase of the project, with the key stakeholders then identified through recording the rationale used in the elimination process.

Once the key stakeholders were identified, each one deemed to have a technical input to the conceptual design process was interviewed in order to gain a comprehensive list of individual requirements. In order to avoid bias during the process, two people from each group were selected for interview, with each chosen according to their seniority. By choosing two levels of seniority within a given group, an impartial view free from bias can be obtained through a 'top-down, bottom-up' type approach. Once an overall set of requirements is gained, the interviewees are asked to rank each requirement with an importance factor between one and five, with a rank of one equating to least important and five the most important. These factors are then used within the functional analysis section in order to understand the criticality of the functions of the cryogenic cooling system.

Finally, each key stakeholder is prompted to select one requirement from each branch group as the most critical, with results and views discussed further. The outcomes for this chapter will be a comprehensive list of overall requirements, fully validated through expert opinion and actual project stakeholders. This chapter provides the basis for the overall systems study, whereby functional requirements can be derived.

4.2. Stakeholder Identification and Selection

The initial phase when taking the system approach to design is to gather data on the various stakeholders involved in the project, in an effort to understand which is most critical in terms of requirements. The initial step is to create a large list of all stakeholders that will eventually be affected by the cooling system, from the early design stages to the end user and operations. These are then grouped according to the type of stakeholder they represent and compiled into a tree diagram for visual representation. A large generic group was compiled using other examples of stakeholder groups shown in the Rolls-Royce Systems Engineering Handbook (Rolls-Royce, 2012).

Eight separate groups of stakeholders were identified:

- *Pressure Groups* – These stakeholders are organisations or bodies that exert pressure on the project, which can come in different guises such as political, environmental, and regulatory.
- *Friendly Parties* – These stakeholders are organisations or companies that will benefit in some way from the technological implementation of the project and its systems, including business partners, research partners, and maintenance.
- *Shareholders and Funding* – These groups are those which have a direct financial stake in the project, and include governments, research councils, and company shareholders.
- *Users* – This group represents anyone who directly uses the technology when it is eventually put into use, such as pilots, ground crews, air traffic control, and passengers.
- *Fuel/Cryogen Suppliers* – These groups or companies are those which must supply and continue to supply the system with the required fuels or expendables.
- *Operators* – These are the groups that will use the technology within their business, such as airline operators, airports, and air forces.
- *Airframe Designers* – Companies who will implement the technology as part of the overall propulsion system, and will have to integrate the technology within their products.

- *Rolls-Royce* – Although this is strictly described in general terms as propulsion designers, since the project is funded by only Rolls-Royce, they can be assumed to be the only party in this group. They are however multi-faceted and different departments of Rolls-Royce are considered due to the technological roadmap these systems will have to follow to eventual implementation.

Once all of the known stakeholders are gathered into these groups they are individually assess through reasoning as to where they fit within the project at its current stage. A map of all stakeholders is shown in Figure 4-1.

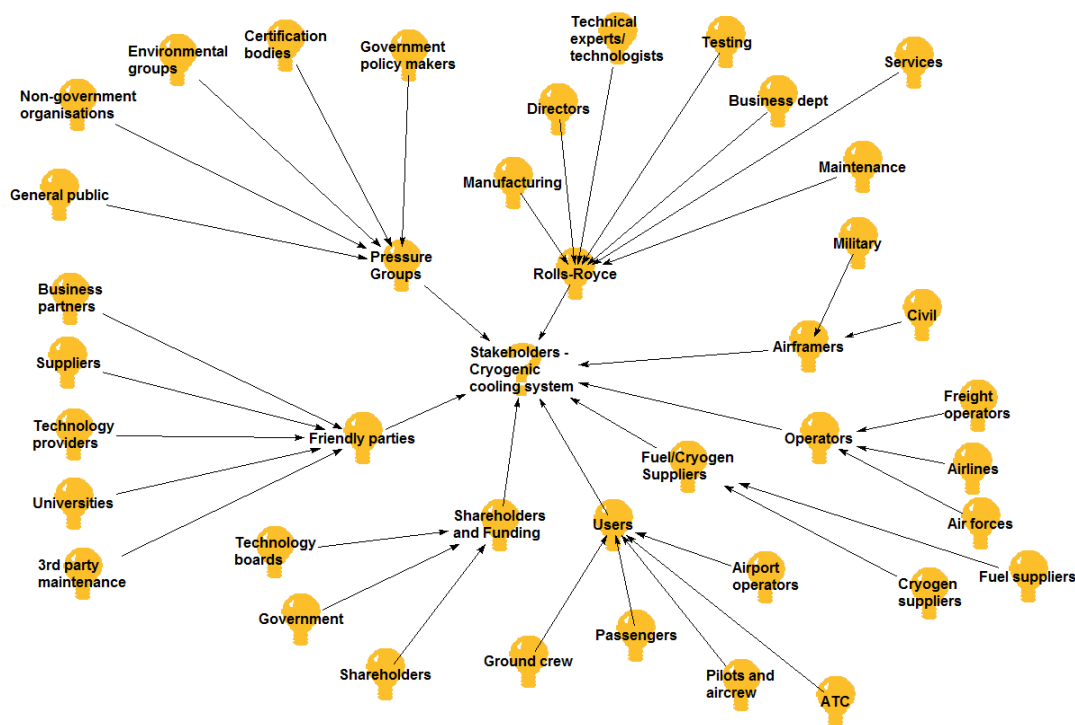


Figure 4-1 – Stakeholder map

In Figure 4-2, the stakeholders shown in Figure 4-1 are gradually eliminated through critical reasoning of their individual level of involvement and the likelihood of relevance at this early concept stage of research. This stakeholder map must be re-assessed as time and technology progresses to accommodate the eventual inclusion of each group. As the likely time frame is in decades, the three year duration of the project alone is not enough to warrant re-evaluation of the stakeholders' involvement; however the map generated provides a strong foundation for future rapid re-assessment. Should the technology enter service in the future, all of these

stakeholders will need to be appeased in some form, ensuring completeness of the systems process and minimising the risk of hidden requirements being overlooked.

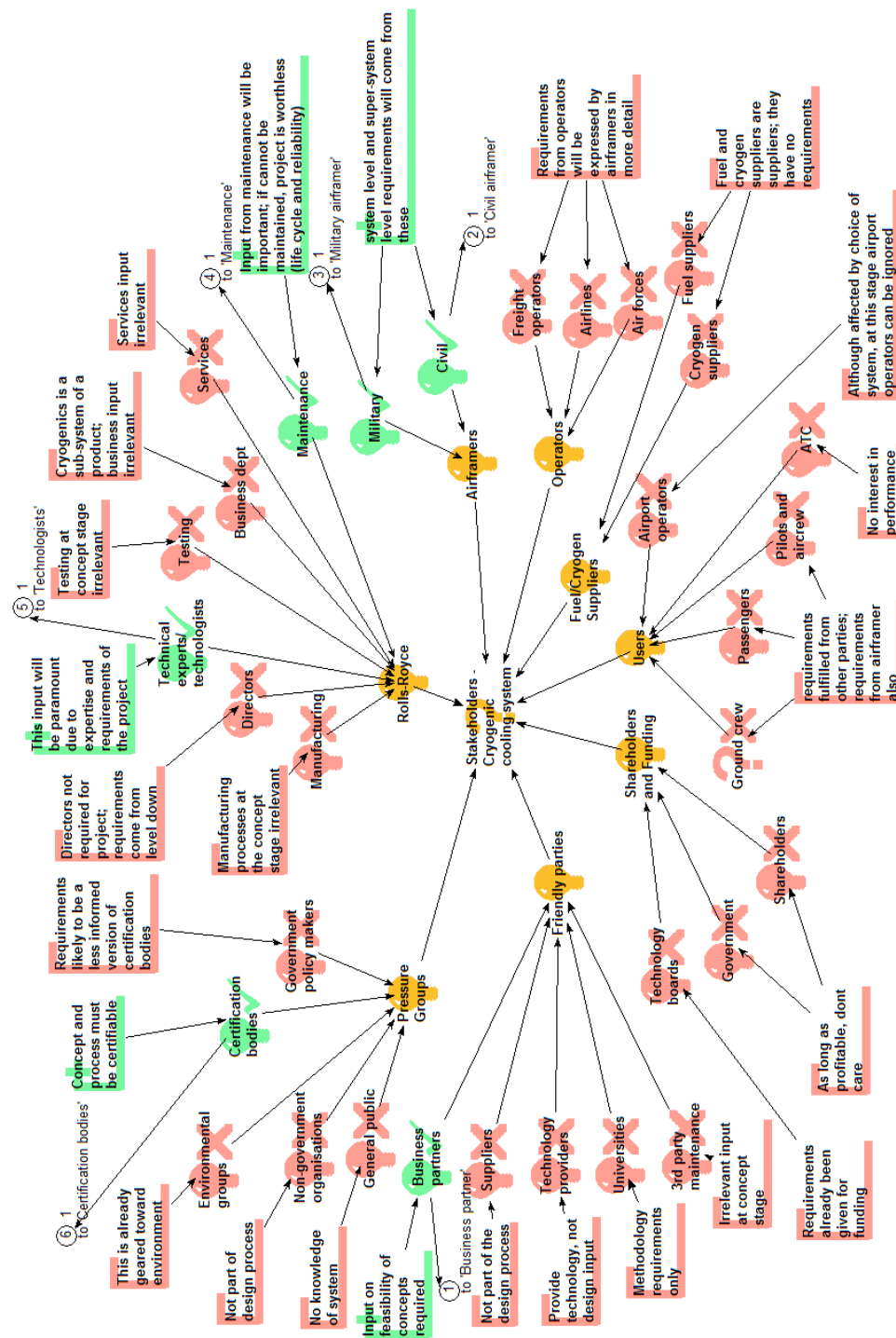


Figure 4-2 – Stakeholder exclusion map with rationale for stakeholder exclusion or inclusion for further study

From the rationale stakeholder map shown in Figure 4-2, critical reasoning has highlighted that the key stakeholders of the project at this stage in design are perceived as follows:

- *Business Partners* – These could be companies or research institutions who are directly involved with the concept phase, whether it be through technology transfer or collaboration agreements. They may be valuable in determining the overall system parameters, such as superconducting electrical machine performance and network requirements.
- *Certification Bodies* – Although at this stage the certification of products is far into the future, aviation rules and regulations must be followed to ensure the system is fully compliant. This may include issues such as redundancy and reliability, whereby strict rules that are already in force regarding electronics in aviation may be transferred to this project.
- *Rolls-Royce Technical Experts and Technologists* – Should Rolls-Royce eventually implement this technology in the future, and considerations such as manufacturing will need to be addressed, at this stage the concept is still very immature, hence only the research teams and relevant experts will need to be involved.
- *Rolls-Royce Maintenance Experts* – Maintenance will be a key qualitative issue whereby the eventual system solution will be required to enable ease of maintenance. Rolls-Royce currently draws over half of its business from its TotalCare® through-life service plans and as a result, maintenance must be considered at the very concept stages. Failure to do so may result in a system that cannot be easily or cheaply repaired or modified, potentially devaluing the system overall.
- *Airframe Designers* – These aircraft manufacturers including military and civil makers will be crucial to understanding the limits and boundaries of the concept, such as weight and size. Understanding the configuration options and limitations is key to this projects goals, as well as their understanding of how the cryogenic cooling system is likely to be in terms of performance, size, and weight is on their airframe designs.

Despite these stakeholders being identified as key, some of these can be ruled out of initial engagement. First of these is business partners, excluding universities. Since the project is at such an early technological stage, the potential implications of divulging sensitive information to outside businesses must be controlled. In order for comprehensive gathering of requirements, business partners would need to be informed to a reasonable level of technical detail on the project aims. Unless there are sufficient protections in the form of non-disclosure agreements in place, it is unreasonable at this stage to interview potential future business partners who aren't directly involved with the project already.

Certification bodies are crucial to the success of any given commercial aerospace concept. However, it is the opinion of the researcher that early involvement of these regulatory bodies could stifle early concept generation by applying potentially moot regulations to early stage ideas. Given the highly conceptual nature of this project and the adoption of the systems engineering process, it is crucial to not rule out potential ideas based on potentially non-applicable aviation regulations. Therefore certification bodies were not contacted during the course of requirements capture.

Maintenance within Rolls-Royce is crucial to the commercial success of a given concept. Maintenance relies on knowing the details of a system that can be manufactured with respect to a known life-cycle. Since the end goal of this project is to specify the concept, no planning overlap exists within the scope of work undertaken; hence maintenance is not consulted within this project. Furthermore, requirements for maintenance are unknown since the concept is unknown. Until a concept can be specified, inputs from potential maintenance stakeholders will be irrelevant, therefore they are not interviewed.

Airframers play a crucial role in the understanding of the concepts likely power requirements and the configuration of propulsors. The cryogenic cooling system can be defined as a support system crucial to the overall propulsion concept. When considering the systems the cryogenic cooling system must interact with, the airframe is on the second order of command. Any communication between the airframe and the cryogenic cooling system is as a function of the superconducting network rather than directly. Requirements expressed by the superconducting

network will mirror those felt by the airframers. Therefore their input for requirements is deemed to be adequately represented by Rolls-Royce aerospace engineers.

4.3. Key Stakeholder Interviews and Requirements Capture

Once the key stakeholders were identified as the technologists and experts at Rolls-Royce, a selection of those stakeholders were interviewed. They were separated according to their relevance to the project given their stake at this stage of the technology in order to gain a large, generic set of requirements. As cryogenic cooling for aerospace propulsion is at such an early stage in terms of development and technology maturity, the key stakeholders interviewed consist of three groups;

- Aerospace research – This is to enable a view that reflects the requirements of airframe designers and to satisfy aerospace compatibility challenges.
- Electrical research – Electrical research is to satisfy the novel electrical challenges associated with superconductivity and novel electrical network design.
- Electrical power and control – This group is to enable understanding of the requirements present from a practical perspective given that this is the department that the project will eventually be transferred to, should confidence in purported benefits increase.

Within Rolls-Royce there are a number of stakeholders that have to be addressed directly within the project. These were deemed to be Electrical Power and Control Systems (EPACS) and the Strategic Research Centre (SRC). Due to the interdisciplinary nature of the project, the SRC must be divided into two categories, the Aerospace Team and Electrical Team. The SRC Aerospace Team at this stage can be assumed to adequately represent the wishes of the airframe designer due to their close interaction on project DEAP with Airbus Group Innovations. To ensure that no one person is responsible for the analysis of requirements from each team, two people are selected from each team to ensure any risk of a single person adding or neglecting requirements not necessary is sufficiently managed.

The selected stakeholders in this case were the team leader and a team member of the SRC Electrical Team, a senior team member and team member of the SRC Aerospace Team, and the chief and a team member of the EPACS department.

Each stakeholder was interviewed separately and prompted to evaluate the requirements tree according to their individual requirements for the perceived system. Each stakeholder was then asked to select one requirement from each tree branch as the key requirement for assessment. This approach was used for two reasons; to understand whether any requirements should be added, removed, or changed, and to understand which of the requirements from each category was deemed important to the project.

To understand the potential cryogenic cooling system, the system must first be defined using a comprehensive set of requirements, which follows the system approach. There are a number of methods for ensuring the requirement set is complete or contains the essential elements for operation and fulfilment of the design specification. The first step is to brainstorm a number of overall, unsorted requirements by imagining the stakeholder is dictating what their requirements for the system are. Each stakeholder deemed in the stakeholder analysis to have a stake in the project at this stage is considered, such that a number of requirements are gathered. The stakeholders themselves are then approached to give critical advice as to which requirements are adequate, which are not required, and whether any modifications to those generated should be made.

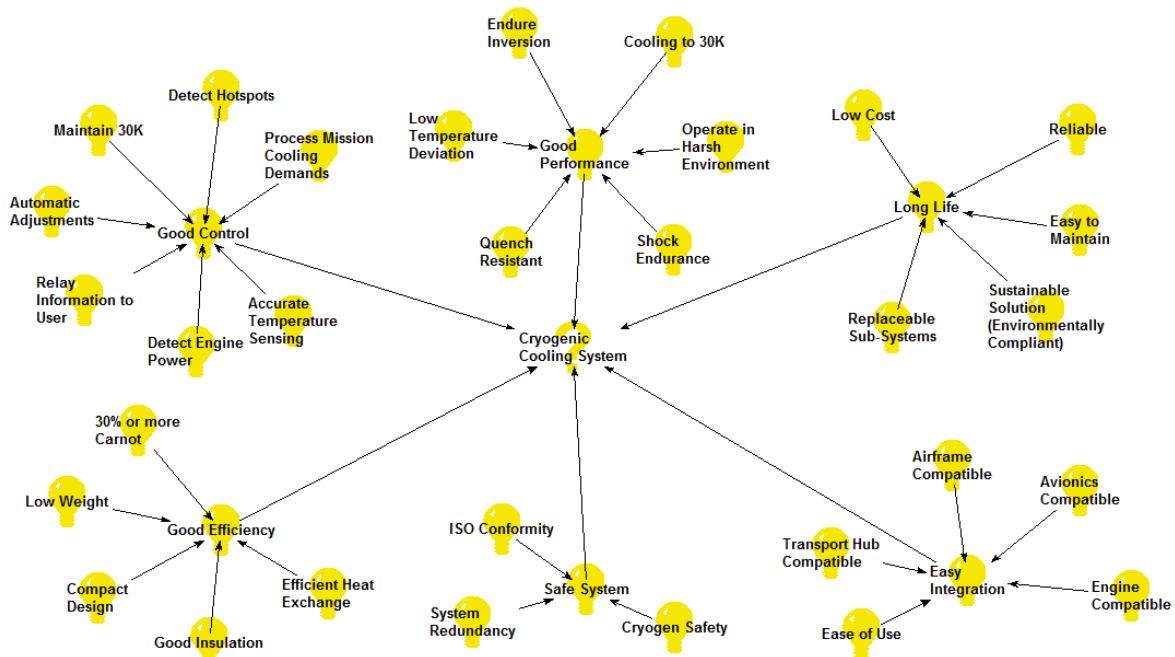


Figure 4-3 – Initial set of requirements tree diagram

The first pass tree diagram shown in Figure 4-3 shows that the requirements initially generated have been grouped into five categories, describing a general characteristic the system must exhibit. They each have a number of subcategories attached them, which describe in more detail how the system must perform or qualities it must adhere to. The overall rationale behind grouping these requirements into categories is to understand whether there are any requirements at this stage that share categories. Some similar requirements such as 'Maintain 30 K' and 'Maintain Temperature' may seem duplicated and unnecessary, however since the former specifies a target temperature whilst the more generic 'Maintain Temperature' requirement could refer to maintaining an intermediate temperature or temperatures at other points within the cryogenic cooling system other than the desired cool area.

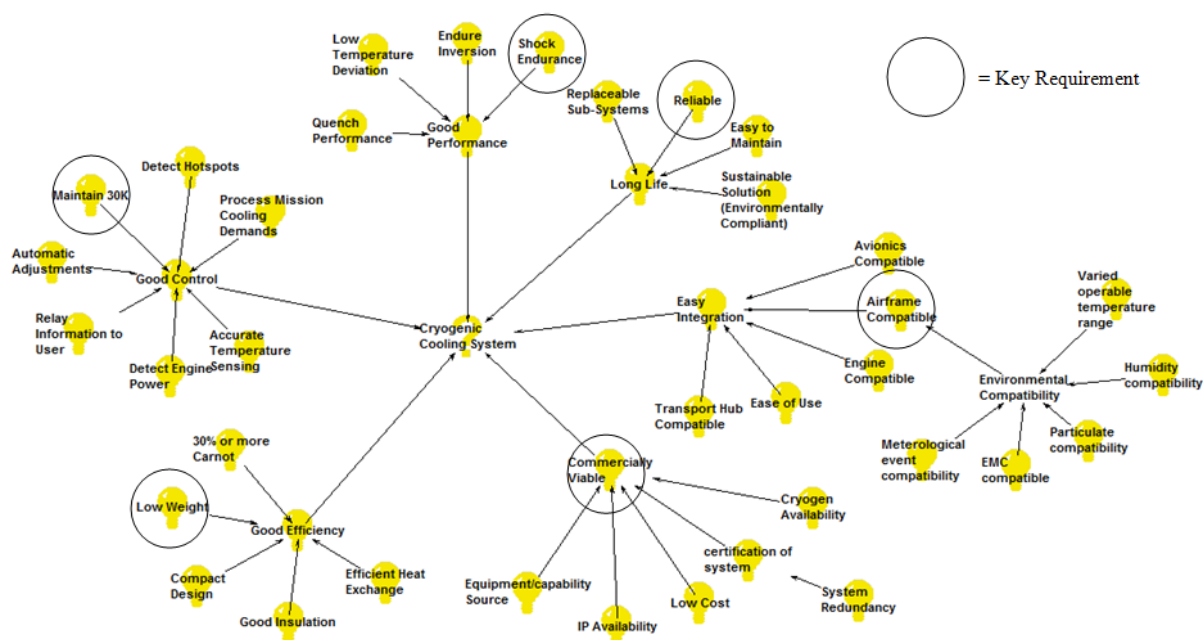


Figure 4-4 – SRC electrical team leader requirements tree and key requirement selections

The first stakeholder interview took place with the SRC Electrical Team leader, with results shown in Figure 4-4. It was recommended that airframe compatibility be treated as a category all of its own, whereby the proposed cryogenic system must be environmentally compatible, and adhere to a number of sub-requirements within this subject. It was also specified that the original 'safe system' requirements was not required, and that it should be replaced by a 'commercially viable' group, to which two more requirements were added. 'Intellectual Property Availability', which will be

significant deviation in performance. It was also suggested that the Operate at 30 K requirement should be placed in the Good Performance branch as well as the Good Control branch, as it can be considered both a performance and control requirement.

It is briefly worth noting at this stage that the agreement on the requirements of both electrical experts is why different groups of stakeholders are used as validation. This is in order to understand how the requirement perspective varies with respective expertise, with the exception of the Operate in Harsh Environments requirement outlined. The rationale behind the inclusion was that other than Maintain 30 K, the other requirements in the branch could be mitigated using outside systems, for example where the team leader had selected the Endure Shock requirement as being key, the team member stated that frames and shock absorbing cradles could be used to ensure shock is not a problem.

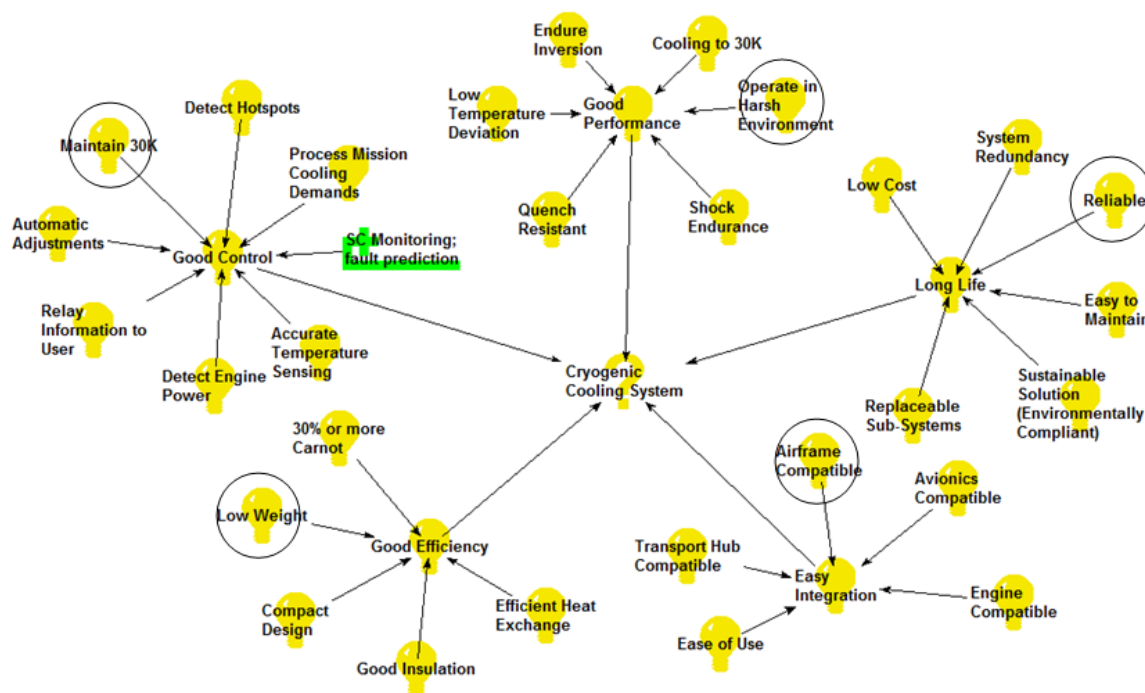


Figure 4-6 – SRC aerospace team member requirements tree and key requirement selections

The SRC Aerospace team member agreed largely with the original requirements set, with the inclusions given and key selected requirements chosen shown in Figure 4-6. The only addition made to the set was to add a requirement for superconducting component fault prediction, to be added to the Good Control branch. Rationale

behind the inclusion given was to be used as a future consideration only, as at present it is not possible to detect faults and mitigate them before they happen. However, it was proposed that perhaps fault-likely mission segments such as take-off where maximum power was being utilised, over-cooling in some form could be used to prevent any possible quench or system electrical heating. Many of the same key requirements were highlighted as with previous interviews, with the aerospace team member agreeing with the electrical team leader on the Shock Endurance requirement. It was perceived that harsh environments may be irrelevant based on solution, such as in the case of LH₂ cooling, although it was agreed that it should be considered in more detail than other requirements

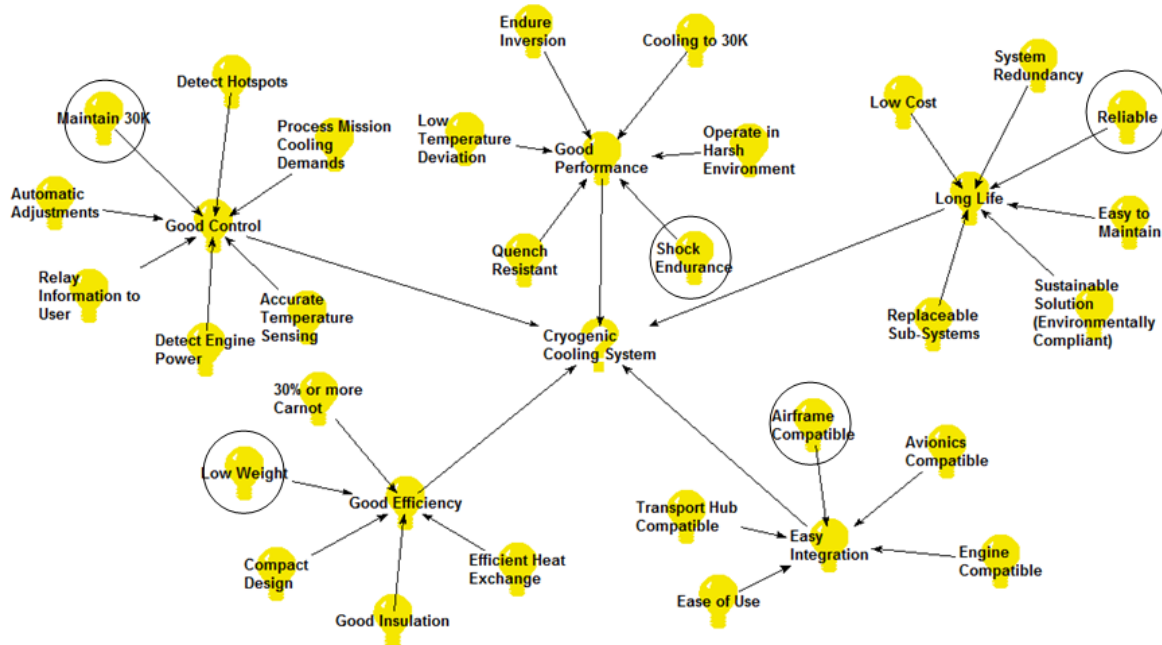


Figure 4-7 – SRC senior aerospace team member requirements tree and key requirement selections

The second member of the SRC Aerospace Team to be interviewed was a senior specialist technician with over 40 years engineering experience. The requirement set, which was now modified to include the Operate in Harsh Environments requirement, was again largely agreed upon, with the exception of the 30% Carnot or More efficiency shown on the Good Efficiency branch of Figure 4-7. It was stated that although if using a cryocooler concept this was favourable, inclusion of this requirement was making an assumption that using cryocoolers is the preferred solution, and this does not allow for LH₂ consideration during future concepts. Since

the scope of the project considers LH₂ only in basic detail, the comments were taken into consideration, despite the cryocooler being the main focus of this project. The recommendation was made to include it in the diagram; however with a proviso stating the requirement is concept specific. The same key requirements as the Aerospace team member and Electrical team leader were selected, with no exceptions

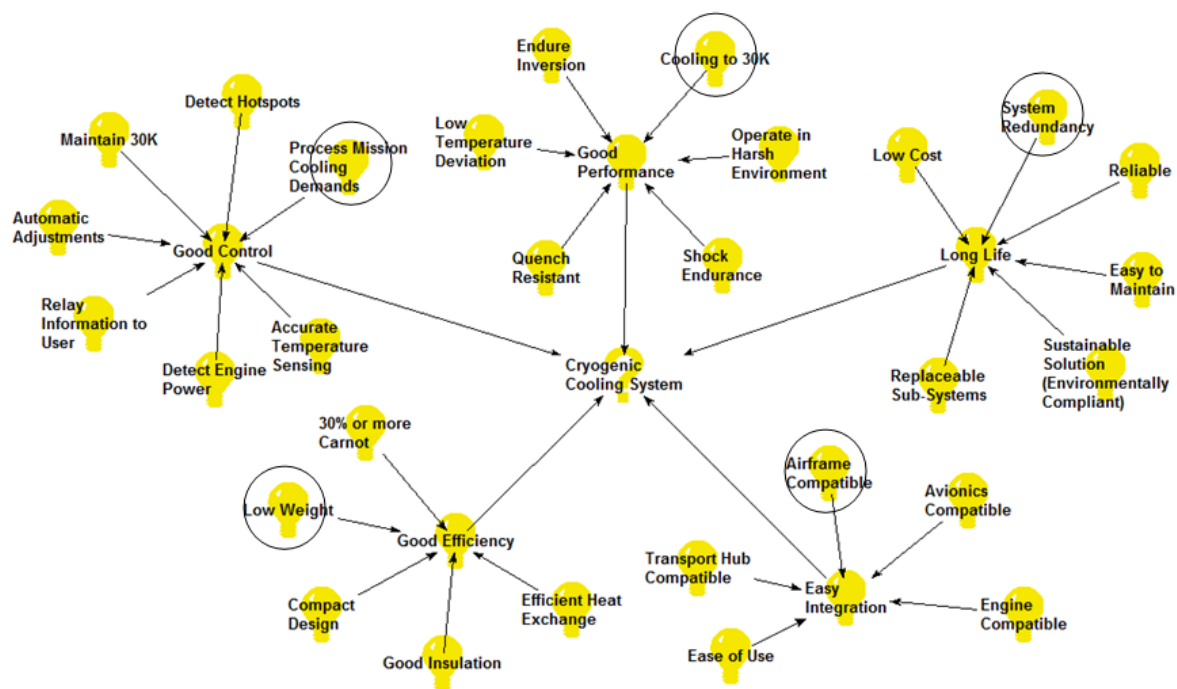


Figure 4-8 – EPACS team member requirements tree and key requirements selections

The EPACS department at Rolls-Royce was included in the stakeholder validation process based on its stake within the project and its expertise in electrical matters on-board current aircraft. The first of these was a team member with past experience with the concept of AETA, providing the basis for an MSc thesis (Cantos, 2010) for which this cryogenic cooling system study is derived, with that persons preferred requirements tree shown in Figure 4-8. Once again the key requirements list was agreed upon, and no additional requirements were included; however slightly different key requirements were selected, highlighting the difference in experience and expertise between stakeholder departments. The rationale behind choosing system redundancy was that CAA and FAA regulations in the civil concept case would require the cryogenic cooling system to be at least triple-redundant. Therefore

reliability was an overall requirement rather than a configuration or performance requirement. Another difference from the majority of other stakeholders was the selection of Process Mission Demands over Maintain 30 K, which was selected on the Good Performance branch instead. The rationale behind this decision was that the cooling system would be required to process mission demands, and a failure to do so would result in the loss of or inadequate cooling of the propulsion systems, potentially leading to catastrophic loss in propulsive power. Although the reasoning behind this selection is robust, due to the other experts' choices of key requirements, this will be ignored at this stage in the project.

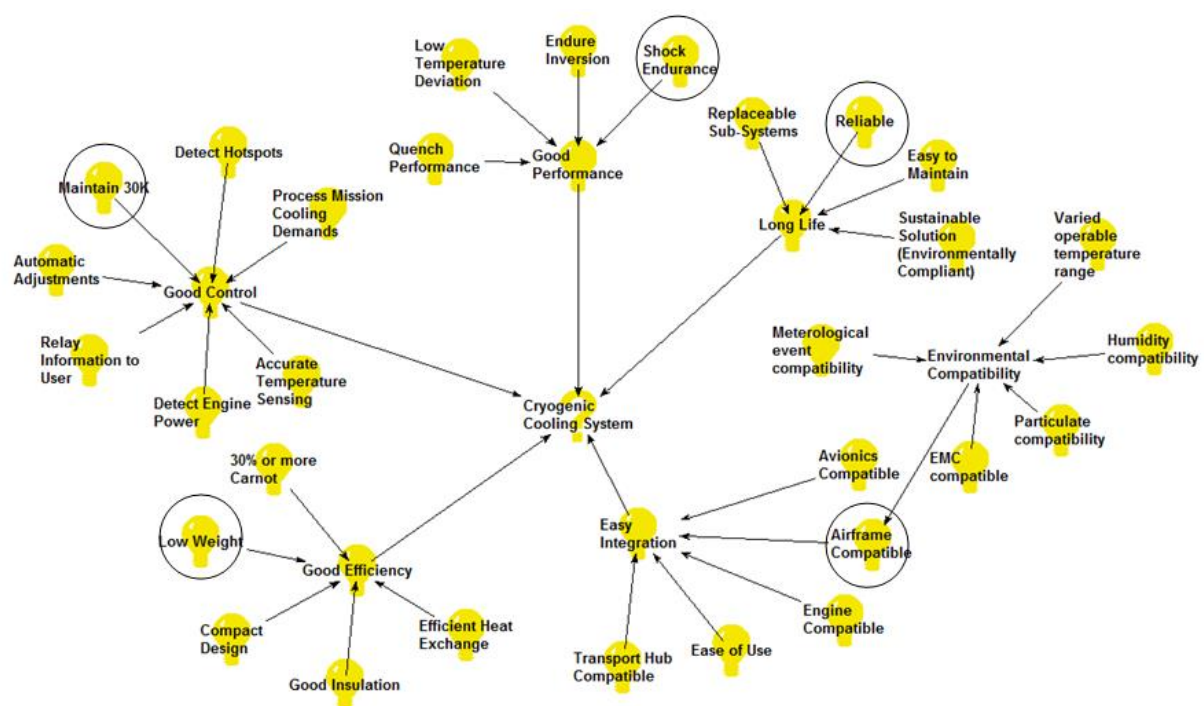


Figure 4-9 – Head of EPACS requirements tree and key requirement selections

The final expert to be interviewed was the Head of EPACS department. As a high-level expert who is directly involved with the implementation of aircraft electrical systems, the Head of EPACS was chosen for the valuable insight that can be gained with regards the requirements and how they should look according to holistic views. The requirements generated in previous interviews were agreed upon, providing final validation of the overarching set shown in Figure 4-9, which at this stage includes the expansion of the Airframe Compatibility requirement. Reliability was a key area of focus, and it was mentioned that reliability would be difficult to assess in terms of selection criteria, unless a concept was decided upon that does not involve new

technology or designs. The key requirements as perceived were again largely the same as previous experts' opinions, completing the choice of criteria with which to initially assess by majority vote as Maintain 30 K, Low Weight, Shock Endurance, Reliability, and Airframe Compatibility.

4.4. Key Requirement and Requirement Type Identification

The consolidated set of requirements generated through stakeholder interviews are shown in Figure 4-10. The key requirements shown were chosen based on the interviewed stakeholders preferences on which requirements were most critical to any successful design.

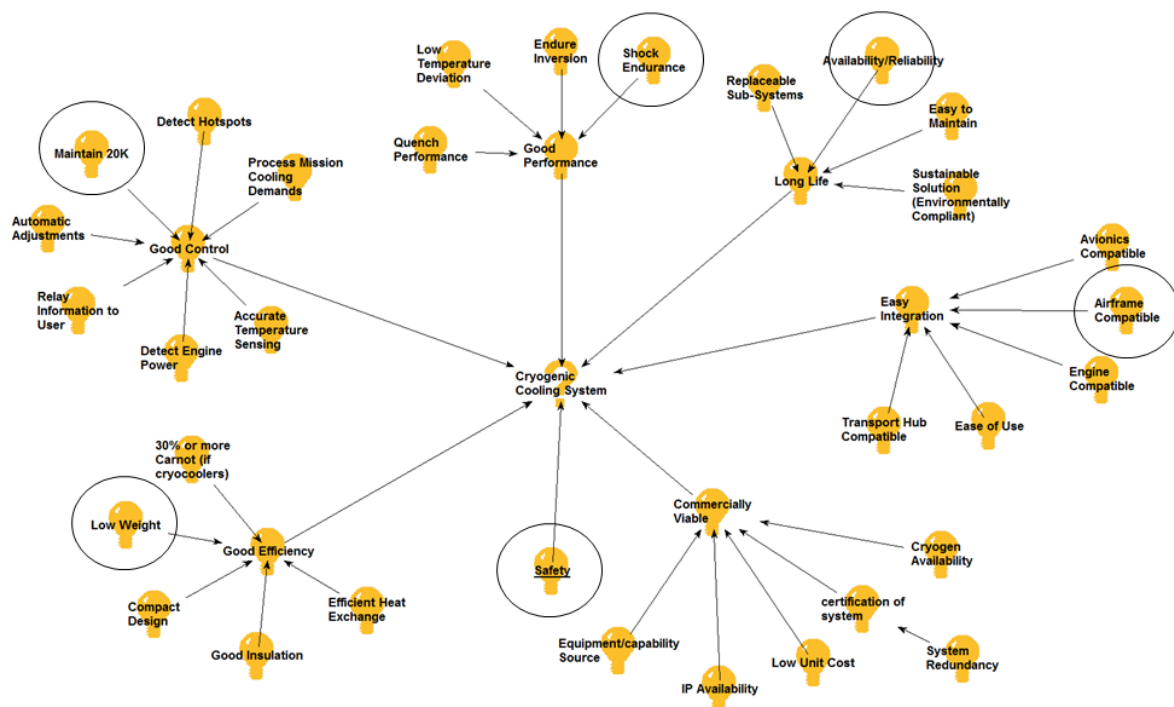


Figure 4-10 – Final set of consolidated requirements with key requirements

It is necessary to explain each key requirement since these will form the basis of selection criteria during the project concept stages.

- **Low Weight** – Keeping the weight low is a high priority on any aerospace system due to the relationship between required thrust and lift to keep a given weight in the air. Any cryogenic cooling system must be as light as possible to minimise its overall impact on the aircraft as an additional required system. It

is difficult to estimate the point at which a concept becomes unrealistic due to excess weight because of the early stage of design.

- **Maintain 20 K** – Originally it was thought that the cryogenic cooling system would have to maintain 30 K temperatures in order to provide sufficient cooling performance. Subsequent interviews with experts have highlighted that superconducting components performance improves with temperature, therefore the 30 K temperature was recommended to be lowered to 20 K. Furthermore, the operating temperature was recommended to be considered a variable. Modelling work during later chapters considers the effect of different operating temperatures on the overall system performance.
- **Shock Endurance** – Aircraft are highly dynamic environments, and any solution to the cryogenic cooling problem must be able to operate in these varying conditions. Shock in the form of repeated landings and turbulence is commonplace, therefore any system solution to cryogenic cooling must be able to operate in these environments with no degradation in performance or reliability. Some cryogenic cooling systems can be interrupted by sudden shaking due to the nature of their moving parts, hence it will be crucial to have robust systems that mitigate or eliminate these challenges.
- **Availability/Reliability** – Superconducting propulsion solutions will mean that cryogenic cooling systems are considered a critical system that cannot fail. Failure of these systems would likely result in catastrophic loss of aircraft, hence reliability is paramount. Further to this, the availability of the system is also crucial in terms of operations. A system that requires maintenance of more than a few hours at a time every flight will be impractical for the reason that the current operational availability of aircraft would have to be reduced. Similarly, long term maintenance must be of a similar time and interval requirement as present day aircraft to avoid making new technology unattractive or overly laborious.
- **Airframe Compatibility** – For a new system to be accepted on to a commercial aircraft, it must be able to fit on board. An example of the type of airframe compatibility that is referred to for this requirement would be volume restrictions. If the cryogenic cooling system is too large in a given dimension, it may not be able to be located on board an aircraft that is optimum for

placement. Since aircraft centre of gravity must take precedent over performance, a large, bulky cryogenic cooling system might have to be located further away from the cooling target, meaning higher pressures and lower temperatures would have to be achieved due to transport losses. Other examples of airframe compatibility would be issues such as noise and vibrations, electrical interference, and knock-on system failure effects, should the cryogenic system fail and other systems be affected.

- Safety – Safety on board modern commercial aircraft is of utmost importance. This early stage concept however should not consider safety a priority. The reasons for this are that at this early stage, what could be considered dangerous at present may have mitigating solutions in the future. An example might be the use of hydrogen; whilst hydrogen presents a clear danger if mishandled, future regulations and handling procedures would likely mitigate any issues encountered. Aircraft are already dangerous vehicles when considering the large amount of high-octane hydrocarbon fuel present, however regulations and safety procedures mitigate dangerous events. Safety considerations at this stage may rule out viable ideas early on before mitigations can be suggested, effectively stifling innovation. Therefore safety is disregarded as a key requirement at this stage until a group of known concepts exists.

Also shown in Figure 4-10 is a branch highlighting commercial viability requirements. These are important to the project sponsor, Rolls-Royce, since any idea would have to be profitable and protectable in order to be successful commercially. Interviewees were not asked to highlight a key requirement on this branch as the branch was added after the last interview was made. However in the context of the concept development, these are used for overall final concept assessment. The commercial viability of the end solution has to be realistic in order for the sponsor to gain benefit from the pursuit of the technology. Without certain aspects of commercial viability, any solution is unlikely to gain future investment.

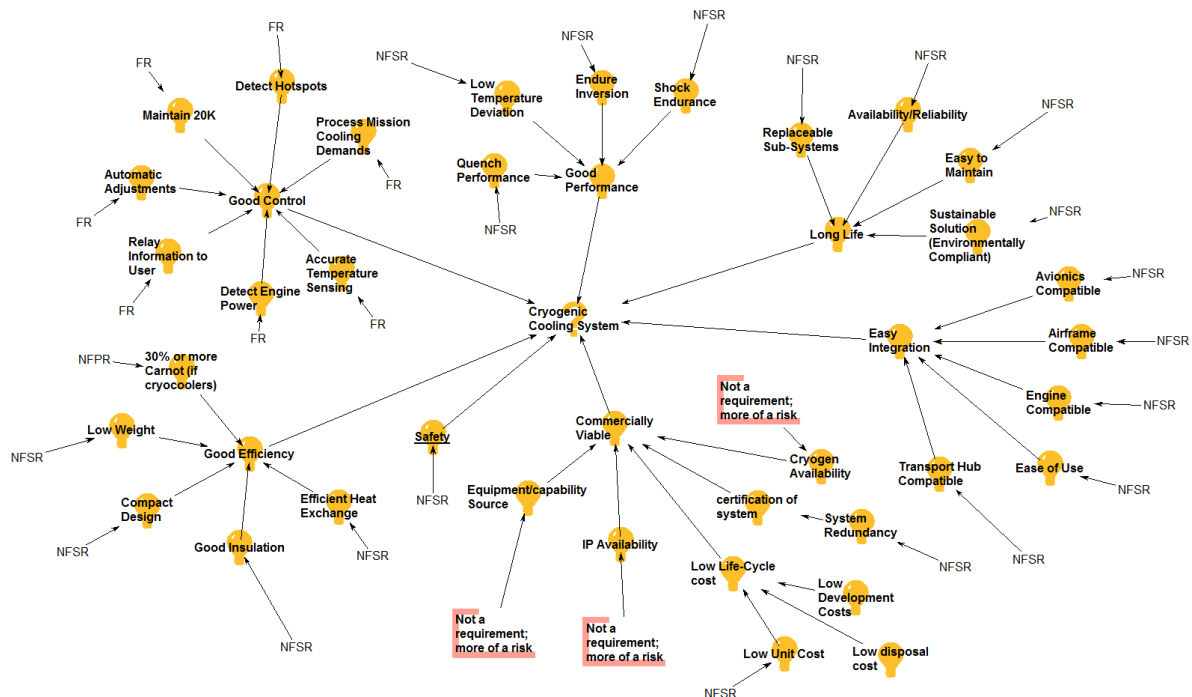


Figure 4-11 – Final set of requirements with requirement type labels and exclusion rationale

For the final tree diagram shown in Figure 4-11, the overall generated set of requirements is compiled, along with designation as to the type of requirement they conform to. There are four main types of requirements:

- Operational Requirement (OR) – This describes what the system must do as a whole. This can be easily described as simply **‘To cool the superconducting electrical network to the desired temperature during each phase of the aircrafts operation’**.
- Functional Requirement (FR) – These describe individual functions that the system must perform. These are numerous, however not immediately obvious, and as such require further analysis and thought to fully generate.
- Non-Functional Performance Requirement (NFPR) – Quantitative performance targets for a specific function. These are at this stage difficult to predict without specifying a solution, and as a results are limited. Further iteration of the system process later during the project may highlight performance targets.
- Non-Functional System Requirement (NFSR) – Non-performance related requirements, or qualitative requirements. These will be the most numerous of

requirements to begin with because they specify generic requirements of the system from how the system must interact with outside systems, to what the system must be capable of throughout its lifetime.

The overall requirements set branches can now be explained in greater detail because they will no longer change during subsequent analysis. The branches are explained below, with the respective components that may be obscure also given brief explanation.

- Good Control – These functions relate to the overall control aspects of the cryogenic cooling system. Requirements such as Maintain 20 K and Process Cooling Demands are essential to the operation of the superconducting electrical system, and are seen as essential to the control of the system, whilst other control aspects are also added. All of the Good Control requirements are FR; however during subsequent functional analysis some of these may be modified or eliminated.
- Good Performance – The Good Performance functions are intended not as performance requirement, but pertain to the types of performance-altering scenarios it may encounter. Shock and Inversion Endurance is considered as key due to the requirement of all aircraft to land, and the possibility of inversion or at least a change in orientation through banked turns and manoeuvres, particularly through turbulence. These are all of the NFSR type.
- Long Life – This branch covers any through-life requirements that may be necessary at this stage, such as reliability and maintenance. At this stage of the design, through-life considerations such as disposal and maintenance are solution dependant, and as a result are put aside for consideration when solutions begin to emerge from the system study. These requirements are all NFSR.
- Easy Integration – This branch of the tree diagram shows the requirements of the system for integration with the systems it must interact throughout its operational lifespan. This includes both the physical systems within the aircraft, the transport hubs where it must be used, and the users who will operate the system and its associated systems such as pilots and ground crews. These requirements are again all NFSR.

- **Commercially Viable** – This branch states the requirements of the cryogenic cooling system to be worthwhile and feasible, such that the route to eventually marketing and manufacturing the technology can be achieved. This branch is very broad in terms of the lifespan of the technology, beginning with IP protection and capabilities, to through-life costs and certification requirements. These are once again all NFSR.
- **Safety** – As a stand-alone requirement, this was agreed by all parties as being critically important throughout the proposed life cycle of the system, including the early stages of this project. Due to its importance as a NFSR, the stand-alone branch highlights that it will be considered separately throughout the project, playing a supplementary role rather than a design or concept generation role. As mentioned previously, over reliance on current best safety practices could stifle innovation, so supplementary involvement rather than major consideration is necessary. Safety consideration examples include cryogenic best practices, hydrogen safety, event simulation such as crashes and hard landings, and failure modes and analyses.
- **Good Efficiency** – These are requirements that directly affect the efficiency of either the aircraft or the cryogenic cooling system itself. This includes weight requirements for the reason that aircraft efficiency is directly and critically affected by weight, which in turn is related to density and volume. Therefore low weight and compact design are key requirements. They are all NFSR, however with the exception of the 30% of Carnot requirement, which is a NFPR. As previously mentioned, this is solution dependant, but important nonetheless.

4.5. Discussion

It is worthwhile to note that whilst the key stakeholders have been identified and interviewed, should any of the other stakeholders identified as key at this project stage suddenly become available, they will be consulted where appropriate. Stakeholders of particular interest might be those who are more difficult to arrange meetings with but may become available during the course of the project, for example airframers and certification body representatives. Although the viewpoint of the airframe designers was largely gathered through the SRC aerospace team members, there could always be considerations that may have been overlooked.

Since the project works closely with Airbus Group on project DEAP, the requirements of the air frame designers will be discussed in Chapter 6 when close collaboration is used for modelling work.

The key requirement selections of each stakeholder are crucial to later assessment of concepts. The choices that have been made by the stakeholders highlight the different facets of those involved. By selecting the range of seniorities and roles available, the approach has ensured a robust methodology has been adopted. This methodology ensures minimal risk of overlooked requirements whilst at the same time avoiding over-complication of the early stages of the project. Stakeholders during interviews were also asked to discuss the other requirements that were not selected, with each assigned a number between 1 and 4. The number 5 was reserved for the key requirements selected. These numbers are used during Chapter 5 for the House of Quality (HoQ) analysis in order to assess the functional models generated. By doing this, the cryogenic cooling system components can be ranked in terms of criticality to the success of the system.

Future revisiting of the requirements stage will be essential. The reason for revisiting is that once a concept has been defined, the more generic requirements can be eliminated and a much more specific set generated. Stakeholders may have changed also, with the likelihood of any outside contractors or business partners being involved increasing due to the need for specialist expertise. It is likely that any final concept will be iterated and changed a number of times as time progresses; however each time the process is repeated the concept does not undergo complete transformation. The transformation would see a step change in fidelity, such that the initial concept high-level design can be developed into a more refined, more defined architecture that could be manufactured. This is the ultimate aim of the project, to initiate the process and to understand whether the systems engineering methodology can be applied to this complex problem. If the systems process can be used, can it be used throughout each stage un-modified? If not, what modifications will the process require to be fit for the purpose such that the process can continue without major methodological changes? These are the crucial questions that this project addresses, with this chapter providing the foundation to begin to answer that important question.

The proceeding section must expand upon the functional parts of the system, to begin to understand how the system will be used, what functions it must perform, and which systems it must interact. The functional requirements generated in this section will form the basis for that analysis, and the rankings and overall key requirements will assess whether the functional models generated are complete and correct.

Chapter 5. Functional Requirements Modelling, and Analysis

5.1. Introduction

Once stakeholders and overall requirements are satisfactorily captured and analysed as presented in Chapter 4, the next step in the research is to capture the functional requirements and model how the functions of the cooling system are performed. This chapter begins by selecting the already known functional requirements from the previous chapter. Any unknown functional requirements are then found by considering the modes of operation the cryogenic cooling system must adhere to, including the likely mission profile of the aircraft.

Once the most critical mode of operation is discovered and functions are satisfactorily well defined for that mode, functional models are developed by assessing how the system handles inputs and outputs. The first step to building functional models is to list the generic inputs and outputs from a super-system perspective. This involves first defining the systems with which the cryogenic system must interact and listing the inputs and outputs to and from each system. The cryogenic system is then considered in respect to how the inputs and outputs are handled within the system itself. This process effectively fills in any unknown functional requirements and highlights redundant requirements, providing a robust model that can be assessed.

The functional model is assessed using three different systems engineering methods, with each designed to test a different aspect of functionality. The methods used are Sensitivity Analysis (SA), Failure Modes and Effects Analysis (FMEA), and the House of Quality (HoQ) method within the Quality Function Deployment (QFD) method. SA is designed to assess the system outputs sensitivity to the system inputs, to highlight any areas of critical function in the system. FMEA highlights where failures of any component function could disrupt the system, and considers the effects and possible mitigations of component function failure. HoQ finally assesses the functional requirements against the overall set of requirements defined in Chapter 4, by looking at the impact and connection strength that each requirements has on each function. Weighting factors for the overall set of requirements are given and rationalised, and final scores highlight which of the functions are most critical to the system from a qualitative perspective.

5.2. Functional Requirement Capture

It is necessary to obtain a more complete set of functional requirements of the cryogenic cooling system in order to understand how the system behaves in different scenarios. There are already a small number of apparent functional requirements outlined in Chapter 4; however this is not a completed set as functional requirements were not the key focus of stakeholder interviews. To ensure the functional requirements are mostly complete, the same first approach is taken as with the overall requirements generation during Chapter 4. A brainstorm is undertaken by the author to gather all of the known perceived functional requirements that the system must perform, and they are grouped into a brainstorm diagram shown in Figure 5-1.

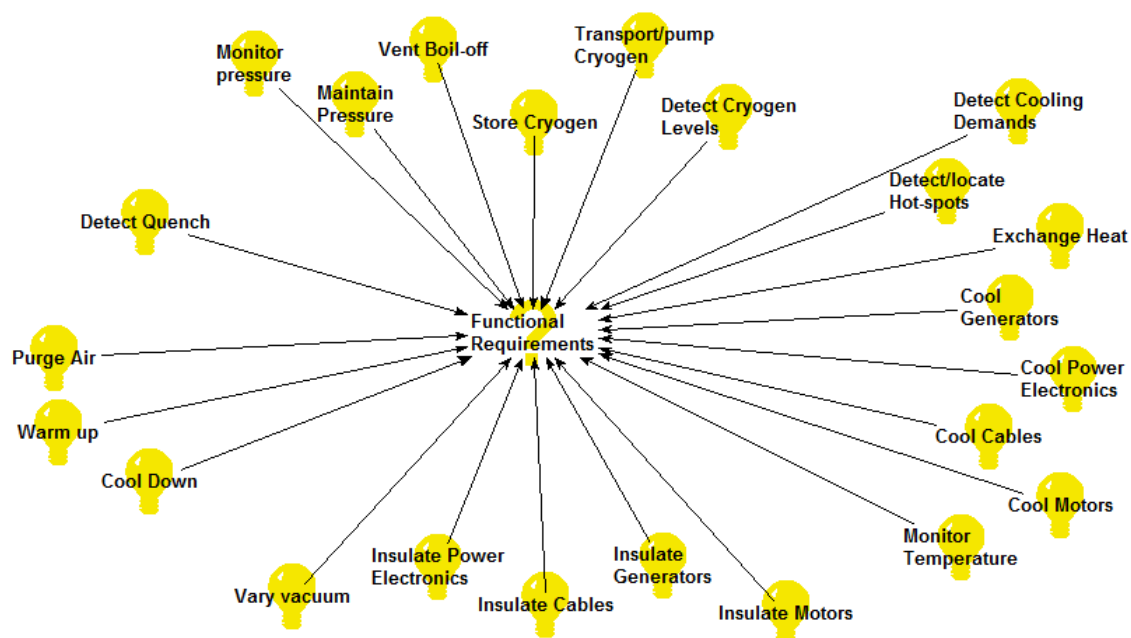


Figure 5-1 – Functional Requirements Brainstorm Results

Once all of the conceivable functional requirements are generated at this stage, they are assessed as to whether any of them are redundant or can be combined, to simplify the system. For example, functional requirements such as 'Cool Motors', 'Cool Generators', 'Cool Cables', and 'Cool Power Electronics' can be grouped into a single 'Cool Components' requirement. This simplifies the functional model since each of the separate requirements will require the same inputs and outputs. Since at this stage in the process it is still necessary to maintain impartiality, some functions defined in Figure 5-1 are likely to be surplus to requirement for the final functional model.

5.3. Mission Profile and Modes of Operation

Once the generic set of functional requirements is satisfactorily defined, the next step is to model the functional system using Functional Flow Diagrams (FFD). FFD's analyse the system inputs and outputs to understand how the system processes them on different scales. The first step is to look at the Modes of Operation, to understand the different operating regimes the cryogenic cooling system will have to adhere to. To understand what modes of operation the system will require, the first step will be to look at mission profiles of comparable aircraft.

Since the NASA study is comparing the performance in recent papers to that of the Boeing 777-200LR aircraft, this project will use the same example in qualitative terms to keep performance assumptions constant and relevant to current studies. The B777-200LR is a new type of long range, large passenger aircraft that has recently entered service, with a 301 passenger capability, a 9,380 nm range, and a maximum take-off weight of 322 tonnes (Boeing, 2011). A basic mission profile is being considered without ranges or timescales, to allow simple model building which can be varied in complexity at a later date. Figure 5-2 shows the basic mission profile of the B777-200LR.

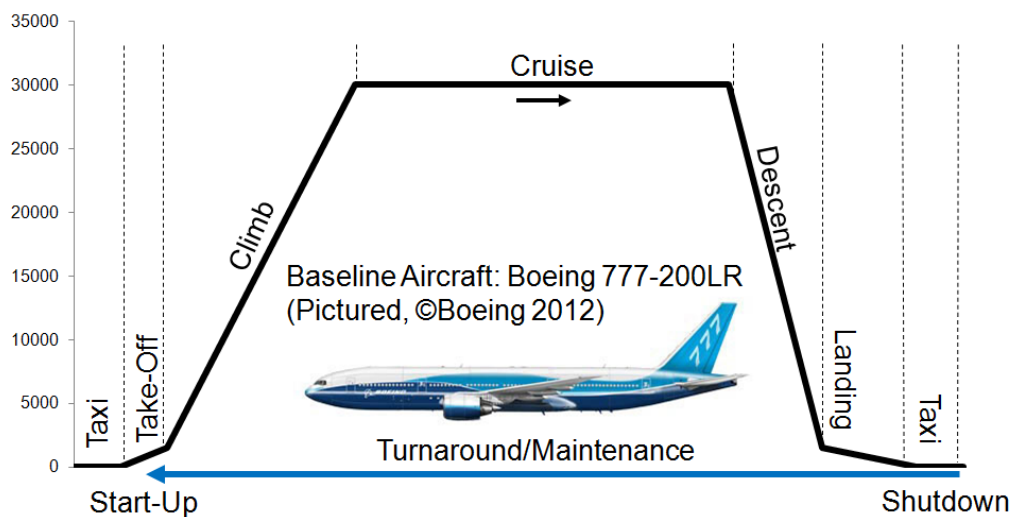


Figure 5-2 – Basic mission profile of the Boeing 777-200LR showing altitude on the vertical axis in feet

The typical mission profile of a Boeing 777-200LR contains the following segments;

- Engine start
- Taxi
- take-off
- climb
- Cruise
- descent
- landing
- taxi
- Engine shutdown

Although the mission profile is basic and does not account for missed landing approaches or aborted take-off, this mission profile is meant as a generic, unconstrained example that can be segmented according to the modes of operation they fit into. Maintenance of the system can be classified as a shut-down/start-up procedure, and added as an extra segment within the mission between them.

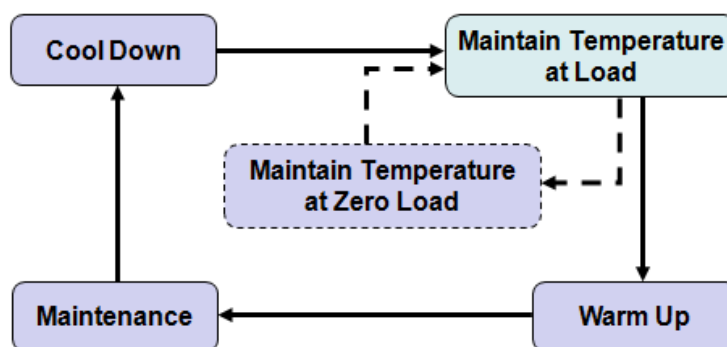


Figure 5-3 – Modes of Operation of the Cryogenic Cooling System

Figure 5-3 shows the proposed modes of operation diagram for the generic cooling system, generated by considering the mission profile and the different functions it must fulfil. The cool down and warm up procedures are self-explanatory and are effectively extensions of the maintenance mode. Maintain temperature at load is assuming that the superconducting electrical system is in operation, whether it be on the ground or in the air. Finally the zero-load maintains temperature is for aircraft turnaround such that for a given mission, it can be kept cool at the end of the flight ready for further operation. This is based on the assumption that it will take substantially more time to allow the aircraft to warm (and then have to cool again) than to keep it cool while ground crews service the aircraft.

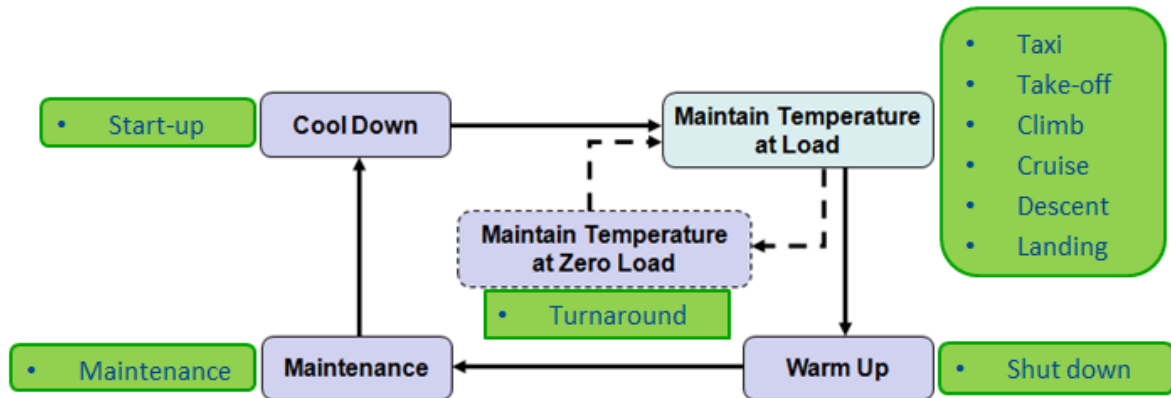


Figure 5-4 – Modes of operation with associated mission segments

Figure 5-4 shows the modes of operation with associated mission segments. It can clearly be seen that the ‘Maintain temperature at Load’ mode has the most associated mission segments. When considering the criticality of mission segments, in-flight segments are most crucial; all in-flight segments are associated with the ‘Maintain Temperature at Load’ mode. It is therefore deemed that for any concept to be considered further from a qualitative perspective, it must satisfy the ‘Maintain Temperature at Load’ mode.

5.4. Functional Modelling

Once the most critical mode of operation is identified, the next step is to begin functional modelling of the system as a whole. The functions generated in Chapter 4 are transformed into a series of functional flow diagrams (FFD’s) to understand the relationships between each function and how they process the various inputs and outputs to the system. The FFD’s are split into two tiers, with the first tier at the higher system level modelling interactions between the system and any outside influences, shown in Figure 5-5. The second tier was to model the system itself, and the likely interactions between the different functions of the cryogenic cooling system.

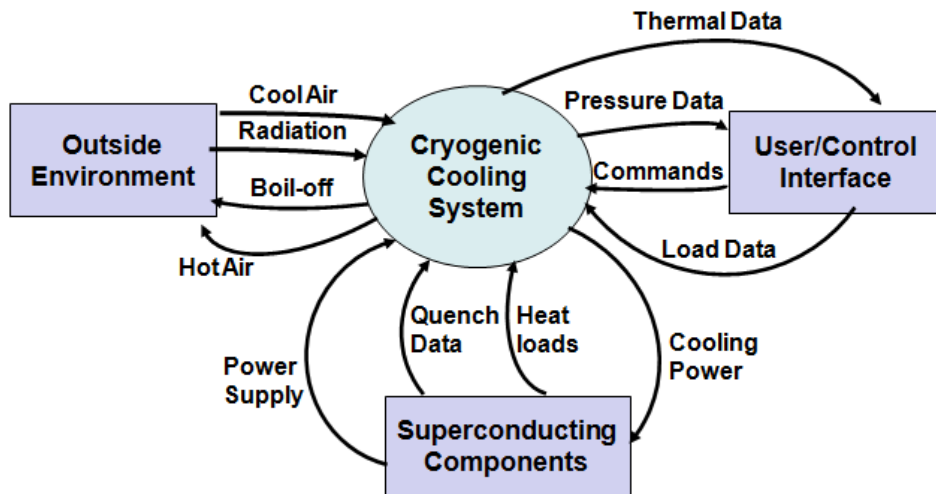


Figure 5-5 – Higher Tier Functional Flow Diagram

Figure 5-5 shows the systems with which the cryogenic cooling system must interact for the 'Maintain Temperature at Load' mode of operation. The diagram describes three systems that are defined as follows:

- **Outside Environment** – This system interaction is energy related, for example any heat in-leak to the system or cooling air that may be required would be seen as interaction between the system and the outside environment. Data from the outside environment is ignored (for example, cooling air temperature or humidity data), since this begins to imply an air-cooled solution. Inclusion at this stage must be minimal.
- **Superconducting Components** – Any superconducting components that exist and have to be actively cooled, including motors, generators, cables, and any power electronics. Unlike with the outside environment, superconducting components are likely to provide energy and data to the system.
- **User/Control Interface** – This will constitute any control interface, whether manual or automatic, responsible for control of the system. This system is a largely data-centric exchange, with most decisions being made here.

One consideration for this level of FFD is the lack of connections between systems outside the cryogenic cooling system. The rationale behind exclusion of these is that whilst there will certainly be connections between all systems, the super-system is not within scope of the project, nor do those connections have any impact on the cryogenic cooling system itself.

For the lower tier FFD shown in Figure 5-6, the inputs and outputs to the system are consistent with Figure 5-5 (Higher tier). Within the cryogenic cooling system, those inputs and outputs from the outside systems must be managed by the system as simply as possible, with as few functions as is necessary. Hence the method is to have a number of functional nodes, to which the known inputs and outputs are added. They are then individually tracked through the system, highlighting where any mistakes have been made, and where functions are either not required or are too complex. For both Figures 5-5 and 5-6, a number of model design iterations were performed, each iteration highlighting further redundant and missing functions. Functions included in the final lower-tier model shown in Figure 5-6 and their rationale is as follows:

- Insulate Components – This function is deemed necessary and separate from any other function. The function itself is generic as it could refer to cryogenic fluid storage, cryostats, or cryocoolers and transfer lines.
- Detect Cooling Demands – Cooling demands could be considered a part of monitor functions; the reason it is not is because cooling demands refers specifically to superconducting components rather than the cryogenic system. Having these separate is necessary when considering operation during flight phases; cooling loads may decrease during cruise, however temperature and pressure is likely to remain constant.
- Monitor Temperature/Pressure – Temperature and pressure within the cooling system are deemed crucial to delivering the correct level of performance. Since they are intrinsically linked, and it is likely that both can be detected by the same components, they are considered to perform similar enough tasks to be combined.
- Detect Quench – Quenching can occur at any point within the superconducting system, and response to a quench must be rapid since the potential for damage to occur is high. Quench is likely to be detected initially through a rise in local temperature and/or loss in transmission efficiency; however the function is treated separately from the monitor functions because it is likely that temperature will not be used as the initial detection method for the reason that this implies retrospective detection rather than predictive. If

damage and loss of function is to be limited, electrical means of detection are more likely to be implemented, hence it is treated separately.

- **Maintain Temperature/Pressure** – This function implies maintenance of temperature and pressure where specific temperature/pressure requirements exist. The method of achieving this function is likely to coincide with other functions, such as transport/pump cryogen or exchange heat; however to maintain genericity it is kept independent.
- **Exchange Heat** – The functional requirement to exchange heat might seem obvious in any cooling system, however the ability to do it in quantitative terms is a challenge, particularly in aerospace systems where weight must be kept to a minimum. The functional model must consider how critical this ability is, hence it is included as a stand-alone function, despite being used in multiple areas of the system.
- **Transport/Pump Cryogen** – This function is again crucial to any potential solution. Any solution that will satisfy the requirements will need compressive equipment; however the method of achieving compression is the subject of discussion during later chapters.
- **Monitor Cryogen Levels** – This is dependent on whether the solution uses open or closed loop system to a large extent, although in any closed-loop helium system, an on-board supply of helium will be required due to the nature of helium and its propensity to leak. Monitoring the levels of cryogen is deemed crucial as any loss of cryogen will likely have a large impact downstream of the system in terms of functionality, although the following sections within this chapter will investigate this fully.
- **Store Cryogen** – The ability to effectively store the cryogenic fluids used will be important. This is somewhat tied to the insulation and monitor levels functions however the storage medium is likely to dictate how viable any open-loop concept will be.
- **Vent Boil-Off** – This function is again dependant on the type of cryogen used. Should a system that does not use latent heat energy in any form, this requirements will become redundant in terms of the word 'Boil-Off'. However, should a sudden quench event happen or for whatever reason a sudden rise in pressure is experienced, the excess will need to be rapidly removed.

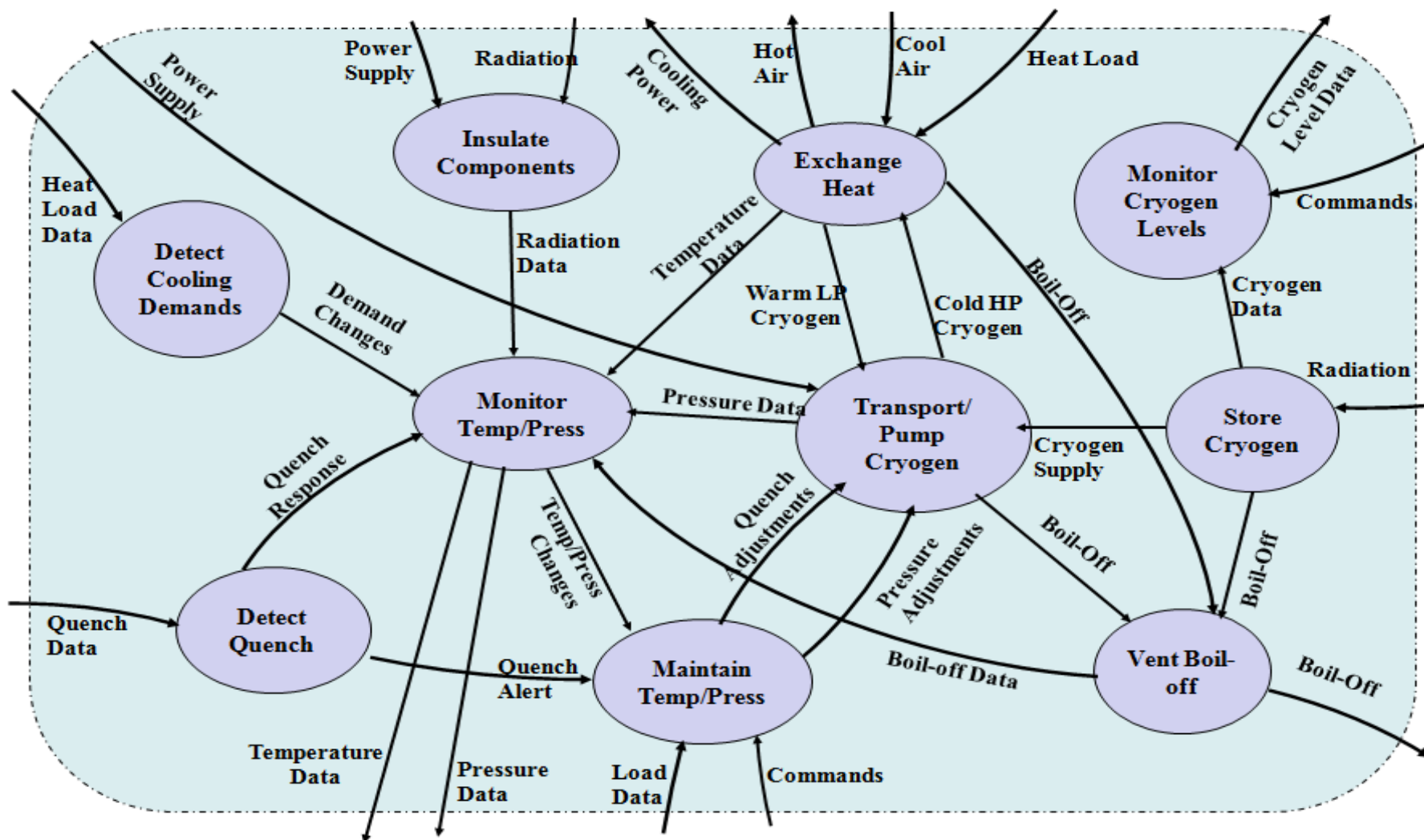


Figure 5-6 – Lower Tier Functional Flow Diagram

The lower tier FFD in Figure 5-6 shows the flow of inputs and outputs through the cryogenic cooling system, with the diagram kept as generic as possible to avoid any design choices to be inadvertently made at this stage of the project. It can already be clearly seen that the most complex part of the cryogenic cooling system will be the 'Monitor Temperature and Pressure', 'Exchange Heat', and 'Transport/Pump Cryogen' functions, by simple adding of the inputs and outputs. It may seem that the 'Detect Quench' function is somewhat redundant, or that it may constitute part of the 'Detect Cooling Demands' function; it is worth noting again that quench detection can come in one of three forms. Current overloading, magnetic field overloading, and temperature rise (all due to the earlier referred-to superconducting phase diagram relationship), can all push a superconducting component to quench; hence simply detecting the temperature rise will be no clear indication of whether a quench is going to happen at any given point in time.

Validation of the models comes in the form of iterative expert opinion. Since at present there are no comparable models or design processes for high-power aerospace cryocoolers, expert opinions at each stage are crucial. As the first model is developed at each stage, experts are contacted to view the models and modify at will, with rationales given. Meetings largely confirmed the system process validity, and no adjustments were made to the final models. The experts involved were those mentioned in Chapter 4 from the SRC, both electrical and aerospace team members. Since this is an early stage concept design, it is not considered critical enough to revisit requirements at this stage, since analysis is yet to be performed as to which functions are most critical.

5.5. Functional Model Analysis

The next step after the FFD models are validated is to perform a number of analysis techniques on them. This is in order to understand how sensitive they are to input variation, how they will respond to failures within the system, and to understand if they meet the initial requirements outlined in the project by the system. This is necessary to recognise the areas of functionality that must be closely monitored, and to properly assess where failures will be of higher consequence than others.

Sensitivity analysis takes place using a method known as a Sensitivity Matrix shown in Table 5-1. This is performed by listing all of the inputs of the system function by

function on the vertical axis, while the top horizontal axis has a similar list of all of the outputs. They are then assessed using a three variable system, where the variation of an input is considered against the variation of the output. If the input is varied and the output is severely sensitive or directly sensitive, it is given the symbol **OO**. If the output is moderately affected, it is given a **O**, and if the input is not at all affected or is insensitive, then it is given the symbol **Δ**. This will then highlight the areas of the system that are most sensitive, and those that should be considered high-risk when looking at concepts.

From Table 5-1, it can be observed that there are two main areas of high sensitivity with many dependant inputs and outputs, the Exchange Heat function and the Transport/Pump Cryogen function. The two cryogen storage related functions are also highly sensitive despite their relative simplicity as functions, along with the Maintain Temperature and Pressure function. The other functions exhibit small areas of sensitivity, however for the time being they can be ignored, due to the critical nature of the other identified sensitive functions. Further discussion is given in the next section once all three methods are shown to build an overall picture of the functional analysis.

Δ		Insensitive		Outputs																			
O		Medium Sensitive																					
OO		Very Sensitive																					
Input	Receiving Function	Heat In-leak Data	Demand Changes	Quench Alert	Quench Response	System Status Data	Press/Temp Changes	Heat	Cooling Power	Temp Data	Warm LP Cryogen	Boil-Off	Press/Temp Adjustments	Pressure Data	Boil-Off	Cold HP Cryogen	Cryogen Data	Cryogen Level Adjustments	Cryogen Data	Cryogen Supply	Boil-Off	Boil-Off Data	
Power Supply	Insulate Components	OO																					
Radiation		O																					
Load Data	Detect Cooling Demands		O																				
Quench Data	Detect Quench			Δ	OO																		
Heat Inleak Data	Monitor Temperature and Pressure					O	O																
Temperature Data						O	OO																
Demand Changes						Δ	OO																
Quench Alert						O	OO																
Boil-Off Data						Δ	Δ	OO															
Pressure Data						O	OO																
Cool Air	Exchange Heat							OO	OO	OO	OO	OO											
Heat Load								OO	OO	OO	OO	OO											
								OO	OO	OO	OO	OO											
Cold HP Cryogen									OO	OO	O	OO	OO										
Press/Temp Changes	Maintain Temperature and Pressure												OO	OO									
Quench Response													OO	OO									
Thermal Load Data													OO	OO									
Commands													O										
Power Supply	Transport/Pump Cryogen												OO	OO	OO	OO							
Warm LP Cryogen													OO	OO	OO	OO							
Press/Temp Adjustments													OO	O	OO	OO							
Cryogen Supply													OO	OO	OO	OO							
Commands	Monitor Cryogen Levels																Δ	OO					
Cryogen Data																	OO	OO					
Radiation	Store Cryogen																	Δ	Δ	O			
Cryogen Level Adjustments																		OO	OO	OO	OO		
Boil-Off	Vent Boil-Off																					OO	

Table 5-1 – Flow Sensitivity Matrix for the Maintain Temperature at Load Mode

The next analytical method used is Failure Mode and Effects Analysis (FMEA), to understand whether there are any major risks associated with any of the functions. The way functions interact within the FFD is scrutinised, and if mitigation is required on any given failure mode, options for how that could be achieved can be suggested before final design choices are made. FMEA can make design choices easier and more obvious also, by highlighting where additional care must be taken within sensitive functions. Configuration choices can also begin to be discussed, since redundancy requirements, particularly in the case of one event leading to a catastrophic failure are discovered and recorded.

FMEA is performed by first theorising all known possible failure modes for each function in the FFD, by simple brainstorm with the stakeholders used to validate the FFD. Since the research is still in the pre-concept phase, failure modes are largely speculative, and are generally kept solution independent. Once a large set of possible failures is gained, the possible downstream effects are considered, using the FFD. The possible causes of the failure are recorded, and the method of detection for each failure is considered. Three numerical factors are considered; severity, occurrence, and detection. Each factor is given a number between 1 and 10, with 1 representing the least severe or most likely for detection, and 10 representing the most severe or least likely to be detected. These numbers are then multiplied together to give a risk priority number (RPN), which highlights the most serious potential failures within the system. Solutions can then be theorised according to the RPN, and a new occurrence number is given to provide a new RPN that considers the mitigating design solutions.

Table 5-2 shows the FMEA for the 'Maintain Temperature at Load' mode. It is important to note that this analysis path, including the Sensitivity Matrix and FFD's, must all be completed for each mode of operation with a full assessment once unknowns regarding concept selection are known. The full analysis on whether each mode of operation can be satisfied by the concept can only be completed once the overall concept is known, since many requirements require definition of the system particularly with reliability requirements. For the purposes of this research, interest is expressed only in the most critical phase for assessment, with the rationale that if the proposed cryogenic cooling system concept cannot adhere to the most critical of modes, then it will be useless for all other modes by default.

Table 5-2 illustrates that the riskiest situations mostly arise within the detection phases according to the Risk Priority Number (RPN). This can be explained by the fact that the RPN is calculated using the severity of the proposed failure out of 10, with 1 being the least severe and 10 being the most, multiplied by the likelihood of occurrence and the ease with which it is detected, with both again graded out of 10. The detection of a quench or heat loads is deemed to be critical to operation. As a result, any failure to process the demands or relay an impending or occurring quench would be both severe and difficult to detect, given that these are supposed to be the functions performing the detection. This highlights the need for a comprehensive monitoring system, much like modern day gas turbine engines currently do. This is listed as a potential mitigating action, and a new risk priority number is given to it based on the opinions of the author on how likely the scenario is to occur.

Another potential failure that has been shown is the insulate components section, specifically the chance of the vacuum spacing leaking or gaining some form of foreign object. The reason this is marked as a potential problem is that due to the temperatures the cold parts of the system will be under, even the slightest air in-leak will cause moisture and the air itself to freeze inside the vacuum, potentially causing the system to rupture due to ice expansion. This could also potentially cause damage to any high-speed vacuum pumps in operation, resulting in total loss of vacuum. This would again be potentially catastrophic, as the secondary effects to a larger rupture would certainly raise the temperature past the critical point and result in loss of superconductivity, and in turn propulsive power. Mitigation step for this could include a dual walled seal, filters on the vacuum pumps, or even multiple pumps, adding redundancy and reducing the load on individual pumps. For some parts, pumping may not be necessary, as hermetically-sealed vacuum insulation can be used. More details are given in Chapter 6.

Finally the last notable inclusion within Table 5-2 is the Vent Boil-Off function, which is designed to vent any cryogen (Closed Loop or Open Loop) that cannot be recycled, to prevent rapid expansion of the fluid inside the pressure system. This shows the system may be susceptible in the same way as the vacuum system such that the system could be blocked in an area where there are no pressure release valves, and the system could rupture due to the huge increase in sudden pressure. When considering mitigation factors for a foreign object situation or icing, the author

was unaware of any way to currently detect foreign objects within the system, as it has never been a major problem for previous cryogenic systems. There has never been a need in the past within these systems to have such detection ability because cryogenics are typically in laboratories or systems that are never opened. For aircraft applications it is highly likely that systems will need replacement, hence foreign objects are much more likely. This discovery may lead to a design process or operational guidelines that see a cryogenic foreign object detection system or procedure, and possibly future intellectual property.

Function	Functional Failure mode	Effects	S	Causes	O	Current Detection Method	D	RPN	Design Suggestions	New O	New RPN
(1) Insulate Components	Loss of power to vacuum pump	Quenching	8	Technical failure	2	Thermal sensors	1	16	APU power available should failure occur	1	8
		Loss of propulsive power	9		1		1	9	Automatic temperature gradient response system put in place	1	9
		Shielding failure	9	Maintenance error, manufacturing fault	1	Thermal sensors, air detectors	2	18	Armoured shielding	1	18
		Shielding contamination	6	Maintenance error, manufacturing/assembly fault	3		2	36	FOD awareness during maintenance and assembly, process control for manufacturing	2	24
	Breach in thermal shielding	Shielding damage	7	Maintenance error, assembly error, operational hazard	3		3	63	Armoured shielding	1	21
	Foreign object in vacuum zone	Vacuum pump damage	8	Maintenance error, assembly error	5	None	5	200	Clean room assembly and FOD awareness during maintenance	2	80
		Vacuum pump failure	9		5		5	225	Multiple pumps for redundancy	2	90
(2) Detect Cooling Demands	Sensors not working	SC system Quenching	8	Faulty sensors, damaged sensors, system damage through maintenance	5	Thermocouples, capacitance thermocouples, thermistors	10	400	Use multiple sensors for high redundancy	1	80
		Cryogen flooding and/or excessive cooling	6		5		10	300		1	60
	Sensors giving wrong readings	SC system Quenching	8		5		10	400	Use multiple sensor types to ensure type is not the problem, also test sensors under different magnetic conditions	1	80
		Cryogen flooding and/or excessive cooling	6		5		10	300		1	60
	Wrong demand Interpretation	Excessive or inadequate cooling, loss of cryogen	7	Software error, sensor damage	2		10	140	Software checking needed, with high rate of redundancy on processing	1	70
(3) Detect Quench	No/Incorrect quench data	SC system Quenching without knowledge, system overheats and permanent damage occurs	9	Faulty sensors, damaged sensors, system damage through maintenance	2	Thermocouples, capacitance thermocouples, thermistors, (boil-off measurement?)	10	180	High sensor redundancy, software maintenance	1	90
		System not quenching, but flooded/shut down for no reason	7		2		10	140	High sensor redundancy	1	70
	Quench Not Detected	Permanent SC System Damage	9		2		10	180	High sensor redundancy	1	90
	Quench falsely detected	Overload cooling system, possibly engine shutdown	7		1		10	70	High sensor redundancy	1	70
(4) Monitor Temp/Press	Incorrect Press/temp adjustments	SC system damage, loss of propulsive power	9	Software error, sensor damage	1	Temperature sensors	1	9	None required	N/A	N/A
	Information processing delay	Possible quench, possible SC system damage	9	Software error, input overload, faulty hardware	1	Tolerance checking, time calibration	1	9	None required	N/A	N/A
	Inaccurate information due to faulty sensors	Quenching, loss of propulsive power	9	Faulty sensors	1	Inconsistency with other sensors	1	9	None required	N/A	N/A
(5) Exchange Heat	Fluid damage to heat exchanger	Cryogen leak	4	Fluid used causes embrittlement or is impure, inadequate surface finish within HE	1	Helium/hydrogen detectors	2	8	Anti-fouling/embrittlement coatings	1	8
		heat exchanger mechanical failure	6		1	Sensor detection, loss in cooling capability	2	12		1	12
		vacuum/insulation breach	5		1	vacuum sensors, fluid sensors	1	5		1	5
	Blockage in heat exchanger	Heat exchanger ruptures	6	Contamination by foreign object(s), embrittlement, HE damage	1	Sensor detection, drop in pressure	1	6	Filters with sensors at entrance and exits of HE's	1	6
		Inadequate cooling capacity	7		1	Rise in temperature	2	14		1	14
	boil-off unable to escape	Cryogenic system ruptures	9	Boil-off valves faulty, poor HE design	1	Sensor detection, drop in pressure	1	9	Regular valve placement, emergency over-pressure valves	1	9
		damage to heat exchanger	6		1	Rise in temperature	2	12		1	12
(6) Maintain Temp/Press	Over/under adjusting pressure/temp	Cooling demands not met; system overheats	6	System not calibrated	2	Thermal/pressure data changes	1	12	Perform system calibration	1	6
		Available cooling power depleted too early; system overheats	6		2		1	12		1	6
	Not adjusting pressure/temp	System overheats/over pressurises; loss of propulsive power	9	Input data incorrect; commands conflict with demand (system overload)	1		1	9	Automatic override, with manual override for emergencies	1	9
(7) Transport/Pump Cryogen	No pressure	Loss of cooling power	6	Blockage in pump, Pump malfunction, loss of power	2	Pressure gauges	1	12	Pump redundancy	1	6
	low pressure	Reduction in cooling power	4	Pump obstruction, contaminated cryogen	2	Pressure gauges	1	8	Pump redundancy	1	4

	high pressure	Excessive cooling power, possible system rupture	7	Pump is pumping too fast, obstruction in HP areas	1	Pressure gauges	1	7	Pump redundancy	1	7
(8) Monitor Cryogen Levels	Incorrect adjustments to cryogen levels	Cooling demands not met/overcooling	6	Inaccurate cryogen data	2	Pressure/temp gauges	1	12	None required	1	6
	No command response to cryogen level changes (i.e. Dump cryogen)	Possible overheating, possible under cooling	6	Component malfunction, incorrect cryogen data	2	Pressure/temp gauges, software/hardware reliability checking through other functions	1	12	None Required	1	6
(9) Store Cryogen	Excessive boil-off	Early depletion of cryogen	6	Vacuum failure, damage to insulation, excessive thermal radiation/conduction exposure	3	Pressure sensors on tank, temperature sensors, boil-off valve mass-flow measurement	1	18	None Required	3	18
	Excessive pressure build-up	Possible tank rupture, loss of cryogenics	10	Emergency pressure valve failure, loss of insulation/vacuum, over exposure to thermal radiation/conduction	1	Pressure sensors, temperature sensors on tank	1	10	None Required	1	10
(10) Vent Boil-Off	boil-off unable to escape	Possible cryogenic system rupture, loss of cryogenics	10	Venting system failure, 'sticky' valves, trapped contaminant blocking valves	3	Pressure sensors	9	270	Method for detecting contaminant required.	N/A	N/A
	excessive cryogen boil-off	Early depletion of cryogen	6	Open 'sticky' valve, valve malfunction	2	Valve pressure sensors	5	60	High reliability valves needed	1	30

Table 5-2 – FMEA for the Maintain Temperature at Load Mode

The final step in understanding the system from a requirements perspective is to perform a Quality Function Deployment analysis, whereby a model is used to assess the relative importance of the initial overall stakeholder requirements against the functional requirements of the system, providing guidance as to which functions are most related to the overall project goals. It can also be used as a method of validation, whereby the visual aspect of having all of the relationships between aspects of the system can be examined, and if certain requirements are not met by at least one function, or if there is an incomplete set, it should become clear.

The QFD analysis for this research is performed by using a 'House of Quality' diagram (HoQ) shown in Figure 5-7. The first step is to list all of the stakeholder requirements on the vertical axis and all of the functional requirements of the system on the horizontal axis. Scores for importance between 1 and 5, with 5 being most important are then given to the customer requirements. This was done by using the previously gathered data on which requirements were considered key for each one of the six stakeholders interviewed, and based on previous expert interviews' considered key requirements and areas of focus.

The next step is to analyse the requirements against the functions, giving them a value within the matrix of 1, 3, 9, or a blank square. A number 1 represents a weak relationship, a 3 represents a moderate relationship, a 9 corresponds to a strong relationship, and a blank square represents no relationship. Each figure is multiplied by the relative importance of the stakeholder requirements, and then added together to form the overall absolute importance figure. The relative importance figure is also given, to show in relative terms the significance of each function. In this case, the customer requirements evaluation on the right side of the House is intentionally vague, as there are no known parameters or methods of assessing what the targets are other than the best performance possible. Should a viable solution exist that warrants further investigation, the HoQ will be revisited with clearer targets, particularly once the detailed targets are known from the air frame designers further into the future.

The QFD shown in Figure 5-7 shows that four of the functions within the system can be considered critical to the success of the project, with scores of above 500 on the absolute importance scores. These are the Exchange Heat, Store Cryogen, and

Vent Boil-Off functions, with the Transport/Pump Cryogen function scoring over 600, making it the most critical function. This is as expected, due to the pump or transport mechanisms probable role in compression of the fluid, meaning the cooling system itself relies on its functional operation. This result is also confirmed by the sensitivity matrix in Table 5-1. The Store Cryogen function is also expected to be critical to operation, which confirms the need for a reliable lightweight tank. This again is expected due to the possible inclusion of a LH₂ coolant; however since LH₂ considerations are out of scope except in the case of a heat sink, this is not investigated in depth. The Exchange Heat function again was realised as critical during the early stages of the project, and the HoQ analysis has confirmed this assumption. The nature of the heat exchange must be examined closely, since this will be crucial to the performance of the system during operation. Although the method of heat exchange is unknown, this analysis result confirms that close attention must be paid to this function in order to ensure the system can function correctly at the level of expected performance. Finally the Vent Boil-Off function was also identified as critical, which is somewhat unexpected. The reason this is an unexpected result is that during functional modelling, Vent Boil-Off is reliant only on inputs to function, which is the boil-off gases from various parts of the system. However, when looked at within the FMEA and HoQ analysis, due to its interaction with a number of the other critical functions, and therefore its requirements to properly function for the dependant functions to work properly, Vent Boil-Off is deemed as critical.

The HoQ also highlights which functions are least of concern, such as the Maintain Temperature and Pressure function and Monitor Cryogen Levels function. Both of these scored below 400 for the absolute importance, and as a result, they may need to be revised in terms of their requirement to exist. They could be combined within the other functions, however doing so will render the system to-date irrelevant, and will constitute iteration. At this stage, since the functions have shown some sensitivity and they depend on being separate from other similar functions for redundancy or independence reasons, they will be included in the further study.

This step now ensures the system has been evaluated thoroughly enough to allow the first stages in quantitative analysis. The qualitative phase of the project must

begin by first gathering all governing laws, equations, and relationships that are physically present within the overall electrical and cryogenic system.

Quality Function Deployment - FFD MTAL Mode

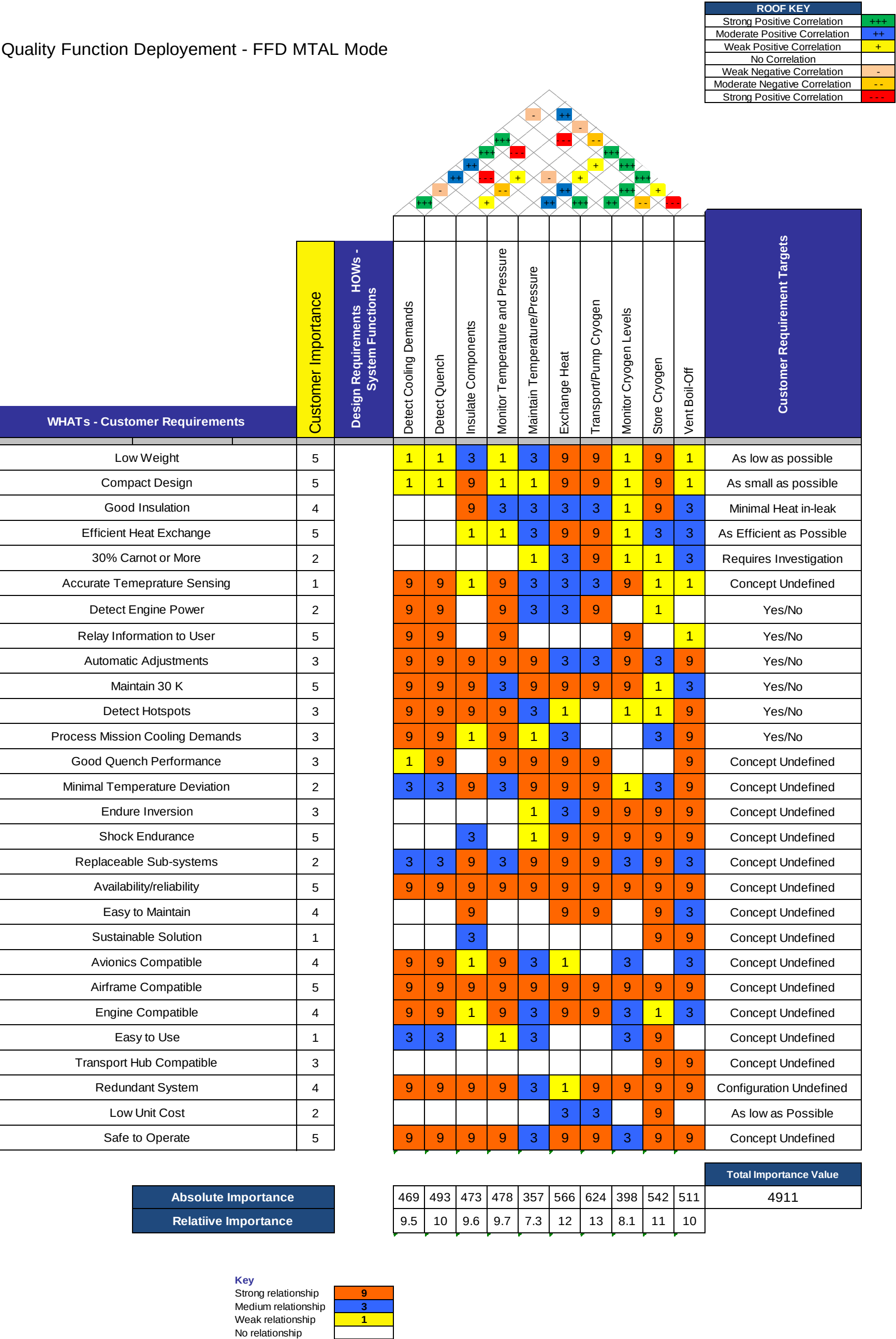


Figure 5-7 – QFD House of Quality for Maintain Temperature at Load Mode

5.6. Functional Analysis Discussion

The outcome for this chapter is the world's first functional mapping of a superconducting network cryogenic cooling system. Despite previous efforts by NASA, the functional behaviour and characteristics of a cryogenic cooling system for the purpose of aviation propulsion support has remained unknown. Qualitative analysis in the case of early stage concept research has proven to be useful within this project. Stakeholders' opinions on each gathered requirement proved to be useful in determining the most critical functions. Since the opinions gathered were from different people, in different engineering disciplines, and at differing levels of seniority and responsibility. This approach led to some differences of opinions on which requirements were most critical; however an overall viewpoint on the system requirements was gained by taking the average closest integer and this method keeps early analysis simple.

Simplicity is crucial at this stage in the concept development. Since the number of variables in the project is already considerable, minimisation in different forms has permeated the research. Requirements were kept simple for generality and impartiality such that design choices could be made at a later date without restriction. The Maintain Temperature at Load mode was selected out of the five hypothesised operational modes, using a simplified mission profile that identified modal pertinence of each mission segment. FFD's were also designed with simplicity as the key consideration. This approach allows multiple function combination to achieve the minimal possible complexity for further analysis, and crucially to reduce the requirement for further iteration. Finally, the methods used to analyse the FFD's were manipulated from typical designs. The QFD process in particular was modified to suit the conceptual nature of the project, since many customer requirements are not known.

The process development is a key aspect to conceptual-level systems engineering-based research. The systems process outlined by Rolls-Royce, although favoured as a method of design and decision making for complex problems with many variables, does not consider that many of these variables are either completely unknown or unquantifiable. An example of this is with superconducting technology, where traditional rules at even the basic physics level, break down completely. In an electrical system where DC resistance is at zero, Ohm's law is no longer applicable,

making losses more difficult to assess. This is one of many similar challenges that make this project difficult, even when using the systems engineering techniques outlined by Rolls-Royce.

When assessing the losses (And therefore cooling requirements) in a complex, as-of-yet undefined electrical superconducting architecture, the challenge of quantification becomes significantly tougher. It is only through simplification that the first steps can begin, initiating an iterative process that grows in process complexity once some of the crucial unknown variables are identified and quantified. Particularly difficult to assess with regards unknown quantities will be the weight of any solution. Typically, weight is assessed first in any aeronautical design as it is crucial for wing sizing. With an unknown system such as this, quantification of the weight is tricky because at present, the solution is a complete unknown, along with the potential for improvement when applying aerospace-grade technology and materials to industrial designs.

Chapter 6. Systems Engineering Process Adaptation and Concept Selection

6.1. Introduction

Systems engineering has been used for decades to manage complex interdisciplinary projects such as NASA's Apollo program (NASA, 2007). The method works by first accurately defining a problem through talking to all involved parties and creating a large set of requirements. For the purpose of this project, systems engineering alone is not sufficient to reach a solution because of the large number of fundamental unknowns, whether those unknowns are in the form of assumptions, requirements, or even basic performance targets.

For the purpose of this research, the Rolls-Royce systems engineering process has been adapted in order to reach a first-pass solution. Certain elements are changed, some are dropped completely, and other methods are defined. This chapter highlights the overall high-level perspective as to why the process was adapted, why elements of the Rolls-Royce systems engineering process were used and others omitted, and how other methods were utilised. Crucially this chapter provides a top-down view of the route used to generate a first concept.

The second part to this chapter suggests potential candidates for concepts for the cryogenic cooling system, using function means analysis (FMA). FMA is carried out by suggesting all known ways of achieving the functions within the earlier defined functional model for the Maintain Temperature at Load mode. Once all known possible concepts, however outlandish or unlikely, are compiled into the FMA, elimination takes places using DREd charts, and an overall set of plausible concepts is generated. From this set of ideas, the most likely best concept is selected for numerical modelling. Discussion at the end of the chapter centres on the transition between qualitative and quantitative analysis outlined in the modified systems engineering process that was adopted.

6.2. Rolls-Royce Systems Engineering Process Overview

Systems engineering relies on a clearly defined process of gathering requirements, deriving the functionality of the system being designed, and then choosing the correct methods of achieving those functions based on the performance of concepts

generated. The traditional process (simplified for diagrammatical purposes) used by Rolls-Royce is described in Figure 6-1.

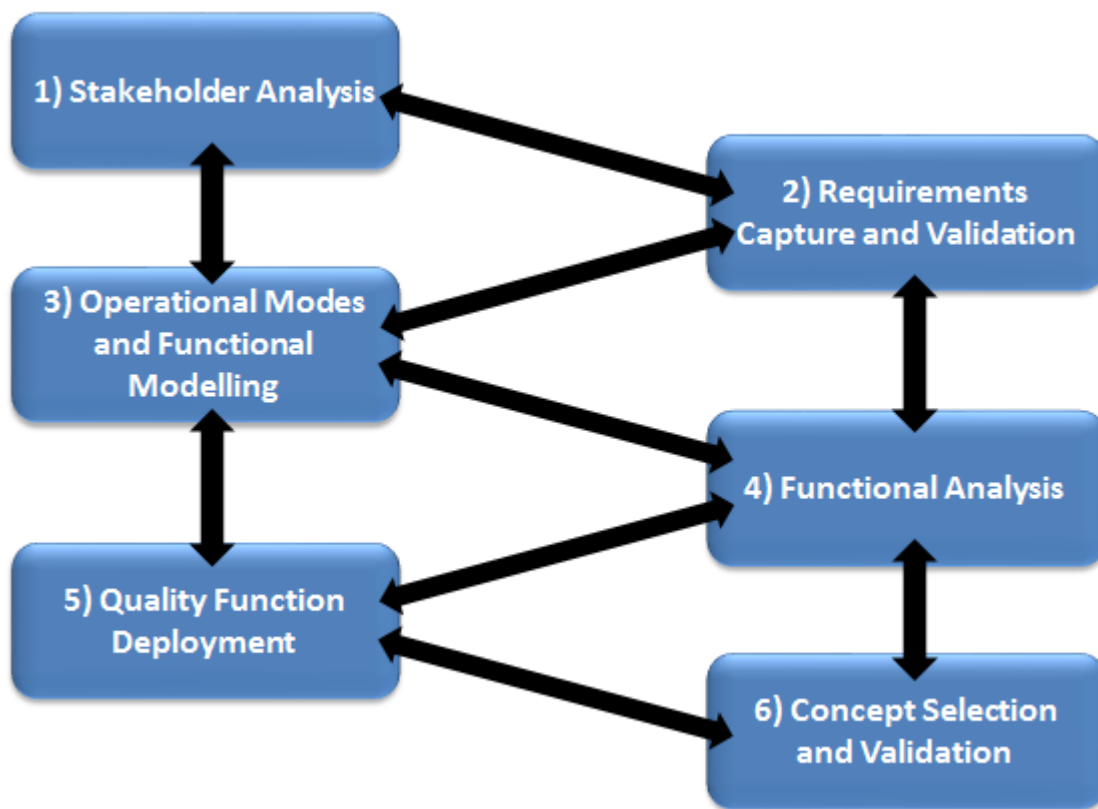


Figure 6-1 – Overall Rolls-Royce Systems Engineering Process

Figure 6-1 gives the process in high-level terms, whereby the systems process is described by six distinct phases. The phases in Figure 6-1 are described as follows, with brief descriptions on the processes, taken from the Rolls-Royce Systems Engineering Handbook (Rolls Royce, 2012):

1. **Stakeholder Analysis** – Stakeholders for the project and their respective roles and influences are defined, and stakeholder participation is used to understand requirements. Stakeholder analysis techniques include brainstorming, tree diagrams, and stakeholder group and elimination rationale diagrams.
2. **Requirements Capture and Validation** – Requirements must be captured using different perspectives, with stakeholders/customers making up a large portion of requirements input. Once stakeholder input is known, the

requirement set is enlarged through techniques such as the affinity diagram, further tree diagrams, and needs means analysis, to see if early stakeholder requirements can be met early on.

3. **Operational Modes and Functional Modelling** – Once requirements are known to a reasonable degree of completion, the system under investigation is functionally considered, by recording the operational modes the system must operate under. The system is then mapped in terms of functionality using FFD's. This is done for each mode, and at the various stages, including for sub-functional processes.
4. **Functional Analysis** – Once a full set of functional models is generated, they are assessed using sensitivity studies, failure modes analysis, and early QFD analysis. This step begins to define the solution, as choices can be made once it is clear which requirement targets are met by early stage concepts.
5. **Quality Function Deployment** – QFD is a method of finalising the requirement set and to assess which functions within the system are most critical to the successful concept. This step typically results in iteration, whereby knowledge gained so far can be inputted in earlier stages, making any final concept more robust as a solution. The methods used are HoQ, N^2 analysis, and logical system architecting.
6. **Concept Selection and Validation** – This is the final stage of systems engineering design, whereby all known methods of achieving the functions within the now-validated functional models are incorporated, and those with the best performance against the pre-defined requirements are selected. Methods for concept selection include the function means analysis (FMA), Pugh matrices, and a further QFD HoQ analysis. The final outcome should be a robust concept solution to the original design requirements.

The systems engineering process is intended to limit any undesired issues occurring at a later stage in design. The primary driver behind this is cost; it is far cheaper to fix a problem sooner rather than later. Figure 6-2 shows the cost of fixing errors at various stages of a project.

systems cost factors	
requirements	x1 (reference)
design	x5
build	x12
test	x40
operations	x250

Figure 6-2 – Table showing the cost factors of fixing errors at various project stages
(UK Systems Eng Council, 2009)

When considering the cost of fixing a system can be 250 times higher once it is in service than fixing the problem at the requirements stage, it is clear to see why a robust method of design is crucial to modern day business. Engineering projects and systems are also increasing in complexity, whereby many different operational parts must cohere, often spanning different engineering disciplines. Systems engineering is seen as the solution to increasing complexity because of its reliance on getting the requirements correct, minimising the risk of undesirable emergent behaviour in any generated solution at a later date.

At present, most engineering problems are solved using a solution-based approach, whereby solutions are suggested to a problem based on the customer brief. This approach, while instantaneous in its visibility, typically leads to undesirable emergent behaviour that inevitably leads to troubleshooting throughout the design process. By focusing on requirements, even complex problems can be solved through thorough understanding at an early stage.

There are however limitations to the Rolls-Royce systems engineering method. Although systems engineering thinking is useful for complex problems, typically most information about a system is known, for example customers know their requirements for performance, safety standards, etc. This project poses many challenges for the traditional systems process followed by Rolls-Royce; hence it must be adapted to suit the needs of this research. The process also takes time.

Many opponents of systems engineering within Rolls-Royce typically state that the time taken to fully understand every requirement can mean losing competitive edge. Simplification is needed in order to make the process more attractive initially, since the benefits of systems engineering are hidden.

This chapter shows how the Rolls-Royce systems engineering process can be simplified for use at early stage conceptual design, in order to both provide early results, and to minimise the risk of undesirable emergent behaviour in any given system.

6.3. Rolls-Royce Systems Process Limits and Adaptation

Throughout this project, the Rolls-Royce systems engineering methodology has been used due to the complexity of the challenges encountered. Systems engineering is a means of breaking down complex problems in a robust and repeatable way such that even very difficult problems become a matter of process. Despite the highly robust nature of the systems engineering process, the research to date has encountered numerous challenges that Rolls-Royce systems engineering process cannot address.

Most of these challenges arise when considering the highly theoretical nature of the project; most of the components that require cooling do not yet exist, and there are no comparable networks or components, hence systems concept selection becomes suddenly difficult. The Rolls-Royce systems process typically has an iterative nature but fairly linear structure in terms of the overall process, whereby functional analysis can translate directly into systems concept selection. This linear (although iterative) process is shown in Figure 6-3. In order to circumvent the issues that arise from theoretical concept design, systems engineering must go hand in hand with basic numerical modelling and solutions thinking. Figure 6-3 also shows the adapted Rolls-Royce process used throughout this project.

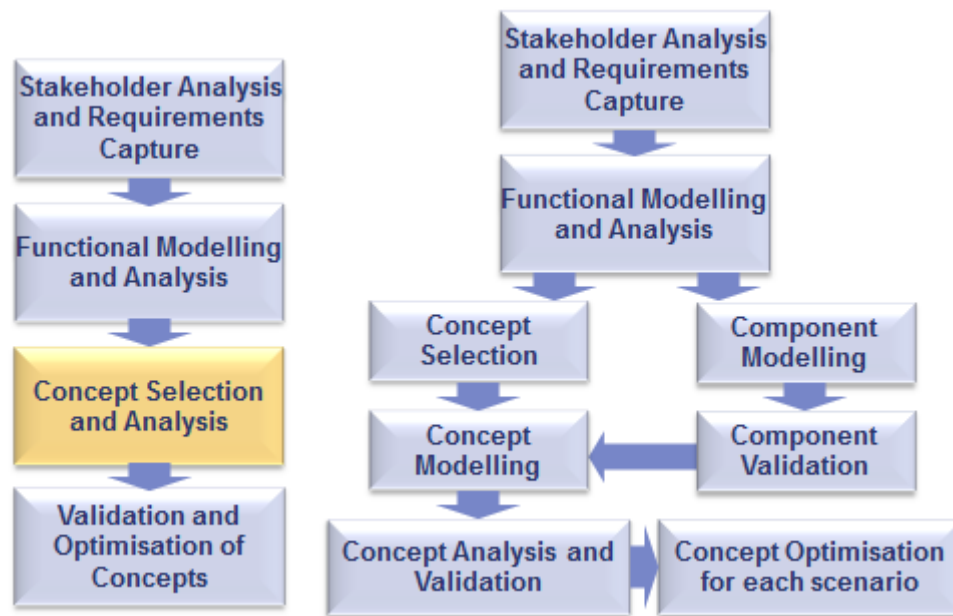


Figure 6-3 – Standard (left) and modified (right) Rolls-Royce systems engineering processes

When the research entered the concept selection stage it became apparent that the sensitivity to heat load for the cryocoolers was high. Any slight change in the required cold power in the superconducting system is likely to result in large changes in cryocooler required power. This is due to the fundamental relationship between cryocooler required input power and cooling output power; typical cryocoolers have cold powers one or two orders of magnitude lower than the required input power. Since the concept may potentially change as and when new information from experimental research becomes available, complexity begins to arise from the combined high sensitivity and high variability of best concept. This highly interdependent relationship between the superconducting network and the cryogenic cooling system coupled with poor understanding of those relationships at present led to a proposed change in the way the Rolls-Royce systems process is performed.

The changes consist of three different key aspects; overall process modification and modelling incorporation, current technique modification, and validation strategy. The process modification is shown in Figure 6-3. On the left the original Rolls-Royce systems process is shown to be largely linear. Since the large number of unknowns means the concept must first be defined, the concept and component level concepts must be performed in tandem. As a concept is defined by the qualitative process

gradually, the likely resulting components are also defined. Once numerical models are developed for components, they are validated through expert opinion. These are then fed back into the overall concept for modelling within the holistic system. The qualitative analysis results are crucial to the successful modelling of any solution, since the choice of cryogenic cycle will determine which equations are used to handle inputs and outputs of components.

To enable rapid first-pass concept generation, the overall process was modified to suit the needs of this project. Of particular note is the HoQ used, shown in Figure 5-7. Typical HoQ analysis is performed once customer requirement targets are known, so any concept can be numerically assessed. In this highly conceptual theoretical problem, it is necessary to put into perspective the problem that arises with the need to know this information. At present, the customer identity is known, yet the customer does not know of the requirement for the cryogenic cooling system. Since the idea of electric propulsion is relatively new, customers do not know their requirement metrics, hence most targets are simply 'As Good As Possible'. This freedom from customer targets is both advantageous and disadvantageous. It allows the complete conceptual design freedom without any concept being ruled out; however it also means any concept that eventually gets selected must undergo further scrutiny, since it will be unknown from the outset whether the concept selected meets the performance criteria.

Within the qualitative analysis, numerous similar simplifications have taken place. The Maintain Temperature at Load mode is selected as the critical mode by assigning the mission profile segments to each mode, and selecting the mode most associated with flight segments. This normally would not take place; in a less theoretical system, each mode would be modelled from a functional perspective, however since the concept could change when new information becomes available, it is necessary to effectively streamline the process. Simplification methods used are as follows:

- Stakeholders are eliminated early on to avoid correspondence with stakeholders that may influence or potentially stifle innovation.

- Requirements interviews are conducted with technical experts only, ignoring other stakeholders identified at the early concept stage for the reason of allowing freedom of design.
- Operational modes are identified and the critical mode is selected by assigning mission segments. The critical mode is then the only mode selected for functional modelling.
- Functional modelling of just the critical mode; level 0 and level 1 modelling is used, level 2 is too detailed since it requires definition of the concept, and at level 0 the relationships between interacting systems are not considered for the reason of simplicity.
- Functional analysis methods are reduced in scale or simplified. Sensitivity analysis and FMEA is performed only on the FFD generated for the critical mode identified. The QFD analysis consists only of the HoQ which is simplified to suit the needs of the project. Customer requirements are not known in detail, and targets from a quantitative perspective are unlikely to be known at such an early design stage.
- Concept selection is limited to only the most critical components as identified by the systems process.

The systems process methods are intended to coalesce together to form a robust decision on design. Concept selection can take place once all the methods have been performed, and consistency between methods is exhibited.

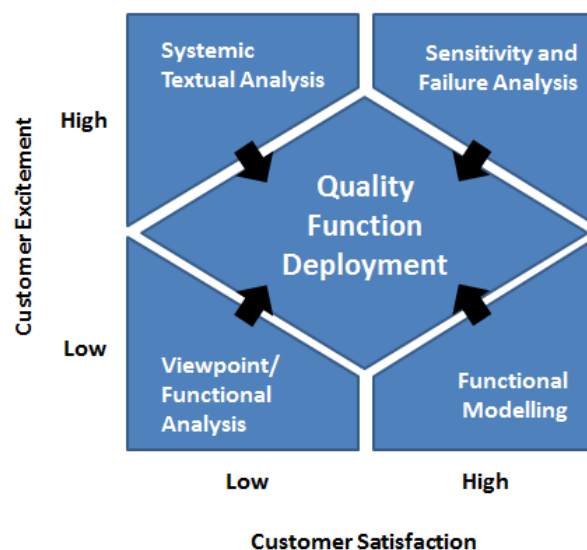


Figure 6-4 – Customer excitement and satisfaction diagram

Figure 6-4 shows how the systems methods used effectively capture and assess the requirements of the system. The diagram shows the order of methods used in two metrics; customer satisfaction and customer excitement. Systemic textual analysis is typically defined by the customer, hence it is likely the customer will be enthused by their own requirements, and thus ranks highly on the excitement axis. However since customers are unlikely to initially define their needs adequately, the overall solution (should only the requirements defined by the customer be used) is likely to disappoint, therefore the customer is less satisfied. Viewpoint analysis is likely to capture more requirements from the designer, but the customer is unlikely to be enthused or excited about requirements generated using this method. Functional modelling is likely to satisfy the customer in terms of a solution as it will uncover functions that could be performed by singular components or similar simplifications; however it is unlikely to generate excitement as it will not define concepts or solutions. Sensitivity and failure analysis is likely to generate both excitement and satisfaction, since it begins defining potential solutions along with highlighting potential failure modes. The final QFD analysis provides validation on the methods used, incorporating the results from each method, and checking for consistency in the functional analysis and sensitivity study. This rigorous approach to design forms a foundation for which concepts can be generated.

- Systemic textual analysis was used to translate the brief given by Rolls-Royce on how the cryogenic system should operate and to analyse what was said through experts interviewed.
- Viewpoint analysis was used when considering stakeholder requirements and relevance.
- Functional modelling was used to understand the functional behaviour of the system, and functional analysis was performed to determine the validity of the FFD's.
- Sensitivity analysis was used to assess the functional models in the event of failure or performance degradation.
- QFD analysis brings all four aspects together by assessing the originally generated requirements against the functional sensitivity of the system.

The critical functions are now defined, allowing concept generation to take place. Using the methods outlined in Figure 6-4, the qualitative analysis of the project is mostly complete, with only qualitative concept selection left to perform. Once a baseline concept is defined numerical analysis can be performed to assess the quantitative aspects of the solution.

6.4. Concept Selection Overview

Concept selection follows on directly from the qualitative analysis by defining (as far as possible) preferred solutions to functions that must be satisfied. Since the concept is still at such an early design stage, some solutions are not possible to define or are not pertinent. The first step is to list all known ways of achieving a function and compile them into a function means analysis diagram (FMA). The FMA solution set is then examined in more detail, exploring the qualitative and known quantitative aspects of each solution in brief using DREd diagrams. Once the most critical functions are defined, numerical modelling can take place, particularly when a thermodynamic cycle is chosen, as cycle choice will determine which set of equations are used. Since there are many requirements, the choices made within the analysis of the FMA will be graded on the most critical requirements, particularly those given a 5 in the HoQ diagram in Figure 5-7. The outcome for this chapter will be a partially defined cryogenic cooling system solution that can be modelled numerically. The final part of the chapter will discuss the solution generated, the concept selection process effectiveness, and how issues encountered during the concept selection and Rolls-Royce systems process adaptation were mitigated.

6.5. Function Means Analysis

Following on from the Rolls-Royce systems process adaptation, the FMA compiles all the functions of the cryogenic cooling system and all of the conceivable means of achieving that function so that overall concepts can be suggested. The procedure for determining the viability of any single functional solution begins with a qualitative analysis. The criteria for inclusion within the FMA is firstly based on whether there are any challenges that cannot in any way be mitigated. The remaining options have varying degrees of viability and are all included at this stage, but when concept selection takes place, they will be quantified as best as possible and ranked

according to their system suitability and performance. Priority is given to solutions that can satisfy multiple functions, simplifying any potential system.

Figure 6-5 shows the layout of an FMA. The functions are listed on the left, and solutions to satisfy each function are hypothesised. Potential concepts must select one solution from each function. This generates individual concepts that can then be compared in merit numerically. Figure 6-5 also shows how different numbers of solutions can exist for each function. Function B in the example shown shows only one solution; this can occur frequently, however it is undesirable since it limits the possible number of concepts. If a single solution function does occur, the concept is selected, however further investigation is essential. If the concept cannot possibly fulfil the requirements due to a single solution function, this highlights a critical technology gap in fulfilment of that specific function. This could lead to intellectual property development.

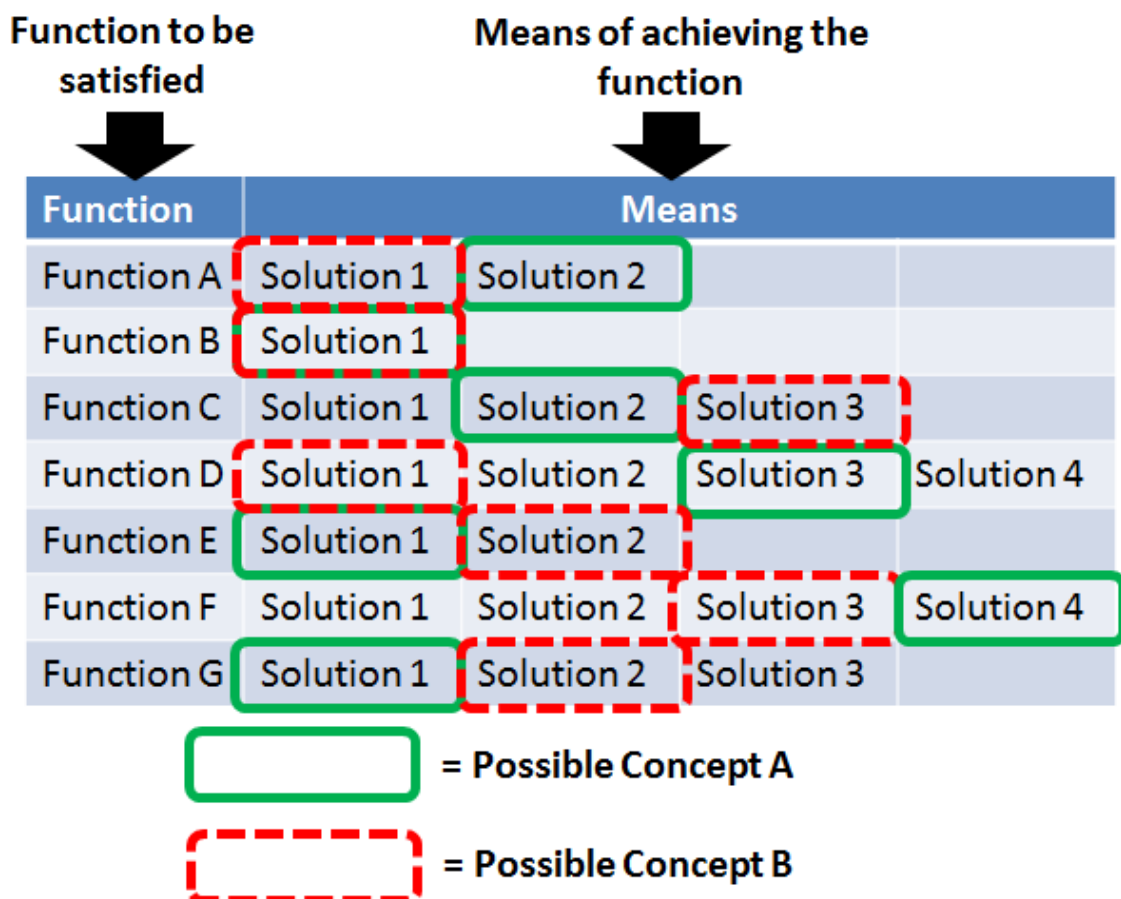


Figure 6-5 – Example of FMA

This section is divided into three phases; basic FMA table and known solutions, solution exclusion rationale and updated FMA table, and concept selection and analysis.

6.5.1. FMA Solutions

This section will show the FMA diagram (Figure 6-6) and list the solutions to each function, providing a very brief explanation by what is meant by each solution where needed.

Functions	Means									
	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7	Concept 8	Concept 9	Concept 10
Detect cooling demands	Computational calculation	Direct measurement of fan rpm	Direct Measurement of temperatures	Measurement of pilots power demand	Electrical power measurement	Efficiency/load calculation				
Detect quench	Pressure Sensors	Direct Temperature Measurement	Electrical fault detectors	Direct performance measurement						
Insulate components	STS ET tank foam	aerogels	vacuum jacketed cryostat	combined polymer aerogel, MLI, and vacuum	2-stage shielded cooling	Multiple stage shielded cooling	Multi-layered insulation			
Monitor Pressure	Pitot tubes	strain gauges	Manometers	piezoelectric detection	Magnetic detection	Capacitive detection	Optical detection	Thermal conductivity (RTD's)	Flow measurement through transporter	
Monitor temperature	Thermocouples	Platinum RTD's	Superconducting magnetic field detection	Silicon diodes	thermistors					
maintain temp/press	Reverse Brayton	GM cold head and compressor	PT cold head and compressor	Magneto caloric effect with closed loop helium circuit (Compressor)	Stirling cooler	Vapour-compression				
Exchange heat	Cross corrugated HX	Tubular microchannel HX	Shell and tube HX	Plate and shell HX	Plate fin HX	Pillow-plated HX	Spiral HX	Coiled HX	Phase change HX	Diffusion bonded block heat exchanger
Transport/pump cryogen	Cryocooler	separate singular pump	Separate multiple pumps							
Monitor cryogen levels	Pressure gauges	Mass flow meters	Float							
Store cryogen	Stainless steel tank	ceramic coated steel tank	Lightweight composite tank	Hydride coated stainless steel tank	Polymer laminate tank					
Vent boil-off	Active valves	Passive valves	Directive boil-off system	Rupture disks						

Figure 6-6 – FMA diagram showing all conceivable means of achieving the functions generated

Detect Cooling Demands

- Computational Calculation – Using pre-determined data from standard values and set points from throttle and airspeed, cooling demands can be calculated based on machine RPM or other parameters easy to track.
- Direct Measurement of Fan RPM – Knowing the fan RPM, cooling demands can be calculated since knowing fan RPM means knowing the motor RPM (gas turbine RPM is already known).
- Direct Measurement of Temperatures – Using an array of thermal sensory equipment, temperature changes can be translated into cooling demand.
- Measurement of Pilot Power Demand – Using the throttle position given by the pilot, loss in the system can be calculated (similar to fan RPM measurement, but from the other end of the system).
- Electrical Power Measurement – Direct measurement of the frequency and current in the system to give the thermal loss, therefore the cooling demands.
- Efficiency/Load Calculation – Knowing the efficiency of the system at different loads, the loss can be derived, meaning no additional equipment.

Detect Quench

- Pressure Sensors – Any quench will be accompanied by a sharp increase in pressure of the cryogen fluid. This could be detected rapidly at source by pressure sensory equipment.
- Direct Temperature Measurement – Temperature measurements at short intervals within windings or cables could detect a quench as it happens.
- Electrical Fault Detectors – Magnetic measurement or circuit breakers could detect a sharp decrease in current or magnetic field, detecting any quench as it happens.
- Direct Performance Measurement – The drop in propulsive power can be detected, leading to the conclusion that a quench has occurred.

Insulate Components

- STS ET Tank Foam – Space Transportation System (STS) External Tank (ET) foam, made of a spray-on polyurethane composition.

- Aerogel – Aerogel is a low density, low thermal conductivity solid, made by dehydrating gel structures under controlled conditions.
- Vacuum Jacketed Cryostat – Essentially two containment vessels separated by a gap that is evacuated with a vacuum pump.
- Combined Polymer Aerogel, MLI, and Vacuum – A multi-solution approach that uses thin layers of polymer aerogel (for thermal conductivity), MLI (for radiation), and a vacuum (for convection and conductivity) to take advantage of multiple desirable properties.
- 2-stage Shielded Cooling – Use of a cooled outer layer within a cryostat, reducing the temperature differential per-stage through the wall of the cryostat. Requires two different temperature cryogenic fluids.
- Multi-stage Shielded Cooling – Similar to 2-stage shielded cooling, except multiple stages are used through novel heat exchange design. 3 or more stages.
- Multi-Layered Insulation (MLI) – MLI consists of multiple alternating sheets of Mylar® (or similarly low thermal conductive material) and reflective foil (such as aluminium). It is commonly used in space applications for its radiative heat shielding properties.

Monitor Pressure

- Pitot Tubes – Measures the fluid flow velocity to give a direct pressure measurement.
- Strain Gauges – Strain gauges placed at strategic points can detect the small deformation of the cryostat in order to calculate the pressure.
- Manometers – Manometers use liquid in a U-shaped tube, measuring the distance the fluid moves up the opposite side to the pressure measurement fluid.
- Piezoelectric Detection – Placing piezoelectric material on the outside of the cryostat, detecting any deflection in the pressure vessel through electrical impulse.
- Magnetic Detection – Small magnetic pieces of material embedded into the cryostat with hall-effect sensor to detect the change in interacting fields.

- Capacitive Detection – Placement of metal plates either side of a tube through which cryogen flows, with change in field across the tube measured through physical change in size, detected through capacitive means.
- Optical Detection – Use of lasers to accurately determine the change in length of a flow tube.
- Thermal Conductivity (RTD) – Resistance Temperature Detectors (RTD) can be used in conjunction with mass flow measurements to determine the pressure of a system by measuring temperature.
- Flow Measurement through Transporter – Measurement of the flow change between the inlet and outlet of the compressor or 'transporter' function gives the pressure change.

Monitor Temperature

- Thermocouples – Use of thermocouples which rely on two different conductive materials at strategic points around the system to directly sense temperature.
- Platinum RTD – Platinum RTD's are commonly used in cryogenic temperature measurement. They are similar to thermistors, except the conductor is metal.
- Superconducting Magnetic Field Detection – Use of superconducting materials to generate a field within the system, using a Hall-effect sensor to detect the self-induced field inside the system with no penetration of the cryostat.
- Silicon Diodes – In silicon diodes, the forward Voltage is dependent on the temperature. These could be placed at strategic locations around the cryostat.
- Thermistors – Use a ceramic or polymer conductor whose resistance varies with temperature.

Maintain Temperature/Pressure

- Reverse-Brayton – Consists of a compressor, turbine, and heat exchangers, and relies on direct fluid flow around the network.
- GM Cold Head and Compressor – Uses a GM cold head and separate compressor, with conductive heat transfer. Fluid flow pumps would be required.

- PT Cold Head and Compressor – Uses a PT cold head and compressor, with conductive heat transfer. Fluid flow pumps would be required.
- Magneto Caloric Effect with Compressor/Helium Loop – Uses a solid conductor ring and high-powered magnets to remove thermal energy. Would require separate fluid pumping and compressor to drive interface fluid.
- Stirling Cooler – Uses a closed-loop fluid to generate temperature differential. Would require a fluid transfer pump for interface between the conductive cold head transfer fluid.
- Vapour Compression – Uses the vapour-compression cycle to remove heat. Does not require incidental equipment, as compressor, throttle valve, and heat exchangers are in-built. Would require low inversion temperature fluid.

Exchange Heat

- Cross Corrugated – Consists of stacked corrugated plates, with the direction of corrugation set perpendicular to each other, allowing perpendicular flow of the two fluids.
- Tubular Microchannel – Consists of many tiny tubular channels in a small space, which significantly increases surface area per unit volume.
- Shell and Tube – Consists of small tubes set inside a long shell with baffled overflow fluid path.
- Plate and Shell – Consists of plate heat exchangers set inside a large shell with baffled overflow fluid path.
- Plate Fin – Consists of many plate heat exchangers with perpendicular flow paths, much like cross corrugated. The key difference is the ability to separate plates.
- Pillow-Plated – Plate heat exchangers that are spot-welded thoroughly throughout the plate, increasing the basic surface area of the plate heat exchanger.
- Spiral – Two sets of spiral sheet metal set inside one another, allowing cylindrical containment of a heat exchanger with high surface area.
- Coiled – A basic shell with a coiled (or number of coiled) fluid pipes inside.
- Phase-Change – A heat exchanger specifically designed to handle liquid to gas phase changes, making use of latent heat capacity of a liquid.

- Diffusion Bonded Block – Similar to cross corrugation in geometry, this method of manufacture allows much smaller heat exchangers to be made at higher rated pressures.

Transport/Pump Cryogen

- Cryocooler – Using the cryocooler (if possible) to drive the fluid around the system to the parts that require cooling.
- Separate Single Pump – Using a single pump in the case of conductive cryocoolers to move cooled fluid around the superconducting network.
- Separate Multiple Pumps – Multiple pumps for redundancy segmented into sections to move cooled fluid around the superconducting system.

Monitor Cryogen Levels

- Pressure Gauges – Using pressure gauges with tank design to calculate remaining cryogenic fluid.
- Mass Flow Meters – Use of mass flow meters to record how much cryogenic fluid goes into the tank and the rate of use.
- Float – Use of a float to record the physical position of the amount of liquid cryogen left in storage.

Store Cryogen

- Stainless Steel Tank – Use of simple polished stainless steel to store cryogenic fluids.
- Ceramic-Coated Steel tank – Ceramic coatings on stainless steel tanks can reduce the leak rate of small molecules that are likely to be used such as helium or hydrogen.
- Lightweight Composite Tank – Composites can offer lightweight solutions to tanks and are less susceptible to embrittlement in the case of hydrogen.
- Hydride-Coated Stainless Steel Tank – Hydride coatings effectively fill molecular spaces that could otherwise increase the rate of leakage of small molecules.

- Polymer Laminate Tank – Tanks that have laminates both have excellent thermal properties and strength. Laminates can include tightly packed molecular structure materials, effectively allowing custom design.

Vent Boil-Off

- Active Valves – Active valves use pressure monitoring sensors to vent in real time reactively. This type of valve would keep the system level in pressure.
- Passive Valves – Passive valves would react to increases in pressure by venting until below a given pressure threshold.
- Directive Boil-Off System – Directive boil-off systems could direct any boil off in any part of the system toward either venting or return cooling. This method would be complex to implement but might provide advantages in fuel saving.
- Rupture Disks – Rupture disks would burst when pressure goes over a certain threshold, saving the system from rupture in other more sensitive places.

6.5.2. Solution Elimination Rationale and Final FMA

To enable the rationale to be effectively presented, design rationale editor (DREd) was used in order to preserve the critical thinking process used to eliminate each solution. Figures 6-7 to 6-14 show each functions design rationale. For each option, not all solutions are eliminated; hence the final FMA will still have options that are difficult to distinguish between. Elimination at this stage using rationale is purely qualitative and relative. For example, a solution could be considered lightweight if the technology is lighter than the majority of other solutions in the functional solution category.

Two functions are ignored at this stage; monitor pressure, and monitor temperature. The reason for exclusion is that the impact of these two functions on the performance of the cryogenic cooling system (from the critical success criteria outlined previously, weight and required input power) is negligible. Regardless of solution, temperature and pressure sensing is highly unlikely to impact the weight or input power, since they are passive metrological components. For that reason, they are omitted in the FMA concept solution, and are considered part of the future detailed design once an overall cryogenic cooling system solution is defined in terms

of thermodynamic cycle and component set. The choice of cycle is likely to influence the solutions for both monitor temperature and pressure functions.

Also omitted in the rationale section is the Vent Boil-off function. The reason for this is that the function is considered solution dependant. Should a system consist only of gaseous fluid, boil-off is not considered a primary issue. Since concepts for management of the function are known, the solution to this function is considered low priority, despite its high criticality score on the HoQ analysis. Once a concept is defined and the design begins to emerge, the function solutions will be revisited to discuss whether the function is relevant, and if so, which solution would be most suitable.

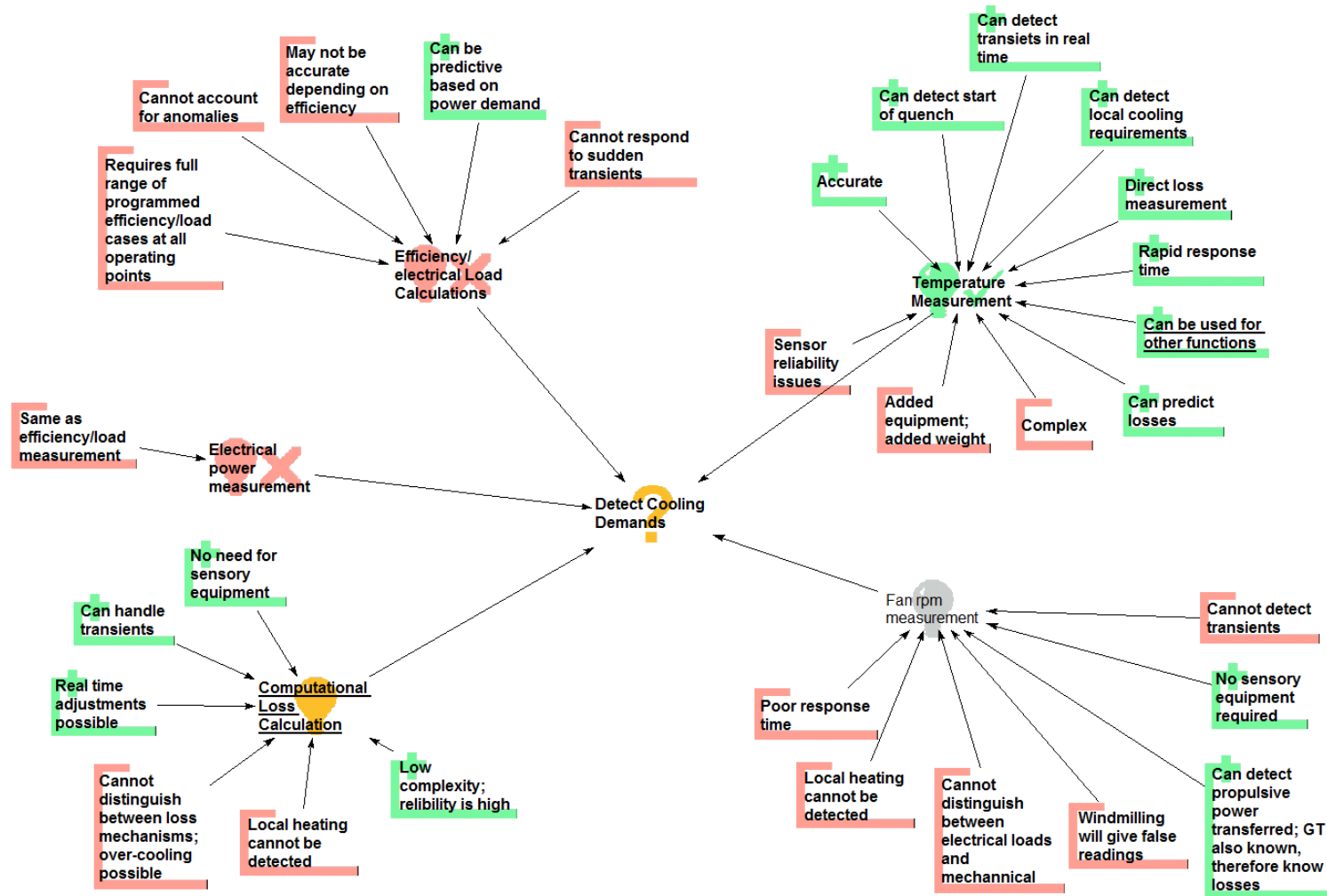


Figure 6-7 – DREd solution rationale for ‘detect cooling demands’ function

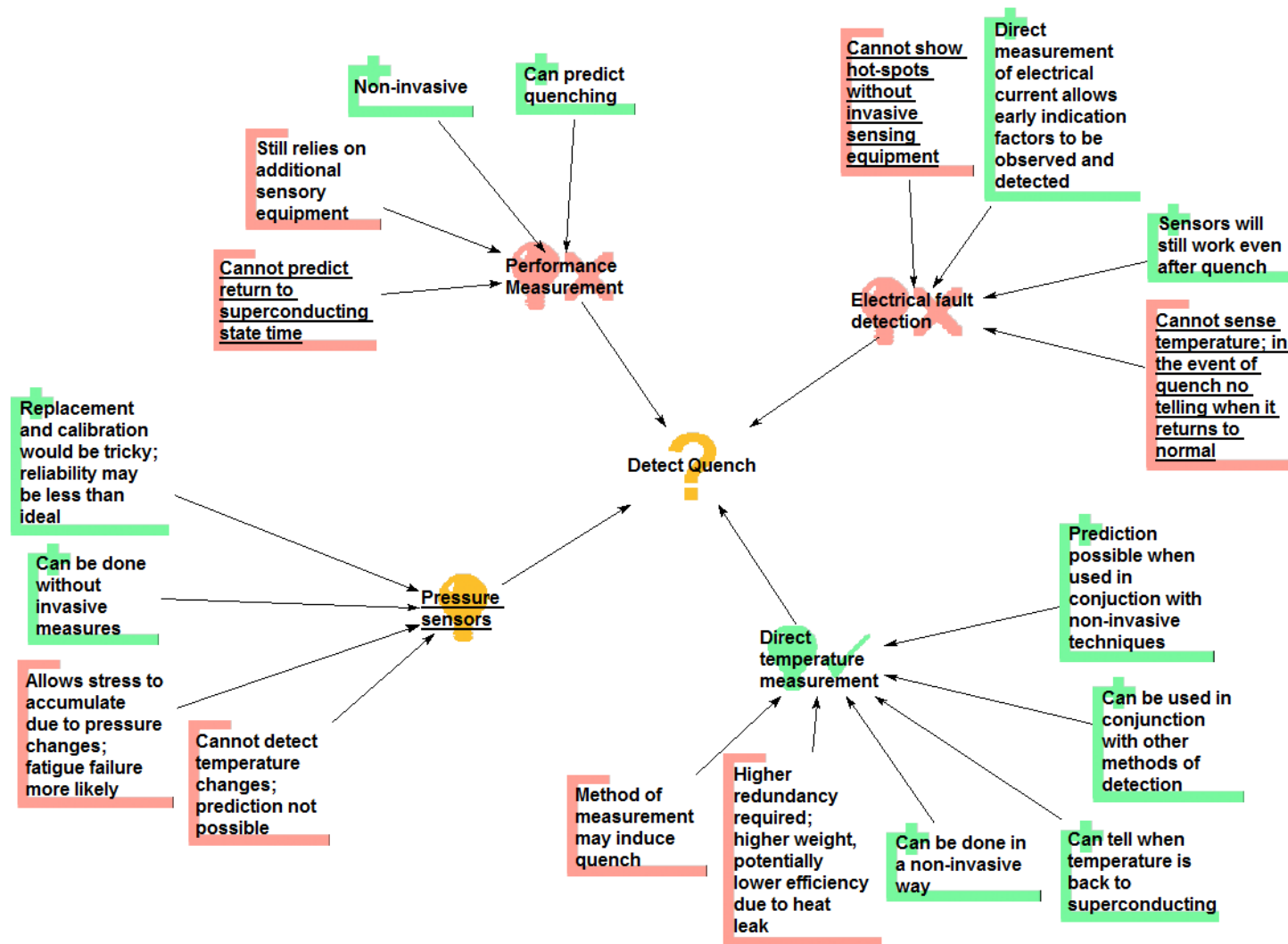


Figure 6-8 – DREd concept rationale for detect quench function

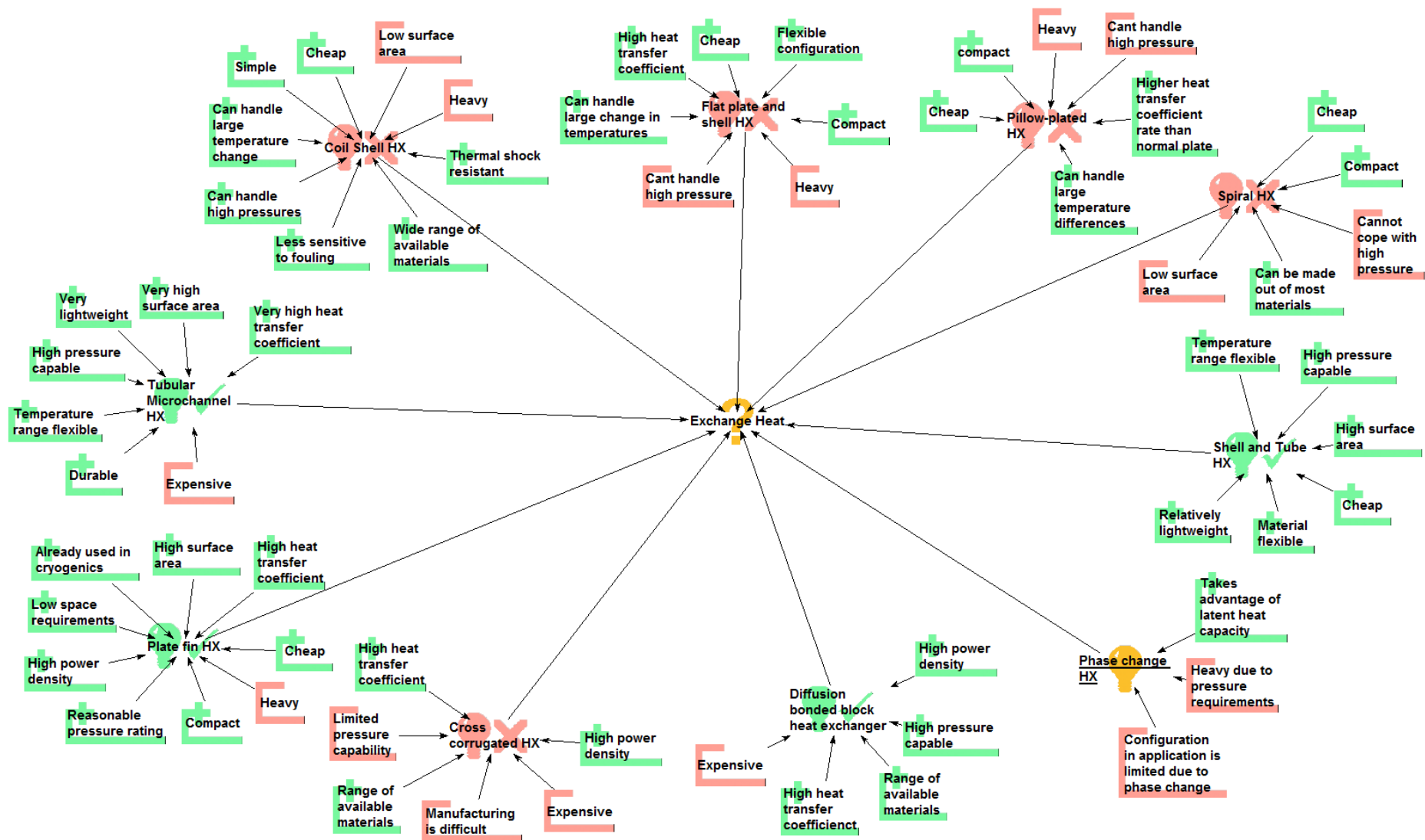


Figure 6-9 – DREd concept rationale for exchange heat function

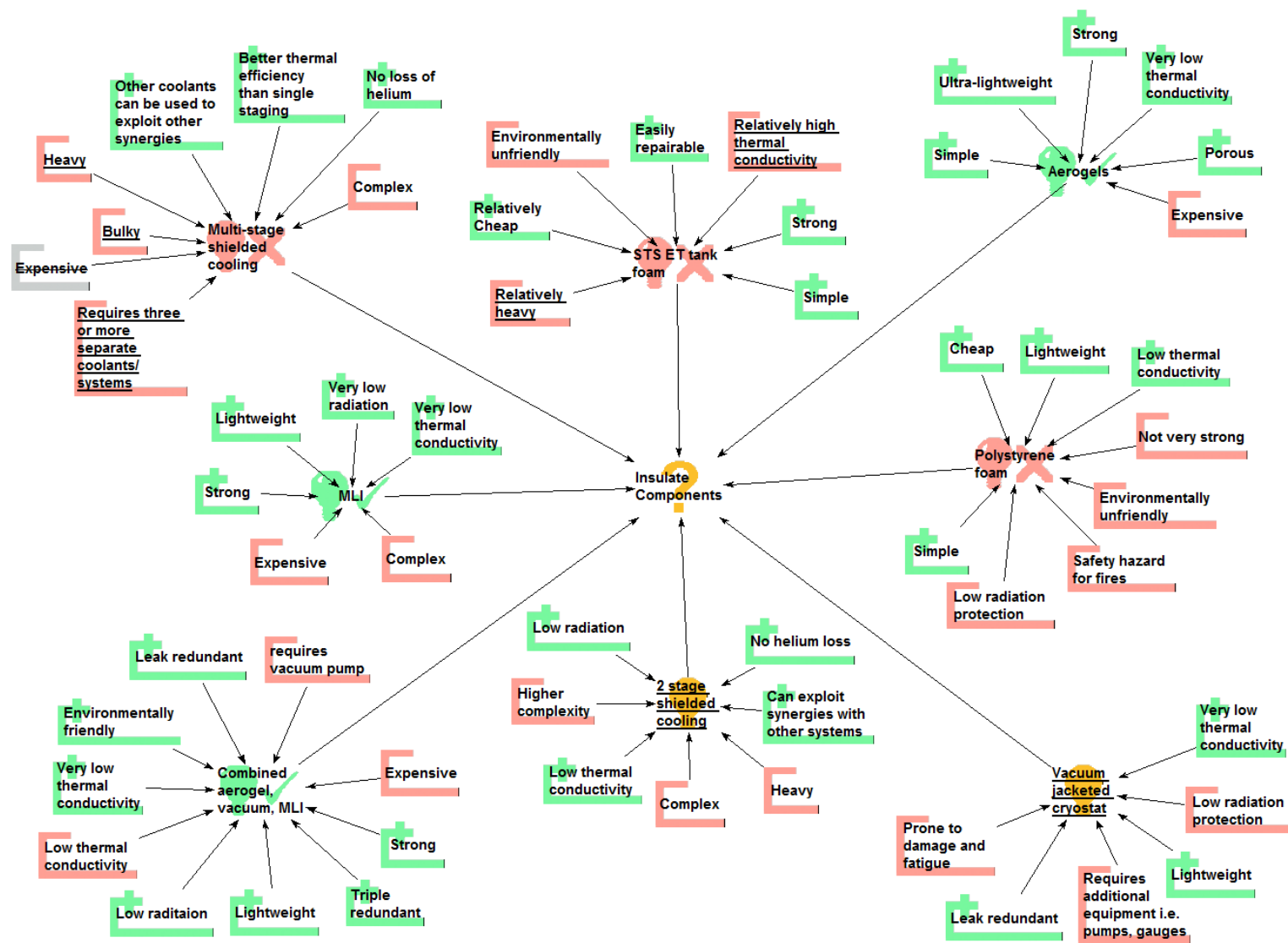


Figure 6-10 – DRED concept rationale for insulate components function

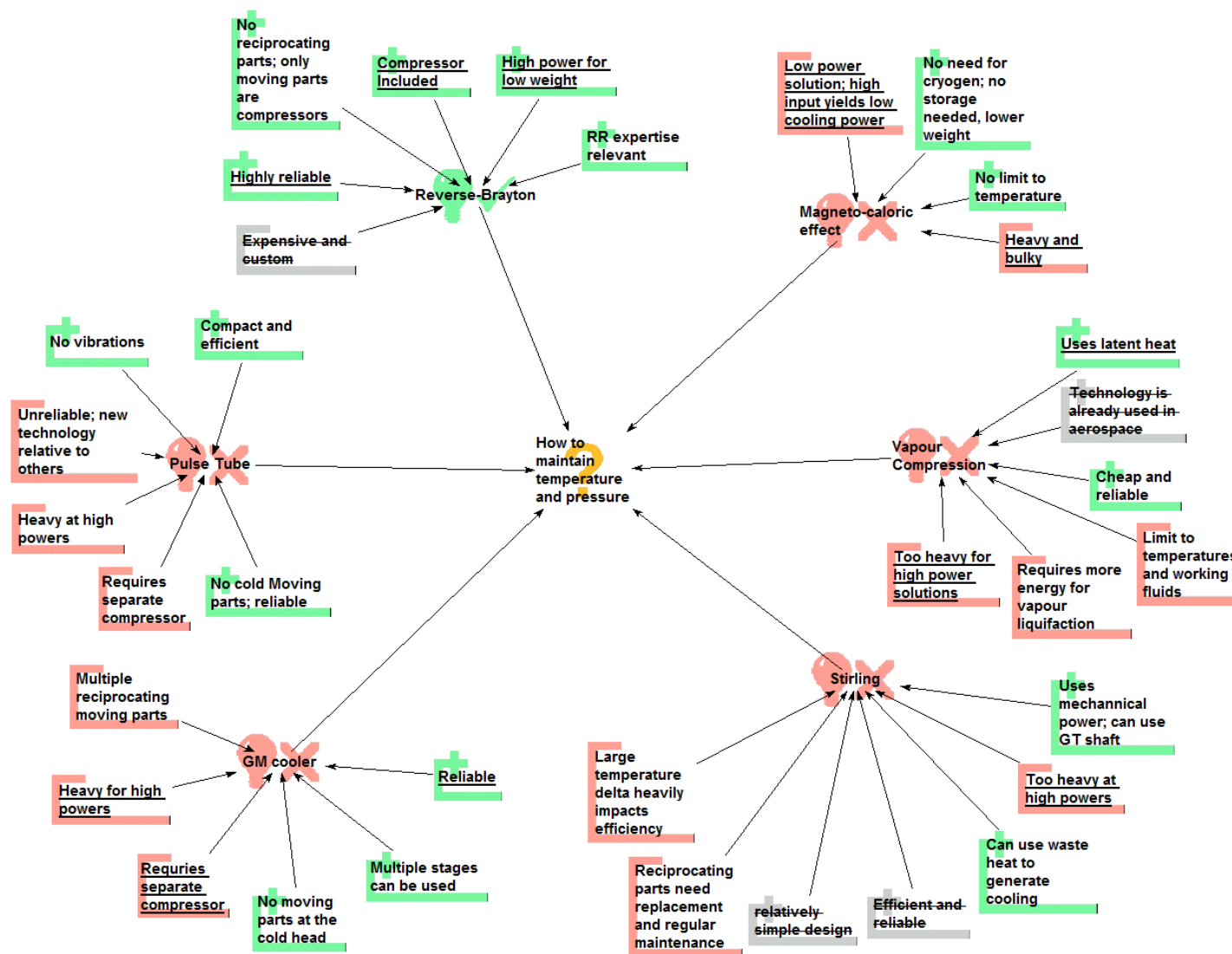


Figure 6-11 – DRED concept rationale for maintain temperature/pressure function

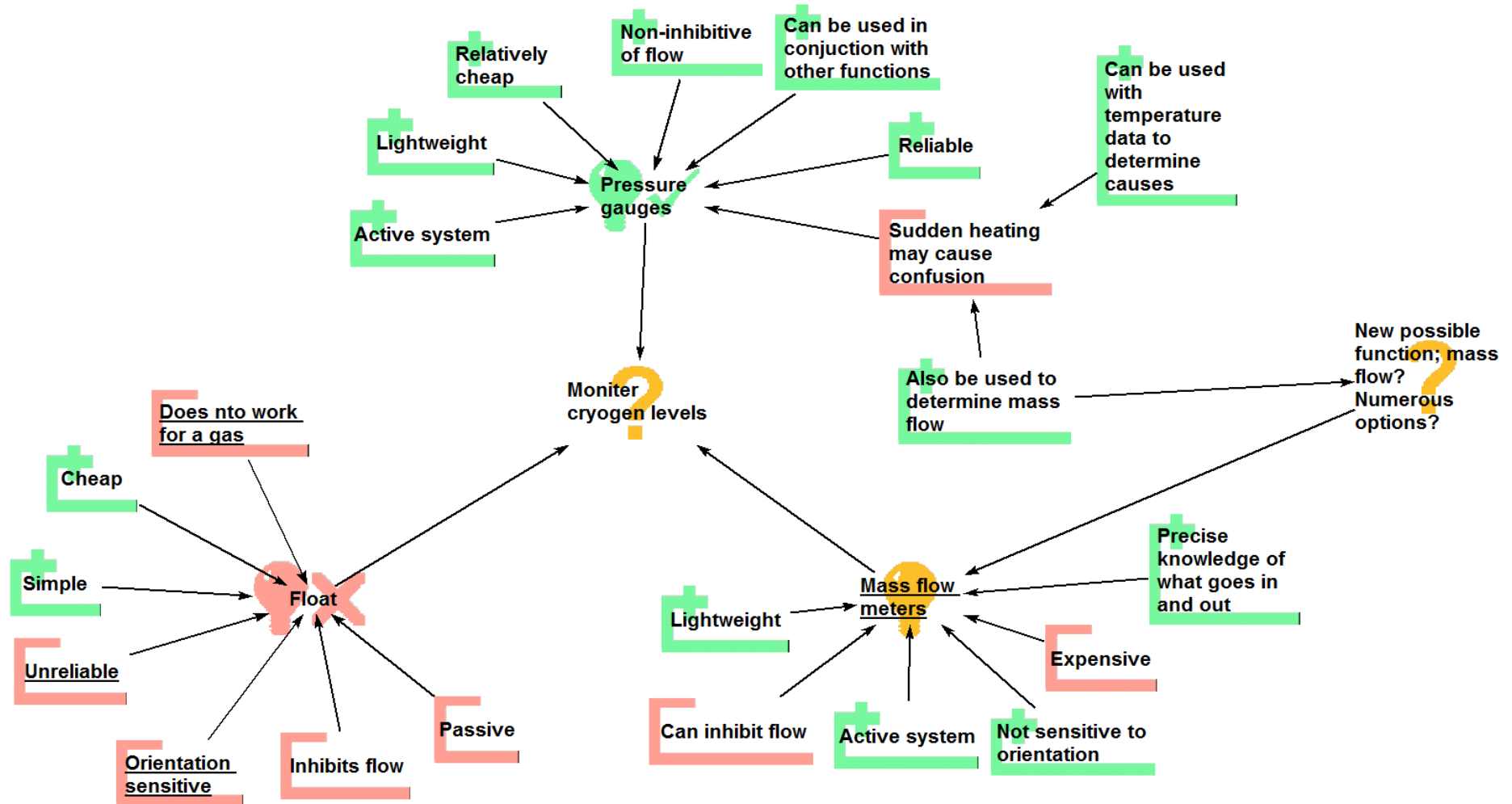


Figure 6-12 – DREd concept rationale for monitor cryogen levels function

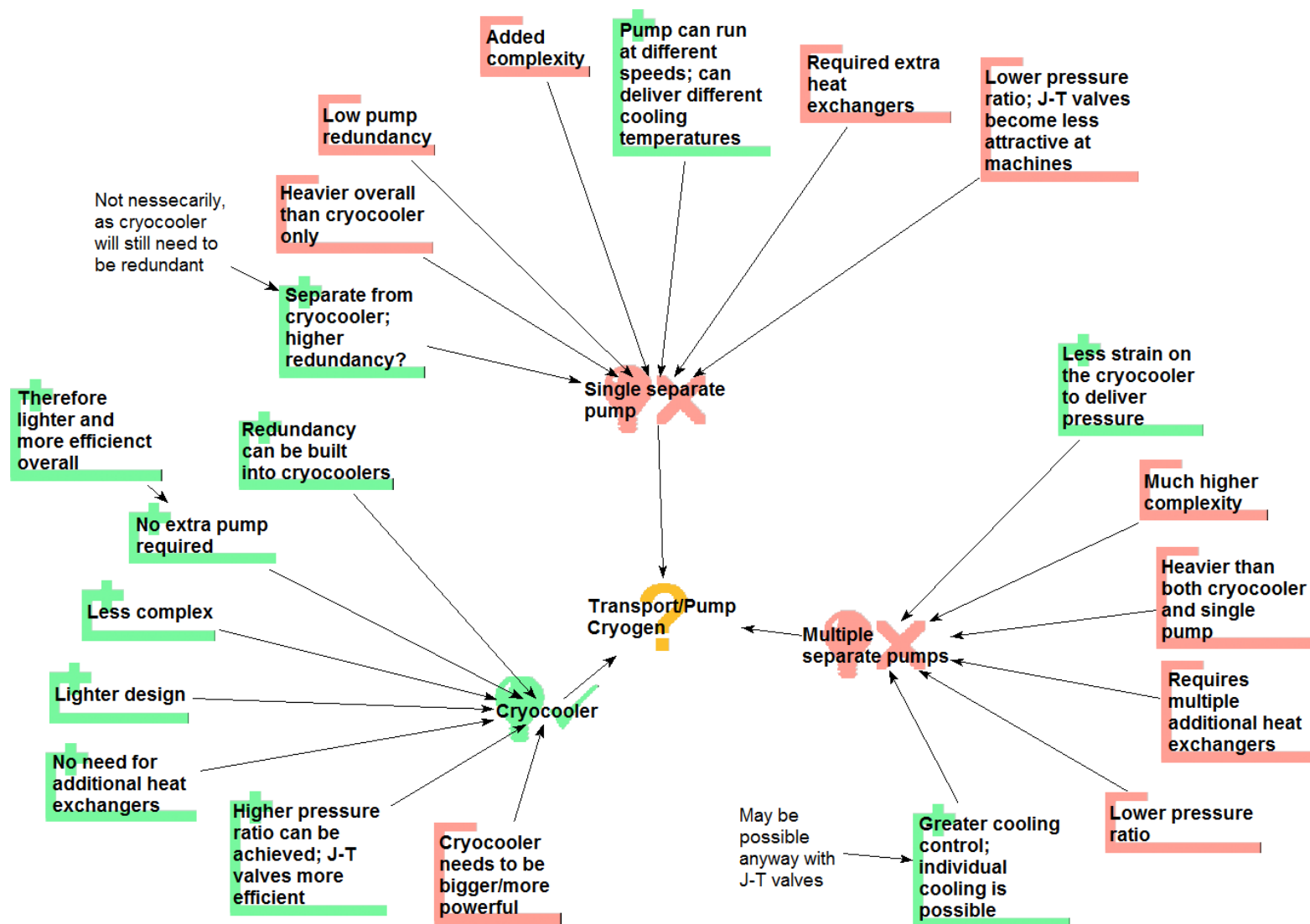


Figure 6-13 – DRED concept rationale for transport/pump cryogen function

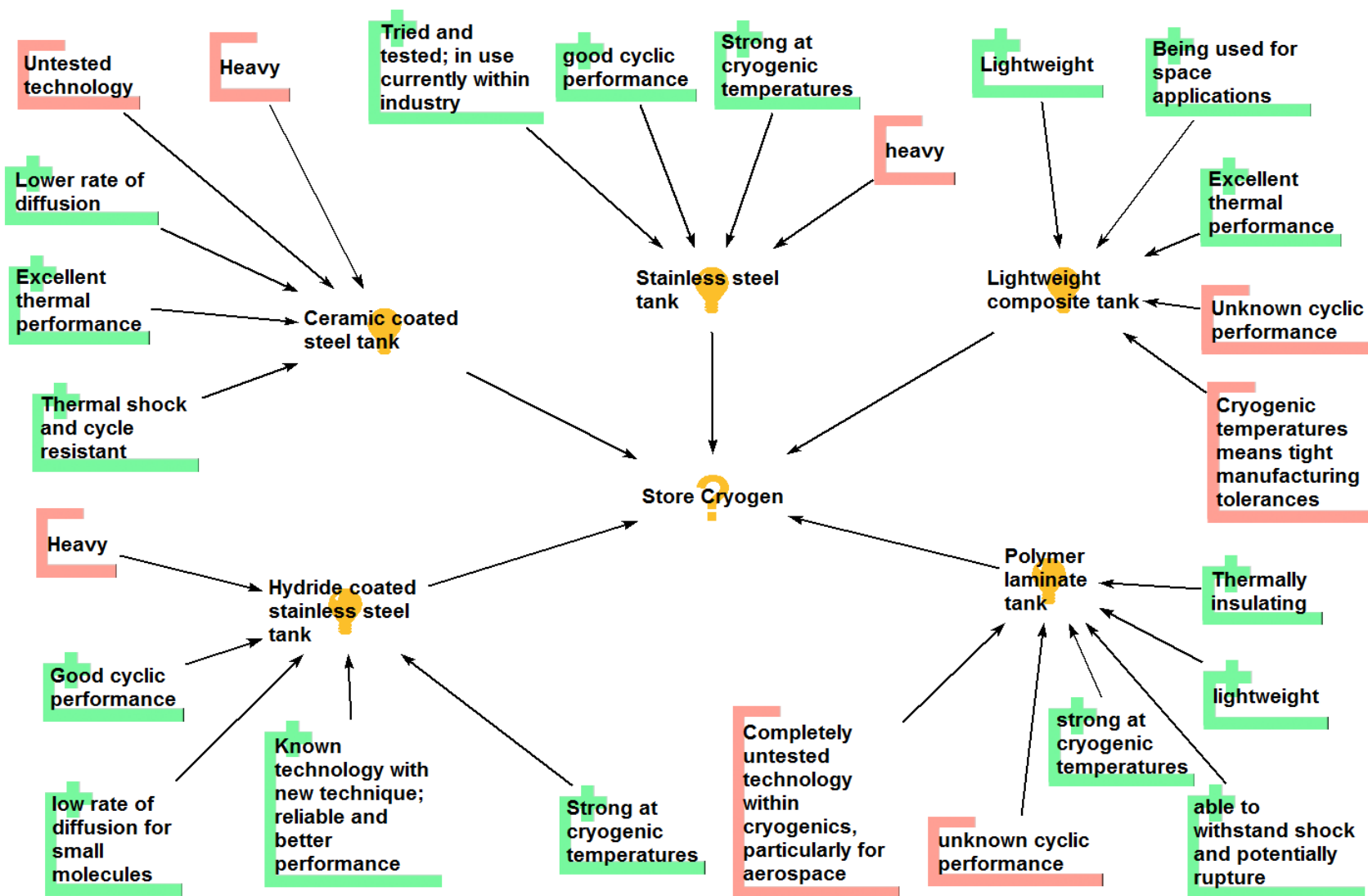


Figure 6-14 – DRED concept rationale for store cryogen function

6.6. Completed FMA and Concept Selection

Figure 6-15 shows the FMA after rationale elimination. There are a number of areas of interest within the diagram. First of these are the excluded functions, Monitor Pressure, Monitor Temperature, and Vent Boil-off. Although the reasons for exclusion have been explained, it is worth noting further this exclusion in broad concept terms. Monitoring cryogenic temperatures and pressures, whilst crucial to the functionality of the overall system, will not significantly affect the efficiency, size, or weight of the final solution. Since the key metrics of success were defined as minimal input power and minimal weight, monitoring the temperature and pressure of any concept is not seen as a barrier to success. Successful methods of pressure and temperature monitoring at cryogenic temperatures exist already, therefore it is considered moot in the wider overall feasibility study.

Vent Boil-off is also omitted in the final FMA. As explained previously, this is for the reason that boil-off may not be present; and the function is solution dependant, therefore the function solution is irrelevant at this stage until an overall cryocooler concept is defined, modelled, and settled upon.

Also worthy of note is that there is a common best solution for both the Detect Quench and Detect Cooling Demands functions in the form of direct temperature measurement. Measurement of the temperatures within the system is considered the fastest way to detect any quench, and the method is not reliant on secondary reactions such as pressure increase or other symptomatic events. It also seems likely to be the best way to detect any cooling demands. Cooling demand is driven by thermal losses in the superconducting system. Increases in temperature can easily predict where local cooling may be required, and can also predict component failure and quench. Knowing the temperatures of each part of the system can allow management of the cooling flow, which can increase the efficiency of the overall solution. Since two functions are performed by the same components, the use of temperature sensors in both cases is obvious.

The FMA has highlighted the preferred cryocooler concept thermodynamic cycle as the Reverse-Brayton cycle for the Maintain temperature/Pressure function. There are three key reasons the reverse-Brayton cycle was chosen. The first is that it is entirely self-contained. The cycle includes heat exchangers, compressors, and turbines;

hence there is no requirement for separate pumps or compressors, or even for tertiary helium coolant cycles for transport. This means for the Transport/Pump cryogen function, the cryocooler solution can be chosen, saving large amounts of weight and power. The second reason is power density; reverse-Brayton cycle cryocoolers have already been demonstrated in high powers, with multi-kilowatt versions commonplace. All other cryocooler types described are much smaller, and are likely to be heavier and more complex due to the large number of required incidental items for normal operation. Finally, the reverse-Brayton cryocooler has shown itself to be highly reliable, with some examples running for over 50,000 hours without maintenance as mentioned previously in Chapter 3. The reverse-Brayton cycle meets all of the critical criteria in relative terms to other concepts; hence it is the clear choice for numerical modelling.

Conversely to the cryocooler solution, there are three functions that highlight further challenges to concept selection. Each of the Insulate Components, Exchange Heat, and Store Cryogen functions has highlighted five plausible solutions. This result in the FMA means that qualitative analysis alone cannot provide answers to which insulation is best to use or which type of heat exchanger is most appropriate. This result confirms that in order to make those decisions, the numerical model of the cryocooler must first be developed to understand parameter magnitude. Heat exchanger required power, maximum permissible efficiency losses, or maximum permissible heat in-leak for any given mission, are all required to enable further solution elimination.

The concept, a reverse-Brayton cryocooler, must now be modelled in numerical terms. Since there are many options within numerical modelling the reverse-Brayton cycle, a number of models must be developed to explore the options available. Also of critical importance is understanding of the magnitude of the loss likely to be present within the superconducting electrical network. Since no reference networks or machines exist, it is necessary to try to better understand the likely sensitivities within the full superconducting system. The next chapter will follow the work to understand the superconducting parts of the system and the process used to model the loss and understand the relationships between the superconducting machines, superconducting network, and cryogenic cooling system.

Functions	Means									
	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7	Concept 8	Concept 9	Concept 10
Detect cooling demands	Computational calculation	~~Direct measurement of fan rpm~~	Direct Measurement of temperatures	~~Measurement of pilots power demand~~	~~Electrical power measurement~~	~~Efficiency/load calculation~~				
Detect quench	Pressure Sensors	Direct Temperature Measurement	~~Electrical fault detectors~~	~~Direct performance measurement~~						
Insulate components	~~STSE tank foam~~	Aerogels	vacuum jacketed cryostat	combined polymer aerogel, MLI, and vacuum	2-stage shielded cooling	~~Multiple stage shielded cooling~~	Multi-layered insulation			
Monitor Pressure	Pitot tubes	strain guages	Manometers	piezoelectric detection	Magnetic detection	Capacitive detection	Optical detection	Thermal conductivity (RTD's)	Flow measurement through transporter	
Monitor temperature	Thermocouples	Platinum RTD's	Superconducting magnetic field detection	Silicon diodes	thermistors					
Maintain temp/press	Reverse Brayton	~~GM cold head and compressor~~	~~PT cold head and compressor~~	~~Magneto caloric effect with closed loop helium circuit (Compressor)~~	~~Stirling cooler~~	~~Vapour-compression~~				
Exchange heat	~~Cross corrugated HX~~	Tubular microchannel HX	Shell and tube HX	~~Plate and shell HX~~	Plate fin HX	~~Pillow-plated HX~~	~~Spiral HX~~	~~Coiled HX~~	Phase change HX	Diffusion bonded block heat exchanger
Transport/pump cryogen	Cryocooler	~~separate singular pump~~	~~Separate multiple pumps~~							
Monitor cryogen levels	Pressure gauges	Mass flow meters	~~Float~~							
Store cryogen	Stainless steel tank	ceramic coated steel tank	Lightweight composite tank	Hydride coated stainless steel tank	Polymer laminate tank					
Vent boil-off	Active valves	Passive valves	Directive boil-off system	Rupture disks						

Figure 6-15 – Final FMA diagram showing eliminated solution (red wording, crossed), accepted viable solutions (Dark green) and plausible solutions (light green)

6.7. Discussion

The key outcome for this chapter is a robust decision on which cryocooler concept is best suited to the overall aim of the thesis using an adapted version of the Rolls-Royce systems engineering that is better optimized for complex, conceptual problems. This chapter follows two key themes that are inherently linked by the need to find a solution to the problem of aerospace high-power cryogenic cooling. The first theme of systems engineering and Rolls-Royce systems process adaptation provides the path to follow to allow a concept to be generated. The second theme shows the concept selection taking place, with the overall outcome of the chapter a final concept that can be numerically modelled. The highly conceptual nature of this project raises a number of challenges, particularly when considering the number of unknowns regarding the pass or fail criteria of any concept. This means that vague statements such as 'As good as possible' must be applied to requirements. A number of realisations have taken place during this chapter that warrant further discussion.

Firstly, it is noted that the current Rolls-Royce systems engineering methodology is long and arduous, regardless of whether a conceptual design or later-stage design challenge is being undertaken. Since it is difficult to ascertain which, if any, methods should be dropped or modified, the research has had to adopt a skeletal approach to the Rolls-Royce systems engineering process. The success of this approach is evident; had the Rolls-Royce systems engineering methods been followed either fully, without adaptation or simplification, the requirements and stakeholder involvement would have been significantly more complex. Furthermore, the added complexity would have yielded little additional insight into which concept would be most suitable for further investigation. Dwelling too heavily on details such as performance metrics in such a conceptual, highly unknown complex challenge can stifle progress. By simplifying the HoQ method and simply identifying the most critical aspects of the system, concept selection can take place at a basic level that allows meaningful numerical analysis. This adaptation has taken place as a result of the typical focus of Rolls-Royce's systems engineering process, which is detailed design products where metrics and the fundamental physics is known.

Also of critical importance is the likelihood of change. Should the Rolls-Royce systems engineering methods be thoroughly conducted at an early stage with so many unknowns, there is a strong likelihood that key aspects of the requirements could change. Particularly of concern is the superconducting network. At the time of writing, even basic architectures have not yet been defined for any solution, making the decision of cryogenic cooling concepts difficult. Orders of magnitude of loss are known, however the sensitivity to changes must be explored more urgently than establishing a final concept. By investigating the sensitivity of the interrelated superconducting and cryogenic systems, the impact of certain design decisions can be identified. This plays a crucial role in further analysis and design decision-making, since basic physical models can be constructed that will be representative of how these system will interact. Since the concept itself is subject to change, knowing the impact of design choices will prove invaluable in saving time and cost.

There are some concerns that must be considered when modifying such a process. The primary concern is that reducing the rigor of the Rolls-Royce systems process in favour of simplification may have undesirable consequences for the robustness of the design process. Although this would be highly likely when considering a normal design exercise, the conceptual and highly unknown nature of the challenge regarding cryogenics for this application means there is no appetite to go into great detail. Keeping genericity at this stage is crucial. Going into detail with projects such as this that are in a constant state of decision-making flux is likely to lead to moot analysis and redundant information. Detail is crucial when a design concept is identified; however before that can take place, basic knowledge must be established.

Crucial to moving forward from the requirements analysis stage is the concept selection phase. This chapter has identified a preferred thermodynamic cycle, the reverse-Brayton, through purely qualitative means. The identification of the reverse-Brayton cycle as the most likely best candidate means that numerical modelling can take place, and also supports the conclusion reached by the NASA N3-X project (Felder *et al*, 2011). Furthermore, with numerical modelling, the conclusions reached by the qualitative analysis can be scrutinised; the most critical components can be identified by varying the input parameters within the models, and the highlighted critical functions can be tested for validity.

Key learning outcomes for the concept selection are as follows:

- The reverse-Brayton cycle has been identified as the most likely best candidate for future concepts.
- Sensory equipment and boil-off management concepts can be side-lined in terms of concept selection at this stage. The main reason for this is relevance to the critical performance metrics of weight and input power required.
- The heat exchanger selection must be given consideration at a later date, with comparison of types likely to form further study.
- Temperature detection should be considered a crucial technology for implementation of any concept. The qualitative analysis and concept selection shows that multiple functions can be satisfied through robust temperature measurement.
- The method of storing the cryogen, whilst not critical, may influence the concept in terms of weight significantly, especially if a cryogenic fuel is used.
- Options for insulation are numerous, and the performance of insulation, while crucial to success, is not considered a problem due to the maturity of the technology.

These assumptions are important to validate, and the validation was performed by discussion with the cryogenics expert previously interviewed during Chapter 3. The interview consisted of an informal conversation with questions relating to the assumptions made during this chapter. The expert independently confirmed that the assumptions would not significantly impact the design decisions, and the expert agreed that the decisions taken to-date are rational and reasonable for a project at such an early conceptual stage. This chapter satisfies the first part of the fourth objective of the thesis, to generate options for cryogenic cooling systems and to assess them qualitatively.

Chapter 7. Superconducting Network Modelling

7.1. Introduction

A critical constituent of the overall aircraft level propulsion system is the superconducting power distribution network. Understanding the network sensitivities with respect to changes in various parameters is crucial to understanding the full propulsion system and cryogenic cooling system quantitative requirements. Exact values are impossible to establish regarding thermal losses and weight of the network; however knowing the system sensitivities will highlight where future research is most valuably concentrated.

This chapter focuses on three constituents; electrical machines, cables, and power electronics. Their basic architectural principles within the context of electrical propulsion are shown in Figure 7-1 for two example networks, AC/AC and AC/DC/AC. These two networks represent the basic architecture principles behind the DEAP aircraft and N3-X aircraft concepts respectively.

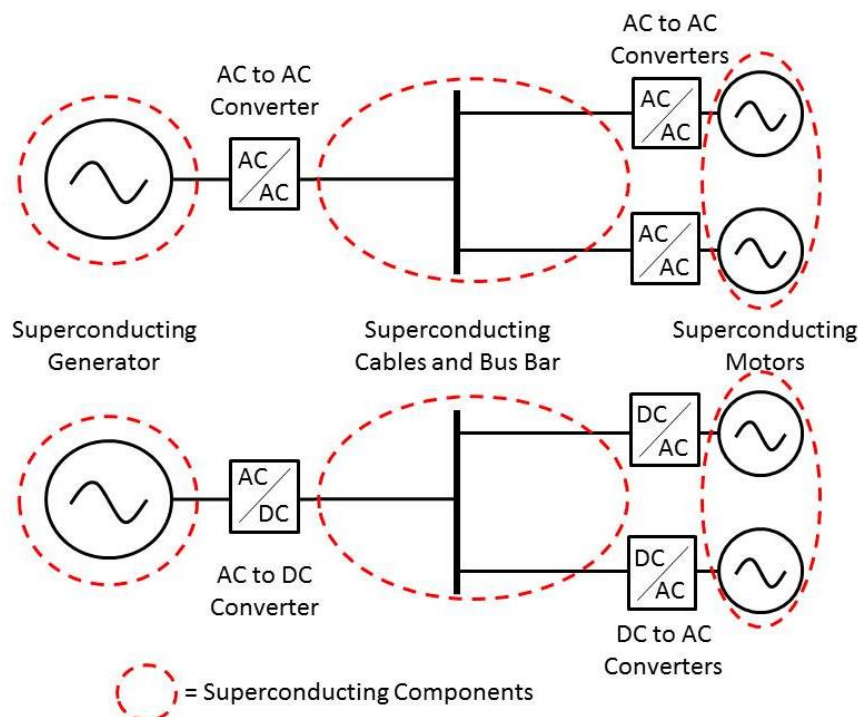


Figure 7-1 – Example schematic power flow networks for AC/AC (Top) and AC/DC/AC (Bottom)

Modelling a superconducting network can be difficult; superconducting components do not follow traditional laws such as Ohm's law. This can simply be proved using an example DC cable; under DC conditions, superconductors have zero resistance. Ohm's law states:

$$V = IR$$

When considering that $R = 0$ for superconducting components, Ohm's law immediately becomes impossible to implement. This makes conventional electrical models impossible to apply, particularly when considering the many other relationships that build upon Ohm's Law. Models were constructed using Simulink within Matlab. Then a step-by-step model generation and validation procedure is derived and undertaken, described in Figure 7-2.

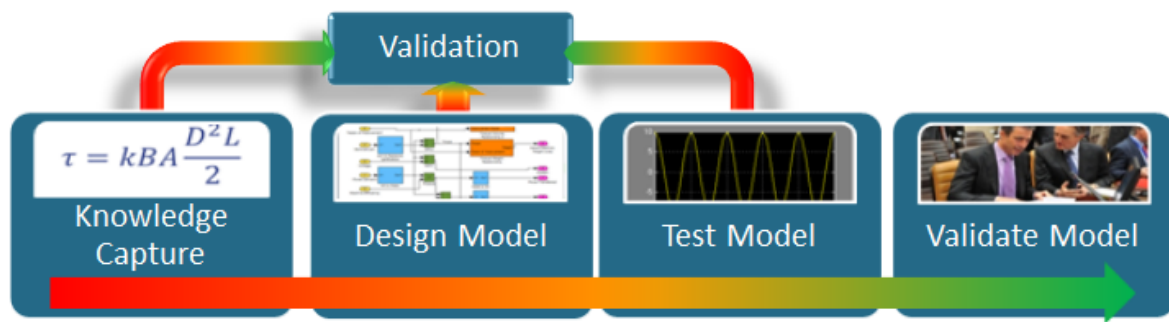


Figure 7-2 – Model validation strategy

The procedure described in Figure 7-2 is crucial to success of the modelling aspect of this project. Since no known examples of fully superconducting machines or networks exist, a process of incremental validation must take place.

1. **Knowledge Capture** – Equations and relationships must first be established before models can be generated. This is obtained through literature survey and workshops with experts. Once a satisfactory level of component knowledge is obtained that can be applied to superconducting components, experts are then used to validate the knowledge and its applicability within numerical models.
2. **Design Model** – Model design is critical to sensitivity studies. The method used to design each model is to structure the knowledge gained previously and to specify known input parameters and desired output parameters. Input

parameters are then used in equations gained through knowledge capture and missing input parameters are identified. In areas of complete unknowns, particularly with mass estimation, surveys are performed to establish relationships between known similarities between conventional and superconducting components. Once a full set of equations and input parameters is gained, the model is run to highlight potential errors. Validation of the model design is through using conventional component data and checking the output results with known parameters.

3. **Test Model** – When models are completed, they are tested rigorously by running a range of input parameter values and recording the output results. Experts then validate the results through firstly checking whether input and output parameters match expected proportional or inversely-proportional relationships, and finally by checking the output values themselves, to see if the results are as expected based on their experience.
4. **Validate Model** – This final step of overall validation is intended to validate the process of model development. The knowledge capture, model design, and testing of the model is scrutinised by experts in both the respective component being modelled and in modelling as a discipline. This ensures that the approach taken is valid to the best of expert knowledge, and that the numbers generated can be relied upon to a first-order degree without returning to the models at a later date.

This method of both constant validation and final product and process validation provides the best chance of accuracy of modelling superconducting networks. At the time of writing, superconducting networks are non-existent and the basic physical principles behind superconducting materials are still poorly understood in the context of complex applications. By using the methods derived in this chapter, network-level assessment can take place with respect to mass and efficiency, without which design and configuration concept viability would be difficult to ascertain in any case.

The discussion part of this chapter comments on the strengths and weaknesses encountered during the modelling, with some basic recommendations given for future superconducting component research based on the modelling outcomes.

7.2. Superconducting Machines

Superconducting machine examples already exist in partial form whereby either the stator or rotor is superconducting. Previous examples have reached into the multi-Megawatt range, and are being investigated for a range of applications from power generation to marine propulsion (Gamble *et al*, 2006). Fully superconducting machines at the time of writing do not yet exist. In order to model superconducting machines, the first step is to list the input parameters that are known. Once initial input parameters are known, conventional machine equations and relationships must be collated. When a set of governing equations is established, the missing input parameters can be established, and the barriers to mass estimation identified. Mass estimation initially takes place by looking at mass-affecting parameters, particularly geometric and electrical parametric relationships such as torque and radii of the machine parts. Once mass estimation can be performed reliably, the model is tested for possible errors by looking at the known relationships in parameters for machines of either conventional or superconducting topology.

The overall goal of developing a mass-sensitive superconducting machine model is to understand the sensitivity of machine output parameters with cooling input parameters when considering the propulsion network architecture in full. Knowing the approximate mass and efficiency sensitivity of machines is invaluable for targeting future research and for concentrating innovation thinking during subsequent research.

7.2.1. Machine Topology

Electrical machines, whether conventional or superconducting come in two forms; generators and motors. Topologically, they are exactly the same, in that they contain all of the same components. The main components of a generic electrical machine are as follows:

- **Rotor** – The rotor is the electrically active rotating part of the machine. The rotor consists of electrical windings or a bulk magnetic material that can be charged or controlled to exert a magnetic field around it. The rotor is spun by the stator, transferring power to the shaft through varying the magnetic fields around its circumference and opposing the magnetic fields generated by the stator. Design challenges for a superconducting rotor include cooling; a

rotating cryogen feed is required for normal operation. Previous rotor designs have included a thermosiphon design that allows flow and return of cryogen despite the rotating design (Aguayo *et al*, 2011).

- **Stator** – The stator is the active static part of the machine that generates a magnetic field through windings around the outside of the rotor. The opposing magnetic field in the rotor causes a rotating motion through Lorentz forces generated by the passing stator current. The stator is typically made from a ferromagnetic material in order to better support magnetic flux lines throughout the machine that are generated by the active electrical parts.
- **Back-Iron/Enviroscreen** – This component is common on high-power machines where efficiency is crucial. The enviroscreen consists typically of a bulk of iron around the stator, responsible for carrying magnetic flux lines around the outside of the stator. The iron (or other ferromagnetic material) provides a more efficient medium for flux to be carried than air. This reduces the losses in flux lines around the outside of the stator and allows more force per unit current to be passed through the stator. Furthermore, the enviroscreen prevents electromagnetic interference to other devices, a critical consideration within aerospace applications.
- **Shaft** – The shaft is responsible for transferring power from the rotor to the propulsor or gas turbine for motors and generators respectively. Within superconducting applications, the shaft must be both electrically and thermally insulating; this presents a significant design challenge when considering the likely torque transfer requirements of aerospace applications.
- **Bearings** – Bearing are responsible for holding the shaft and rotor in place with the stator. Significant mechanical loads are expected when considering multi-Megawatt sized machines paired with propulsors and gas turbines, along with high rpm values. Furthermore to the problem is thermal isolation; bearings in a cold space will generate significant heat.

These parts are common to both conventional and superconducting machines; however superconducting machines require two more components:

- **Shaft Seal** – The shaft in a superconducting machine will require shielding from ambient temperatures. Heat in-leak poses a unique challenge when

considering cryogenics; even small leaks of thermal energy to the machine can raise the temperature of the superconductor past its critical temperature. Shaft sealing is likely to be highly complex; the machine may require vacuum sealing, rotate at high rpm ($>10,000$ rpm), and protect the superconducting parts from heat in-leak.

- **Cryostat** – The cryostat is used to thermally shield the superconducting components from ambient temperature. Cryostats are typically layers of insulation such as MLI, supplemented with a vacuum shielding system, with the inner and outer layers usually made from stainless steel. A cryostat will be critical to the success of any practical superconducting machine design, as it will likely be the heaviest part of the system (as it essentially wraps all other parts, it will geometrically be the largest by material volume).

Figure 7-3 shows an example superconducting machine topology with all parts to scale, generated through work on Project DEAP (Wright *et al*, 2015). The diagram shows the enviroscreen outside of the cryostat as one option; the other option is to enclose it within the cryostat.

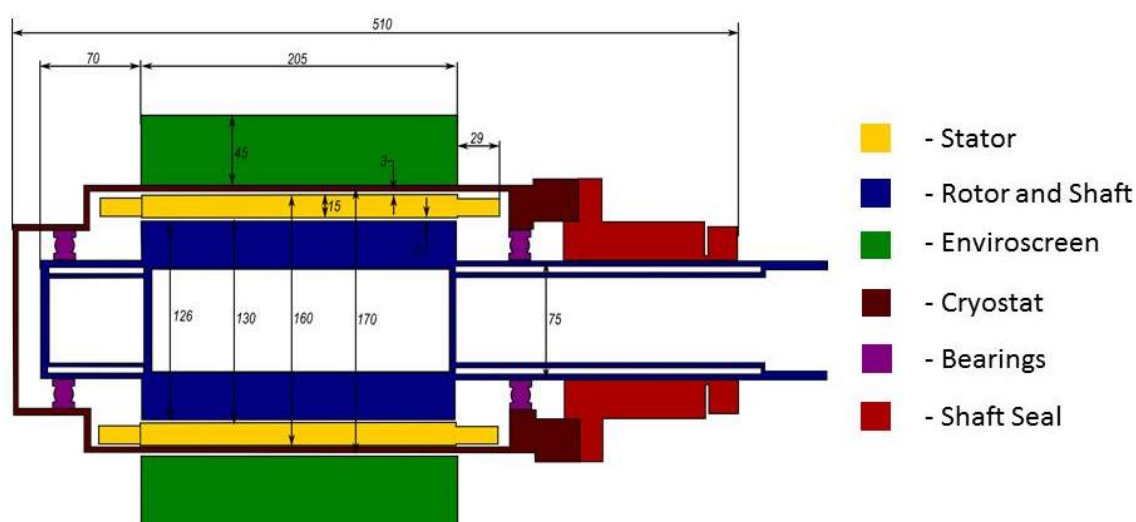


Figure 7-3 – The major parts of a superconducting machine (Wright *et al*, 2015)

Loss mechanisms in an electrical machine were discussed in the first of three workshops held with two electrical machine experts. The losses in an electrical machine were described as follows, with a summary of losses and mechanisms given in Table 7-1:

- **Bearing Losses** – Losses in the bearings are mostly generated in the form of friction, with vibration and noise making up a small portion. Bearing location within superconducting machines is likely to be outside of the machine cryostat, and as a result the bearings will not require active cooling. Magnetic bearings are also a possibility; since large currents and electrical powers are available, it may be advantageous to use active magnetic suspended bearings since losses are largely negligible (<0.1% of total losses).
- **Windage Losses** – Windage loss occurs within the air gap of an electrical machine between the rotor and stator. Windage losses are not an issue within superconducting machines for the reason that the rotor must operate inside a vacuum. When considering the issue of cryostats, separately sealing the rotor and stator in individual cryostats will be unmanageable. Varying magnetic fields will induce currents within the rotor and stator cryostats causing early cyclic fatigue, the air gap between rotor and stator will increase (decreasing the magnetic interaction efficiency between rotor and stator), and the power per unit mass will decrease since two separate cryostats are required instead of one for the whole machine. Therefore windage losses can be ignored.
- **Eddy Losses** – Eddy loss occurs in the iron parts of the machine as the varying magnetic fields induce EMF in the iron. These losses are primarily expressed in thermal energy. Therefore these are of primary concern for future machine designers. Previous work by Pei *et al*, 2013, has shown that iron losses increase progressively as the temperature of the iron reduces; for a wire loss of 0.5 W per metre in all other loss mechanisms, a 2 kW loss was recorded in the iron parts of the rig. Mitigation has been suggested in the form of using iron-doped epoxy resin or other composite material for traditionally iron-made parts. Despite this, Eddy currents will likely make up the majority of the thermal loss within machines, with previous work showing efficiency of a fully superconducting machine is likely to be >99.9% based on first-generation wire testing.
- **Hysteresis Losses** – These losses occur as the iron or ferromagnetic parts of the machine experience reversal in magnetic direction, i.e. when the northern pole of the material reverse to south. Hysteresis losses are a function of the machine rpm, or the electrical frequency. These losses also

manifest themselves as thermal energy, hence they are important considerations. Since it is unlikely that iron will be present in the machine, hysteresis losses are unlikely to be an issue with superconducting machines; experts within the workshop have confirmed this assumption.

- **Resistive Losses** – Resistive losses are present within the stator, and typically make up a large portion of the loss in conventional machines due to losses in the copper used in windings. However, superconducting components will decrease the losses within any conductive parts of the machine; therefore resistive losses can be ignored.
- **Enviroscreen Losses** – Losses in the enviroscreen are likely to be high, since the losses increase with field strength. There are developments being considered for the future however; an enviroscreen made of iron present a significant problem within aerospace applications. Iron is typically heavy, and to have a thick surrounding case of iron around the outside of the machine will significantly increase the weight (and critically, the cross sectional area) of any machine concept. Furthermore, losses may be induced within the enviroscreen (if contained within the cryostat) that prohibit the use of cryogenics due to sheer loss magnitude. Should the enviroscreen be located outside of the cryostat, the rapidly varying, high-power magnetic fields will effectively induce currents within the cryostat, making thermal and electrical insulation a significant challenge.

Loss Type	Primary Energy Loss Mechanism	% of Total Losses in Superconducting Machine	Relevant to Superconducting Machines?
Windage Losses	Drag, Shock at high Mach numbers	<0.1%	No
Bearing Losses	Friction/Thermal, Noise, Vibration	10-15%	No (outside of cryostat)
Eddy Losses	Thermal, Rotor Mechanical Drag	30-40%	Yes
Hysteresis Losses	Thermal	<1%	No
Resistive Losses	Thermal	<1%	No
Enviroscreen Losses	Thermal	30-40%	Yes

Table 7-1 – Superconducting machine loss types, mechanisms, suggested percentage share, and relevance to cryogenics

7.2.2. Input and Output Parameters and Relationships

Once machine topology is understood, the input and output parameters used in modelling must be stated, along with the relationships that link them. Despite their differences in operation, motors and generators will have the same input and output parameters. This can be proved given the example of power and speed; for motors, the fan propulsor must have a design rpm and propulsive power. Generators are sized according to the gas turbine optimum shaft speed and power; therefore the models for both motors and generators will contain power and speed as basic input parameters. These can be related to produce a torque value, which can be used to size the machine.

This method of input parametric gathering and relating to outputs ensures that missing inputs are found and missing relationships are identified and generated. Table 7-2 shows the inputs, outputs, and equations used within the model. Electrical equations used were taken from known electrical machine information sources (Bumby, 1983). Machine physical dimensions and mass estimation was derived for this study and is explained in the next section.

Input Parameters	Transfer Functions	Output Parameters
Machine Rotational Speed (rad/s)(ω)	$\tau = \frac{P}{\omega}$	Torque (Nm)(τ)
Machine Power (W)(P)	$I_p = \frac{\pi A D_s}{2n}$	Phase Current (A)(I_p)
Winding Factor (K_{w1})	$V_p = \sqrt{3} \cdot I_p \cos \varphi$	Phase Voltage (V)(V_p)
Electric Loading (A/m ²)(A)	$TRV = \frac{\tau}{V_r} = \frac{\pi}{\sqrt{2}} \cdot k_{\omega 1} \cdot BA$	Active Machine Length (m)(L)
Flux Density (T) (B)	$\frac{\tau}{TRV} = D_r^2 L = V_r$	Active Machine Diameter (m)(D_s)
Number of Turns (n)	$R_{LD} = \frac{L}{D_r}$	Active Machine Volume (m ³)(V_m)
Power Factor ($\cos \psi$)	$D_s = \sqrt[3]{R_{LD} D_r^2 L} = 2R_s$	Active Machine Weight (kg)(M_m)
Machine Efficiency (%) (η)	$R_s = \frac{\frac{(1.144R_s)}{(1 - \bar{F}_s)} + 83.03}{1 + \frac{(1.144\bar{F}_s)}{(1 - \bar{F}_s)}} = \frac{D_s}{2}$	Output Frequency (Hz)(f)
Mean Stator Radius Factor ($\bar{F}_s$)	$V_m = \frac{\pi D_s^2 L}{4}$	Cryocooler Thermal Load (W)(Q_m)
Pairs of Poles (p)	$M_m = \rho_a V_m$	Power Density (W/kg)(P_p)
Length/Diameter Rotor Ratio (R_{LD})	$f = \frac{\omega p}{60}$	
Active Density (kg/m ³)(ρ_a)	$Q_m = P \left(1 - \frac{\eta}{100} \right)$	Torque Density (Nm/kg)(τ_p)
	$P_p = \frac{P}{M_t}$	
Cryostat Weight Portion (%) (m_{cstat})	$\tau_p = \frac{\tau}{M_t}$	Total Machine Weight (kg)(M_t)
	$M_t = M_m \left(\frac{m_{cstat}}{100} + 1 \right)$	

Table 7-2 – Superconducting machine model inputs, outputs, and transfer functions

7.2.3. Machine Dimension and Mass Estimation

In order to estimate the mass and dimensions of a superconducting machine, a geometric approach must be taken as there are no known examples of fully superconducting machines to compare to. By estimating the dimensions of a superconducting machine, the mass can also be estimated by breaking down the constituent parts of the machine and assessing the relative mass portions. It is known that electrical machines, regardless of the type of conductor, scale proportionally in size with torque based on electrical machine surveys. This can be easily proved when considering an arbitrary example machine of a given electrical current at two different rotor radii:

$$\text{Let: } R_1 = 1 \text{ m}; \quad R_2 = 2 \text{ m}; \quad L = 2 \text{ m}$$

$$\text{Let: Current, } I = 20 \text{ A}; \quad \text{Magnetic field, } B = 1 \text{ T}$$

Using the force exerted by a single conductor using the Lorentz force law:

$$F = IlB$$

Where F is the force exerted, l is the length of the conductor, and B is the magnetic field strength. This now becomes a simple moment analysis. It is clear that applying the same force at two different moment lengths will result in a difference in torque:

$$F = 20 \times 2 \times 1 = 40 \text{ N}$$

$$\tau = FR$$

$$\tau_1 = 40 \times 1 = 40 \text{ Nm}; \quad \tau_2 = 40 \times 2 = 80 \text{ Nm}$$

Furthermore, machine size is also linked to slower designs by the relationship:

$$\tau = \frac{P}{\omega}$$

As torque increases for a given machine power, speed must decrease. In order to estimate a machines size, the electrical and performance requirements can be used through knowing how machine size is affected by other parameters.

To estimate a superconducting machines mass, the machine must be broken down into two parts; the active parts and the inactive (cryostat) parts. Firstly, the rotor volume is found using the torque per unit volume method (Dorrell *et al*, 2011). Once this is known, a variable must be introduced in order to continue; the length-diameter ratio must be defined. It was found during studies of active length vs active diameter (L/D) for conventional machines that the ratio is typically between 0.1 and 1.5, as shown in Figure 7-4. There is seemingly no correlation between the machine volume and the L/D ratio for examples surveyed. The graph does however illustrate the range of known L/D ratios for conventional machines. It is not expected that for a superconducting machine the ratio will vary significantly. The key factor in dimensional change from conventional to superconducting machines is cooling and

insulation, which will be present throughout all parts of the active machine; hence the ratio will remain the same.

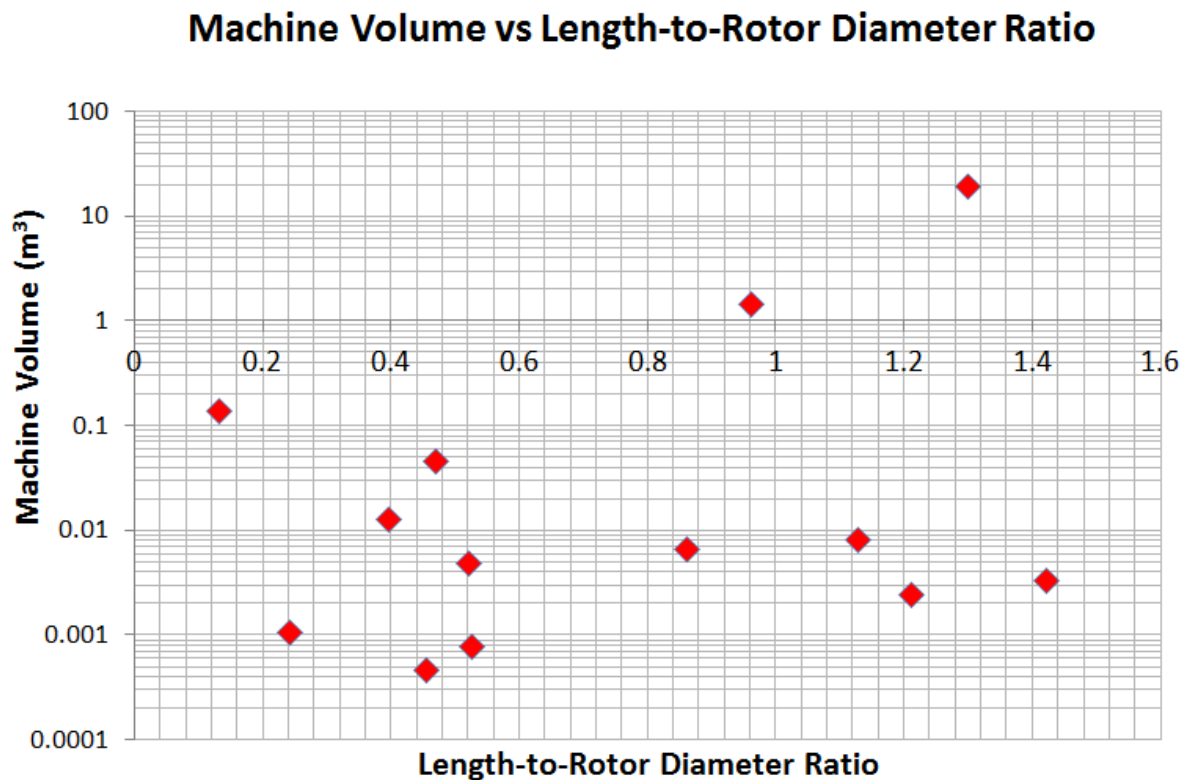


Figure 7-4 – Survey of conventional machines for active length to active outer diameter ratios against volumes

Using an L/D ratio, both the length of the machine and diameter of the rotor can be determined. To determine the outer diameter of the active part of the machine, another survey was employed, looking at both known partially superconducting machines and conventional machines. A relationship (shown in Figure 7-5) was found to exist between the rotor outer diameter and stator outer diameter in all cases. Figure 7-5 shows the clear correlation between machine rotor and stator diameters. Two trend lines were used to generate a rule, one linear log rule and one power log rule. The linear rule was shown to be marginally better when considering the regression analysis, with an R^2 value of 0.9891 as opposed to the power log rule of 0.9887. Figure 7-5 illustrates three partially superconducting machine examples where the dimensions are known. In each case, the superconducting machines stator is larger for a given rotor diameter. This is likely attributable to the partial mature of the superconducting machine; in all three cases, the rotor is

superconducting; hence the rotor must be shielded from heat in-leak from the stator. The necessary cryostat between rotor outer diameter and the stator inner diameter results in an increased stator outer diameter for a given rotor diameter. It is expected that for fully superconducting machines that the relationship shown between conventional machines will be effective.

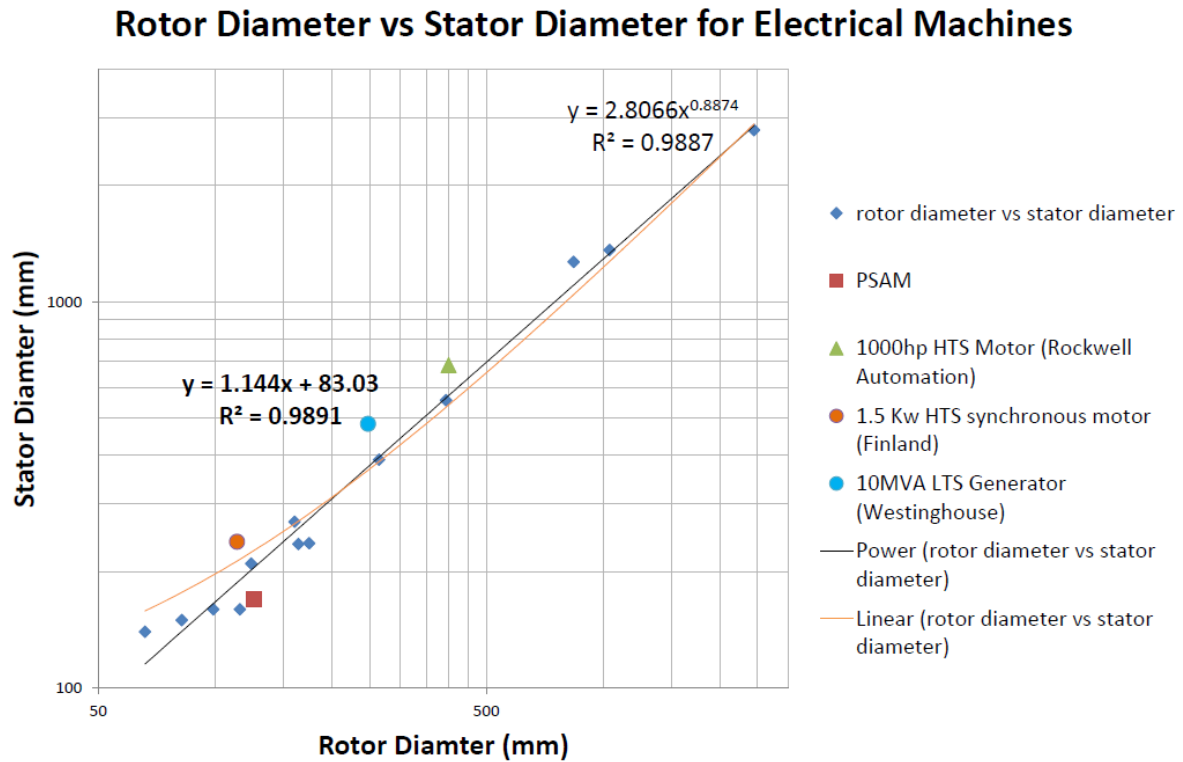


Figure 7-5 – The relationship and curve fit for stator and rotor diameters of known conventional and partially superconducting machines

The machine active dimensions can now be estimated using the generated rule, since the rotor diameter is known from using the TRV method previously outlined. In order to estimate the mass of the active machine portion, an average estimated density is used to multiply with the volume of the machine. The maximum and minimum machine density is taken to be 8000 kg/m³ and 2600 kg/m³ respectively. This reflects the respective densities of both the densest (steel) and least dense (MgB₂) materials found within active machine parts. When considering the likelihood of the use of alternative materials such as epoxy resin, the average machine density is likely to fall significantly, since less iron or steel can be used. For modelling purposes, it is reasonable to assume a density of 4000 kg/m³ for active parts of the machine for this early stage conceptual study.

Since superconducting machines require thermal shielding to operate, the overall machine mass must also be calculated that includes the active parts of the machine as well as the cryostat. During discussions with a cryogenics industry expert, it was noted that cryostats can be made extremely lightweight. Cost is the largest affecting factor; the more a project is likely to spend on a cryostat, the more lightweight it can be made. When pressed to give a figure for the cryostat weight portion as a percentage of the component being cooled, a range of between 10% and 50% of the active parts was suggested. Since the application being considered is aviation-centric, it is assumed that the cost is less of a concern than performance. Furthermore, the likely aviation mass addition range could be between 10% and 20, with a likely average added mass of 15%. This average added mass is incorporated into the machine model.

There is a limitation with this method however; the density of the active part of the machine in turn affects the cryostat weight, even when all other parameters such as dimensions remain constant. This consideration must be addressed in subsequent models for future iteration, however for this early stage conceptual design; it is not of primary concern, since the density in this case is not considered a key variable. At this early conceptual stage, basic physical relationships must first be established that enable sensitivity analysis. Exact mass and dimensional figures are likely to vary; however relationships that define sensitivities will remain constant, and are crucial to understanding where to focus future research efforts.

7.2.4. Final Machine Model Overview

The final machine model is shown in Figure 7-7. The constituent parts of the model and its operation processing of inputs to outputs can clearly be seen from the Simulink overview. The model performs as expected, with the relationship shown in Figure 7-6 showing the expected relationship between machine mass and machine power and speed. Figure 7-6 illustrates the sensitivity of the machine mass to power and speed when fixing all other variables. The model assumptions made for the graph were based on expert recommendations and can be found in the appendix.

There are however model limitations in its present form. When considering the primary objective of this research to investigate cryogenic cooling system possibilities, understanding the losses in the wider system is critical to making the

correct early conceptual decisions. Within the developed machine model, the machine efficiency figure is simply multiplied by the overall machine power level to give an assumed thermal loss. This method does not accurately portray the loss sensitivity to key aspects, such as machine speed and current. It is expected that machine speed will impact the losses proportionally, since the ac loss experienced will increase.

Another key limitation is the electrical aspects of the machine model. Since the machine is topologically undefined at this stage in the research, any number of arbitrary values for parameters such as winding factor, number of turns, and transmission voltage, must be estimated. Phase current determination is a critical aspect of assessing the likely losses in a superconducting machine, particularly when considering the likely magnitude of current within the machine windings. Future modelling recommendations are given in the discussion section of this chapter highlighting where efforts must be concentrated in future machine model iterations.

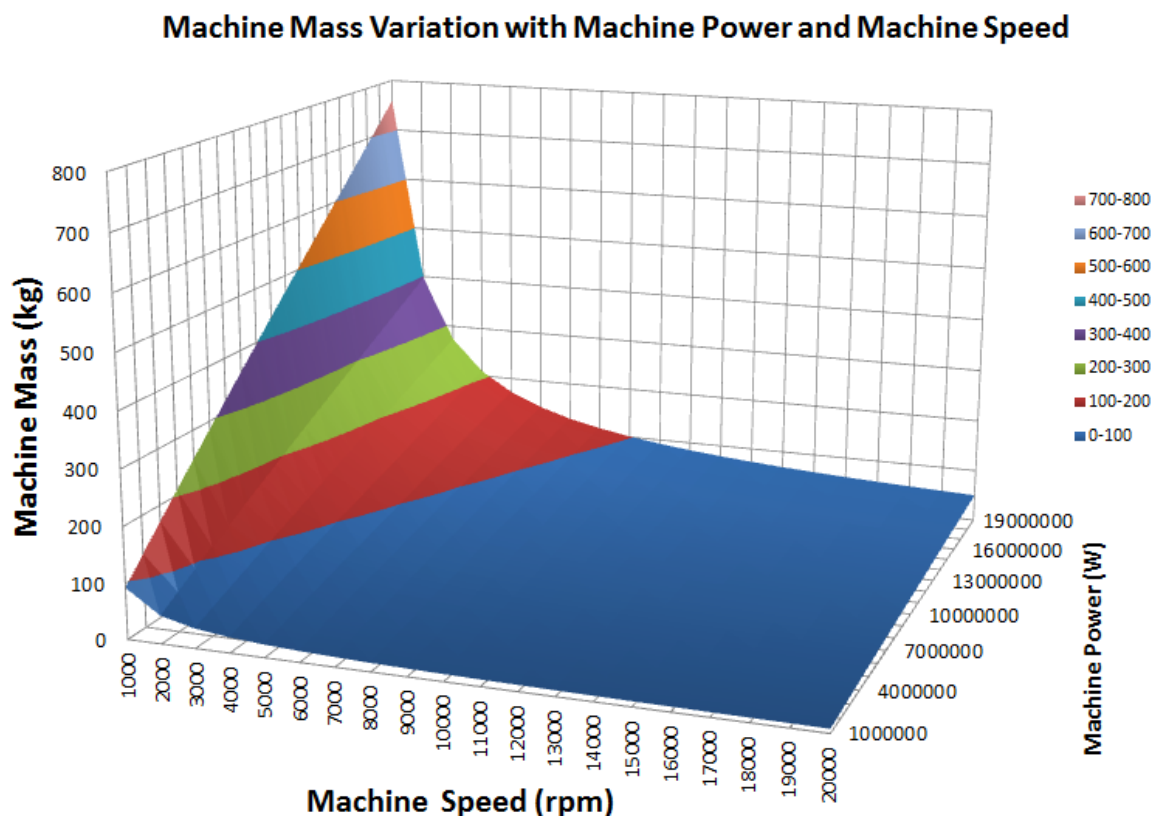


Figure 7-6 – Graph showing the machine model generated variation in machine mass with machine power and machine rpm

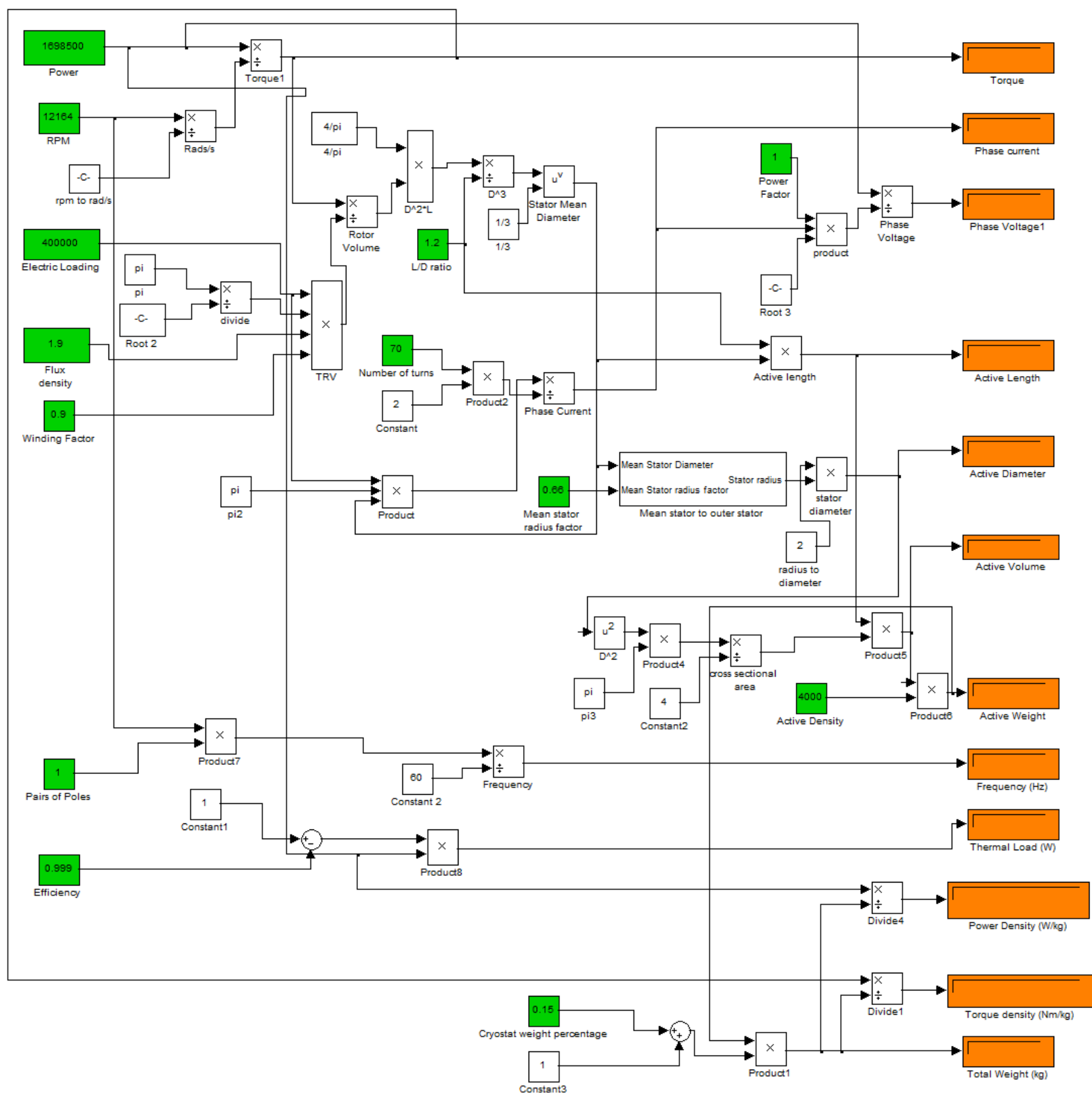


Figure 7-7 – Superconducting machine model overview in Matlab Simulink

7.3. Superconducting Cables

Superconducting cables have long been used and understood for DC applications such as power distribution and MRI scanners. For aviation purposes both AC and DC power distribution networks are being considered and as a result, both AC and DC superconducting cables must be examined in more detail. Since DC losses in superconducting cables are zero, AC cables must be investigated in order to better understand the implications of using ac distribution. This section focuses primarily on AC cable modelling.

When considering cooling demands, AC distribution will increase thermal losses incurred within the distribution system, therefore increasing the required cooling input and likely mass of the cryogenic solution. Despite the prospect of having no losses, DC distribution requires the use of inverters in order to change the AC generator output to DC, and then back to AC at the motors. This inevitably incurs a penalty of efficiency. This design trade-off between AC or DC distribution will impact the outcomes of the cryocooler power input and mass significantly. By understanding which factors within the superconducting component affect the thermal losses, and by understanding the relative sensitivities, early design decisions can be confidently made.

This section initially describes a typical AC superconducting cable topology, along with an overview of the Matlab Simulink model developed by Manchester University for use within DEAP. A brief discussion will follow the model description that recommends future research opportunities that will allow better understanding of the losses within superconducting cables.

7.3.1. Superconducting Cable Topology

Superconducting cables exhibit a number of key differences from conventional cables. Two key constituents are present in any conventional or superconducting cable; conductors and insulation. Both parts are more complex for superconducting technology, and require more design effort. As previously highlighted in Chapter 3, superconducting materials conduct current through the outer surface of the conductor, or London penetration depth. Cable design therefore will benefit from adding many strands of superconductor, to increase the effective surface area of a conductor relative to its length. Multi-strand wires however are more susceptible to

AC losses; magnetic fields are more likely to interact with an increased number of strands, hence a trade-off exists between these two design options. Research is ongoing to identify the optimum scenario for different design cases.

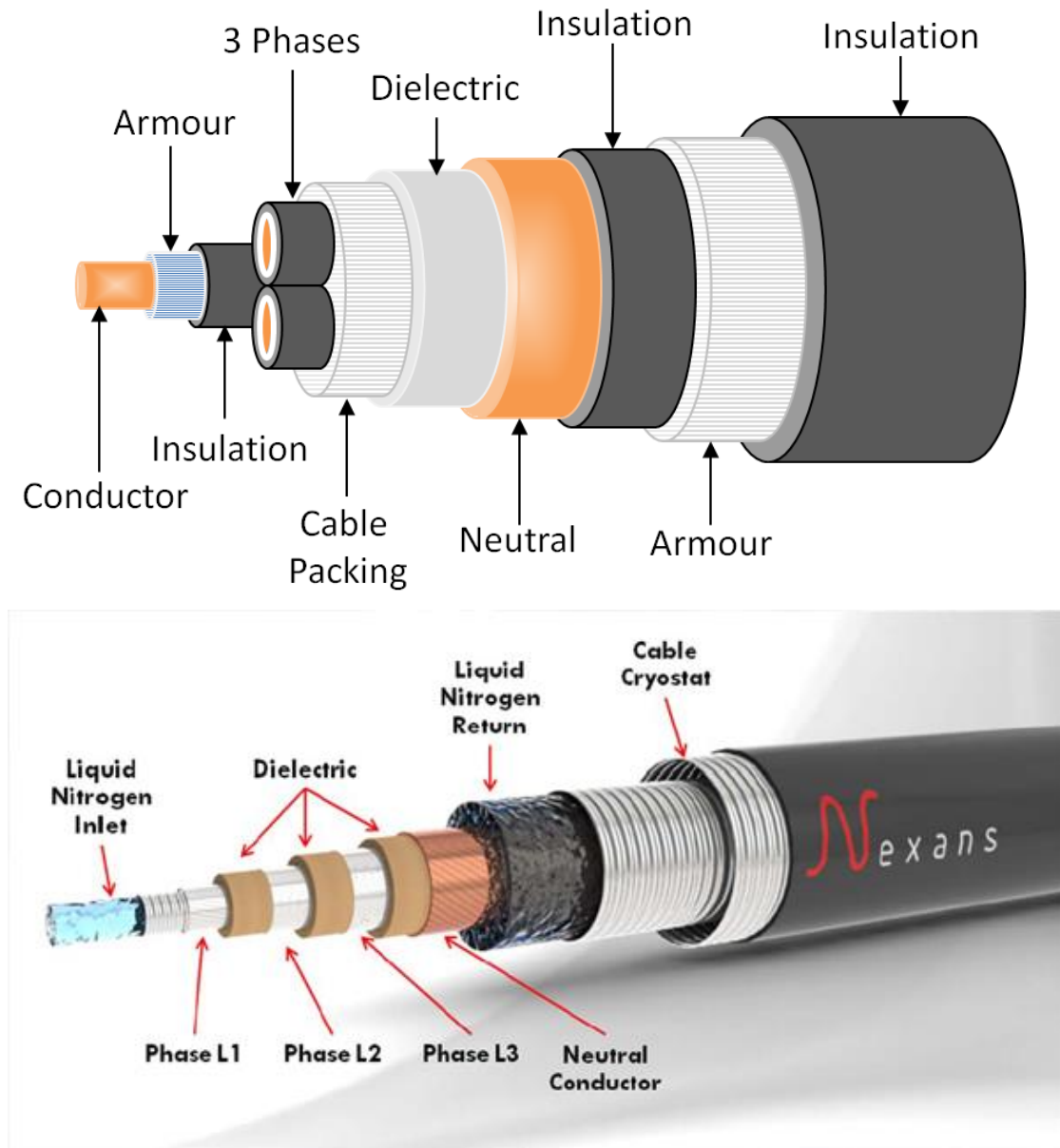


Figure 7-8 – Typical cross-section cutaway view of both conventional (top) and superconducting (bottom) 3-phase AC cable examples (Nexans, 2012).

Figure 7-8 shows typical 3-phase examples of conventional and superconducting AC cables. The key difference between them is thermal insulation. The conventional conductor requires no active cooling, as the copper conductors can operate at ambient temperature normally. Superconducting cables operating at cryogenic temperatures are typically cooled using a fluid coolant, most commonly liquid

nitrogen for HTS cables. The superconducting cable shown in Figure 7-8 shows the flow and return paths for the liquid nitrogen. The lower temperature flow is passed through the centre of the superconductor to allow lower thermal leak from the fluid to the outside environment. The return then shields the neutral conductor from thermal leak through the cryostat. The cryostat itself is made from high-reflective corrugated metal, commonly stainless steel, to allow both flexibility and strength. The space between the inner and outer cryostat walls is evacuated to provide further thermal insulation.

7.3.2. Superconducting Cable Model Overview

The superconducting cable model used in the DEAP study was developed at Manchester University (Smith *et al*, 2015). The model was constructed using known relationships within superconductors and using results obtained during experimental work carried out on strands of MgB_2 . This section will present a model overview including a brief explanation of some of the relationships used and analysis of key parameters of interest to the investigation of thermal loss. The outcome for this section is a greater capability for investigation of the likely interaction between the superconducting machines and cables that might affect the required cooling power of the system.

Two key variables are of interest for the cable that can be merged with the outputs of the machine model to provide sensitivity data; frequency and cable current. Both parameters are machine model outputs, and the interaction between these parameters is likely to show either optimum design points that illustrate trade-offs in design.

Although one of the largest efficiency-affecting parameters is likely to be superconductor operation temperature, it is assumed constant throughout this chapter at 20 K since the relationship is well understood.

The losses for the wire are calculated by using the Norris model for superconducting wires (2) (Perez *et al*, 2003). The model is intended for use within simple superconducting wires, of uniform shape, no outside interference (magnetic or otherwise) and of uniform manufacturability.

$$P_N = \frac{v\mu_0 I_c^2}{2\pi} [(2 - \beta)\beta + 2(1 - \beta) \ln(1 - \beta)] \quad (2)$$

Where v is the frequency, μ_0 is the magnetic permeability ($4\pi \times 10^{-7}$ H/m), I_c is the critical current, and $\beta = I_p/I_c$, where I_p is the peak current.

For the purposes of this model it is assumed that the ac losses are dominant over other forms of loss. As frequency diminishes, it is likely that the ac loss is overcome by other loss mechanisms. This study is looking at typically high-rpm machines; therefore frequency is likely to be high in any case investigated.

Mass of the cable is calculated by combining two methods; assessing the cross-sectional superconductor area multiplied by its length and known density, and by adding a per-metre value of weight for the cable cryostat. Previous examples of real-world superconducting cables show that 3 kg/m is typical for land-based superconducting cables. Subsequent simulations of the pessimistic and optimistic values for cryostat weight will be set to 3 kg/m and 1 kg/m respectively, based on discussions with the aforementioned cryogenics expert.

Figure 7-9 shows the superconducting cable model. The model is divided into two parts, single strand and multi-strand analysis. For the purposes of this project, the single strand is assumed to avoid complication and to investigate the worst-case loss scenario. Single strands as opposed to multi-strand exhibit the highest possible losses for a given cross-sectional area due to the London penetration depth. The model shows the difference in losses and cable mass for both the single and multi-strand versions of the cable. Shown in magenta are the model blocks of interest, the Norris model sections and the total weight calculation section. The additional blocks used within the model contain information on MgB₂ wires that were obtained through experimentation at a test facility at Manchester University. A table of assumptions made that are fixed for the analysis used in this chapters discussion section can be found in the Appendix B of this report.

For the purposes of this chapter, the only parameters investigated will be frequency and current within the machine model, to compliment outputs from the machine model. This allows the first multi-component trade-off identification to take place. The results of the cable model and machine model sensitivity study is shown in the discussion section of this chapter.

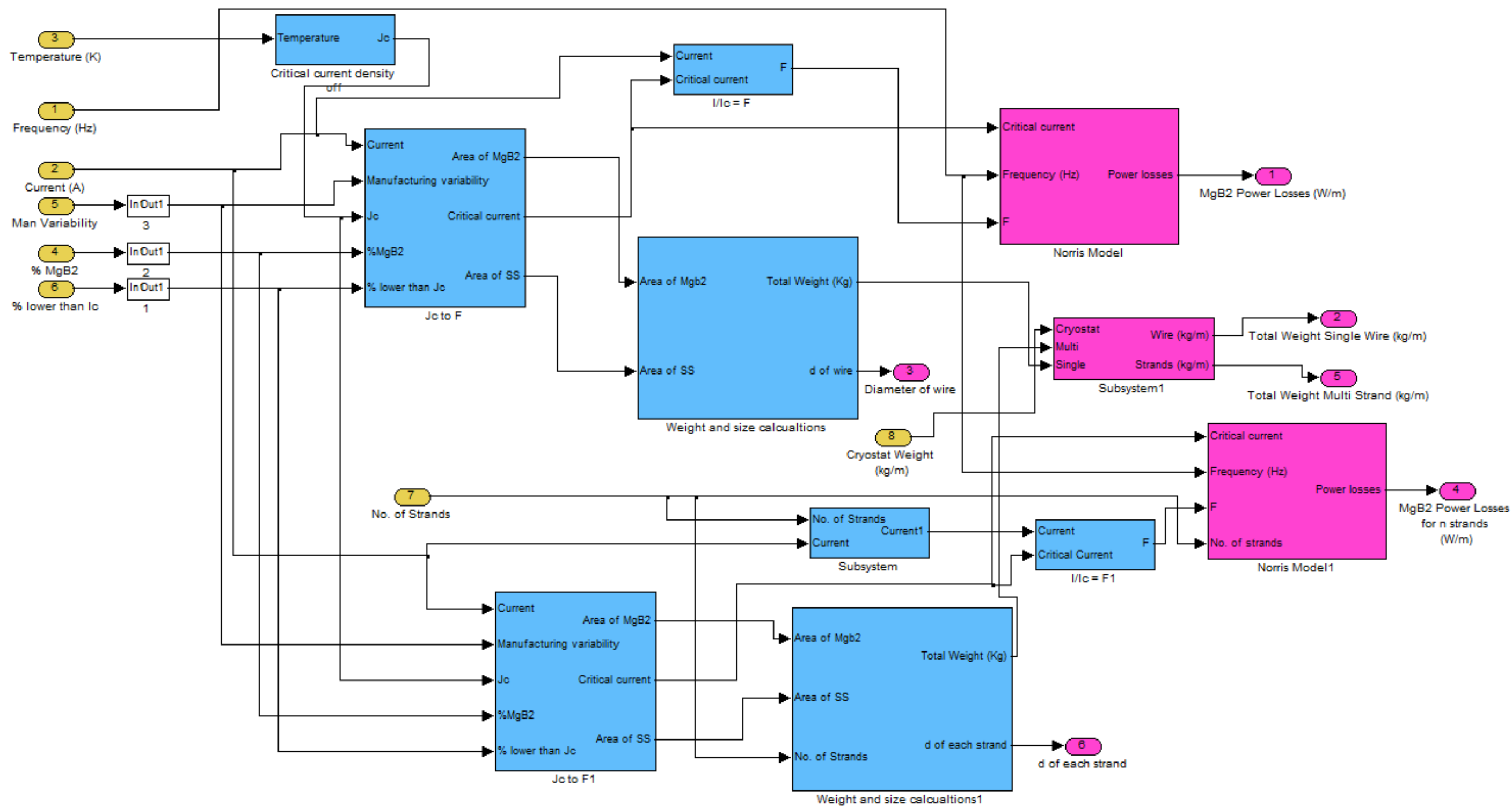


Figure 7-9 – Superconducting cable model overview

7.4. Power Electronics

Power electronics (PE) will be necessary in practical configurations for future superconducting networks. It is not yet known whether the power electronics components themselves will be superconducting or conventional, since superconducting PE does not exist at the time of writing this research thesis. This section describes what types might be present on practical solutions, and why PE is being omitted in modelling for this research.

There are four types that are currently thought to be likely present in practical distributed propulsion electrical networks. These are:

- **Inverters/Rectifiers** – These change electrical current types from ac to dc or vice versa. They will be essential for AC-DC-AC networks, and are likely to be used on board AC-AC-AC networks as a means of limiting losses in cables. Superconducting versions are not currently known to exist, although high-efficiency cryogenic versions are known to exist and exhibit high efficiencies of around 99.8% (Mueller and Mueller, 2000).
- **Fault Current Limiters (FCL)** – FCL are essential within superconducting applications for preventing damage to sensitive components caused by high transient currents. Protecting key electrical components from high short-term currents will be important. Superconducting versions of FCL already exist for power applications; however in their present form at the time of writing, they will require significant size and weight reduction (Pei, Smith, and Barnes, 2015).
- **Switchgear** – Switchgears are used to isolate the different parts of the superconducting system. For AC networks, switchgear is relatively simple as isolation can be performed whilst the current value is zero. DC configurations however are much more challenging; no known DC superconducting switchgear exists. A key challenge for either AC or DC switchgear within superconducting applications is the quality of connection; by nature of superconductivity and its requirement for precise connection, it is likely that significant thermal losses will be present in mechanically operated switchgears. Magnetic switchgears that raise the local resistance may be possible.

A number of reasons lead to the omission of modelling of PE for this research. The primary concern is uncertainty; the type of each PE solution and the uncertainty around electrical network configuration means that the number and nature of individual PE components is unknown. This means that solutions may vary wildly in performance with greatly diminished validation accuracy. Furthermore, any sensitivity observed in a configuration through modelling will be more difficult to attribute to any single component or section, slowing progress in network component interaction understanding. Since the basic types of each component and its constituent parts are presently unknown, PE modelling is deemed too complex and uncertain to pursue in this phase of research. Future modelling must take place as soon as knowledge is gained on likely candidate architectures and preferred PE technology.

7.5. Discussion

The key outcome for this chapter is the development of the world's first expert-validated conceptual superconducting machine sizing tool, and contribution towards a similar superconducting cable tool. Modelling superconducting networks is essential to understanding the relative component sensitivities that are likely to be present in distributed propulsion design solutions. Models of both superconducting machines and superconducting cables have been generated through collaborative efforts between Cranfield University, Rolls-Royce, and Manchester University. Machine models were developed using a combination of existing knowledge of conventional machines and expert advice, while cable models were generated through application of both theoretical and experimental knowledge. Both models were validated through expert opinion, peer review and comparison with known existing components and both were found to be adequately accurate for the purpose of sensitivity analysis and basic configuration design.

The validation approach taken throughout the modelling is crucial to success. Validation at each step of the modelling process ensures that reasonable steps were taken to prevent any relationships between parameters being incorrect or disproportionate in the relative context they are used. In order to accurately assess the sensitivities between machines and cables, and between parameters within the models themselves, the variability must reflect reality to the best of current

knowledge. Since no known examples of fully superconducting machines exist at the time of writing of this thesis, the rigorous validation approach ensures the risk of error is kept sufficiently low. Future modelling work must increasingly incorporate experimental data in order to advance knowledge in the field and to minimise potential errors in the inevitable increasingly complex models.

This discussion section highlights the basic observed sensitivities between the machines and cables that will be of importance to cryogenic cooling system modelling. Machines have already been shown to decrease in size for a given power rating when the speed of the machine is increased. By increasing the machine speed however, the frequency is also increased, leading to increasingly significant losses in the cables. Figure 7-10 shows the impact of frequency increase for increasing current values on the cable power loss for the assumptions outlined in Tables B-1 and B-2 in Appendix B.

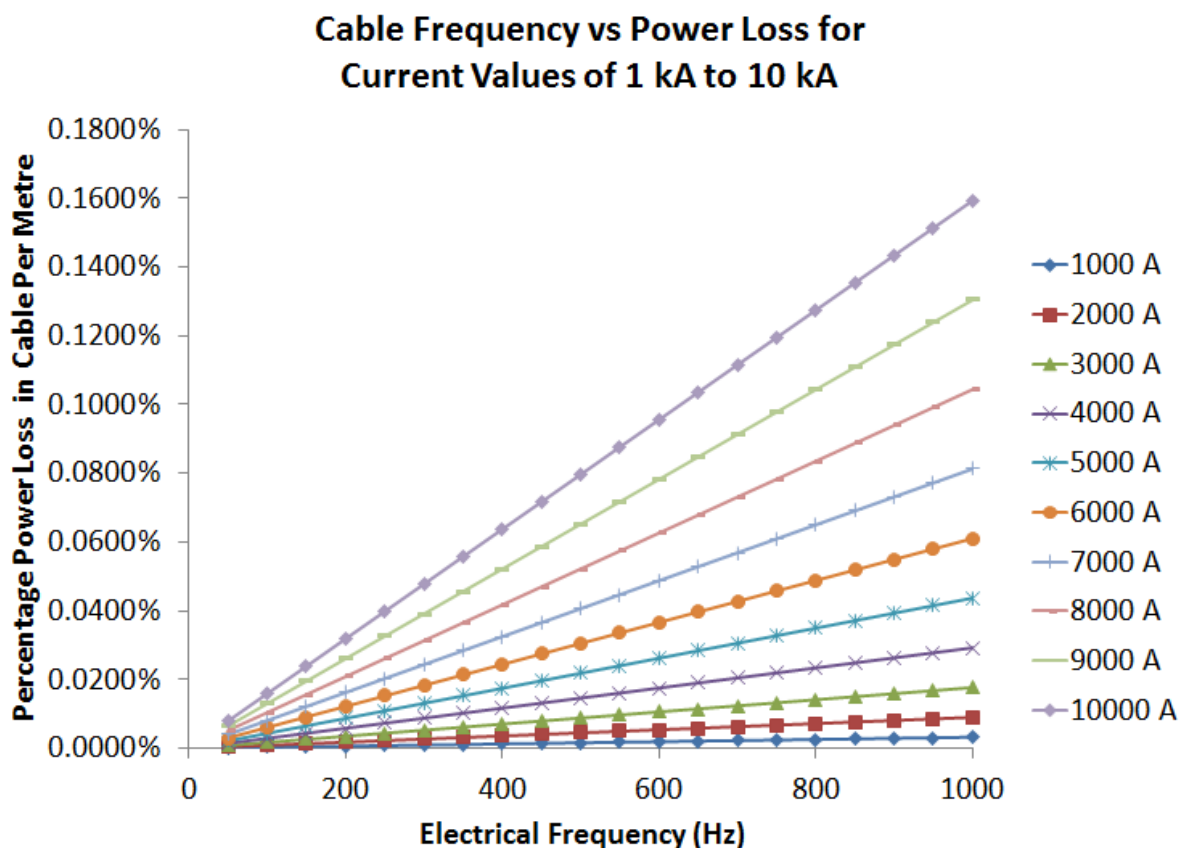


Figure 7-10 – The relationships between different cable current (A) values and frequencies (Hz) on the cable losses

Figure 7-10 shows that by increasing the frequency of a superconducting cable, the percentage losses per metre are increasingly large. Furthermore, as the current is increased, the effect is magnified, leading to proportionally greater losses per metre in the superconducting cable. Since superconducting cables are likely to transport large currents, this relationship cannot be ignored. This trade-off between machines and cables becomes more critical when considering the cryogenic cooling system. When considering the added mass and required power input of the cryocooler, the choice to use faster machines becomes less attractive as losses increase from both an efficiency and mass perspective. Chapter 9 further highlights the impact of this design variable. The machine and cable interaction must also be considered with respect to mass.

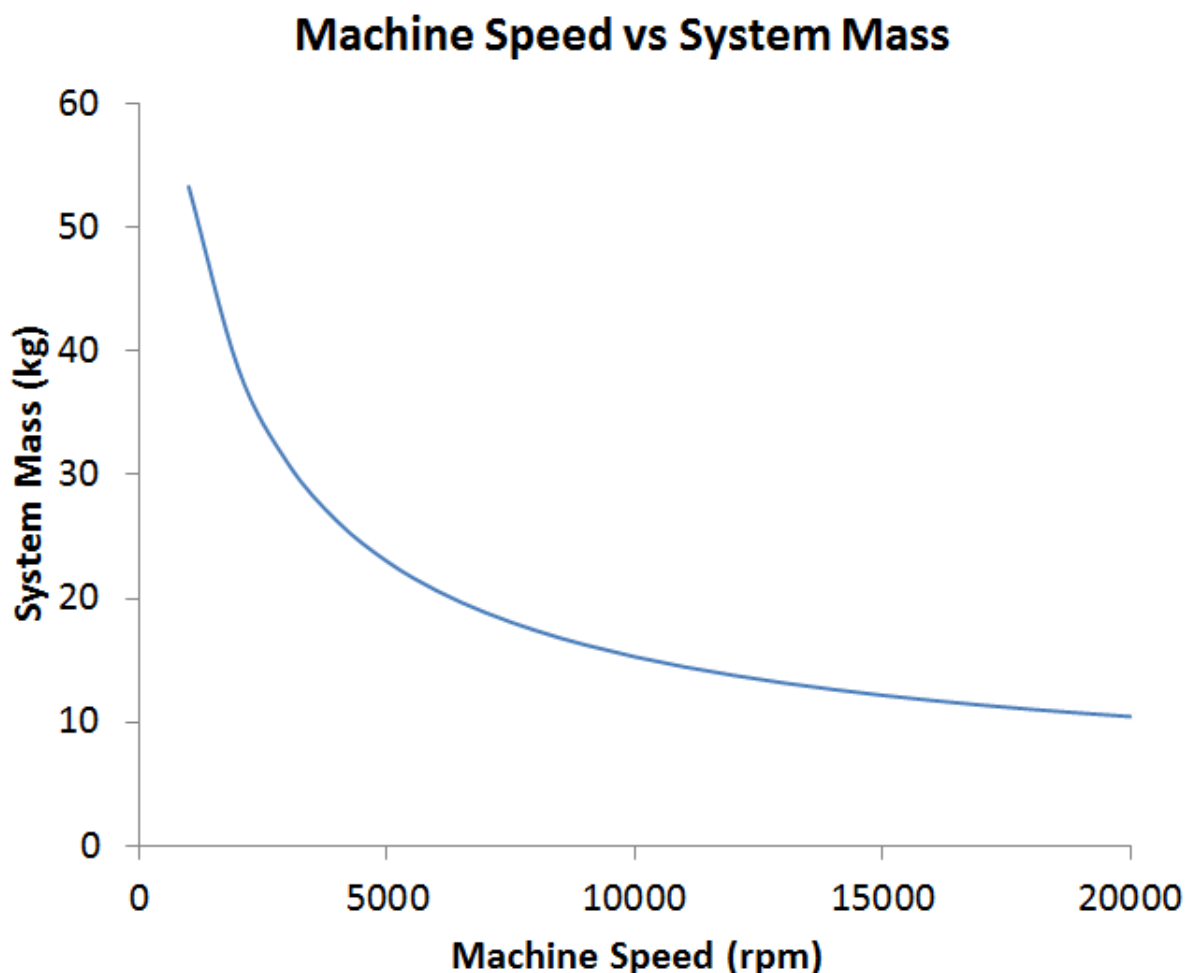


Figure 7-11 – The variation in generator-to-cable system mass against machine speed for assumptions outlined in Tables B-1 and B-2 in Appendix B

Figure 7-11 shows the variation in a generator-to-cable system mass to the machine speed. The values for cable current were fed into the cable model from the machine model, along with the frequency. The relationship in Figure 7-11 suggests that increasing the machine speed delivers diminishing returns in system mass as the rpm of the machine is pushed past 10,000 rpm. Furthermore the variation in cable mass was deemed insignificant to the overall mass change. This can be directly attributed to the large mass difference between the conductive parts of the cable and the cryostat. As the current increases in the conductor, the difference in mass for the cable is negligible, hence Figure 7-11 mainly shows how machine mass varies with machine speed. This leads to the conclusion that cable current can be increased with little mass penalty when considering only the cable; however the system is more sensitive to frequency variations at higher currents, and therefore loss will be increased. Cryocooler modelling must assess whether the increase in loss at higher frequencies is worthwhile when considering the positive impact on the machine mass.

Models were developed that have allowed comparison of two key components in the superconducting network that have enabled some system sensitivities to be observed. Limitations were identified within the machine model that must be addressed during future research. The key limitations are:

- Poor loss prediction – The machine model cannot account for increases in loss as machine speed is increased. This must be better understood in order to allow confident decision making when considering high speed or low speed superconducting machines.
- Poor machine density understanding – The machine density is estimated using known examples of partially superconducting machines, with many aspects of practical design unknown at this early conceptual stage in research. Future research must address this by better understanding the likely materials and configuration that will be present in fully superconducting machines.
- Poor current and voltage prediction – The method used to predict the current and voltage is dependent on other parameters; future machine model iterations should be able to allow voltage to be fixed. Electrical results cannot

be relied upon until superconducting materials are better understood in terms of current and voltage prediction.

- Obscure inputs – Some inputs for the machine model are likely to be decided at a later date, particularly the number of turns and number of machine poles. These design decisions are likely to impact the machine model significantly, however since practical figures are unknown, they are fixed. Future modelling must examine the effect endured on overall machine mass when these are varied.

The cable model developed at Manchester University (Smith *et al*, 2015) has proven to be useful for predicting interactions between the machine and cable regarding losses and mass. The key outcome for the merging of these models is the mapping of sensitivities between system mass, system loss, and what impact some key variables have on these parameters. The next step in this research is to assess how the necessary cryogenic support system will impact these sensitivities. At this stage of the research, the conclusions would support a high-speed machine when considering mass and a low speed machine when considering loss. When cryogenics are added to the mass and loss figures, a more defined overview will develop regarding whole-system design choices. It is highly likely that the conclusions derived from only modelling the electrical system will change significantly when cryogenics are included in power and mass performance analysis.

Chapter 8. Cryogenic Cooling System Modelling

8.1. Introduction

There are numerous ways of achieving cryogenic temperatures, as stated in Chapter 2. This chapter will reiterate the reasons that the reverse-Brayton cycle (RBC) was chosen and state the basic principles behind how they operate and the variants on the basic cycle design. This chapter covers four key areas in development of cryocooler models:

- The basic thermodynamic principles behind RBC cryocoolers;
- The schematic layout and system walkthrough for single and two-stage RBC designs;
- The configuration options and differences between them;
- The models and methods used to develop them.

Modelling results take place in Chapter 9 on design space mapping. The outcomes of this chapter are:

- A detailed understanding as to why the choice was made to use RBC over other cycles.
- Clear understanding of how RBC works in both theoretical and practical principles.
- Detailed overview of how each model block was developed and the assumptions made for modelling.
- Information gained on available alternative configurations and their implications on modelling.

Chapter 9 has detailed the implications for design of cryogenic cooling systems highlighted by modelling work. Furthermore, design solutions can be made through the modelling work in this chapter and their impact on the wider superconducting network performance.

8.2. Reverse-Brayton Cycle Cryocoolers

This section presents the RBC basic concept and a brief recapitulation as to why the cycle was chosen over other designs. The overarching qualitative assumptions are

stated along with reasons given why each was chosen and how they will affect the modelling. The single and double stage RBC basic principles are outlined with diagrams and step-by-step walkthroughs of the processes in each. Finally, other configuration options are outlined through diagrams and discussion, with brief comment on how they may affect both theoretical and practical concepts.

8.2.1. Overview

The RBC has been selected as the most promising thermodynamic concept for cryocooling at high power densities through qualitative methods. Previous studies by NASA have also arrived at the same conclusion within the N3-X project (Felder *et al*, 2011). Before the quantitative aspects of RBC design are described in detail, it is worthwhile summarising the qualitative reasons for selection as the most suitable concept. It is also useful to re-introduce the thermodynamic cycle principles at this stage, such that the proceeding sections can be more easily absorbed without re-reading other chapters of this thesis.

RBC advantages over other methods of refrigeration include:

- High reliability – Examples of RBC cryocoolers have achieved in excess of 50,000 hours of continuous maintenance-free operation. Stirling cycle cryocoolers are also capable of such reliabilities, but not at the same power densities as RBC (Brake and Wiegerinck, 2002).
- Self-contained cycle – Self-containment means all components required are present within the system. Conversely, Gifford-McMahon and Pulse Tube cryocoolers require external compression systems that typically raise the system weight by an order of magnitude.
- Fluid coolant – Use of a fluid coolant negates the need for thermal conduction paths throughout the electrical network. Fluid coolant is capable of faster cooling response to thermal events, shorter cool-down times, and is not impeded should hot-spots along the cooling path become apparent. No other type of cryocooler uses fluid cooling without separate systems that incur additional loss.
- Low weight – RBC cryocoolers possess favourable input-power-to-weight ratios (better than 136 W/kg, Chow *et al*, 2005) and as a result are often the

cryocoolers of choice for space missions. For comparison, Stirling, GM and PT cycles typically exhibit ratios of no more than 226 W/kg for aerospace optimised designs (Ladner, 2011).

These reasons combined show that for this weight-sensitive, high power application, the RBC cryocooler is qualitatively the most suitable thermodynamic cycle to choose.

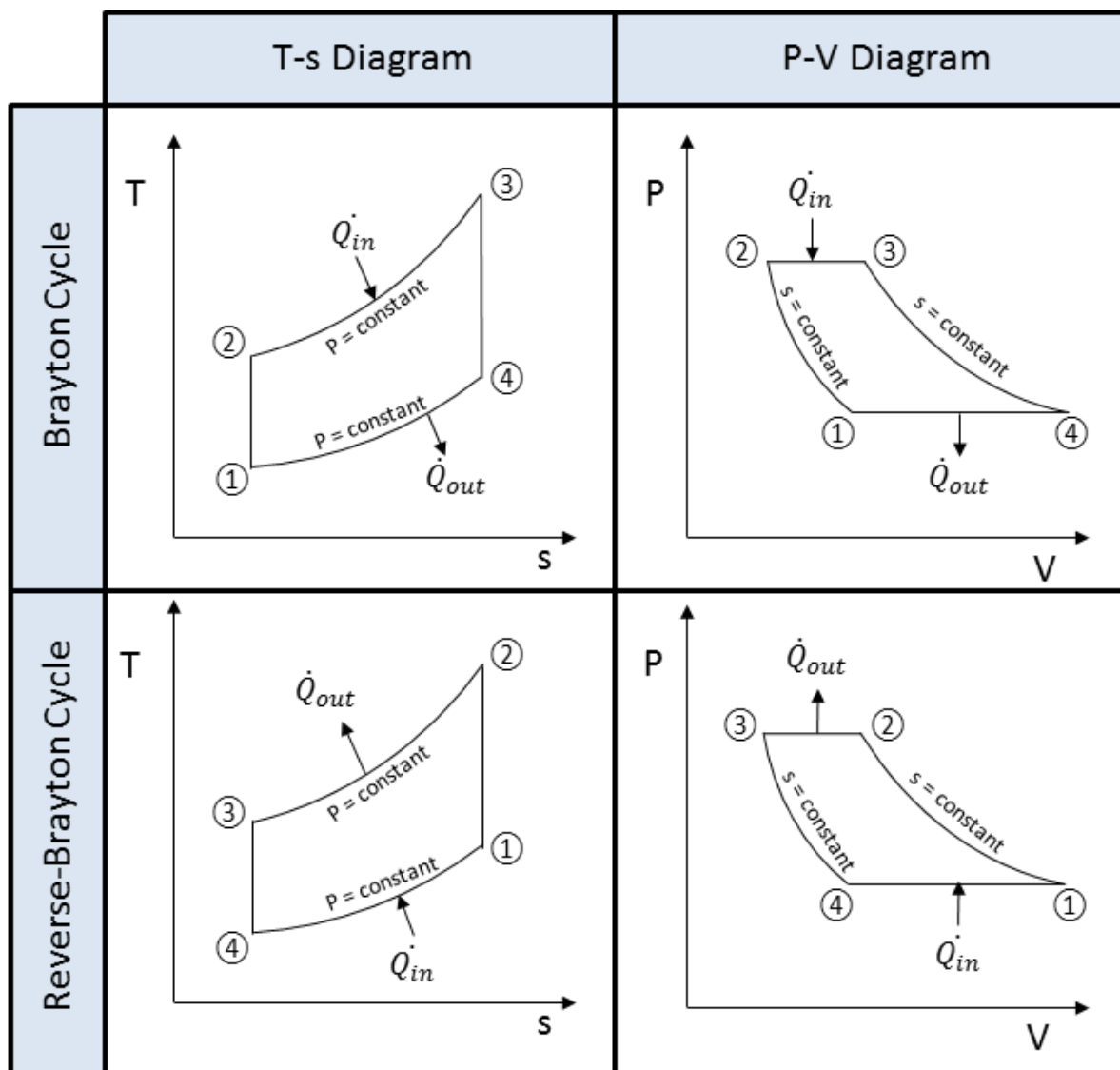


Figure 8-1 – The difference between Brayton and reverse-Brayton cycles for both temperature-entropy (T-S) and pressure-volume (P-V) graphs (note: both cases shown are adiabatic for comparison purposes)

The Brayton and reverse-Brayton thermodynamic cycles are shown in Figure 8-1 for both temperature-entropy (T-S) and pressure-volume (P-V) graphs. The cycle operation can be described as follows, with reference to the original cycle.

Brayton Cycle

1-2: Compression

2-3: Combustion

3-4: Expansion

4-1: Expulsion

Reverse-Brayton Cycle

1-2: Compression

2-3: Heat out

3-4: Expansion

4-1: Heat In

The key difference between the Brayton and reverse-Brayton cycles is purpose. Whilst the Brayton cycle is typically used to produce work or thrust using an open-loop cycle, the reverse-Brayton cycle requires a work input in order to move a closed-loop fluid for low temperatures to be achieved. Despite these fundamental differences, Figure 8-1 highlights how the cycles are similar in nature. At the component level they also require all of the same active components, with some minor differences. Both require a compressor and turbine, however in place of the combustor within the Brayton cycle a heat exchanger is used for the reverse Brayton, with the addition of a cold heat exchanger between the turbine and compressor stages.

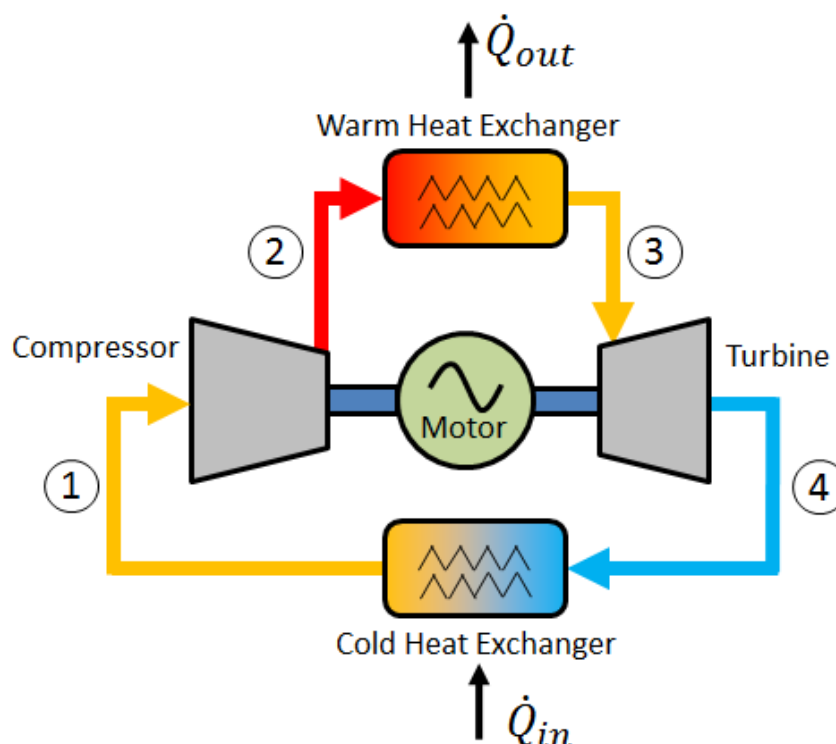


Figure 8-2 – A reverse-Brayton cycle refrigerator showing components and relative thermodynamic process points 1-4 as shown in Figure 8-1

Figure 8-2 shows the reverse-Brayton cycle basic schematic. The operation of the cycle is described as follows:

1. The fluid enters the compressor at ambient temperature, to be compressed and sent to the warm heat exchanger.
2. The fluid has gained temperature and pressure through compression and enters the warm heat exchanger. The warm heat exchanger decreases the fluid temperature.
3. The fluid has now cooled and is ready to enter the turbine. The turbine fulfils two functions; the pressure decrease results in a drop in temperature, and the turbine also recovers work from the fluid through expansion.
4. Once the fluid has been expanded and cooled, it is passed through the target cold area. The heat gained in the cold area brings the fluid back to ambient or near-ambient ready to repeat the cycle.

8.2.2. Assumptions

In order to fairly compare concepts and to yield clear conclusions from simulation data, a number of assumptions must be taken when modelling RBC cryocoolers. Assumptions made in modelling are listed with rationale explaining why the assumption was made. For each assumption made, the effects are considered, and should any issues arise from assumptions made that create significant problems, mitigation is suggested. This approach ensures that assumptions do not adversely affect the credibility or overall validity of the models gained. The assumptions are:

- **No transport losses** – Transport losses refer to losses experienced in the fluid pipes that carry fluid between components. Losses manifest themselves in the form of pressure loss and heat loss/gain, with numerous reasons for each such as compressibility, pipe wall friction, fluid viscosity, and outside heat leak being some of the major reasons. This assumption can be reasonably made because components modelled will be capable of assessing the impact of either thermal change or pressure loss. The impact on overall efficiency is not negligible, particularly for large systems with abundant pipework. However, by negating these losses, critical components can be identified, and should the pressure losses in constant pressure components

(such as the heat exchanger) be significant, subsequent modelling can address the issue by including pipework. Thermal losses are not considered an issue since insulation methods are highly effective, and pipe residency time is likely to be small. Therefore this assumption is considered reasonable.

- **The system is closed** – There is no external heat transfer to the system apart from through either heat exchanger. The compressor and turbine gain and lose heat without external heat transfer. Heat transfer from the outside environment to the system will negatively impact efficiency, however at this early stage conceptual level, many details are unknown. Operating environment temperature is both unknown and likely variable (at different altitudes), the type and performance of the insulation used for final design is unknown, and the temperatures of the system are also speculative, therefore potentially giving incorrect indicative values. For these reasons, the system is assumed closed to outside heat sources or sinks other than those defined within heat exchange parts and the input from the motor/s.
- **Constant specific heat capacity values** – Specific heat capacity is highly variable from fluid to fluid, however for helium which is the chosen working closed-loop fluid, the variability for specific heat for the likely temperature range is negligible (10 K to 300 K, variability of 0.002 kW/kg.K (McCarty, 1973)). The warm heat exchanger heat sink fluid could be much more variable, hence the minimum value of specific heat is used within the given temperature range, such that a minimum mass flow rate can be obtained for heat sink operation where necessary. Although a small effect will be felt by assuming a constant specific heat value, this assumption is considered reasonable for first-order simulations, as the component sensitivities are not yet known.
- **50% specific and latent heat capacity share** – Within the warm heat exchanger, the latent heat capacity is shared in a 50% split with specific heat capacity (i.e. for a given energy exchange, half of the energy is dissipated using latent heat energy and half by raising the temperature through specific heat capacity). The reason for this is that if the latent heat capacity was assumed to constitute 100% of the energy exchange, this would automatically assume the largest heat sink fluid mass flow rate. By limiting the latent heat

exchange energy to 50%, an average figure is gained for heat sink mass flow, without resorting to the immediate worst-case scenario. Keeping this fixed throughout the modelling will ensure a fair comparison between concepts.

- **The motor used is superconducting** – As there is already cooling available, the use of conventional machines would add to the weight of any given system unless operating at very high rpm. Although it may make more sense in a practical solution to use conventional machines for safety purposes, the high power levels indicate that superconducting machines, should they already be viable for use in propulsion, would also provide similar benefits in space and weight saving. Therefore the machines within the cryogenic cooling system are all considered fully superconducting in nature.
- **Numerical assumptions taken are from current best practice for similar aerospace grade single stage reverse-Brayton cryocoolers** – Numerical assumptions for modelling are taken from literature available on RBC cryocooler designs. This is to ensure that numerical values used throughout are both reliable and realistic.

8.2.3. Single Stage

Single stage RBC cryocoolers are used throughout the cryogenics industry, most commonly on satellites and in low temperature small-scale physics. They consist of one set of each component, although some variations are possible on the design shown in Figure 8-3.

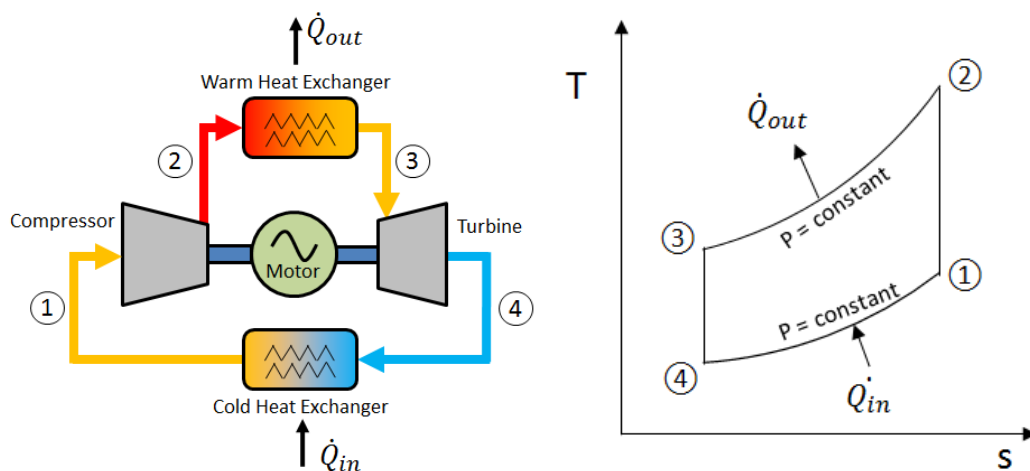


Figure 8-3 – A single-stage simple RBC and its associated T-S diagram

Figure 8-4 shows one possible variation, which is recuperation of the outflow from the warm heat exchanger with the outflow of the cold heat exchanger. This configuration allows separation of the hot and cold parts of the cycle, such that smaller temperature differentials are required when compression and expansion takes place. This allows a reduction in the size and therefore mass of the compressor and turbine, but at the weight penalty of adding another heat exchanger and more cryogen transport lines. Therefore there clearly exists a design trade-off for this concept. If the single-stage RBC cryocooler is shown to provide acceptable performance in its most basic form, recuperative cycles can be investigated in greater detail.

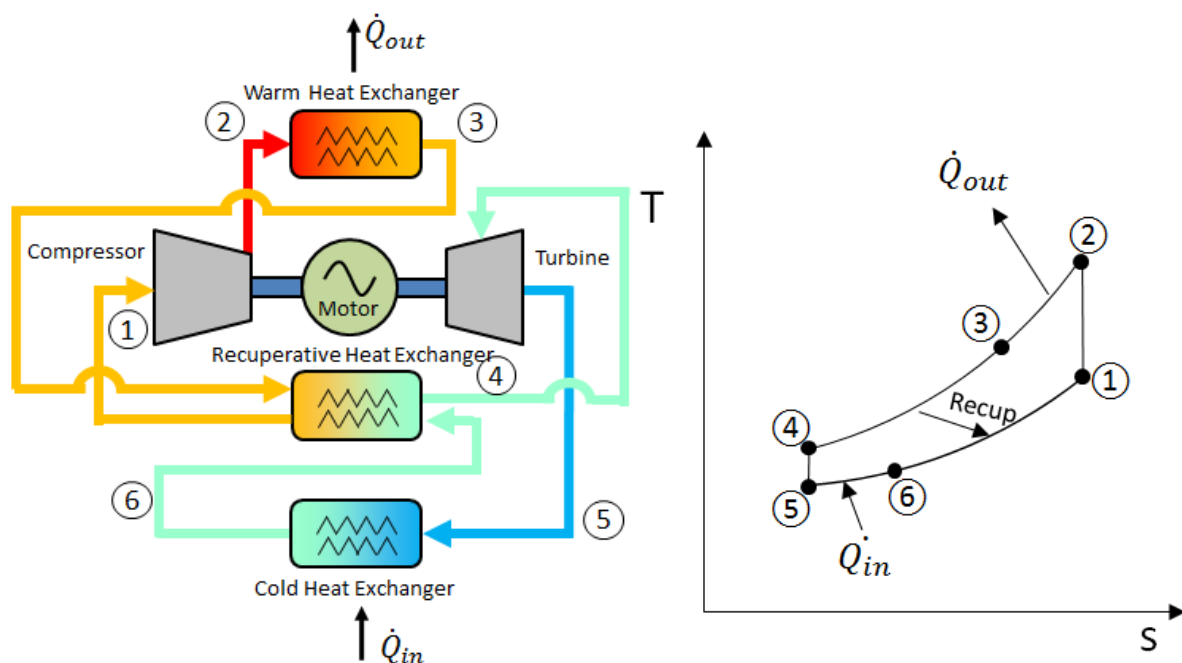


Figure 8-4 – A single-stage recuperated RBC and its associated T-S diagram

Another single-stage RBC concept is to use intercooled compression, as shown in Figure 8-5.

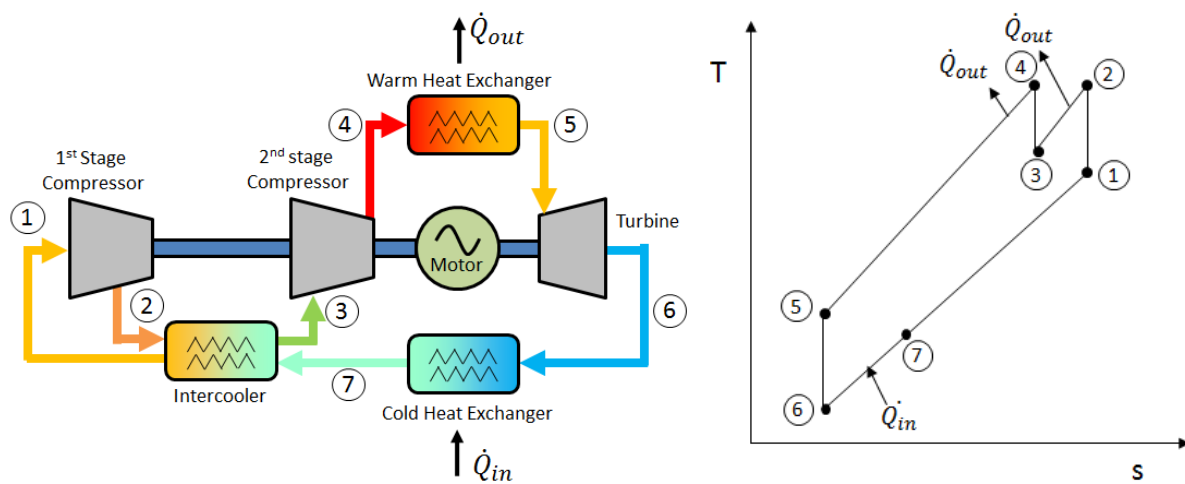


Figure 8-5 – A single-stage intercooled RBC and its associated T-S diagram

By using an intercooler between compression stages, the pressure ratio over the expander can be increased without significantly increasing the compressor outlet temperature. This can limit the amount of compression per-stage, reducing power input, and the rejection temperature at the warm heat sink can be lowered, increasing the Carnot efficiency of the cycle. This variation is mentioned for reference only, since the modelling analysis must establish differences in major concept decisions rather than component-level designs choices.

8.2.4. Double Stage

Double stage, commonly referred to as ‘two-stage’ RBC cryocoolers, effectively reduce the temperature difference between the warm and cold heat exchangers through staging (Figure 8-6). By using two RBC cycles and combining them such that the warm heat exchanger on the cold cycle is merged with the cold heat exchanger on the warm cycle, the Carnot efficiency per-stage can be increased. This configuration however comes at a cost; each component is multiplied by a factor of two. This is likely to add significant weight to the overall concept.

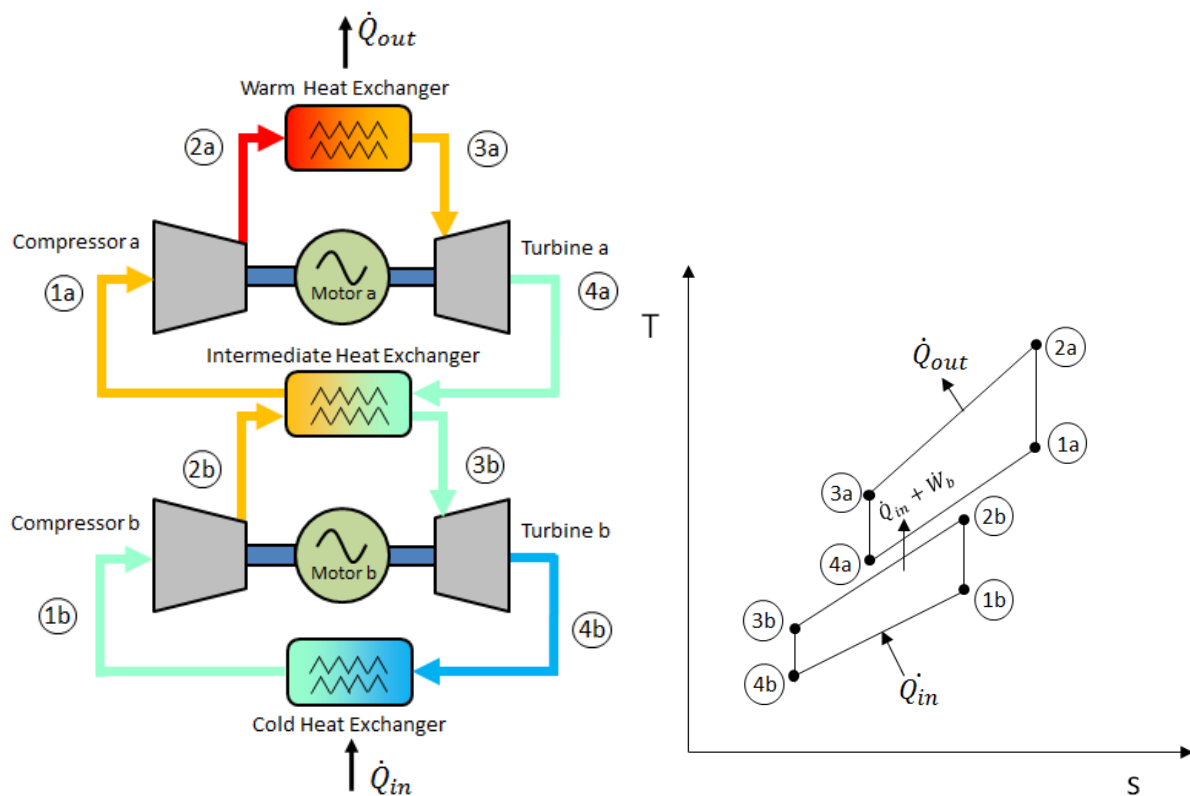


Figure 8-6 – A two-stage RBC with its associated T-S diagram

The two-stage design has all of the same components of a single stage design except for the intermediate heat exchanger is shared.

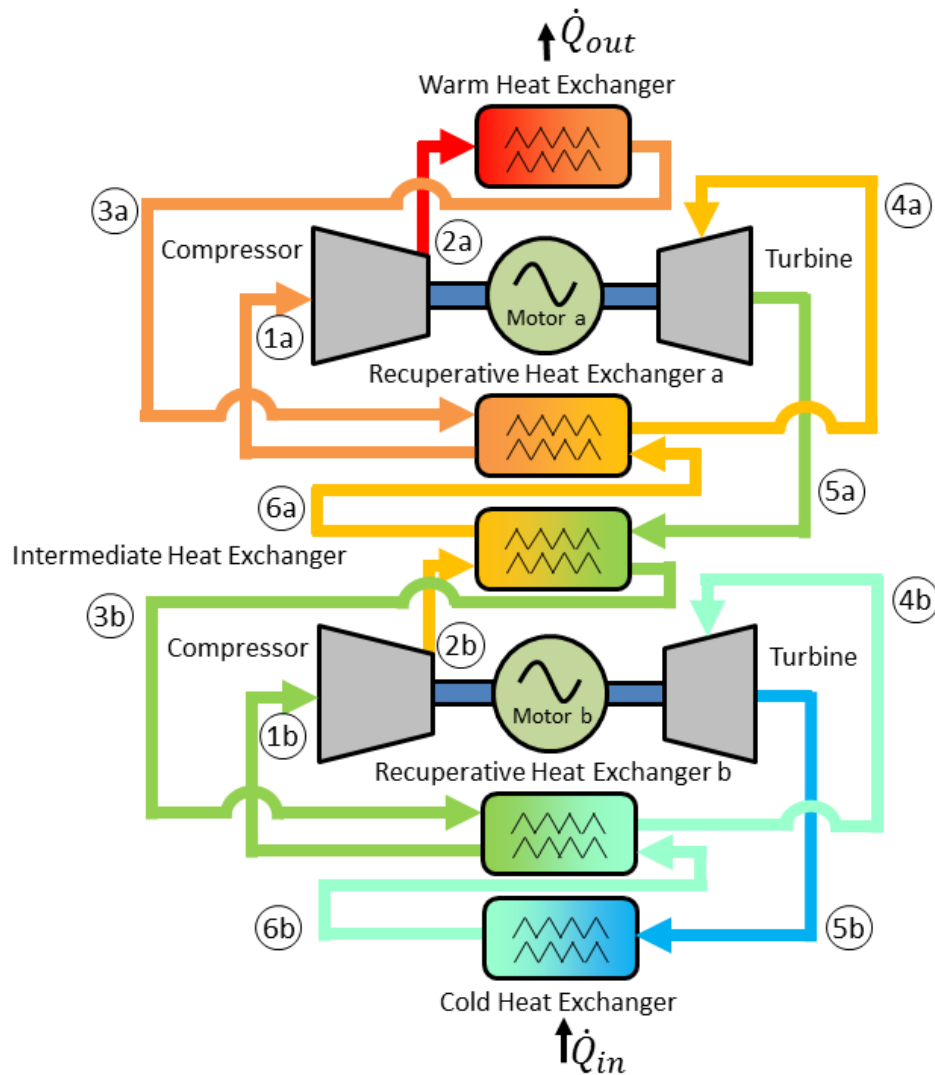


Figure 8-7 – A two-stage recuperated RBC design

As with the single-stage RBC design, the two-stage design can be modified to increase performance, such as by recuperation (Figure 8-7) or by intercooling. As with the single-stage design, modelling efforts will focus on the worst-case scenario to establish whether there is merit in pursuing either type. By focusing modelling work around unmodified designs, a clearer view of which components drive inefficiency and mass estimation methods will be more effective.

The key design trade-off within the two-stage design analysis must involve both efficiency and mass. The key question of whether the mass increase that is inevitable with two-stage designs can be offset by the Carnot efficiency gains made, or whether any other mitigating factors arise must be answered.

8.2.5. Other Configurations

A number of other cooling ideas can be incorporated into RBC designs that can also improve performance or provide other advantages over standard designs. First of these is the use of a Joule-Thomson valve (Figure 8-8). The Joule-Thomson effect occurs to fluids when forced through a throttle valve, whereby if the fluid is below its respective inversion temperature when it passes through the valve, the fluid cools as it expands. The effect is most commonly observed in household deodorant cans. If the fluid is forced through the valve above its inversion temperature however, the effect is reversed. Since the working fluid is helium in the considered RBC designs, the inversion temperature for 1 atm pressure is around 40 K, with an absolute maximum of 55 K for low pressure helium (McCarty, 1973). This inversion temperature, although low, makes it potentially ideal for localised cooling.

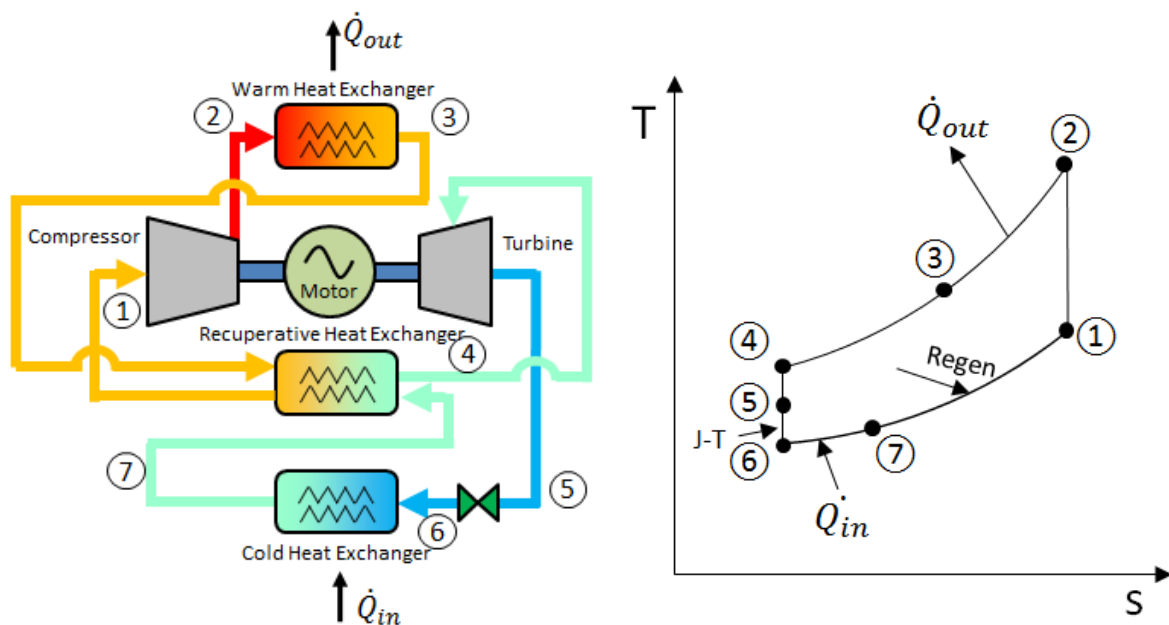


Figure 8-8 – Single-stage recuperated RBC with J-T expansion valve and its associated T-S diagram

Local cooling using J-T valves may be advantageous in a number of ways. It does not require any moving parts and is therefore 100% reliable at its design condition. Fluid can be transported at a higher temperature toward the cooling target and expanded locally, reducing potential transport losses. Furthermore, the J-T valve does not add to the mass directly, and may reduce the mass of the turbine since only partial expansion would be required. There are however caveats to these

advantages; by taking expansion energy from the turbine, the compressor will require more input power. This will mean an increase in compressor mass to compensate for the reduction in energy recovery as the compressor must account for the increase in net energy input to the fluid. Further research into how J-T valves can be exploited is required.

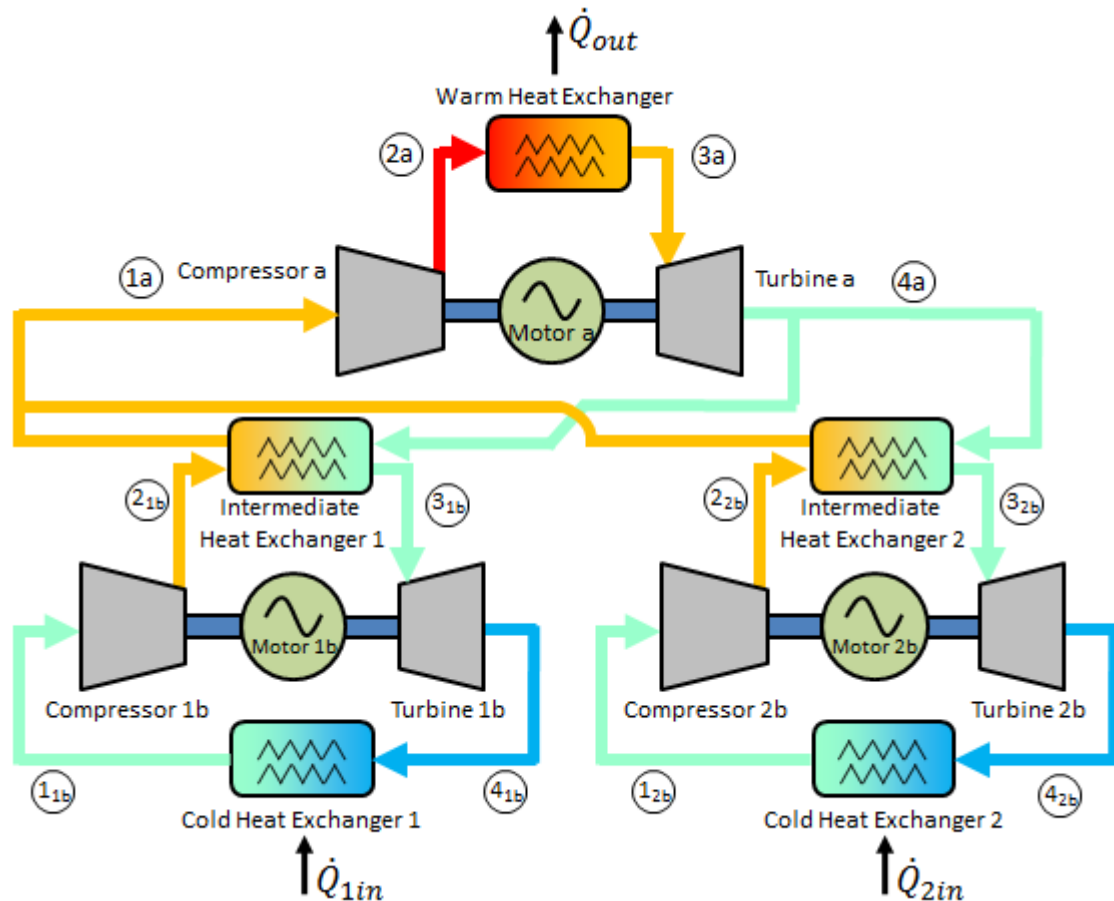


Figure 8-9 – Two-stage, multiple b-stage RBC design

Figure 8-9 shows how multiple b-stages can be connected to a central, larger a-stage. This concept allows localised cooling at a cost of overall efficiency as smaller, local cryocoolers will sacrifice efficiency for convenience. Another advantage to multiple b-stage designs is that they provide some redundancy to the system. Should one of the b-stages fail, there is still some cooling available from the remaining b-stage. Furthermore, since the a-stage can be made larger and more central, the a-stage will be likely more efficient, and transport losses are likely to be minimised due to the higher distribution temperature. Some analysis is performed on this concept within this thesis, however further investigation is required to fully

understand the benefits if the preferred concept is concluded to be the two-stage RBC over single-stage designs.

8.3. Modelling

Modelling RBC cryocoolers must follow the same strict regimen of validation as with the superconducting network. Cryogenic cooling system modelling for an unknown load and unknown configuration is complex and presents a challenge when trying to validate simulation data. Initially it is wise to specify the same modelling format as with superconducting network modelling; steady-state Simulink-based theoretical models.

This chapter section first outlines the modelling process taken, which models are being made and the reasons behind the decisions, and the methods used to create them, including mass estimation strategy. Finally, numerical assumptions for the models are given and the models themselves are clearly defined step-by-step, written as a guide to potential future users. The outcome will be a set of models that are then ready for use in simulation analysis for both the cryogenic cooling system and the wider superconducting network analysis.

8.3.1. Modelling Method and Mass Estimation

Cryogenics are modelled in this research in the same format as with the superconducting network; Matlab/Simulink is used to create steady-state design tools that allow rapid design iteration based on known numerical input values. The key difference between the superconducting component models and the cryogenics models is fidelity. While the machine model outlined previously combines known information into a single mask model, the RBC cryocooler models are separated into individual components. This method is adopted in order to assess component level performance impact on overall power and weight metrics. By using this method, the outcome is to show where component research efforts must be concentrated and to compare and contrast the qualitative methods used in the systems process with the numerical methods used within the solutions process. The outcome will also highlight potential issues with the newly defined systems-solutions effort for complex conceptual design.

Equations and relationships for the RBC are well known and understood by the scientific community, and the modelling work on RBC's in this report is based on equations outlined by Swift, 1993. Some unknown relationships were derived, particularly with mass estimation, and require more explanation into the process used.

Mass estimation for RBC cryocoolers is particularly difficult. There are a number of reasons as to why:

- **Custom design nature** – RBC cryocoolers are not off-the-shelf components. The reason is because of the direct fluid cooling nature of RBC rather than conductive which are commonly 'plug and play'-type devices that can attach to most target cooling rigs. This makes their design highly variable by purpose, and their custom nature also makes information about their mass scarce except in aerospace cases where it is pertinent.
- **Mass often unknown** – As previously stated, many examples masses are unknown, since many designs are for industrial purposes where mass is not of concern. Aerospace examples typically occupy the multi-Watt or milliwatt range, whilst industrial examples typically operate at the high kilowatt range. It is essential to determine how industrial and aerospace RBC designs vary in terms of mass differential for a given power.
- **Configuration differences** – Practical designs are often not simple. Many contain multiple compression stages, intercooling, recuperation, and other configuration variables. This further complicates design efforts, particularly when considering mass.
- **Scarcity** – Due to the custom nature of RBC cryocoolers, there simply are not many examples available for comparison. The most common types are typically industrial designs that give no mass, whilst aerospace designs are often defence-related or satellite based, and as a result the mass is not released.

In order to estimate the mass of reverse-Brayton cryocoolers, a survey was performed on the few known systems that were found to establish a guideline correlation between mass and input power. The method was taken from an earlier NASA presentation (Barrett and Johnson, 2005). The presentation shows mass

estimation curves of space-borne Brayton power generators, and although they perform a different function to cryocoolers, they are directly comparable. The key difference is that power is being generated through heat, rather than heat being removed through power.

The components are identical; the Brayton power cycle works in a closed loop, with compressor, turbine, generator, and two heat exchangers. There are likely to be small caveats with this type of mass estimation; use of helium as a closed loop fluid is expected to increase the mass of compressor and turbine components. The primary reason for this is that helium is monatomic and very low mass; hence the tip clearance of any dynamic compressive components means efficiency is lowered, and the mass for fixed target compression ratio is going to be higher. For these superconducting systems however, the heat exchanger on the cold end can be assumed to have zero mass. The superconducting components themselves are designed as heat exchangers. Therefore any increase in mass in other components can be adequately compensated for.

Figure 8-10 shows the NASA curve used as the baseline method (Barrett and Johnson, 2005). The plot shows the alternator power against the specific mass of the system.

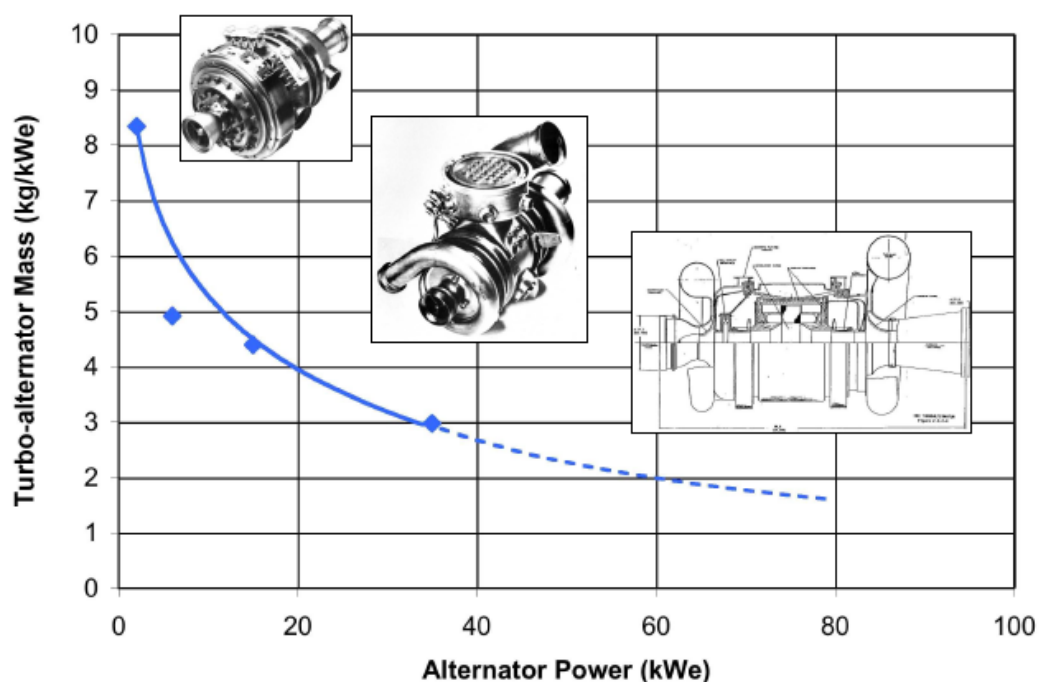


Figure 8-10 – Specific mass curve for space Brayton turbo-alternators

A small number of mass-specific examples were found for reverse-Brayton cryocoolers. Due to the reasons previously outlined, the known examples have to be comparable. The first requirement is that they must be single stage, i.e. they must contain only one set of compressors, turbines, and two heat exchangers. The second is that they must have known mass and input power. Mass is essential because it cannot easily be calculated. Input power can be calculated if enough information is known, such as overall efficiency and available cold power. Table 8-1 shows the examples found that match the criteria.

Mass (kg)	Cooling Power (W)	COP	Cold Temp (K)	Pc/Tc	Input Power (W)	Specific Input power	Specific RB mass (kg/W)	Input Power (kW)	Specific Mass (kg/kW)
22	30	0.010	18	1.667	3000	136.3	0.73	3	7.3
15.5	0.45	0.002	35	0.013	200	12.9	34.44	0.2	77.5
11	0.45	0.003	35	0.013	160	14.5	24.44	0.16	68.7
11	2.95	0.011	35	0.084	260	23.6	3.72	0.26	42.3
270	1000	0.050	95	10.526	21000	77.7	0.27	21	12.8
21	7	0.018	70	0.100	400	19.0	3.00	0.4	52.5
8000	24000	0.025	77	311.688	1000000	125.0	0.33	1000	8.0

Table 8-1 – All known reverse-Brayton cryocoolers with masses given (Breedlove, Magari and Miller, 2008, Chow *et al*, 2007, Crespi, 2012, Davis and Abhyankar, 2004, Swift, 1993, Swift *et al*, 1999, Zagarola *et al*, 2009)

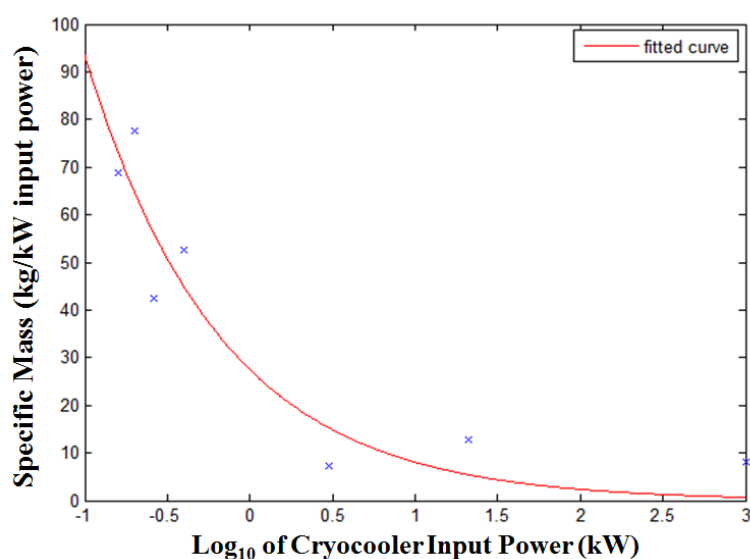


Figure 8-11 – Relationship between cryocooler specific mass and Log₁₀ of cryocooler input power for known RBC cryocooler examples

The data was then collected, plotted, and a rule generated. Figure 8-11 shows the plot. In Figure 8-11, the curve shown in solid red is the curve fit applied. However there are two other scenarios worthy of note. The dotted lines shown represent aerospace and non-aerospace optimised versions. The data collected was not purely aerospace-related, due to the limited number of examples with the required data available. The top curve highlights the expected non-aerospace relationship, while the lower curve shows aerospace optimised versions. In order to estimate aerospace potential for mass savings, previous work was completed on improvement potential (Palmer *et al*, 2012). A weight saving of 80% and a volumetric saving of up to 90% was found to be plausible on current industrial designs. The curve fit (solid line, Figure 8-12) shows this improvement on non-aerospace versions found, hence it can be deemed acceptable for the purposes of this study. Aerospace predictions begin to narrow with the actual curve fit when input powers rise above 100 kW.

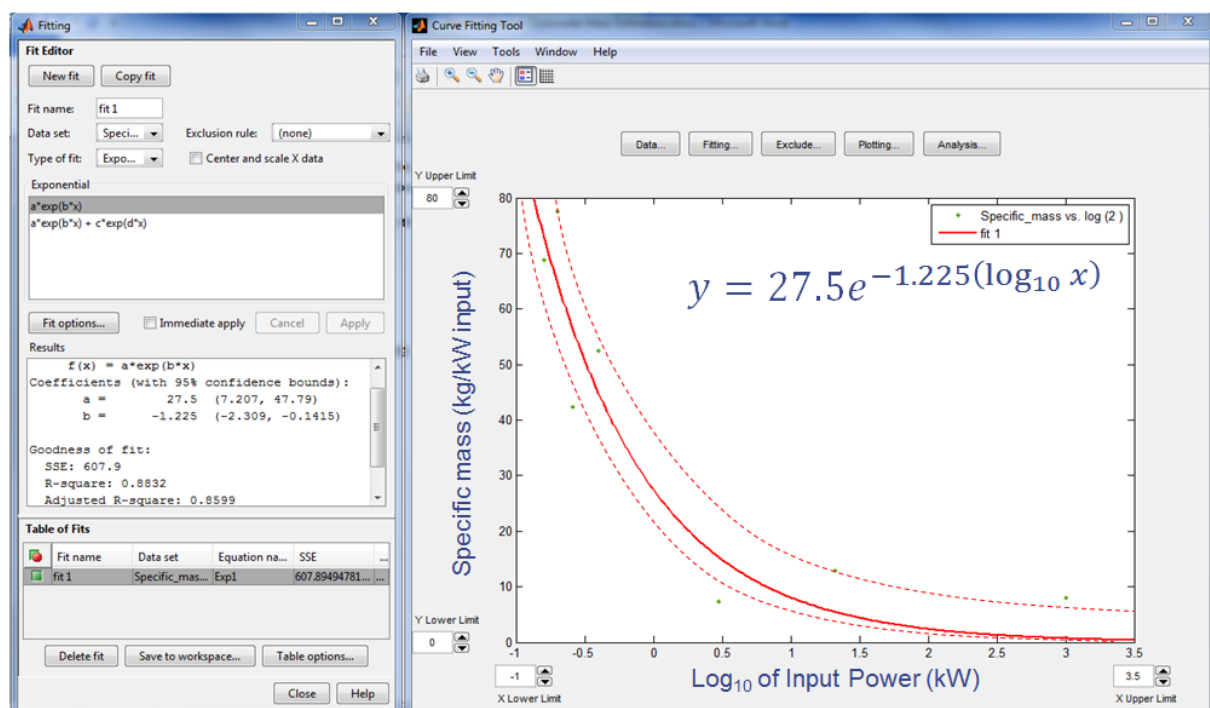


Figure 8-12 – Curve fit for all known reverse-Brayton cryocoolers with generated equation shown

Overall error on the curve fit with known examples show an R^2 value of 0.855, which is acceptable for the purposes of this study. The R^2 value corresponds to the statistical 'goodness of fit' of the data to the regression curve generated in Matlab, and is calculated by taking the ratio of the sum of squares of residuals by the total

sum of squares. In terms of percentage error, a value of 0.855 represents an overall margin of error of 14.5% for the data range selected. When considering the values furthest away from the curve, such as those at the higher end of the x axis, mitigation can be found in the aforementioned study on improvement potential, which would inevitably push the R^2 value higher for the given range, assuming the regression curve did not change. Since it is the higher input power part of the curve that is of interest, the remaining values can be ignored, as the overall R^2 value is well within the permissible error margin for an early stage concept design which in this case is denoted by Pareto's 80:20 rule, or above 80% confidence level.

8.3.2. Single Stage

The single-stage model is developed using a combination of methods. Firstly, a set of known physical rules were collected using available literature (Swift, 1993). Once a series of relationships were established, a 'parametric feedback' method of assessing parametric values was used, shown in Figure 8-13.

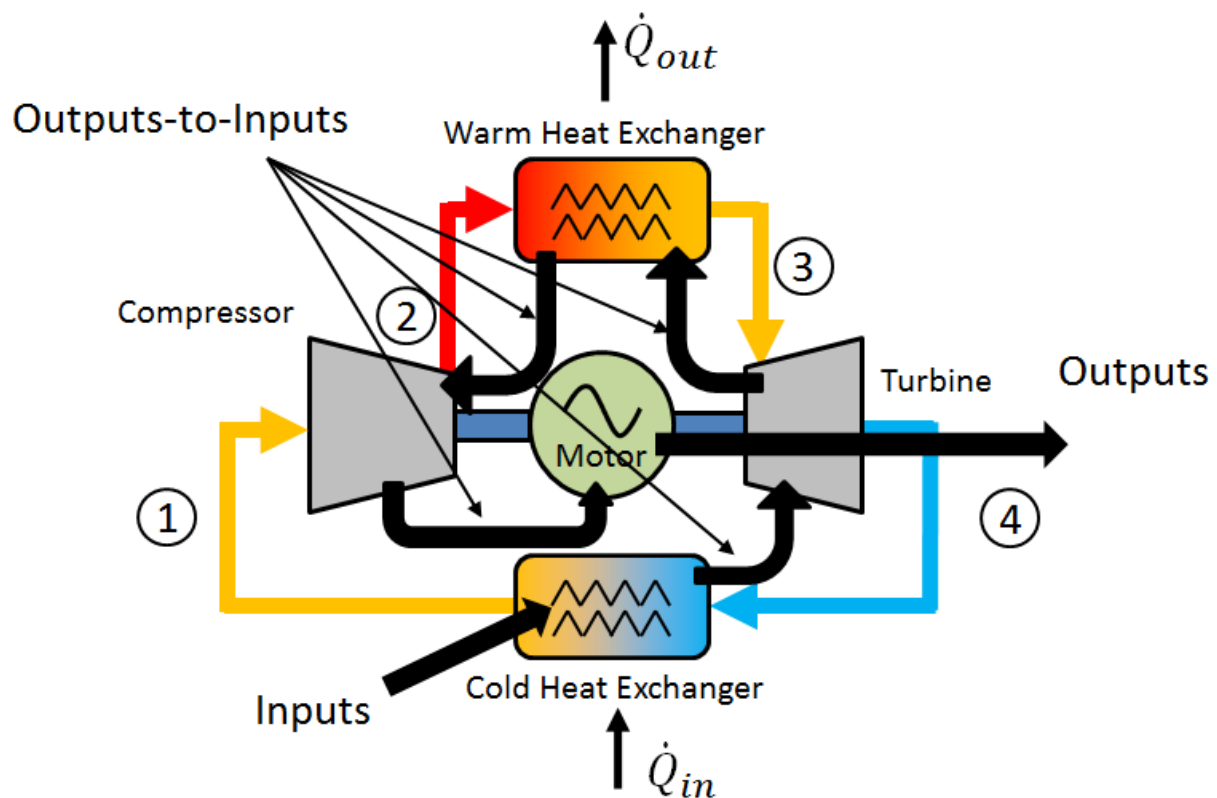


Figure 8-13 – Single-stage RBC cryocooler with input-output flow shown by thick black arrows

Parametric feedback starts with the model block where most knowledge is known; the cold heat exchanger. From the cold heat exchanger, the inputs values are all determined by the user. Heat exchanger equations are then applied in ‘reverse’ order, with the term ‘reverse’ referring to the flow of parameters opposite direction of travel to the fluid in the cycle. This continues through the turbine, warm heat exchanger (HSHX) or transfer heat exchanger), and finally the compressor and motor blocks. Throughout the process, inputs are added where necessary and outputs that terminate at a given block are either exported to the workspace or shown in a display screen. The model block is shown with inputs and outputs,

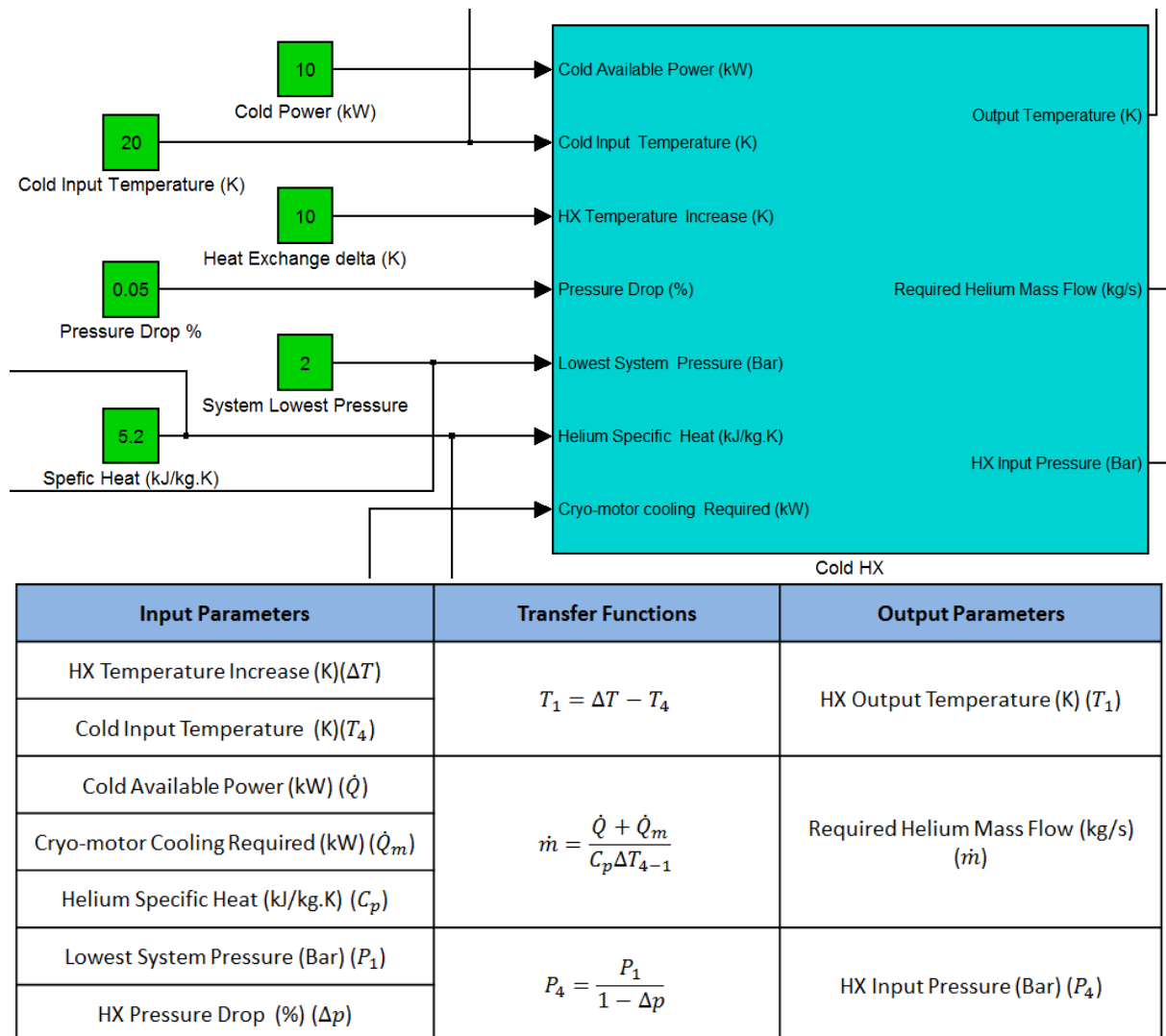


Figure 8-14 – Cold heat exchanger model block and table of inputs, transfer functions, and outputs

Figure 8-14 shows the cold heat exchanger block with all inputs, transfer functions and outputs. The relationships below the model block can clearly be seen, with the parametric flow direction leading to the turbine. The motor cryocooling required is not calculated until the overall cryogenic cooling input power is known at the final part of the model.

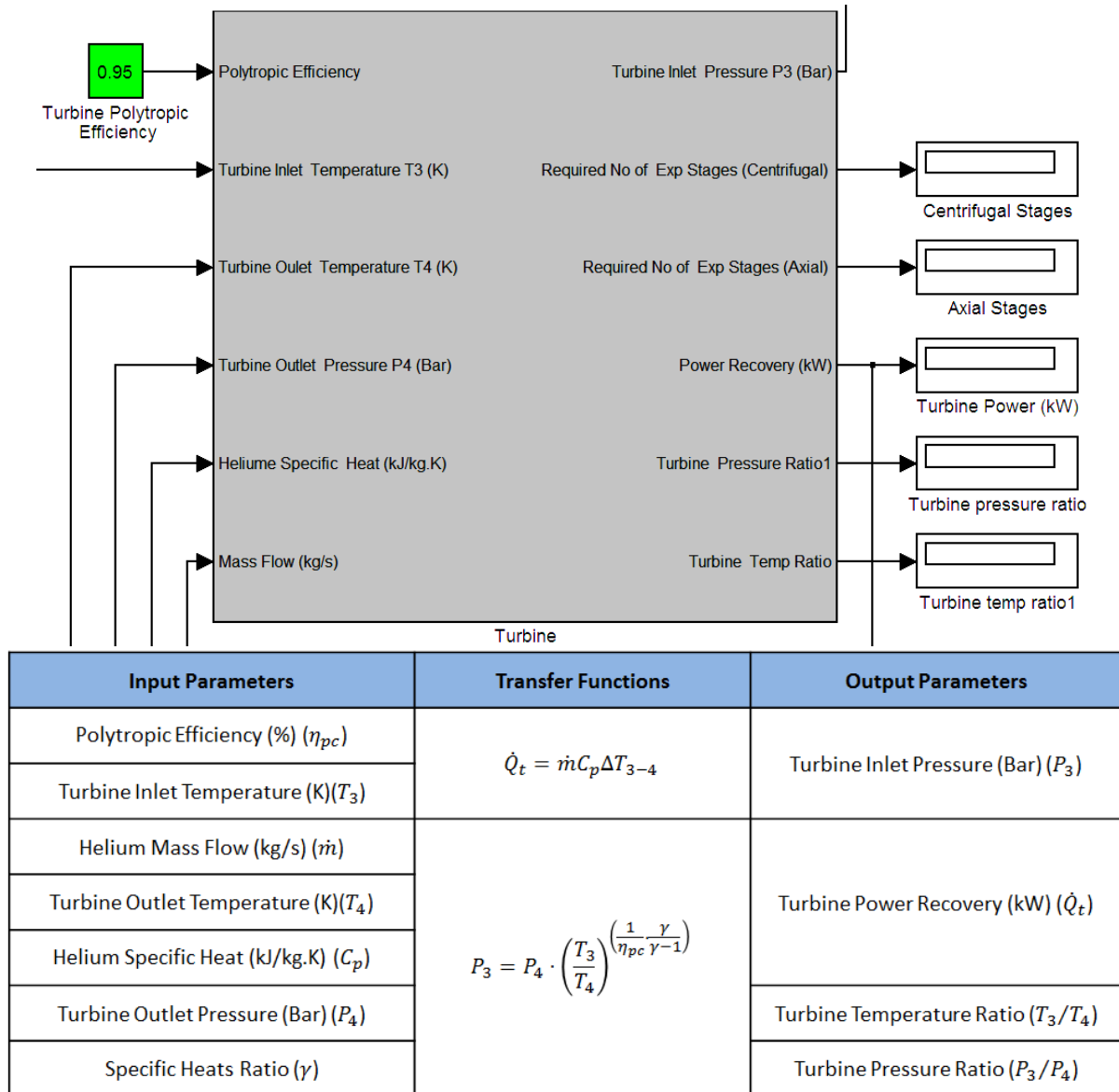


Figure 8-15 – Turbine model block and table of inputs, transfer functions, and outputs

The relationships shown for the turbine model block in Figure 8-15 are derived from previous work performed by Swift, 1993, on RBC thermodynamics.

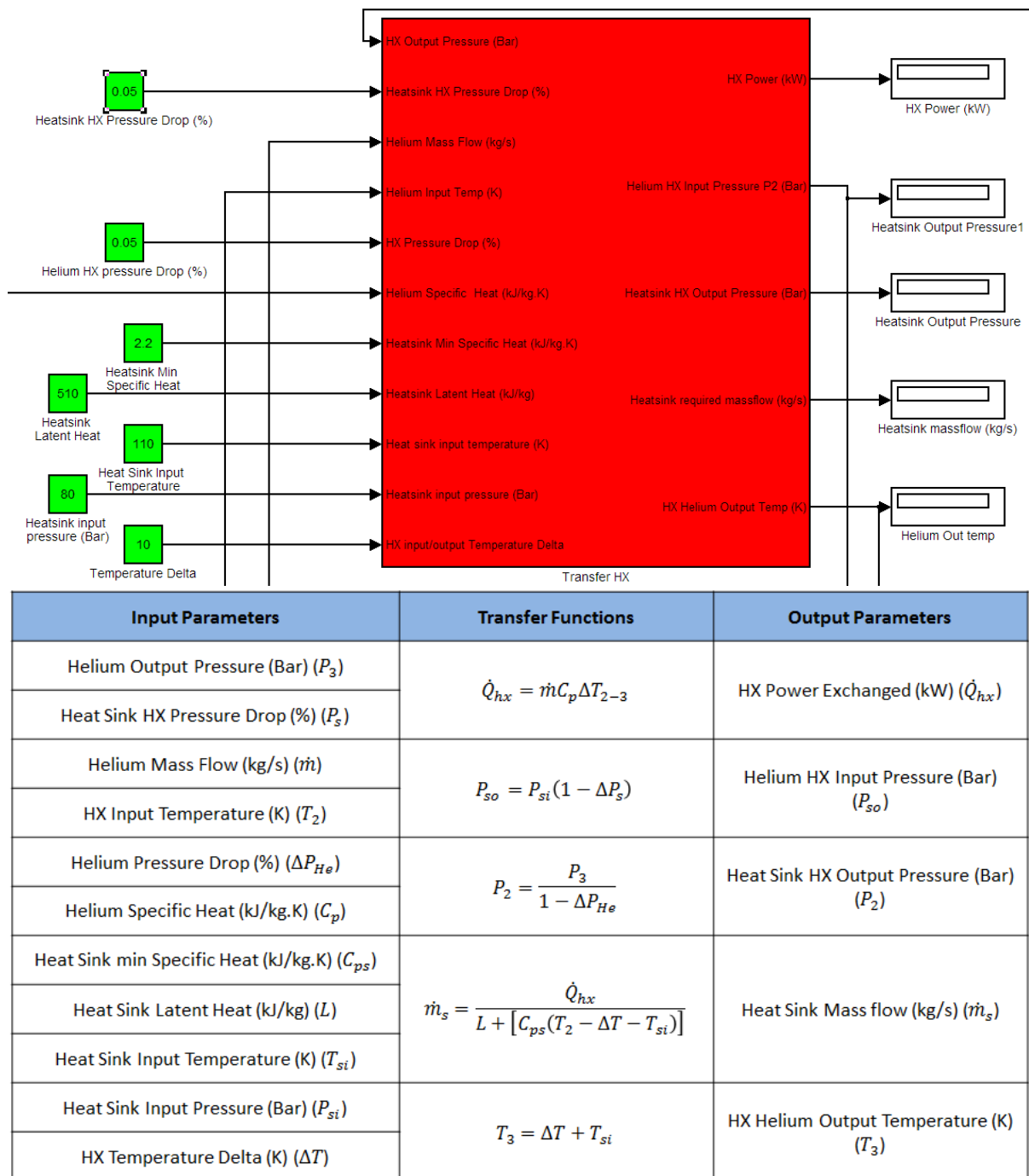


Figure 8-16 – HSHX model block and table showing inputs, transfer functions, and outputs

Figure 8-16 shows how the helium and heat sink material interact within the HSHX. A particular challenge when considering the heat sink fluid is the determination of temperatures and pressures. For this research, the pressures are assumed to be irrelevant since the fluid will likely need recompression should it need to enter the gas turbine. As the effects of fuel and fuel burn in the wider system as a result of

changes are out of scope for this project, the overall mission fuel requirements and fuel burn is not analysed; project DEAP however has used these models in wider aircraft-level system context. Information can be derived from knowing the impact of using different heat sinks on the overall aircraft.

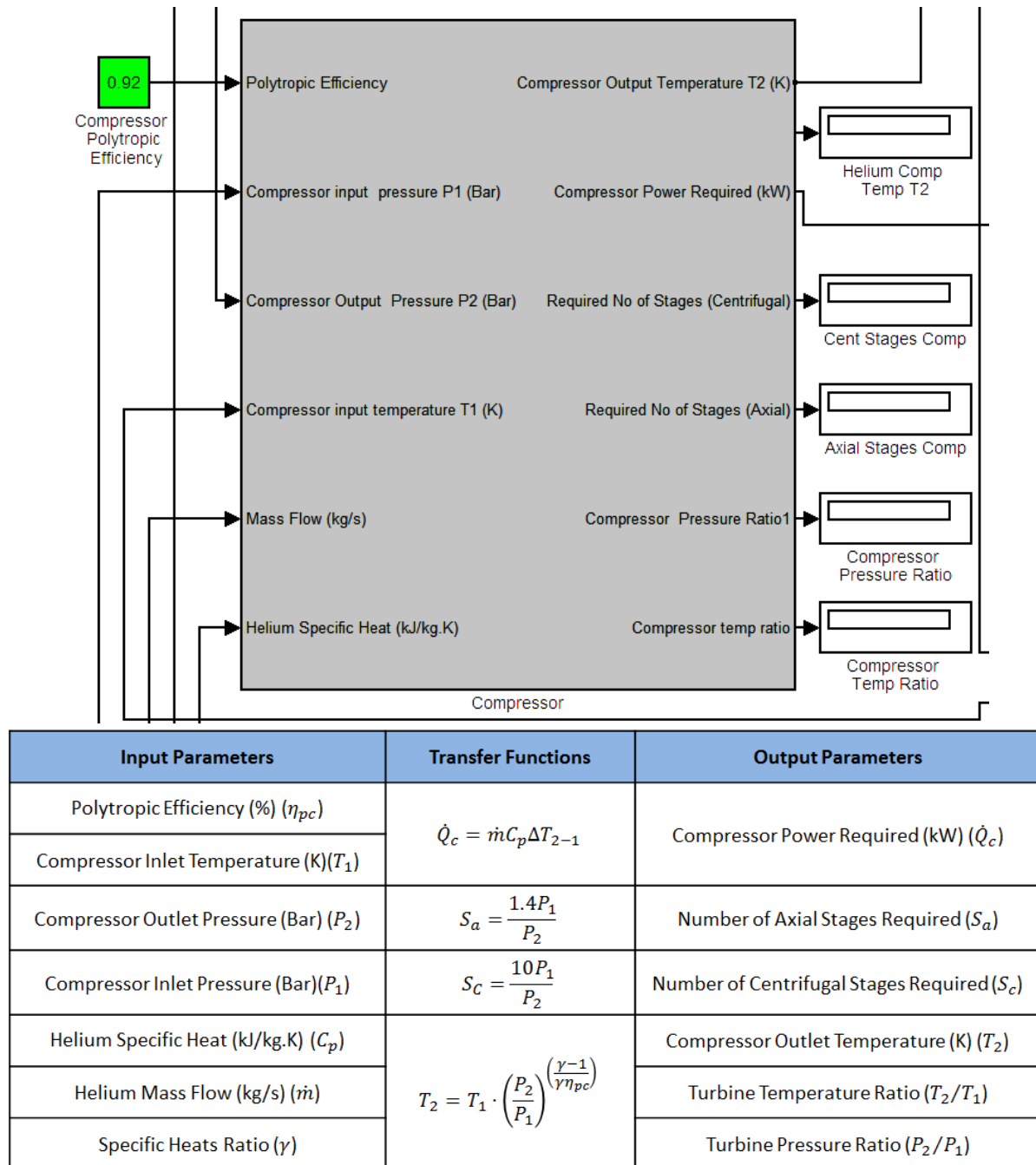


Figure 8-17 – Compressor model block and tables showing inputs, transfer functions, and outputs

While Figure 8-17 shows the model motor section, the model mask is the same as the motor outlined in Chapter 7. Also key to note within Figure 8-18 is the motor mass. The total mass is inclusive of the motor mass, since the motor mass is included in all surveyed designs. The cold motor load is more of a crucial consideration, since it will need to be cooled by the cryocooler. This creates a parametric feedback loop where for each case the model converges on the steady-state condition.

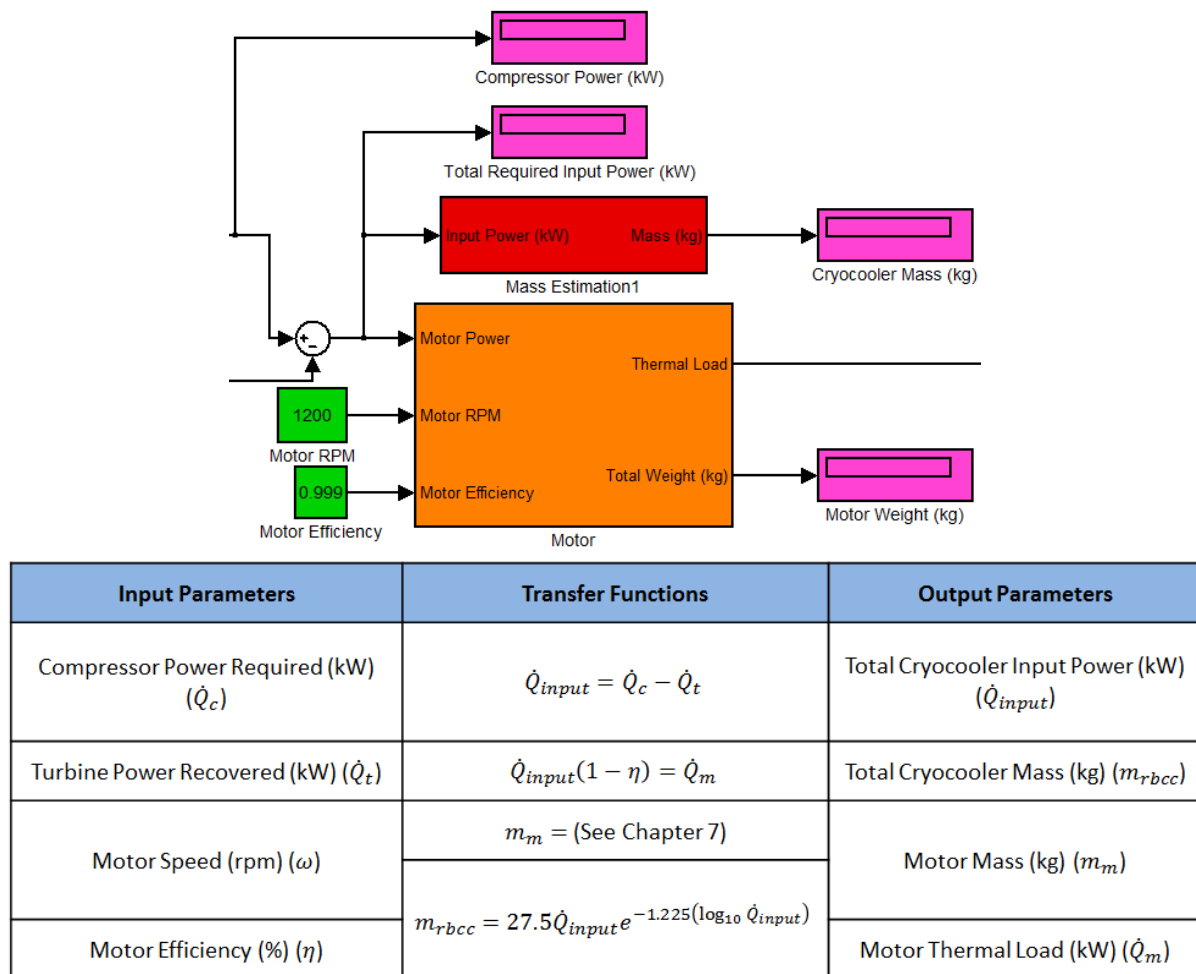


Figure 8-18 – Motor, mass estimation, and input power model blocks with table showing inputs, transfer functions and outputs

Figure 8-19 shows the model in full. The model input and output parameters can clearly be seen as described in Figures 8-14 to 8-18.

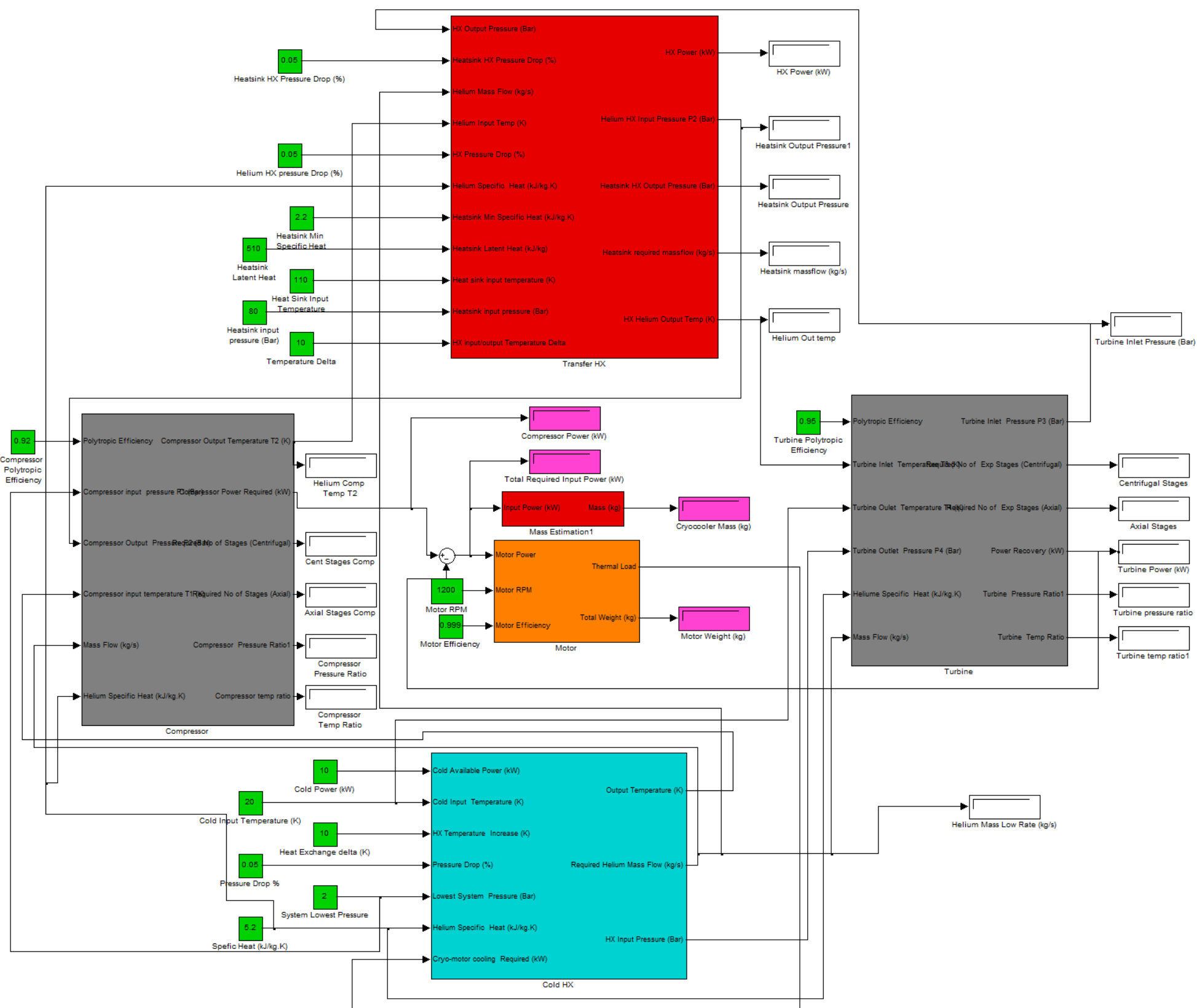


Figure 8-19 – Full-model over view of the single stage RBC Simulink model

8.3.3. Double Stage

Modelling the double stage RBC concept is similar to the single stage in terms of relationships (Figure 8-20). An additional component exists however with the two-stage design; the intermediate heat exchanger. The intermediate heat exchanger acts as the cold stage heat sink and the warm stage cooled component. By doing this, the temperature gradient between the heat sink (warm heat exchanger) and the cold component (cold heat exchanger) can be reduced, effectively reducing the likely need for additional compression stages or very high pressure ratios. This advantage however is not without cost. The additional stage means additional mass is inevitable, and the efficiency of twice the number of components must be considered. This means design space modelling must take into account these likely issues and consider the impact of having these additional components on both single and two-stage designs.

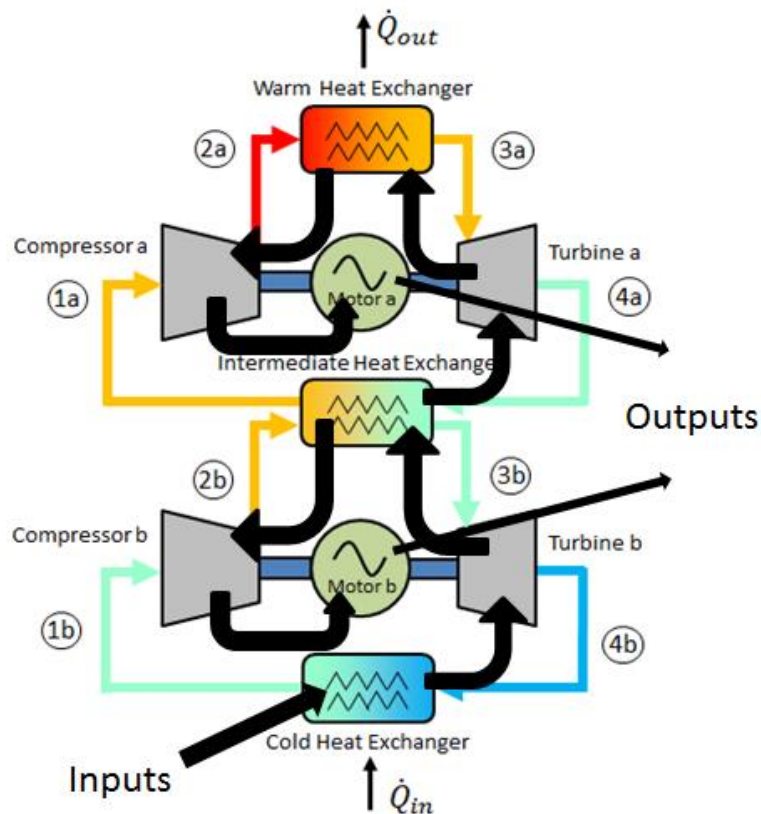


Figure 8-20 – Two-stage RBC showing parametric flow direction with black arrows

The first step with the two-stage design is the same as the single stage. The cold model block is identical in the transfer functions it performs and the inputs and outputs, shown in Figure 8-21.

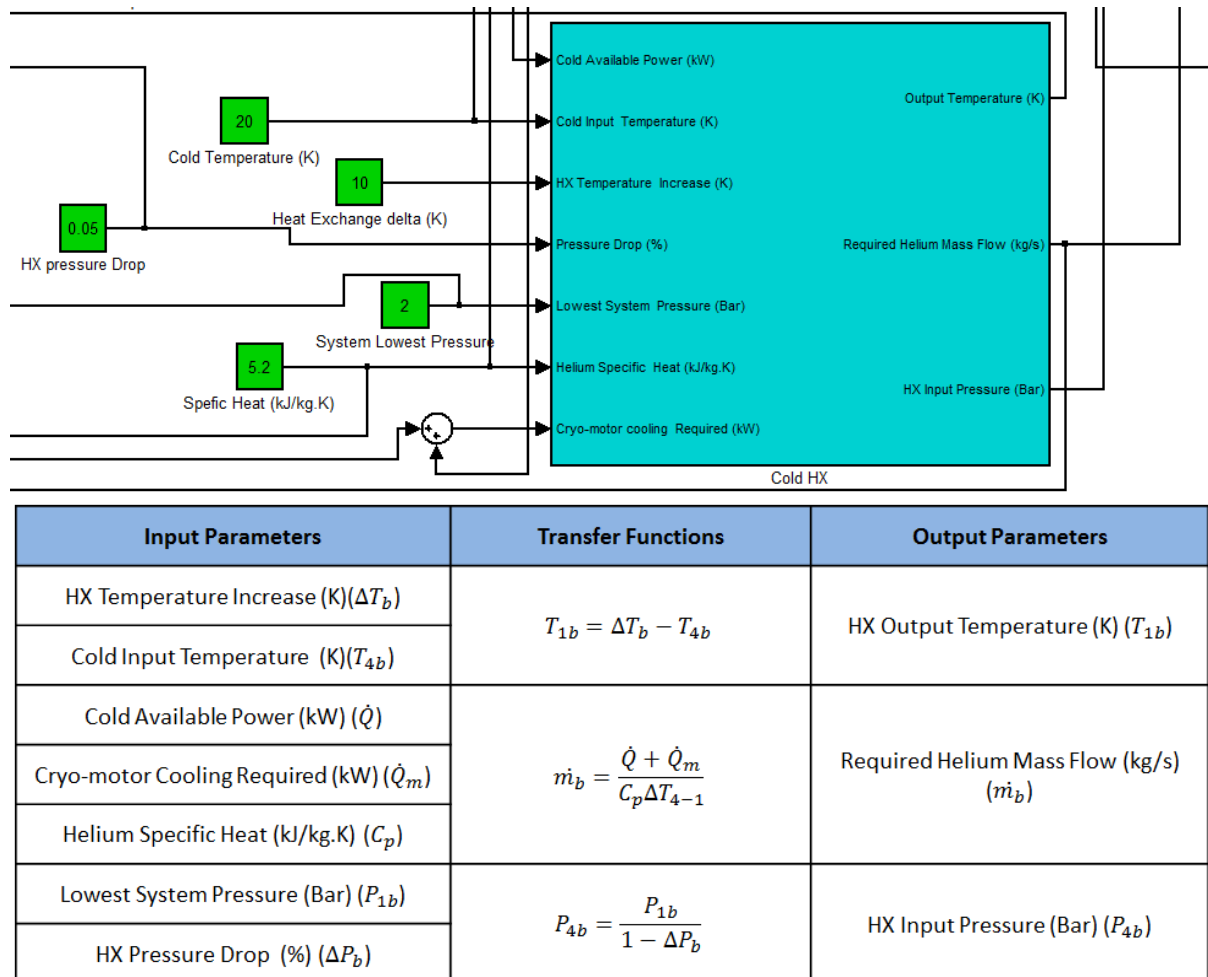
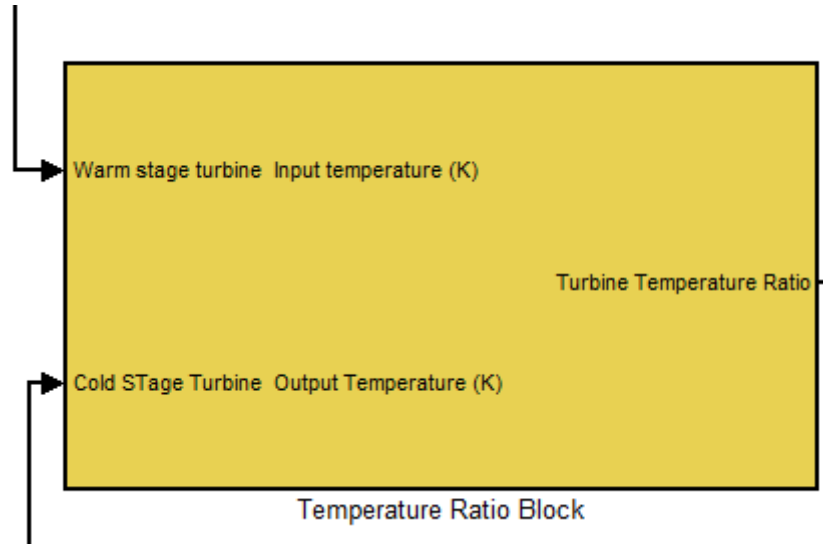


Figure 8-21 – Cold stage cold heat exchanger model block and table showing block inputs, transfer functions, and outputs

An issue arises however when considering the next block, the cold stage turbine block. Previously with the single stage model, the turbine outlet temperature T_4 and turbine inlet temperature T_3 are known, with the former defined as the target superconductor temperature and the latter defined by the heat sink inlet temperature. For the two-stage design, the stages split into a and b stages, whereby T_4 becomes T_{4b} , and T_3 now becomes T_{3a} . Therefore T_{4a} and T_{3b} must be specified before the parametric flow can continue.

The method chosen for this research is to create an equal Carnot efficiency share between stages. In order to reach the optimum scenario for fair system level comparison, each stage must be equally efficient to highlight the differences between single stage and double stage designs. Figure 8-22 shows the model block used to share the temperature ratios and the equation associated



$$\frac{T_{3b}}{T_{4b}} = \sqrt{\frac{T_{3a}}{T_{4b}}} \quad (3)$$

Figure 8-22 – Stage-to-stage temperature share model block and transfer function equation

Equation (3) shown in Figure 8-23 shows how the cold stage turbine outlet temperature (T_{4b}) can be used with the warm stage turbine inlet temperature (T_{3a}) to obtain an optimum average temperature for the intermediate heat exchanger. The Carnot efficiency, commonly called the coefficient of performance (COP) for a refrigerator is given by the equation:

$$COP = \frac{T_c}{T_h - T_c}$$

When considering both stages of the cryocooler, then the COP must be equal for optimum stage-to-stage performance. Using the equation (3), the overall temperature ratio between T_{4b} and T_{3a} is found and square-rooted. The result is then multiplied by the cold stage turbine outlet temperature T_{4b} to give the optimum

intermediate temperature (T_{3b}). It is known that the actual outlet temperature of the intermediate heat exchanger will not be an ideal case, hence the model block shown in Figure 8-24 (IHX) allows for the inclusion of a temperature differential between input and output stage-to-stage helium loops.

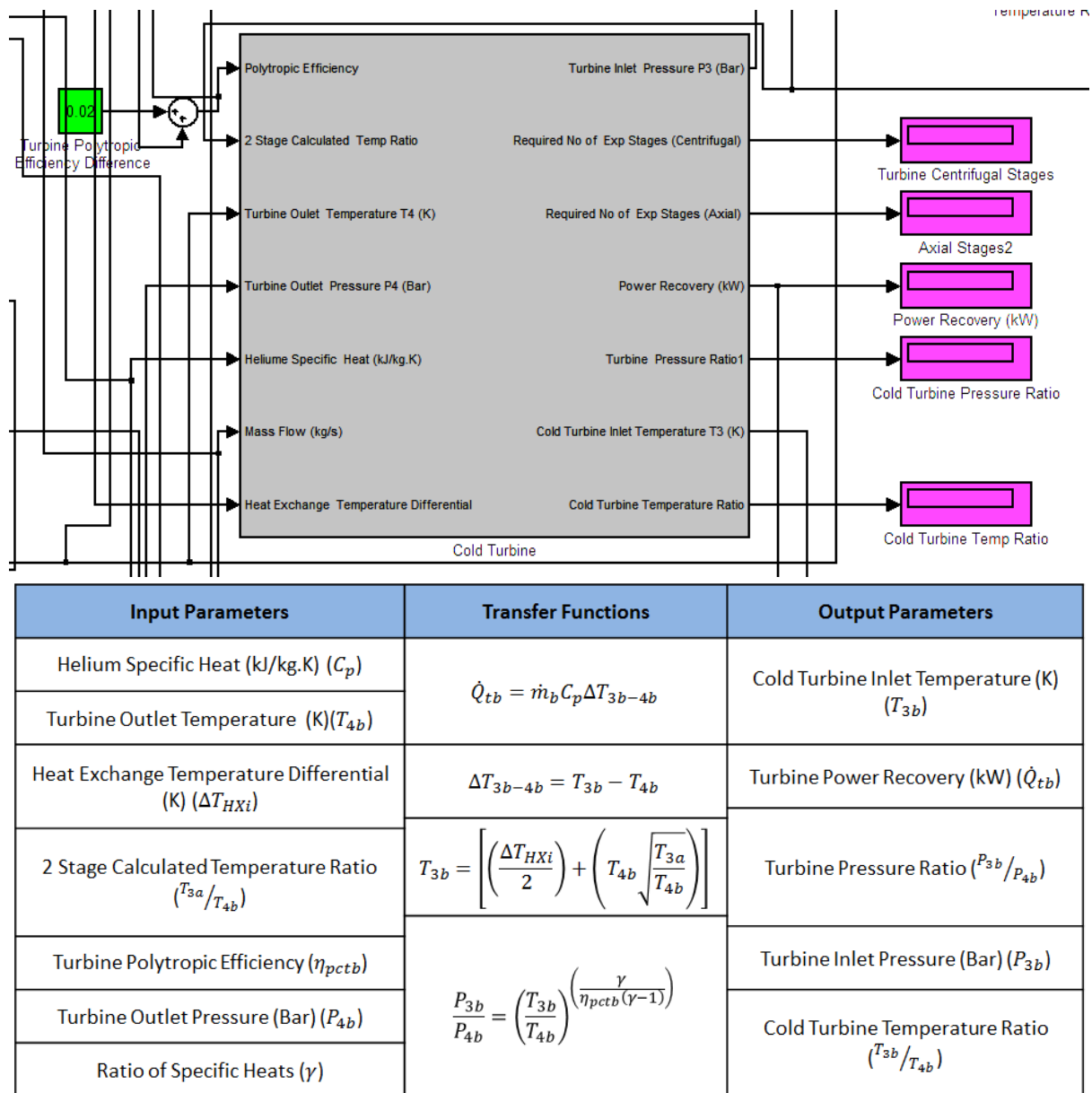
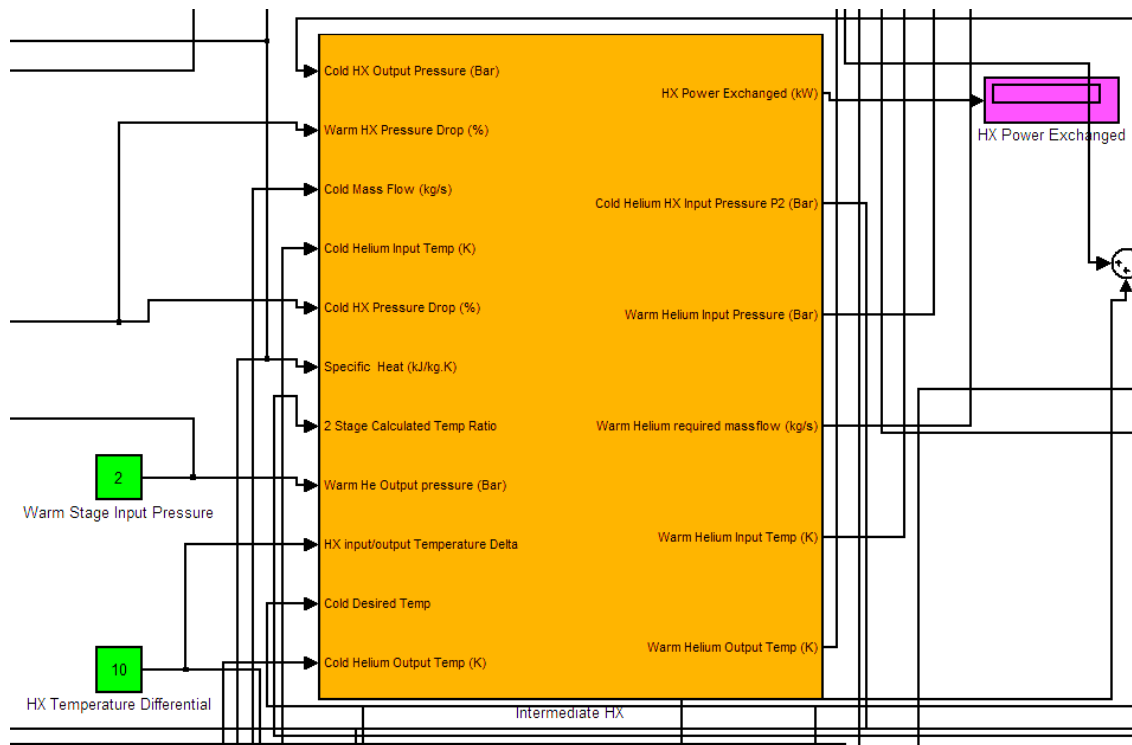


Figure 8-23 – Cold stage turbine model block and table showing inputs, transfer functions, and outputs

Using the temperature derived using equation (3), the cold stage turbine block can now be defined, shown in Figure 8-23. The intermediate heat exchanger block

shown in Figure 8-24 then follows on, with the aforementioned input showing the input-to-output temperature differential in green at the bottom of the block. The mass flow rate is assumed to be equal, therefore the intermediate temperature inputs and outputs for both stages are assumed either equal or equally different. For example, if a temperature differential of 10 K is defined, the cold stage input will be 10 K higher than the warm stage output, and similarly the cold stage output will be 10 K higher than the warm stage input.



Input Parameters	Transfer Functions	Output Parameters
Cold HX Output Pressure (Bar) (P_{3b})	$\dot{Q}_{HXi} = \dot{m}_b C_p \Delta T_{2b-3b}$	HX Power Exchanged (kW) ($\dot{Q}_{HXi}$)
Warm HX Pressure Drop (%) (ΔP_{HXia})		
Cold Mass Flow (kg/s) ($\dot{m}_b$)	$P_{2b} = \frac{P_{3b}}{1 - \Delta P_{HXib}}$	Cold Helium HX Input Pressure (Bar) (P_{2b})
Cold Helium Input Temperature (K) (T_{2b})		
Cold HX Pressure Drop (%) (ΔP_{HXib})	$P_{4a} = P_{1a} (1 - \Delta P_{HXia})$	Warm Helium Input Pressure (Bar) (P_{4a})
Helium Specific Heat (kJ/kg.K) (C_p)		
2 Stage Calculated Temperature Ratio ($\sqrt{\frac{T_{3a}}{T_{4b}}}$)	$\dot{m}_a = \frac{\dot{Q}_{HXi}}{C_p \Delta T_{2b-3b}}$	Warm Helium Required Mass flow (kg/s) ($\dot{m}_a$)
Warm Helium Output Pressure (Bar) (P_{1a})		
HX Input/Output Temperature Delta (K) (ΔT_{2b-3b})	$T_{1a} = T_{2b} - \Delta T_{HXi}$	Warm Helium Output Temperature (K) (T_{1a})
Cold Desired Temperature (K) (T_{4b})		
Cold Helium Output Temperature (K) (T_{3b})	$T_{4a} = \left[\left(T_{4b} \sqrt{\frac{T_{3a}}{T_{4b}}} \right) - \left(\frac{\Delta T_{HXi}}{2} \right) \right]$	Warm helium Input Temperature (K) (T_{4a})

Figure 8-24 – Intermediate heat exchanger model block and table showing inputs, transfer functions, and outputs

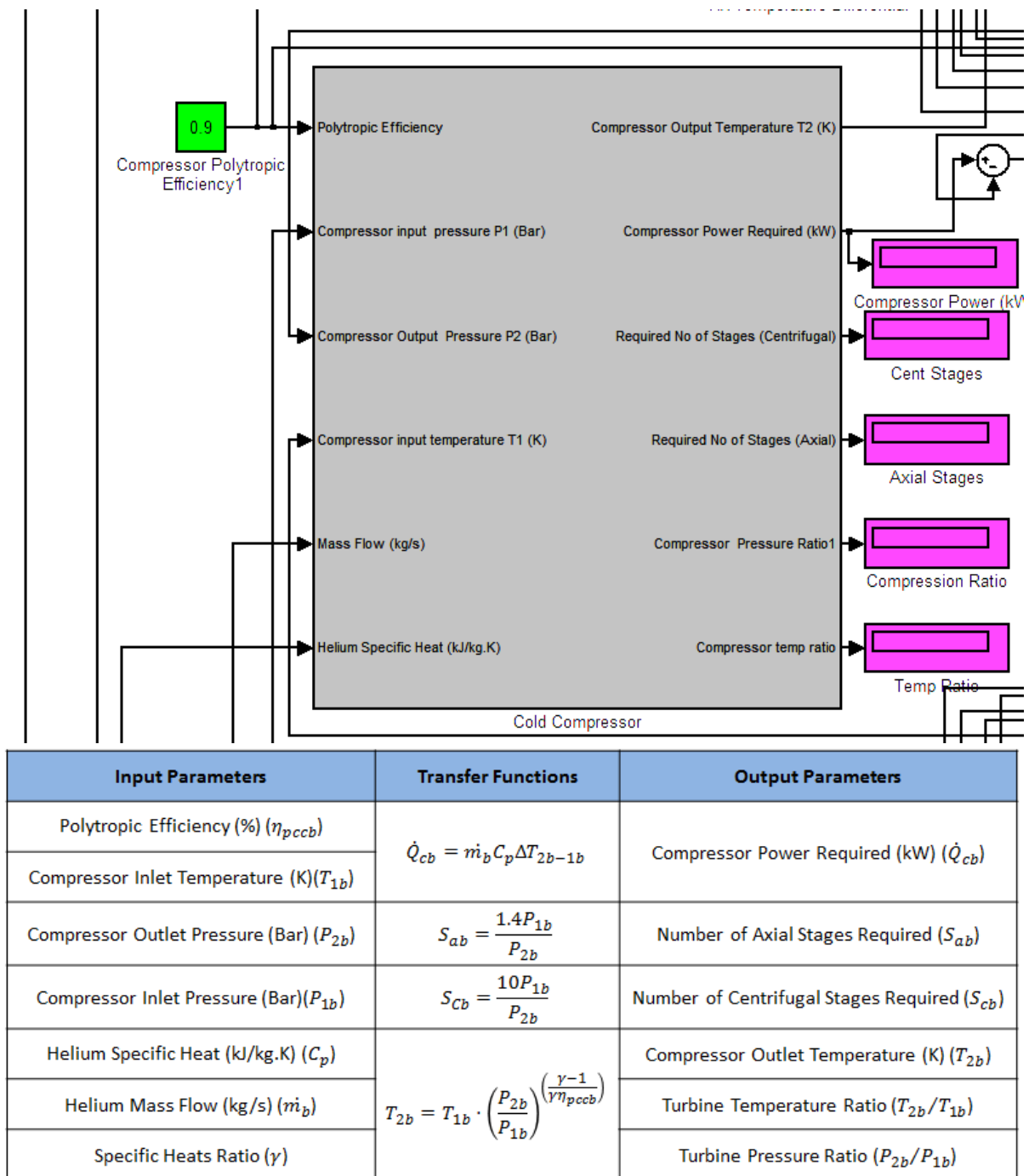


Figure 8-25 – Cold stage compressor model block and table showing inputs, transfer functions, and outputs

The cold stage compressor block and associated motor blocks are the same model block designs as previously used for the single stage model.

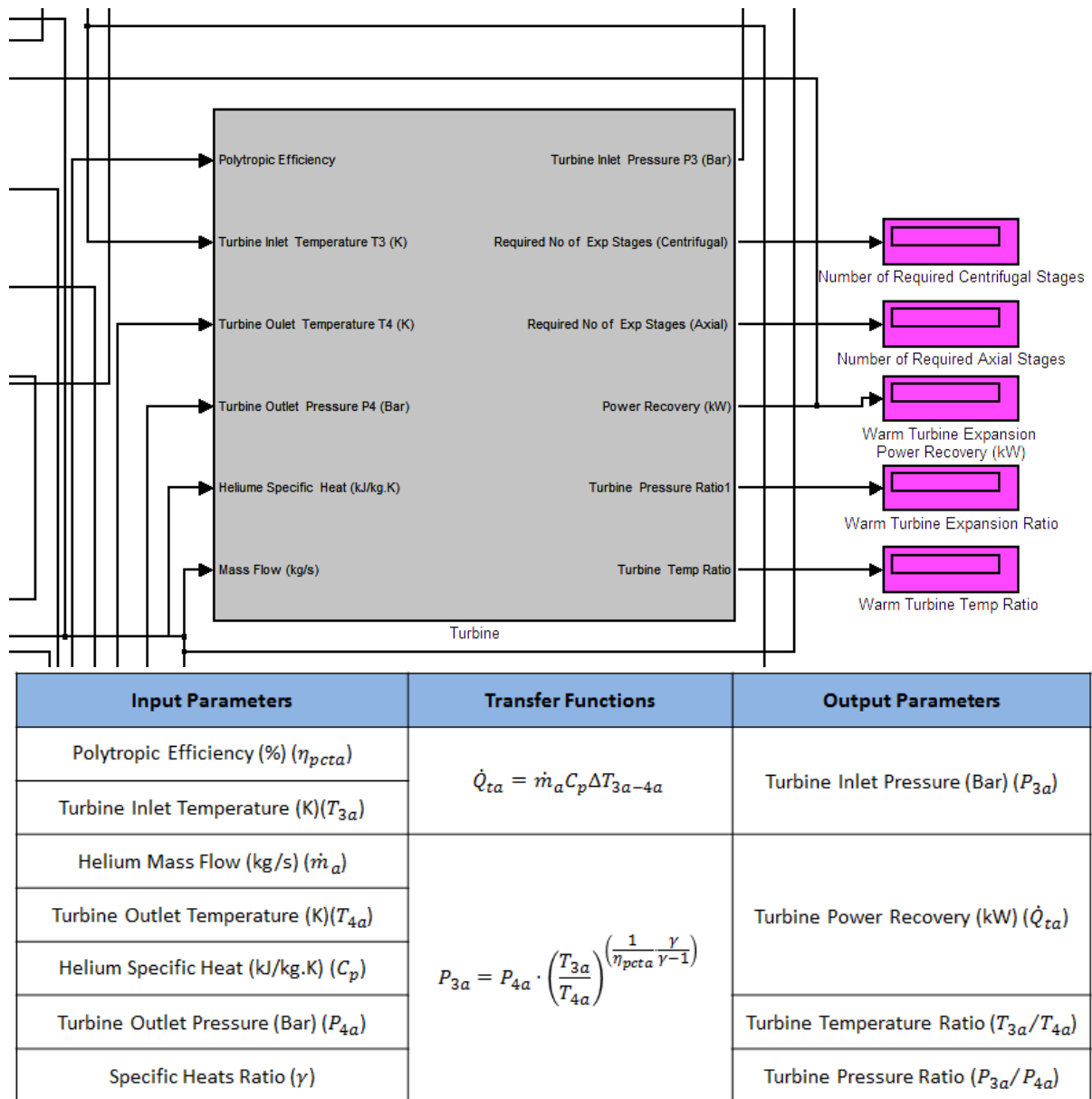


Figure 8-26 – Warm stage turbine model block and table showing inputs, transfer functions, and outputs

Figures 8-26, 8-27 and 8-29 all show that the warm stage model blocks are identical to those used in the single stage model.

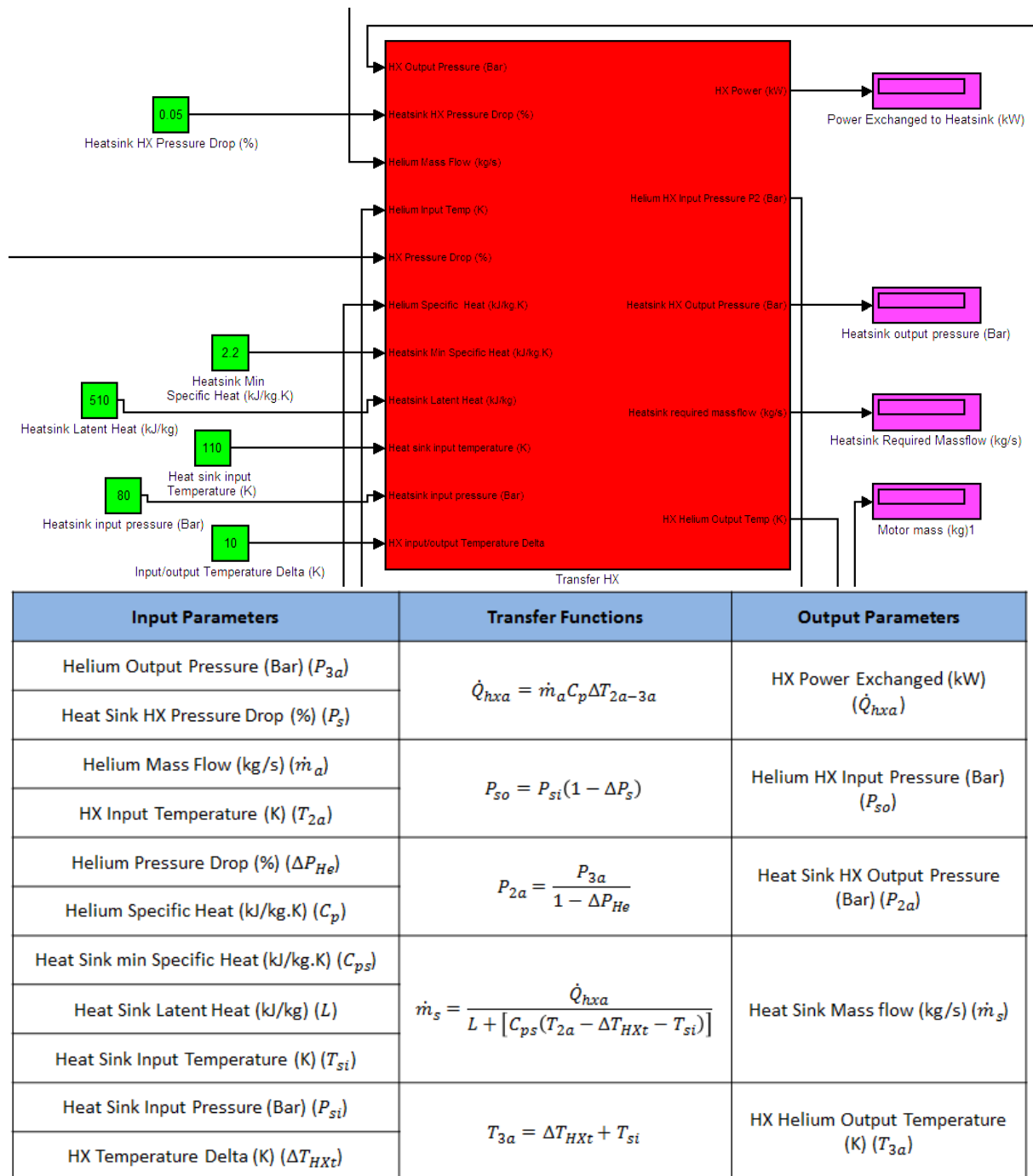


Figure 8-27 – Warm stage heat sink heat exchanger model block with table showing inputs, transfer functions, and outputs

The final aspects of the two-stage model are the motors and mass estimation. Since there are two sets of components, the mass estimation is performed per-stage and then added for a final value. This method of mass estimation is deemed valid since each stage has one warm heat exchanger; the intermediate heat exchanger is assumed to be of zero mass to the warm stage, and the cold heat exchanger is likely

to be integrated into the superconducting components. Therefore the cold stage cold heat exchanger mass can be ignored, and the mass estimation method is reasonable.

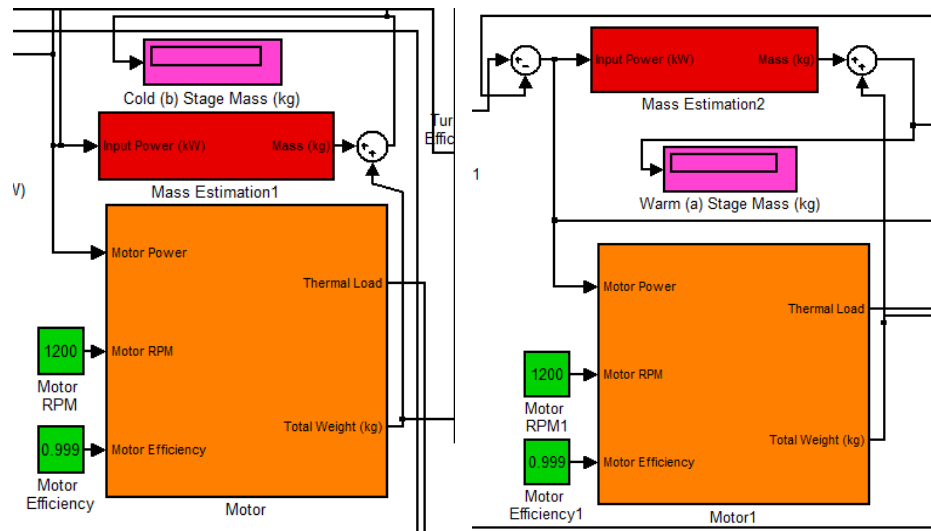


Figure 8-28 – Warm and cold model blocks for the two-stage RBC model

Finally, an overview is provided of the whole model so the parametric flow can be followed by the observer, shown in Figure 8-30.

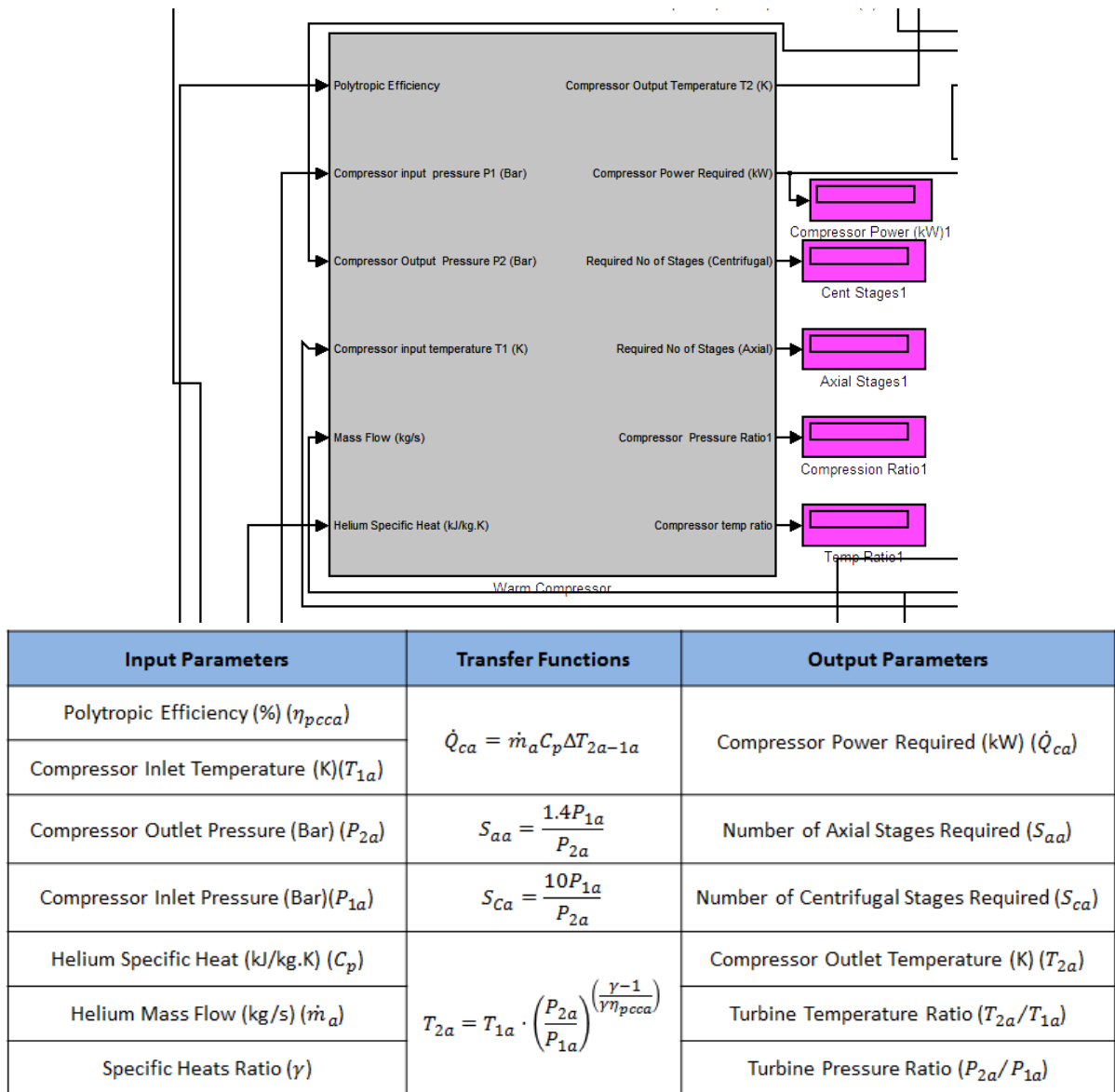


Figure 8-29 – Warm stage compressor model block and table showing inputs, transfer functions, and outputs



Figure 8-30 – Two-stage RBC model overview showing all components of the model, inputs, parametric flow, and outputs

8.4. Discussion

The outcome for this chapter is a set of two conceptual cryogenic cooling system models for the reverse-Brayton cycle cryocooler. Furthermore, the models were designed to be adaptive in nature, making them unique, and are able to be used in numerous configurations and concepts in order to test different configurations within the design space. The reverse-Brayton cycle (RBC) has been properly defined and the variants explored in this chapter, with two concepts being chosen for further modelling; single and two-stage RBC. The reason these two were chosen was to be able to derive the design space sufficiently such that the concept design space can be explored. The variants shown in this chapter have highlighted the high-level variables that can be explored once a preferred concept is chosen.

The two models constructed were chosen based on the uncertainty surrounding RBC design, particularly at high cooling powers. The method used allows fair comparison between the models as the methods used are consistent. New methods also had to be adopted; a new method for estimating the mass was derived, along with a method for determining the intermediate temperature between the hot and cold stages in the two-stage design. These novel modelling methods adequately facilitate the analysis during the next chapter to explore the relationships between key thermodynamic parameters and mass. Without these derived methods, mass estimation and fair parametric comparison would be largely invalid or impossible due to the high level of uncertainty surrounding mass.

The models themselves are deemed fit for the purpose of design space mapping. By constructing and understanding these models and taking a rigorous validation approach, the design space in different scenarios can be mapped, creating a level of understanding previously unknown regarding high-power aerospace cryogenics. Once the design space is understood in relation to specific parameters, a decision table can be constructed. This allows future designers to rapidly assess concepts based on minimal input parameters, and determine how the thermodynamic cycle must be architected. This method of rapid design iteration saves significant amounts of time during the design process.

The next chapter will focus on how effective these models are in mapping the design space, and will lead to a number of conclusions regarding whether modelling work used in the system process in the methodology specified is suitable. The ideal outcome will be confirmation of the validity of the approach and a first order component level understanding of which parameters are the key drivers for inefficiency within RBC concepts.

Chapter 9. Modelling Results Analysis

9.1. Introduction

This chapter focuses on the exploitation of the developed models to derive conclusions about the design space for cryogenic cooling system design. During this chapter, the impact of parametric variability will be explored to understand the subtleties present within the cryogenic cooling system and wider superconducting electrical system. The structure is to present the component-level and system-level variances first, which then feeds the analysis of the multi-system sensitivities. The outcome for this chapter will be a detailed numerical understanding of both the cryogenic and electrical systems, and how the key outputs such as required input power and mass vary according to certain design variables. There will also be a discussion on how the results can be interpreted moving forward, particularly the implications on future design work and analysis.

9.2. Cryogenic Cooling System Observations

9.2.1. Single Stage Model

The first section of the single stage cryocooler results focuses on two key input parameters and six key output parameters. The input parameters are:

- **Compressor Polytropic Efficiency** – This input parameter is designed to highlight the sensitivity of output parameters to input parameters and to reveal whether the compressor (and as a result the turbine) is a critical component as qualitative methods suggest. This figure is varied between 75% and 92% in order to reflect the best and worse-case compressive scenarios envisaged in aerospace design when taking the helium working fluid into account.
- **Heat Exchanger Pressure Drop** – Since pressure largely dictates the efficiency of a compression system, the pressure drops should be varied across the heat exchangers available; this has two effects. The first is that it compensates for the assumption of no transport losses in pressure terms, and the second is that it allows the potential elimination of future heat exchanger pressure sensitivity concerns. This parameter is varied between 1% and 15% to reflect available heat exchanger pressure drop data found from various

sources. The 15 % figure is intended to be overly pessimistic such that the likely range of values for heat exchanger pressure drop is captured.

The output parameters used are:

- Required Input Power – This shows how much power is required at that design condition for a given cryocooler to operate.
- Mass – This shows how much mass the cryocooler has at any given design point.
- Required Pressure Ratio – This indicates the required pressure ratio for the compressor to deliver at a given design point.
- Overall Efficiency – This shows the overall efficiency of the cryocooler taken from the difference between input power and output cold power.
- Percentage of Ideal Efficiency (Carnot) – This shows as a percentage how much of the ideal efficiency (Carnot) is achieved at a given design point.
- Target Specific mass – This shows the target specific mass of a cryocooler at any given design point, and provides an indication of feasibility for future practicality.

This section will highlight the effect of various input parameters on these six output parameters. Some results are discussed in later sections when it is necessary to compare the single stage results to those of the double stage cryocooler concept. For the purposes of the six-output parameter single stage comparison, the temperatures are fixed to $T_c = 20$ K and $T_h = 110$ K. This variable will be explored during the latter part of this chapter.

The first of these is input power, shown in Figure 9-1. The graph illustrates that the heat exchanger pressure drop makes little difference to the required input power when compared to the compressor polytropic efficiency. As can be observed from Figure 9-1 a 10% change in pressure drop results in a required input power increase of between 10 and 100 kW (Taken between 75% and 92% polytropic efficiency lines). When the same 10% difference is applied to the compressor polytropic efficiency however, a significantly larger increase of between 480 and 550 kW is observed (Taken at the 5% and 15 % pressure drop points). This indicates early on that the compressor polytropic efficiency is significantly more critical than the

pressure drop when considering the efficiency of a cryocooler. Furthermore, the compound effect observed shows that the pressure drop impact on required output power is worsened as the compressor polytropic efficiency falls, and vice versa. This would suggest that although the compressor polytropic efficiency is shown to be significantly more critical, that the heat exchanger pressure drop (and by association the transport pressure losses) should not be ignored.

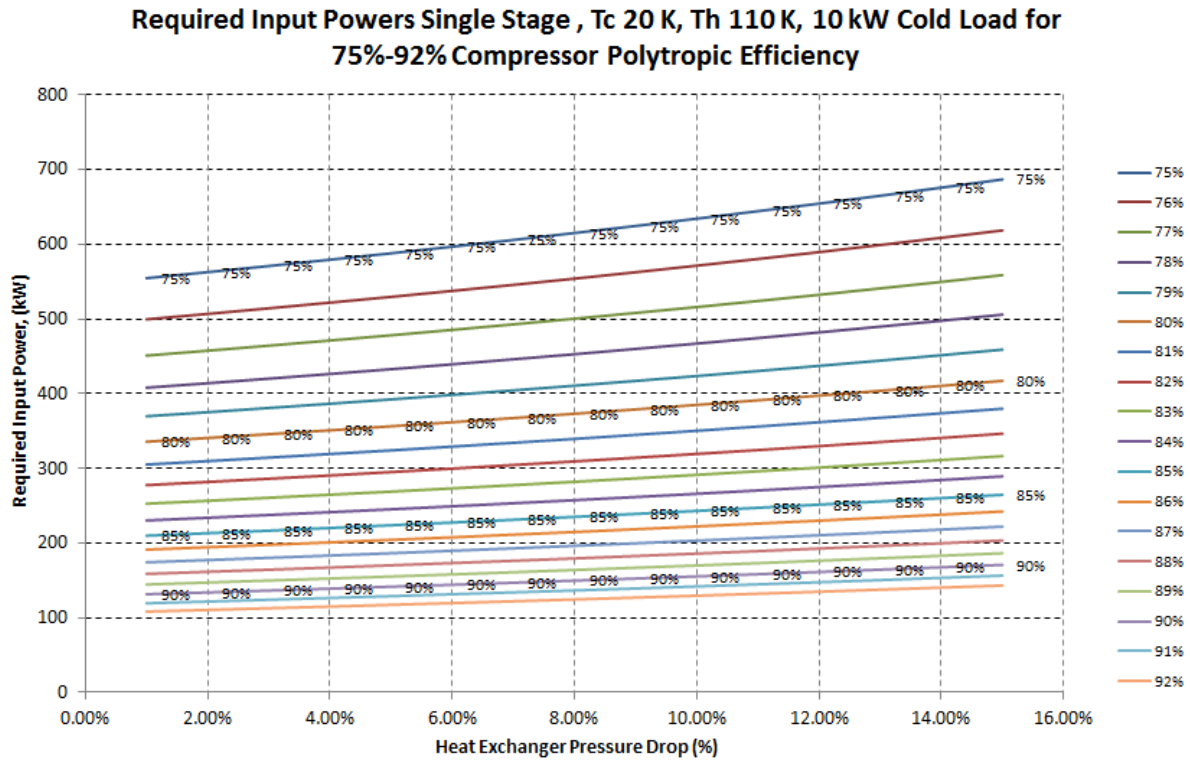


Figure 9-1 – Required input powers for a single stage cryocooler

Figure 9-2 shows the corresponding masses for the powers shown in Figure 9-1. The figure indicates that for the least efficient compressors, the mass is around double that of the most efficient. The translation of power into the mass equation highlights that despite having nearly 400% more required input power, the mass increase of an inefficient concept is limited by the damping effect of the exponent of the mass equation originally shown in Figure 8-12:

$$m_{RBCC} = 27.5 P_{input} e^{-1.225(\log_{10} P_{input})}$$

Furthermore, the minimum associated mass with a cryocooler means that as the input power reduces, the mass decrease diminishes increasingly, leading to a less

sensitive mass relationship. The mass also dampens the compound effect described previously with Figure 9-1, with the highest and lowest efficiency concepts showing relatively little difference to their nearest counterparts.

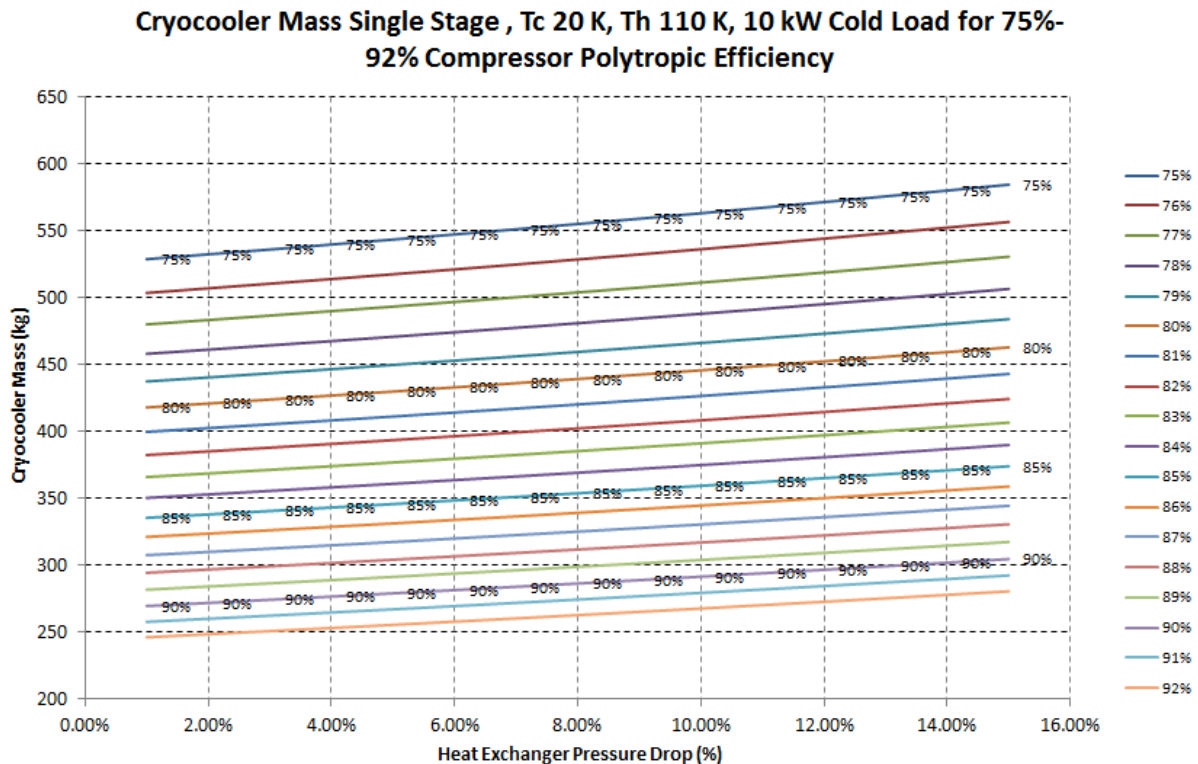


Figure 9-2 – Cryocooler mass for a single stage cryocooler

Figure 9-3 shows the pressure ratio required for the compressor for the 92% polytropic compressor efficiency case. This graph is intended to check the feasibility of construction of a real world example. Since the physics of the model allows comparison of any parameter within and without reason, the feasibility of a concept can easily be overlooked. Figure 9-3 shows that for even the most efficient single-stage cryocoolers, at the temperatures defined the pressure ratio is completely unrealistic. Figure 9-3 shows the 1, 2 and 3 stage compressor regions. It is assumed that the maximum pressure ratio for a single stage compressor is 10:1, assuming a high-efficiency centrifugal or axial-centrifugal compressor. Since the mass estimation rule begins to break down as more compressor stages are added, it is assumed that 30:1 as an overall pressure ratio is considered the maximum practical limit.

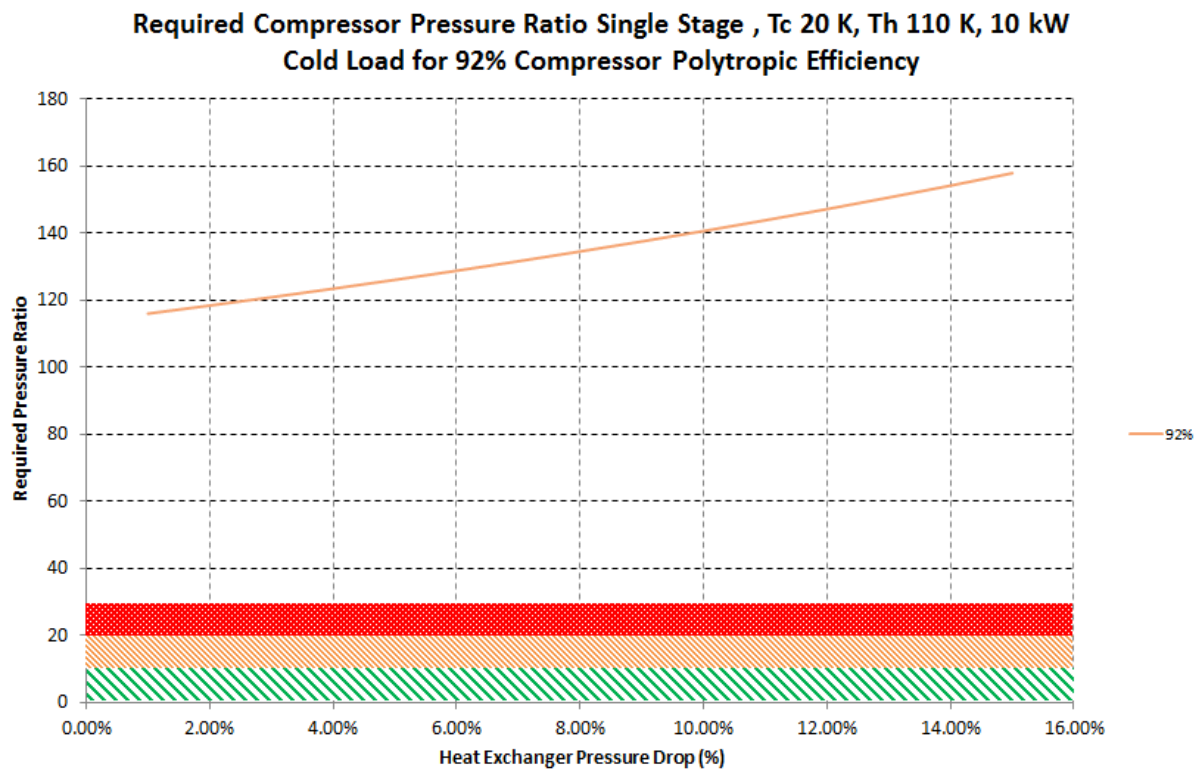


Figure 9-3 – Required compressor pressure ratio for a single stage cryocooler with 1, 2, and 3 stage compressor regions shown between ratios 0 and 30

At 92%, the single stage concept requires pressure ratios in excess of 100 and rising to over 150 for the highest heat exchanger pressure loss cases. This is deemed unfeasible; hence the single stage concept is unlikely to be the final concept. Reasons for such unfeasibility are the temperatures of operation; since the temperature change from the T_c to T_h parts is 90 K, it is highly likely that for lower temperature delta concepts, the single stage will become more viable. Moving forward, it is worthwhile exploring the other remaining three output parameters for sensitivity and relationship understanding purposes.

Figure 9-4 shows the predicted overall efficiency for the single stage concept. The graph shows a significant variation in efficiency from the most to least polytropic efficient compressor lines, with an average variability from 75% to 92 % of 6.35%. The heat exchanger average efficiency change from 1% to 15% loss is 0.81%. This confirms that of the heat exchanger and compressor components, the compressor is the most critical efficiency driving component.

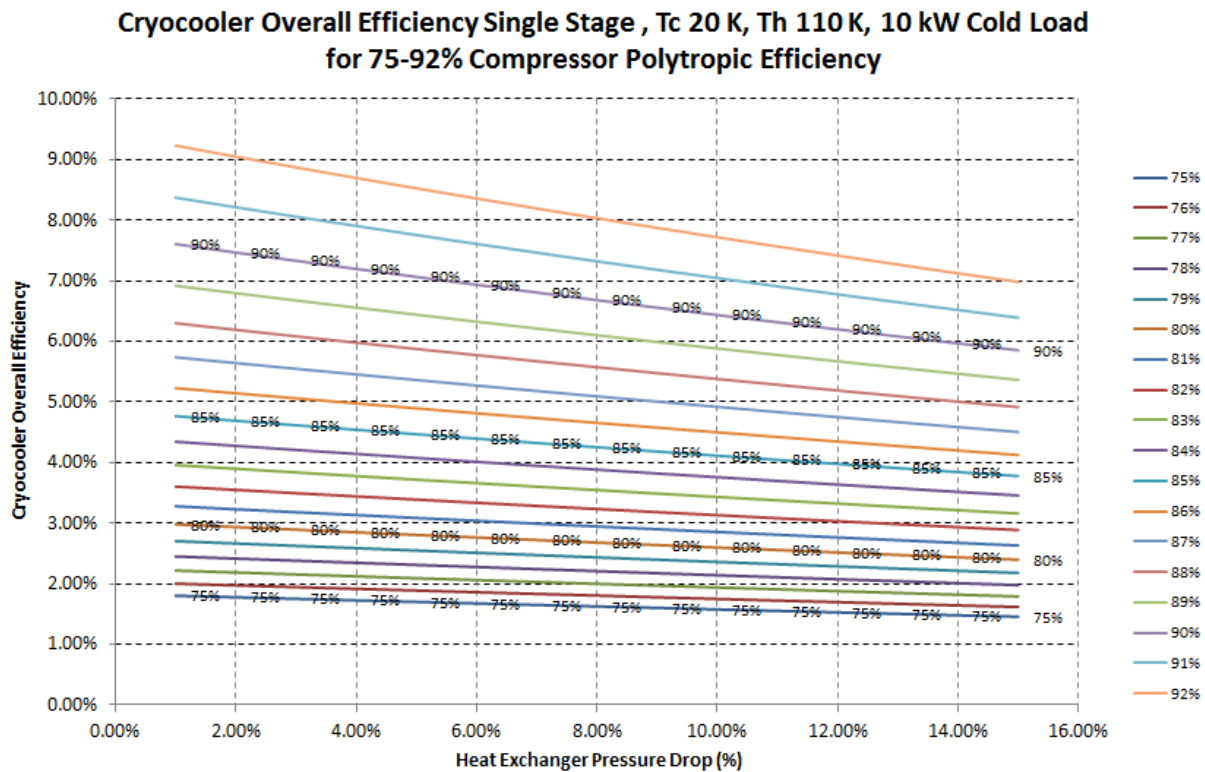


Figure 9-4 – Cryocooler overall efficiency for a single stage cryocooler

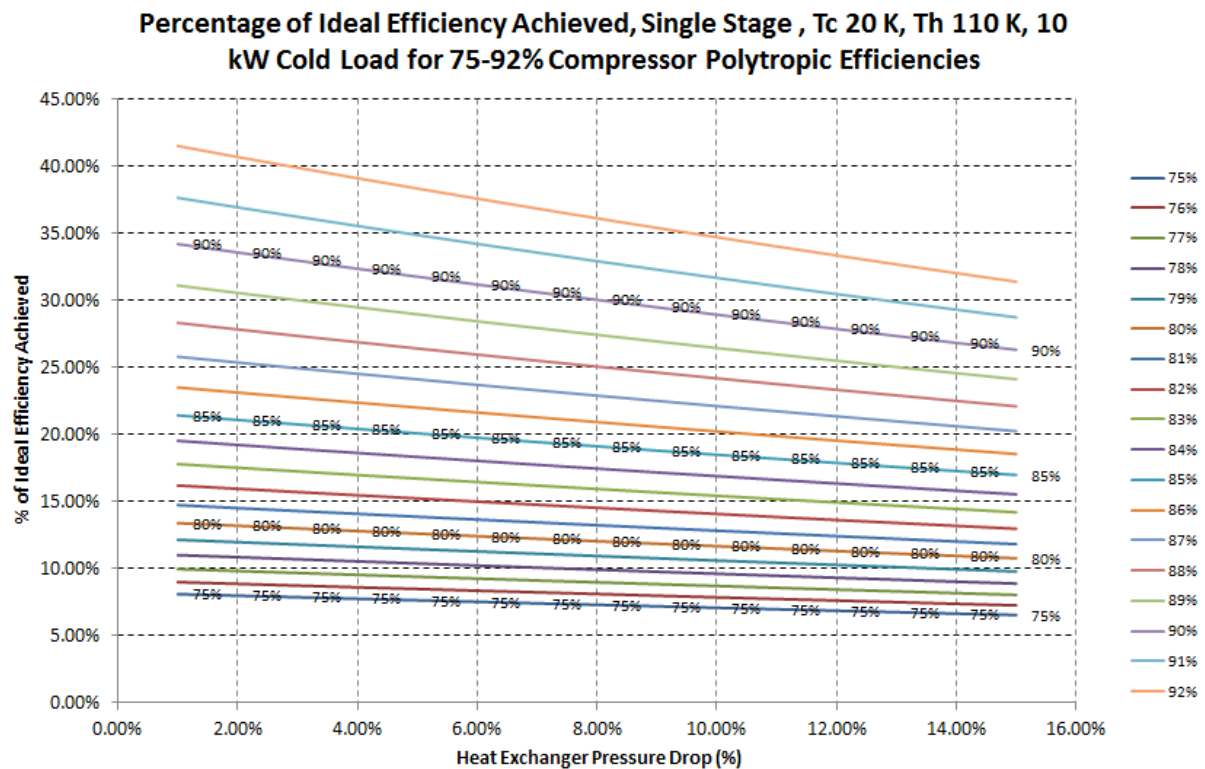


Figure 9-5 – The percentage of ideal efficiency achieved for a single stage cryocooler

Figure 9-5 shows the percentage of the ideal efficiency for the single stage cryocooler design space. The reason this figure is important in this investigation is that it is one of NASA's key technological targets for cryocoolers to hit 30% of Carnot efficiency (Felder *et al*, 2011). Figure 9-5 suggests that for that to become a reality for single stage cryocoolers, both pressure drops and compressor polytropic efficiencies will need to be optimised. Although the pressure ratio figures for this concept are unfeasible, this analysis gives an indicative view of the likely development work that must take place to make high-efficiency components a reality, and provides a performance target beyond the overly simplified figure of 30% of Carnot.

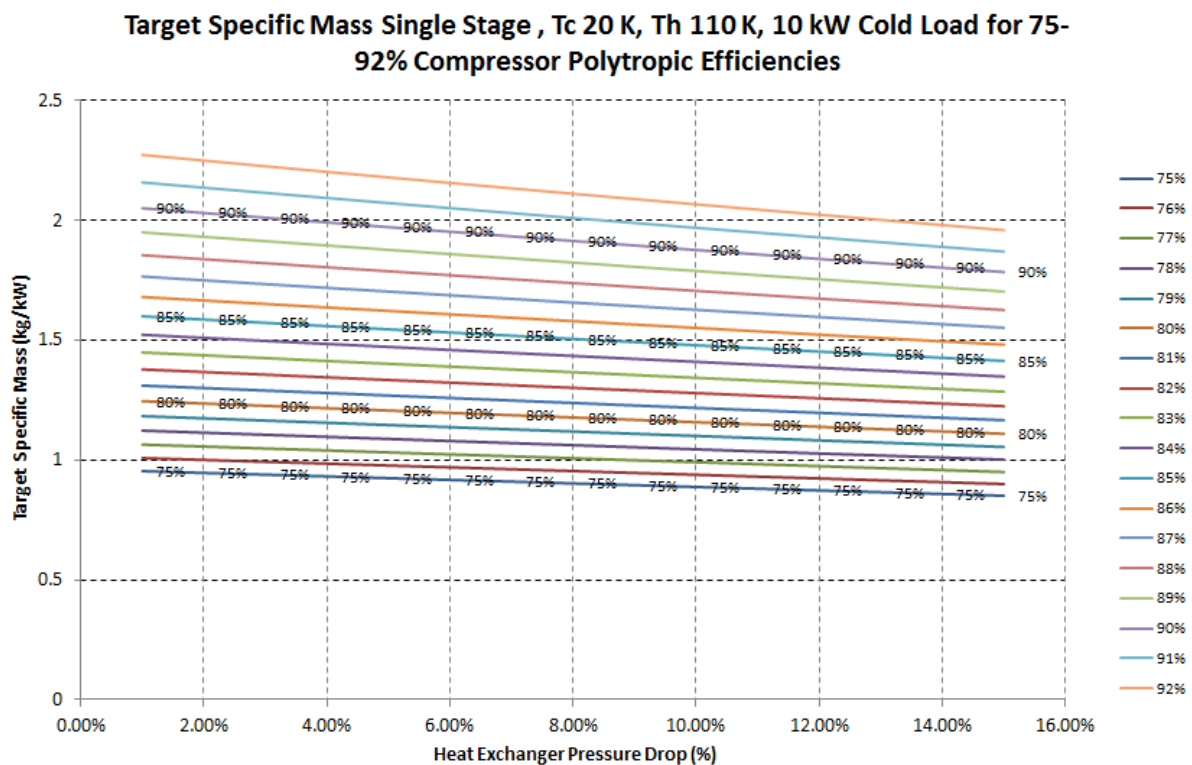


Figure 9-6 – The target specific masses for a single stage cryocooler

Figure 9-6 shows the specific mass target for the cryocooler at given design points. This comparison is useful as a measure against NASA's 3 kg/kW input power target stated previously. Using the figure as a guide, the single stage again shows infeasibility as a concept, as no value or range meets this 3 kg/kW target.

From these analyses, it is clear that single stage reverse-Brayton cryocoolers are not viable for the temperature conditions outlined ($20\text{ K } T_c$, $110\text{ K } T_h$). This is likely to

change however when considering different heat sinks and their respective temperatures. There are three potential heat sinks in consideration; liquid hydrogen at 21 K heat exchanger inlet temperature (LH_2), liquid methane/liquid natural gas at 110 K heat exchanger inlet temperature (LCH_4), and ambient air, at 300 K heat exchanger inlet temperature. There are numerous aircraft-level and wider airport infrastructure level implications for using each of these three heat sinks, however those are not considered in this study; this study is looking only at the cryogenic system implications and potential wider electrical system implications.

The other major variable to be examined is the cold temperature. Since there are a number of different superconducting materials, it is worthwhile investigating how the two major assumptions within NASA's N3-X concept affect the overall performance of a cryocooled solution. MgB_2 and BSCCO (Bi-1222 configuration) are considered, with respective operation temperature between 10-30 K and 55-75 K respectively for this study. The operation temperature is chosen to reflect the safety margin required below a superconducting materials critical temperature for use in practical operations without the threat of quenching. Furthermore, this temperature range for each superconductor allows the prospect of sufficiently high magnetics fields to be generated without quench.

By assessing whether each potential heat sink and superconductor can meet targets outlined, the single stage cryocooler analysis can be completed to a reasonable degree of confidence, with decisions robustly made on which configurations can feasibly result in its use. The analysis assumes a constant pressure drop and constant compressor and turbine polytropic efficiency, with a fixed temperature difference in each heat exchanger (except the heat sink) of 10 K.

Figure 9-7 shows the temperature cold targets against the required input power for the three heat sinks. The LH_2 heat sink is not considered for the 55 K BSCCO case since its boiling temperature at atmospheric pressure is below the target temperature. The graph shows the large difference in required input power for each concept, with the LH_2 concept requiring low input power to remove the 10 kW heat load. The LCH_4 cooled 55 K concept for the single stage also shows a low required input power. The graph highlights the impact that temperature has on required input power, with the characteristic exponential rise in required input power shown for the

lower temperature concepts. Based on Figure 9-7, the single stage concept may only be useful for the 55 K LCH₄ cooled or 10 K LH₂ cooled configurations.

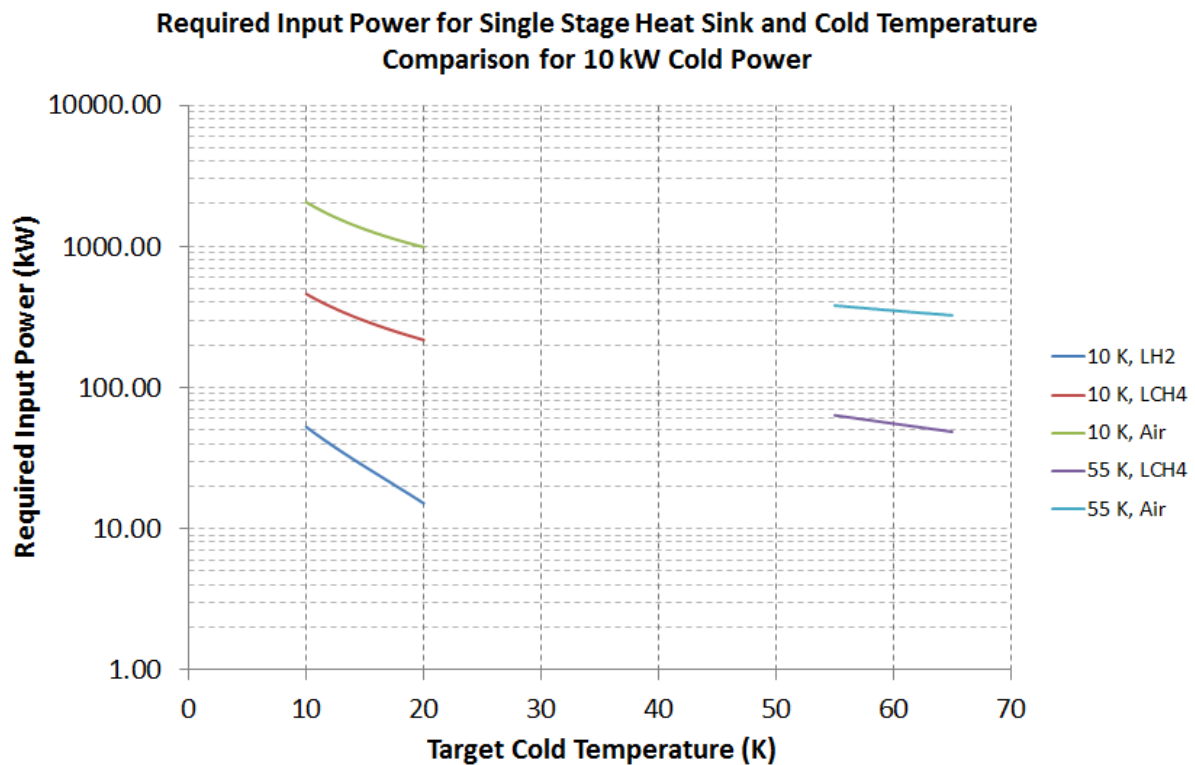


Figure 9-7 – Required input power for heat sink and target cold temperatures for single stage cryocoolers

It is necessary to perform the same feasibility check on all concepts as previously with Figure 9-3, by examining the required pressure ratios. Figure 9-8 shows the pressure ratios for the five concepts outlined in Figure 9-7. As previously mooted, the only feasible concepts are the 10 K LH₂ concept and the 55 K LCH₄ concepts, with pressure ratios below 30, allowing feasible practical fabrication. The other concepts show high-to-extreme pressure ratios required, with the air concept requiring pressure ratios of over 10,000.

Figure 9-9 also supports the previous conclusion; the target specific masses for the feasible concepts are above the NASA target of 3 kg/kW. This supports the final conclusion on the single stage analysis that only the LH₂ concept can be feasible with a single stage cryocooler when using MgB₂ as the superconducting material, and the LCH₄ concept when using a BSCCO superconductor.

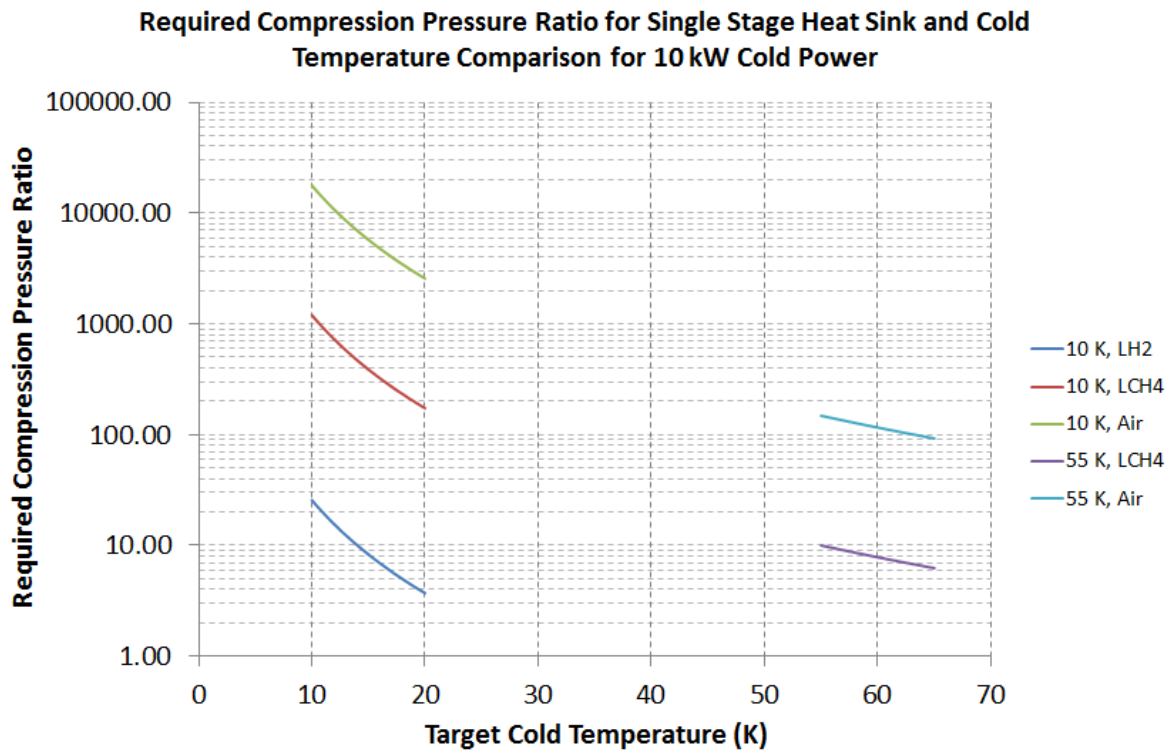


Figure 9-8 – Required pressure ratio for single stage cryocooled concepts at different heat sink and target cold temperatures

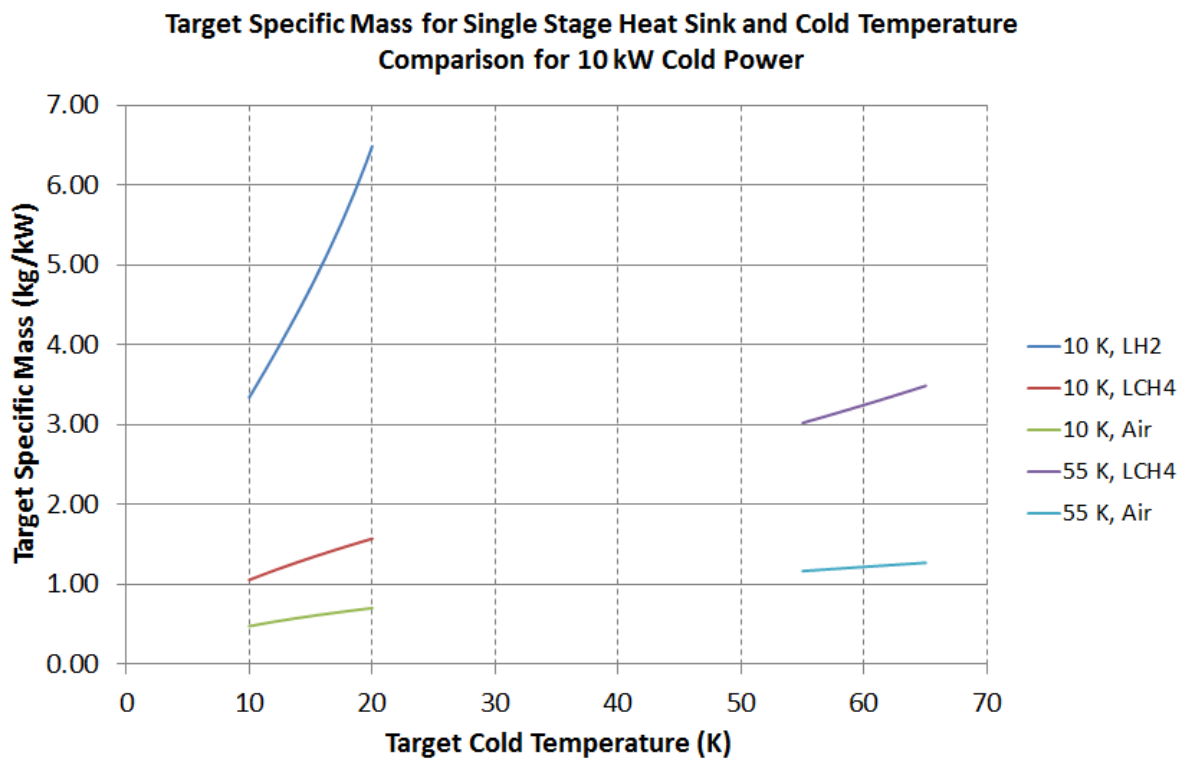


Figure 9-9 – The target specific masses of the heat sink and cold target temperature concepts for the single stage cryocoolers.

9.2.2. Two-Stage Model

The two-stage model analysis is conducted in the same way as the single stage analysis, whereby the pressure drops and polytropic compressive efficiencies are first analysed, with the analysis moving towards the heat sink and temperature concept cases. The two-stage analysis will use the 20 K T_c and 110 K T_h assumptions for the six output cases outlined previously, as well as the 10 kW heat load assumption.

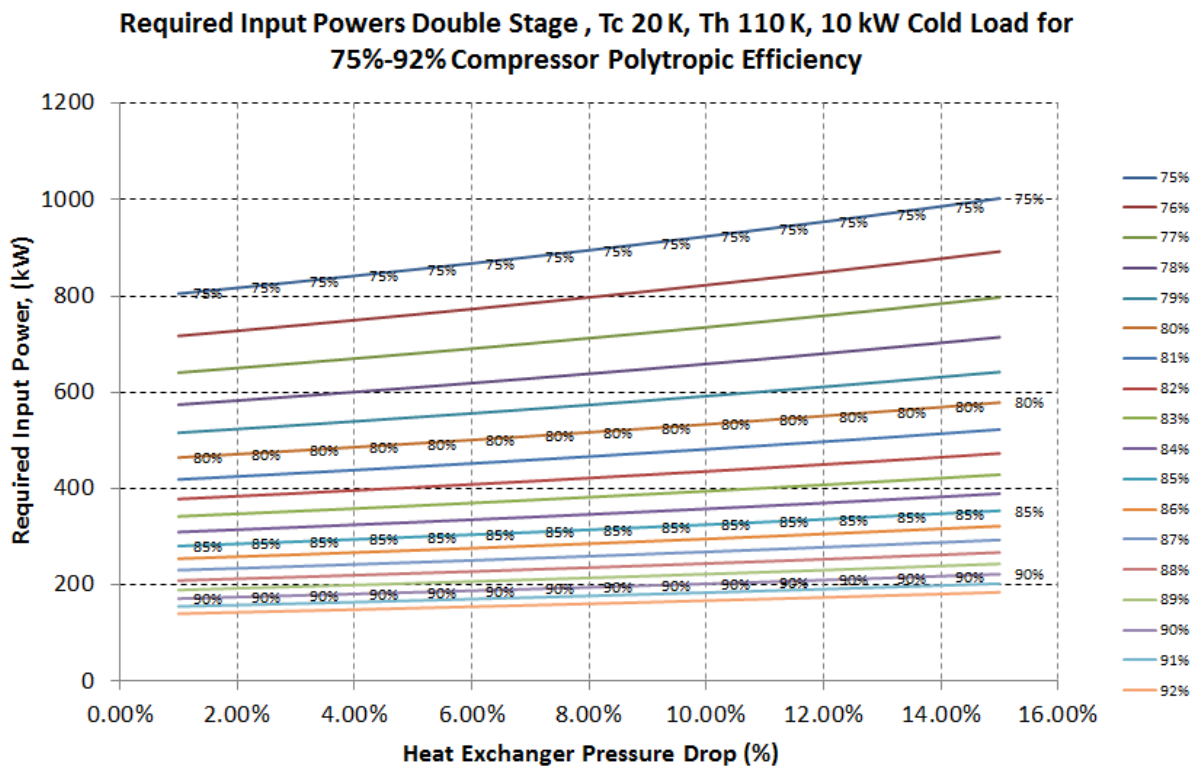


Figure 9-10 – Required input power for two-stage cryocooler

Figure 9-10 shows the variation in required input powers for the two-stage model. As with the single stage model, the compressor polytropic efficiency is shown to be the most critical parameter over the heat exchanger pressure drop, with the same compounding effect observed as with Figure 9-2. The overall power amount is higher when considering the single stage concept, which can be attributed to the efficiency impact of having two stages instead of one, therefore applying the same inefficiencies twice.

Figure 9-11 shows the corresponding mass increase for Figure 9-10. The masses are higher than with the single stage model, however the minimum associated mass

is doubled due to the two-stages instead of one, hence the mass increase is larger than expected. The mass increase is significant; between a 70% and 80% overall mass increase from the single stage design is observed, compounded by the minimum associated cryocooler mass effects and the higher overall required input power.

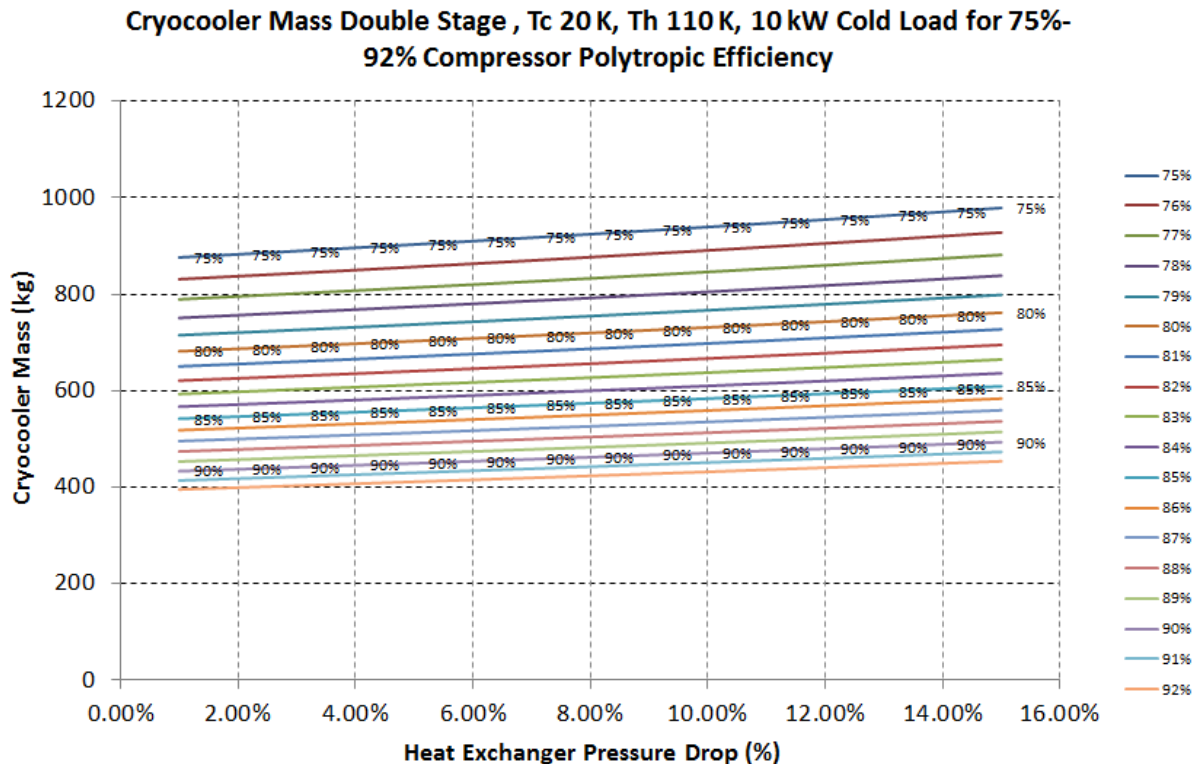


Figure 9-11 –The masses of a two-stage cryocooler

However, since the single stage design is severely limited by its feasibility given the required pressure ratios, the two-stage design pressure ratios shown in Figure 9-12 are far more reassuring. In all cases in Figure 9-12, the two-stage concept meets the 30:1 pressure ratio feasibility limits, with many of the higher compressor polytropic efficiency values allowing a two-stage compressor rather than a three-stage. This is a significant result for the 20 K cold target 110 K heat sink concept, since it potentially allows feasible design studies to take place. The higher associated mass and required power input is detrimental to the concept. However the reality of feasibility means that two-stage designs are far more viable for cryocooling over single stage designs at higher heat sink temperatures and larger temperature differentials between hot and cold stages.

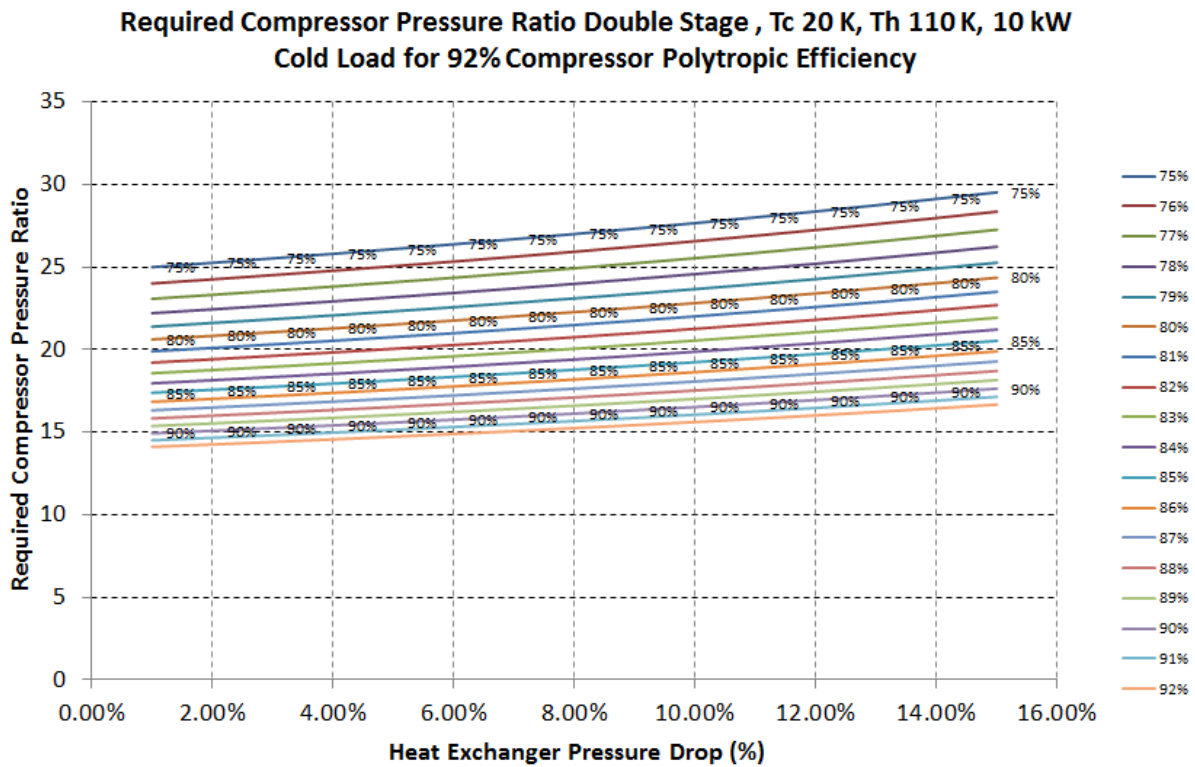


Figure 9-12 – Required compressor pressure ratios of a two-stage cryocooler

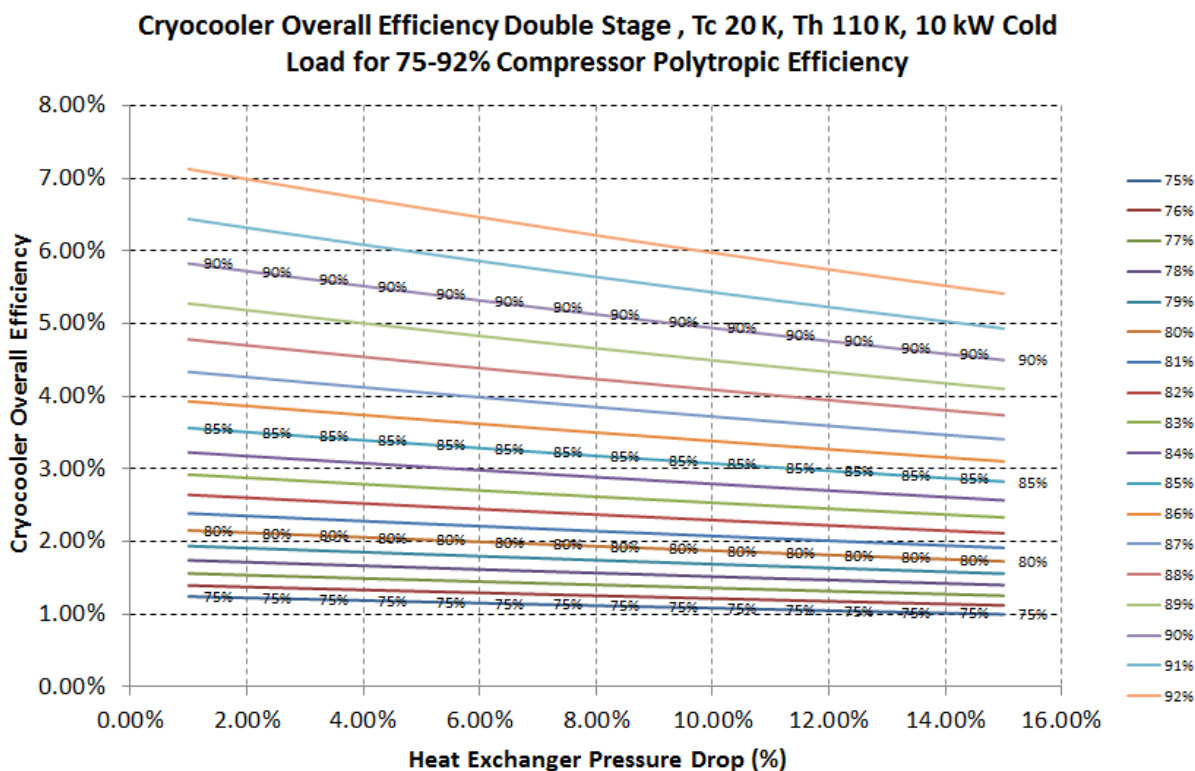


Figure 9-13 – The overall efficiency of two-stage cryocoolers

Figure 9-13 shows that the overall efficiency of the design is severely impacted again by the compressor polytropic efficiency. Interestingly, the efficiency range is smaller than with the single stage graph of similar nature (Figure 9-4). This would suggest that the two-stage cryocooler is less susceptible to component performance sensitivities than the single stage cryocooler design.

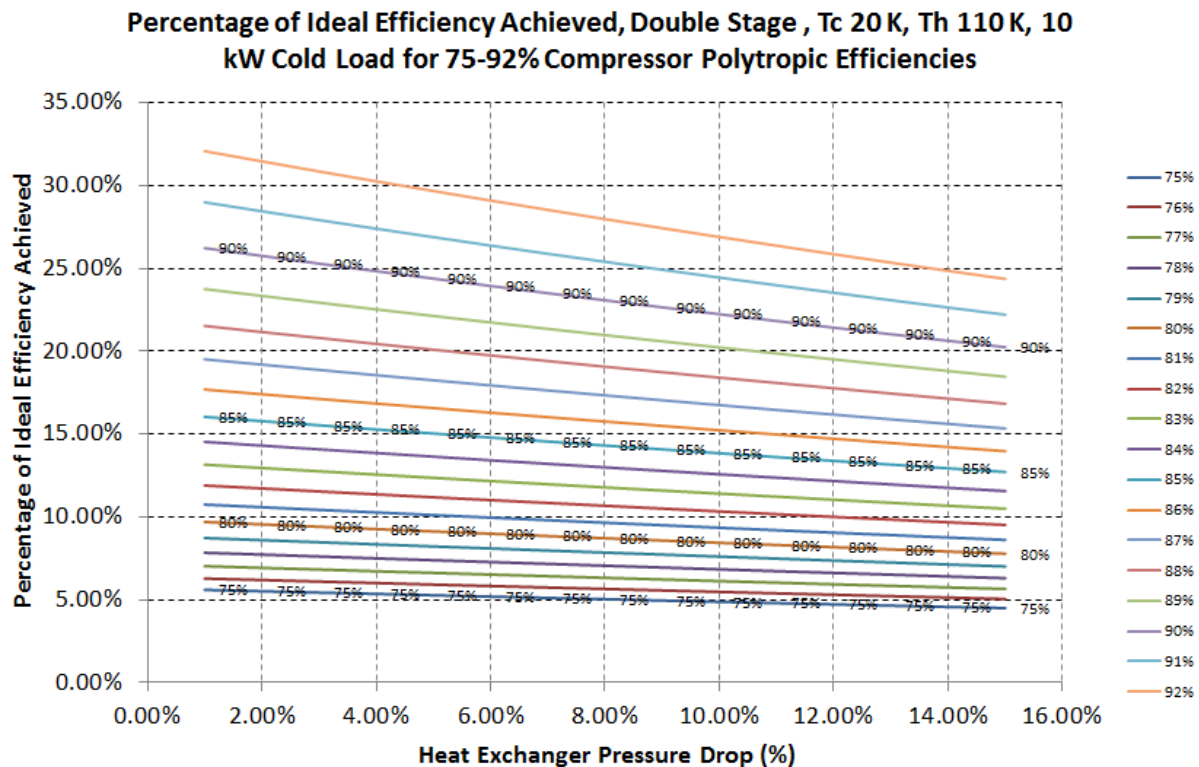


Figure 9-14 – Percentage of ideal efficiency achieved by a two-stage cryocooler

Figure 9-14 shows the expected drop in ideal efficiency of the two-stage design given the higher required input power for the same cold load. As with Figure 9-13 however it can be seen that the overall ideal efficiency differential from most efficient to least efficient compressor design is smaller. This again suggests a lower sensitivity to component performance than with single stage designs for two-stage versions. The NASA target figure of 30% of Carnot is achieved by the two-stage design at the highest component level efficiencies for both compressor and heat exchanger pressure drops. This suggests that although not unfeasible, the NASA goals are highly aggressive and could be challenging to meet.

Similarly, Figure 9-15 shows the concept target specific masses for the two-stage design. The results suggest that the two-stage concept will struggle to meet the

NASA specific mass target of 3 kg/kW in the configuration case used for component analysis, however the targets are far more achievable than with the single stage results of the same concept shown in Figure 9-6. From a feasibility perspective the two-stage design appears far more palatable, with targets for specific mass more likely to be met earlier with developments in compressor and heat exchanger technology as research progresses.

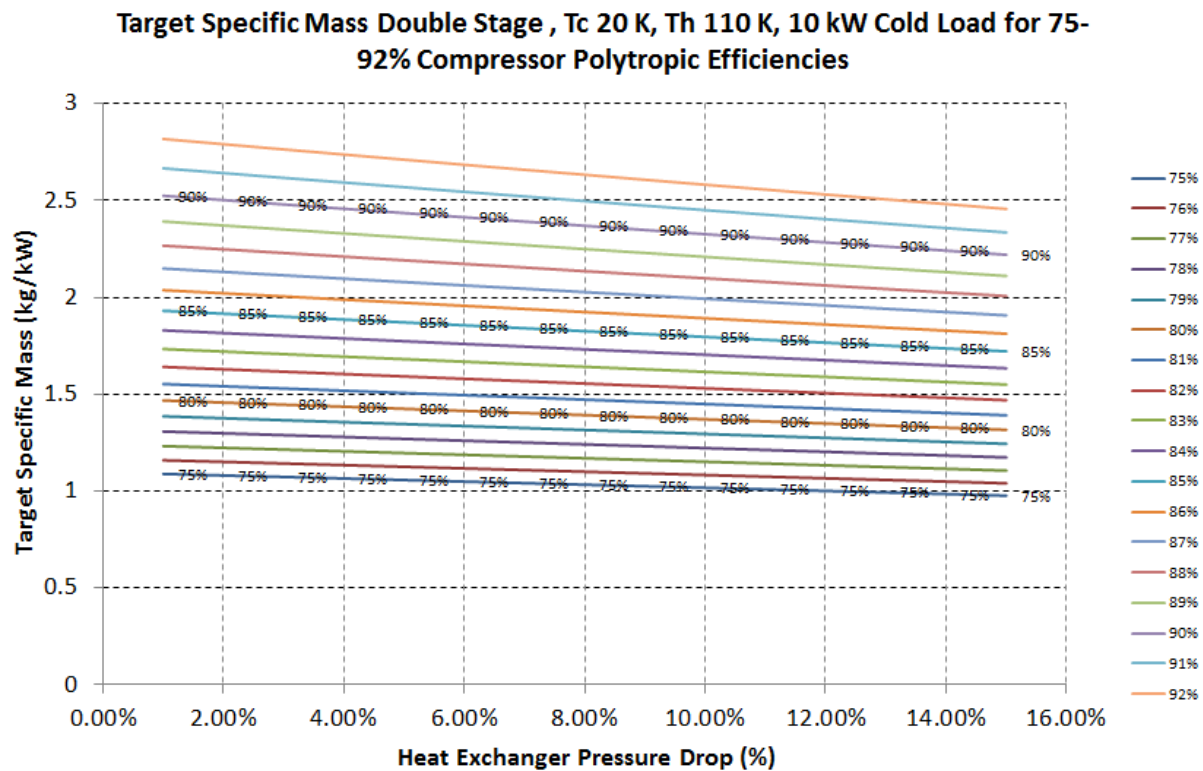


Figure 9-15 – The variation in target specific mass of a two-stage cryocooler

It is when considering the viable range of temperatures however that two-stage designs begin to realise their advantages over single stage designs. Figure 9-16 shows the required input power for the heat sink and cold temperature target cases previously described in Figure 9-7. The required input power in all cases is higher than those of the single stage designs for reasons previously stated. However when considering the feasibility factors of pressure ratio and target specific mass in Figures 9-16 and 9-17 that the advantages become clear.

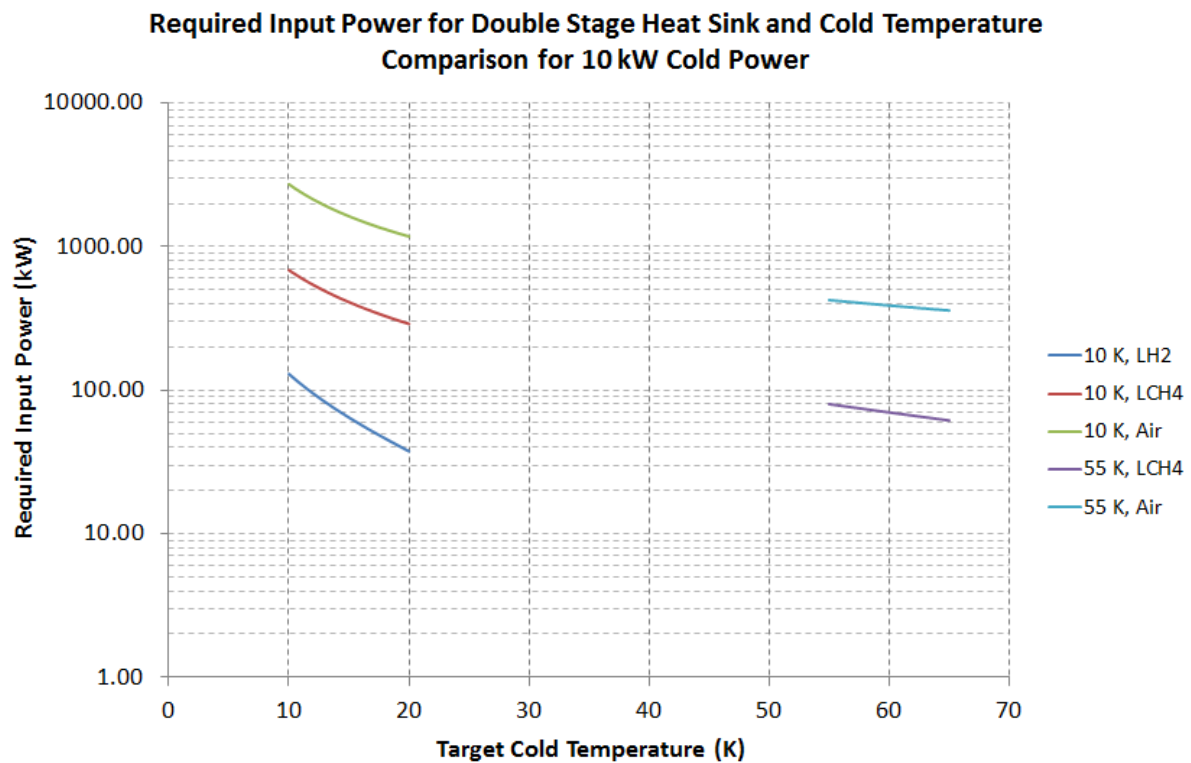


Figure 9-16 – The required input power for two-stage cryocooler at different heat sink and cold target temperatures

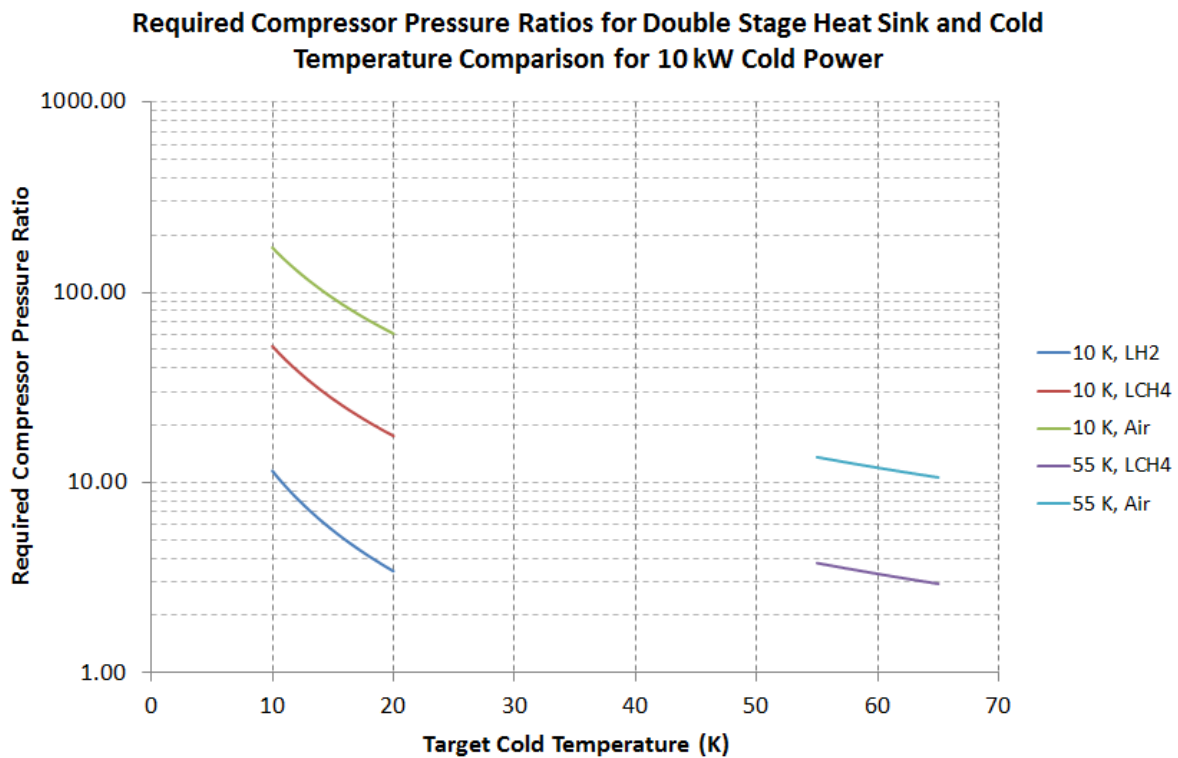


Figure 9-17 – The two-staged average required compressor pressure ratios for two-stage cryocooler at different heat sink and cold target temperatures

Figure 9-17 shows that the required compressor pressure ratio is feasible for four out of five concepts, with both BSCCO concepts showing high feasibility with lower than 20:1 pressure ratios. The MgB_2 concepts show high feasibility also, with only the air heat sink proving unviable. The LCH_4 heat sink concept in Figure 9-17 shows a transitional pressure ratio range of between 52:1 and 18:1, showing that the cold desired temperature has a large impact on the design requirements of the compressor.

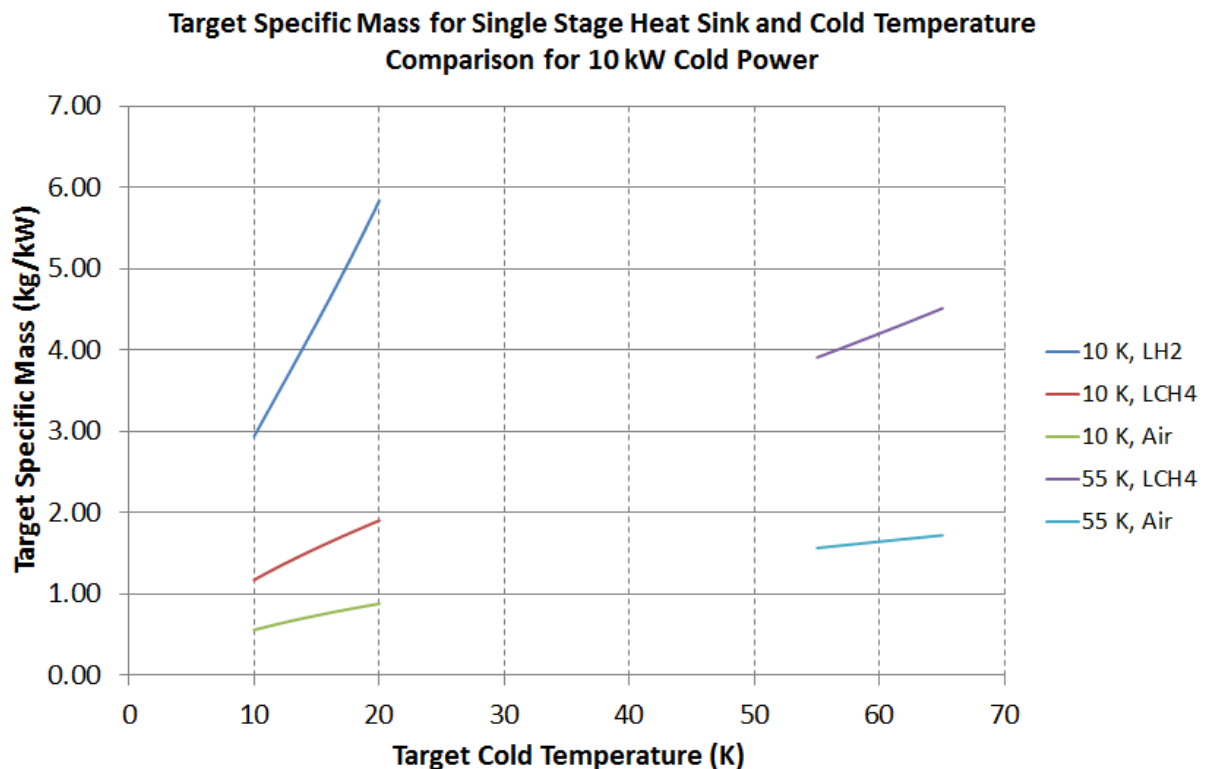


Figure 9-18 – Target specific masses for two-stage cryocoolers for various heat sink and cold target temperatures

Figure 9-18 shows the range of target specific masses for the two-stage design. Contrary to the pressure ratio results shown in Figure 9-16, the feasibility of the LCH_4 -cooled MgB_2 concept is reduced, suggesting that a minimum target specific mass of 2 kg/kW is necessary before even the highest cold temperature can feasibly be realised. The LH_2 cooled concept shows promise as with the single stage, suggesting that even using present day technology, cryocoolers can feasibly be constructed to meet the specific mass target outlined by NASA. Further to the previous graphs for the two-stage design versus single stage, Figure 9-16 also suggests that future improvements within compressor technology will impact two-

stage designs more than with single-stage. This assertion is corroborated when considering how two-stage designs require a minimum of two separate compressors; although detrimental performance affects are doubled, so are performance gains. This would suggest that not only are two-stage designs more feasible over a larger temperature range, but they will also show more improvement in the future with compressor efficiency improvements and other performance developments.

9.2.3. Concept Comparison

It is necessary to compare and contrast both the single stage and two-stage cryocooler concepts in order to establish design boundary conditions for each potential configuration option. This section will cover the previous set of generated data in detail in comparison for the 20 K cold temperature 110 K heat sink temperature configuration. Then an overview of the different temperature configurations will be briefly commented upon with a summary of findings for each temperature case. The format will once again focus on the two input variables (Compressor polytropic efficiency and heat exchanger pressure drops) as previously. There are six comparisons as before.

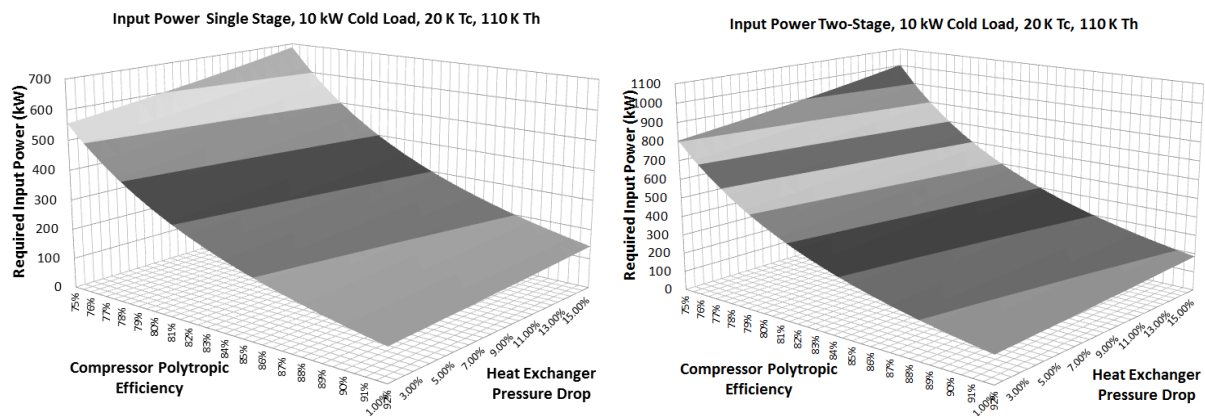


Figure 9-19 – Surface plots showing the required input power for both single stage (left) and two-stage (right) cryocooler designs

Figure 9-19 shows the difference in required input powers between single and two-stage cryocoolers. The graphs show that the two-stage model has a greater range of required input powers, with a larger overall input power requirement. As previously suggested, this confirms that although the single-stage design appears unfeasible, where possible it is beneficial to employ a single stage over a two-stage since they

are more efficient. This result was repeated through the five different temperature cases outlined in the previous sections for varying heat sinks and cold target temperatures with the same result.

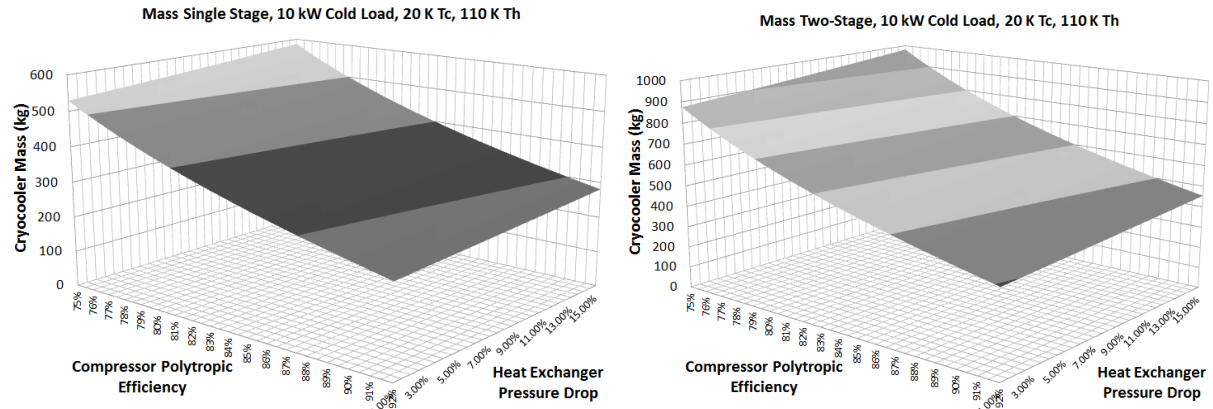


Figure 9-20 – Surface plots showing the cryocooler mass for both the single stage (left) and two-stage (right) cryocooler designs

Figure 9-20 shows the corresponding masses to Figure 9-19. Once again a larger range of results coupled with a higher overall mass for similar input parameter cases confirms the assertion that where possible the single stage cryocooler should be considered.

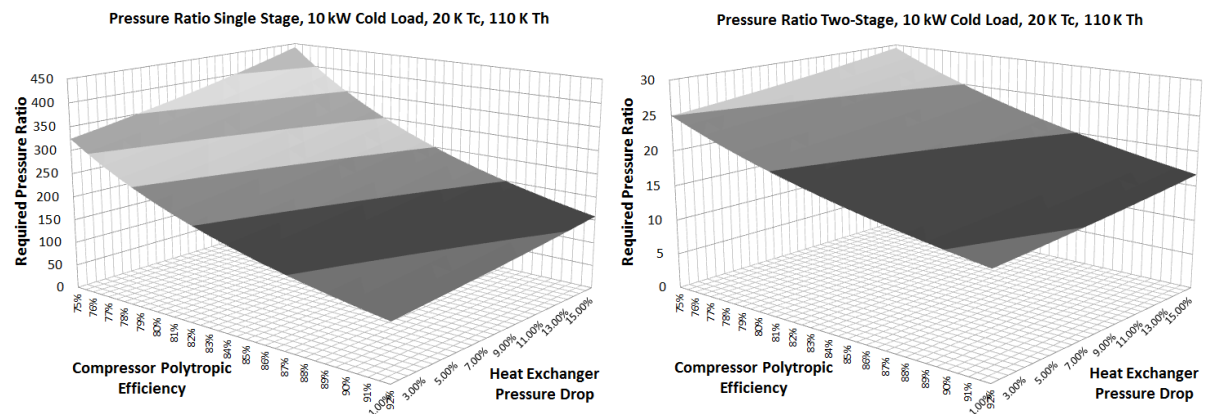


Figure 9-21 – Surface plots showing the required pressure ratios for both the single stage (left) and two-stage (right) cryocoolers designs

Figure 9-21 shows the large difference in pressure ratios between single stage and two-stage concepts. This measure of feasibility clearly shows that for the MgB_2 cold target and LCH_4 heat sink temperatures the single stage cannot meet practicality standards. As with previous results however, when considering LH_2 for the heat sink,

the single stage not only becomes viable, but preferable over the two-stage design for its lower input power requirement and therefore mass. The effect of staging the cryocooler is highly evident in Figure 9-21. Pressure ratios are reduced from over 100:1 to lower than 30:1, making concepts far more feasible. Pressure ratios of over 100:1 (Compression ratio for helium for 100:1 pressure ratio is 16.025:1) have been achieved in fixed displacement configuration compressors. The relationship between compression ratio and pressure ratio is favoured by the high ratio of specific heats (γ) value of helium at 1.66 (McCarty, 1973), leading to potentially viable lightweight fixed displacement compressor designs. This will require significant development however, as helium is notoriously difficult to seal at high pressures.

Figure 9-22 highlights the difference in both efficiency range and overall efficiency between single stage and two-stage cryocooler designs. Although the difference is small in all cases, the effects of component level efficiencies increasingly impact the overall system efficiency for the single stage design more than the two-stage. This draws two conclusions. The first is that the single stage design is more receptive to improvements in component level improvements; however the second conclusion is that the two-stage design is less susceptible to performance decreases. This suggests that although the single stage concept is preferred where feasible, the two-stage design is more stable within its design space due to the splitting of component level efficiencies between two sets of components.

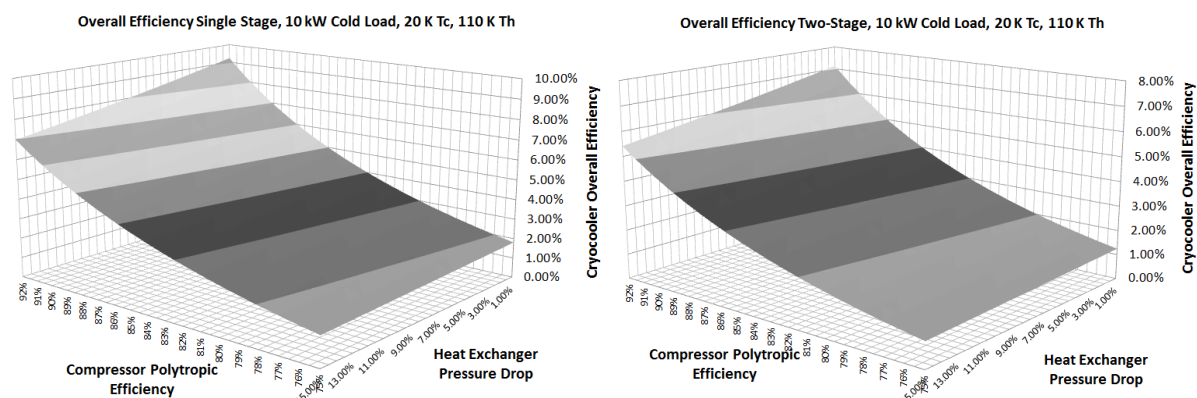


Figure 9-22 – Surface plots showing the overall efficiency for both the single stage (left) and two-stage (right) cryocooler designs

Figure 9-23 shows the percentage of the ideal efficiency achieved for both single and two-stage designs. The previous conclusion from Figure 9-22 is supported by Figure

9-23 that the single stage concept is preferred over the two-stage cryocooler where possible given its higher efficiency at any given point on the graphs. Similarly the conclusion about stability is also mirrored; the two-stage concept is less susceptible to performance drops at the component level. NASA's target of 30% of Carnot will be difficult to achieve given this temperature range. Furthermore it seems that the ideal efficiency is highly sensitive to component level efficiency, with even the previously benign heat exchanger pressure drop contributing a significant differential between maximum and minimum input values.

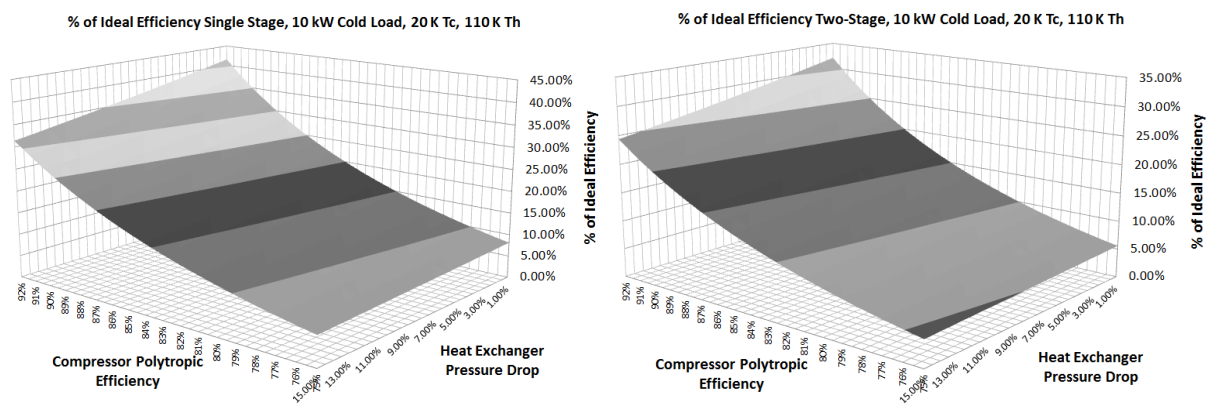


Figure 9-23 – Surface plots showing the percentage of ideal efficiency achieved for both single stage (left) and two-stage (right) cryocooler designs

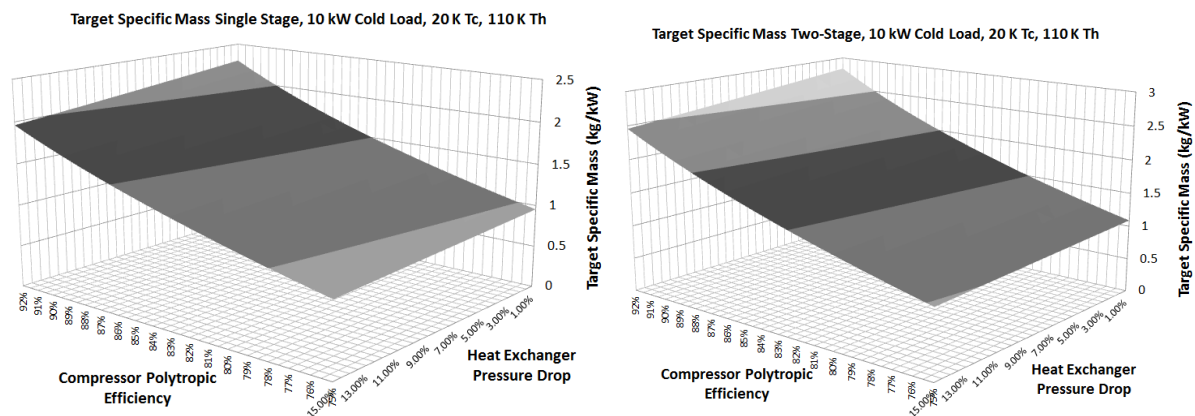


Figure 9-24 – Surface plots showing the target specific masses for both the single stage (left) and two-stage (right) cryocooler designs

Figure 9-24 shows the target specific masses for the single stage and two-stage cryocooler designs. The single stage design exhibits a smaller sensitivity than the two-stage design, suggesting that improvements in compressor or heat exchanger technology will not have as significant an impact on overall specific mass. The

values of specific mass target for the two-stage design are also higher, leading to the conclusion that as technology improves, the two-stage design will become viable before the single stage.

Comparisons were also carried out for the five temperature cases previously outlined on both the single stage and two-stage designs, which conclude that neither concepts that are air-cooled can meet specific mass targets when considering future component level performance improvements. The LH_2 cooled concept will benefit from using a single-stage cryocooler, while the LCH_4 cooled cases can be viable only when choosing a two-stage configuration. Three stage concepts were also considered; however the returns diminish given the increase in mass. Although component level performance increases show that three-stage designs will further benefit over two-stage designs from component performance increases, the additional complexity and component size reduction means that the advantages are likely negated.

9.2.4. Model Limitations

During the course of the cryocooler modelling, a number of limitations were discovered within the model that can limit the effectiveness of the results. They are summarised thus:

- The models cannot assess concept feasibility – Although the feasibility of a concept can be derived through assessing the pressure ratios, the models do not prevent calculations on unfeasible concepts, leading to potentially erroneous results. Single stage designs were nearly all shown to be unrealistic, leading to the need for future work on feasibility.
- Mass estimation does not account for additional compression stages – The simplicity of the mass estimation method cannot be avoided given the highly conceptual nature of this research. However, future models must begin to take individual component variability into account, since concepts requiring differing numbers of compression do not show the correct likely amount of mass increase.
- The models cannot assess the impacts of geometric designs – Heat exchangers typically vary considerably from type to type, hence future models must begin to take into account the variables. The models in their present

form cannot account for this, although since the initial design work has been successful, future work is likely to centre on component level considerations.

- The models cannot assess cycle variability – Many permutations on the reverse-Brayton cycle exist that can alter the performance characteristics of a concept. Recuperative and regenerative heat exchangers, different compressor technology, and numbers of cryocoolers and stages can all be varied in reality, while the model is unable to account for these. Again future work must look at component level details in greater fidelity, to understand whether small gains can be made on already promising concepts identified by this research.

9.3. System Level Interactions and Sensitivities

Cryocoolers are at this point in the research well understood; input power is largely dictated by hot and cold temperatures, component efficiency (critically compressor polytropic efficiency), and required cold power. This however must be understood within the wider superconducting system context in order to fully understand the cryogenic system design choice implications and what impact certain electrical design choices may have on cryogenics. This is performed by using the superconducting machine and cable models previously described and varying the input parameters from -10% to +10% in 5% increments whilst keeping all other parameters fixed. This allows observation of which design choices will most affect the cryogenic cooling system within the superconducting network and vice versa. Furthermore, it also highlights where models require increased capability or fidelity for future research.

Superconducting machines were first examined, with the sensitivity graph shown in Figure 9-25, derived from data shown in Table 9-1. The superconducting machine 0% values were arbitrarily chosen based on studies performed in Project DEAP (Wright *et al*, 2015). From Figure 9-25 the superconducting machine mass is shown to exhibit high sensitivities towards the geometric inputs of the model. This correlation is expected, particularly considering the method of mass estimation used for the machine model which centres on active densities rather than full geometric calculation. Interestingly the machine mass is shown to exhibit high sensitivity to variations in number of machine turns in windings. Machine turns, along with the

winding factor (overlaid above the flux density), show the highest inversely proportional mass relationships with the machine model. The proportional relationship sensitivities are as expected; machine density and machine power are the biggest drivers of proportional mass increase.

Table 9-1 – Machine mass sensitivity to outputs

		Mass Percentage Change				
		-10	-5	0	5	10
Machine Power (W)	2000000	-8.28%	-4.14%	0.00%	4.14%	8.23%
Machine Speed (rpm)	10000	9.14%	4.35%	0.00%	-3.92%	-7.54%
Electric Loading (A/m)	200000	9.14%	4.35%	0.00%	-3.92%	-7.54%
Flux Density (T)	1.9	9.14%	4.35%	0.00%	-3.92%	-7.54%
Winding Factor	0.9	9.14%	4.35%	0.00%	-3.92%	-7.54%
L/D Ratio	1.2	-1.81%	-0.86%	0.00%	0.86%	1.72%
Number of Turns	70	0.00%	0.00%	0.00%	0.00%	0.00%
Machine Active Density (kg/m ³)	4000	-10.00%	-5.00%	0.00%	5.00%	10.00%
Machine Efficiency (%)	99.9	0.00%	0.00%	0.00%	0.00%	0.00%
Cryostat Weight Percentage (%)	15	-1.29%	-0.65%	0.00%	0.65%	1.29%
Mean Stator Radius Factor	0.66	12.41%	6.08%	0.00%	-5.82%	-11.47%

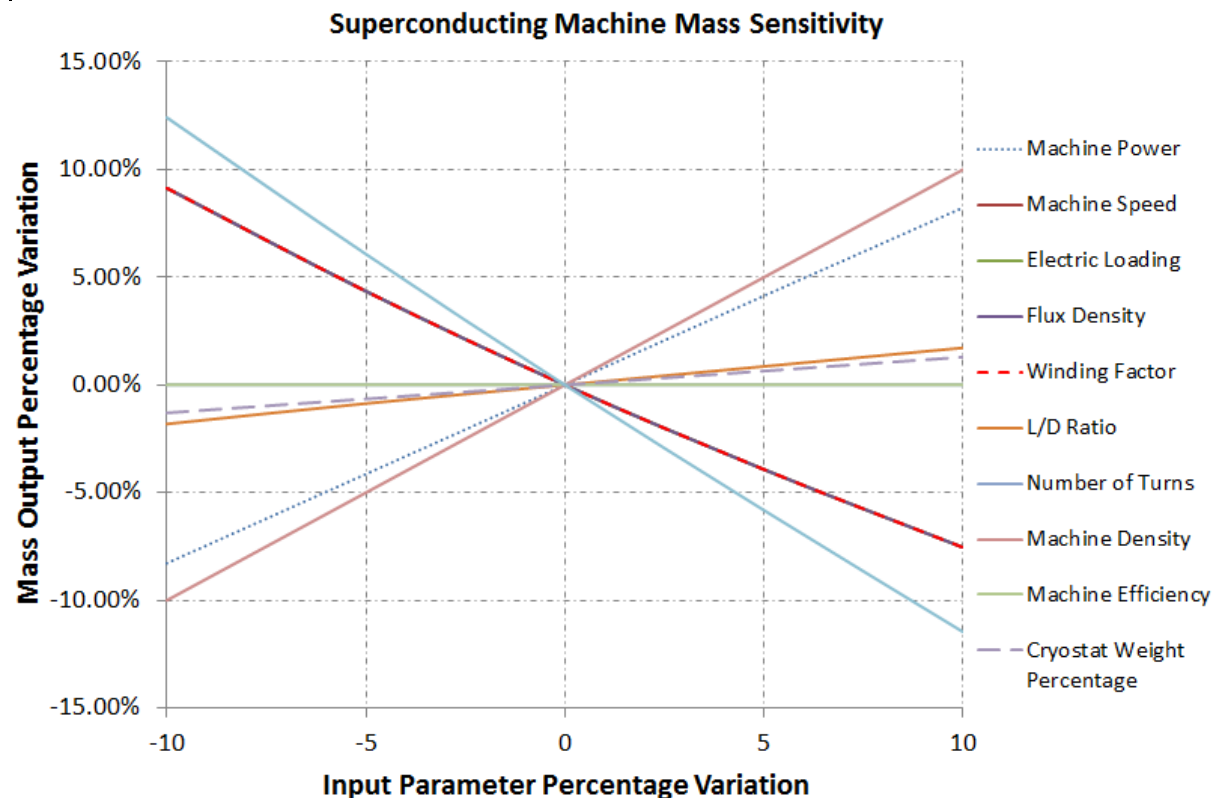


Figure 9-25 – Sensitivity graph showing percentage mass variation against percentage input variation

The power and frequency outputs of the machine model were also considered; however as can be seen from Tables 9-2 and 9-3, graphical representation is not necessary. Tables 9-2 and 9-3 highlight the need for more detailed models before full network implications can be properly assessed. Table 9-2 shows the proportional change in machine loss to only two input parameters, machine power and machine efficiency. Until future experimental work can confirm the relationship between efficiency and other machine parameters, the model derived in this research cannot account for other mechanisms of loss, particularly AC losses encountered through higher rpm machines.

Table 9-2 – Table showing the machine loss sensitivities to changes in input parameters

		Loss Percentage Change				
		-10	-5	0	5	10
Machine Power (W)	2000000	-10.00%	-5.00%	0.00%	5.00%	10.00%
Machine Speed (rpm)	10000	0.00%	0.00%	0.00%	0.00%	0.00%
Electric Loading (A/m)	200000	0.00%	0.00%	0.00%	0.00%	0.00%
Flux Density (T)	1.9	0.00%	0.00%	0.00%	0.00%	0.00%
Winding Factor	0.9	0.00%	0.00%	0.00%	0.00%	0.00%
L/D Ratio	1.2	0.00%	0.00%	0.00%	0.00%	0.00%
Number of Turns	70	0.00%	0.00%	0.00%	0.00%	0.00%
Machine Active Density (kg/m³)	4000	0.00%	0.00%	0.00%	0.00%	0.00%
Machine Efficiency (%)	99.9	10.00%	5.00%	0.00%	-5.00%	-10.00%
Cryostat Weight Percentage (%)	15	0.00%	0.00%	0.00%	0.00%	0.00%
Mean Stator Radius Factor	0.66	0.00%	0.00%	0.00%	0.00%	0.00%

Furthermore, the key cable loss driver frequency is only affected by two parameters, the machine speed and the number of poles within the machine, shown in Table 9-3. Since the pole number cannot be varied by percentage, the pole number is excluded, however the relationship between pole number and electrical frequency is well understood; the frequency will double if the pole number is doubled. The machine speed shows high frequency sensitivity as expected, with a near-equal proportional relationship. Given the relationship known between AC losses and frequency, this sensitivity suggests that slower machines will incur lower thermal losses. This can be concluded despite not understanding the relationship fully. Therefore it can be stated that for a lighter, smaller cryogenic system, the machine rpm should be kept as low as possible.

Table 9-3 – Table showing the machine frequency sensitivities to changes in put parameters

		Frequency Percentage Change				
		-10	-5	0	5	10
Machine Power (W)	2000000	0.00%	0.00%	0.00%	0.00%	0.00%
Machine Speed (rpm)	10000	-10.02%	-5.04%	0.00%	4.98%	9.96%
Electric Loading (A/m)	200000	0.00%	0.00%	0.00%	0.00%	0.00%
Flux Density (T)	1.9	0.00%	0.00%	0.00%	0.00%	0.00%
Winding Factor	0.9	0.00%	0.00%	0.00%	0.00%	0.00%
L/D Ratio	1.2	0.00%	0.00%	0.00%	0.00%	0.00%
Number of Turns	70	0.00%	0.00%	0.00%	0.00%	0.00%
Machine Active Density (kg/m³)	4000	0.00%	0.00%	0.00%	0.00%	0.00%
Machine Efficiency (%)	99.9	0.00%	0.00%	0.00%	0.00%	0.00%
Cryostat Weight Percentage (%)	15	0.00%	0.00%	0.00%	0.00%	0.00%
Mean Stator Radius Factor	0.66	0.00%	0.00%	0.00%	0.00%	0.00%

Conversely, the machine mass reduces as the speed is pushed higher; leading to a critical trade-off that must be investigated further. It may be necessary where possible to use gearboxes where high rpm rotors are unavoidable. A key advantage to superconducting machines is that although the machines typically scale with torque (and therefore conductor cross sectional area as per Lorentz's force law), additional current capacity at little to no additional weight can be achieved. This leads to the conclusion that despite high complexity and low technology maturity, superconducting machines should be considered within future research for more detailed scrutiny. If difficulties are overcome, the rewards of a system that is barely sensitive in mass or efficiency terms would be highly lucrative for commercial parties.

Superconducting cables are also crucial to understanding how the cryogenic system must perform. Since cables are likely to experience lower losses than the machines, they are likely to take secondary consideration, however some input parameters could increase the losses experienced within the cable to levels that might negate any advantages gained elsewhere. Initial cable input values were similarly chosen arbitrarily at sensible levels. Since the model has the capability for both single and multi-strand loss and mass calculation, the single strand case was chosen. Single strand wires for superconducting cables are typically the worst-case scenario dictated by the London penetration depth and current carrying nature of superconductors as discussed previously during Chapter 3.

Table 9-4 – Mass percentage variability with varied input parameters

Parameters	Start Value	Mass Percentage Change				
		-10%	-5%	0%	5%	10%
Frequency (Hz)	500	0.00%	0.00%	0.00%	0.00%	0.00%
Current (A)	10000	0.00%	0.00%	0.00%	0.00%	0.00%
Temperature (K)	20	-0.03%	-0.02%	0.00%	0.02%	0.03%
Percentage of MgB ₂ in Wire	20	0.17%	0.07%	0.00%	-0.03%	-0.03%
Percentage Manufacturing Variability for J _c	20	0.00%	0.00%	0.00%	0.00%	0.00%
Current Safety Factor Percentage	50	0.03%	0.03%	0.00%	0.00%	-0.03%
Cryostat Weight	3	-9.99%	-4.99%	0.00%	4.99%	9.99%

Table 9-4 shows the superconducting cable mass percentage sensitivity to input parameters, with Figure 9-26 showing the graphical representation. The result is as expected; since the cryostat mass dominates practical superconducting cables with three orders of magnitude larger mass per metre, the cryostat shows the most proportional sensitivity. The second largest mass-affecting input parameter is the percentage of MgB₂ to steel in a given wire. As the amount of superconducting material in a steel sheath is reduced the natural current carrying capability is reduced at a fixed diameter. However since the model calculates the necessary diameter based on the current carrying requirements, the diameter increases and therefore so does the mass. Despite this relationship, the increase is insignificant in comparison to the cryostat mass.

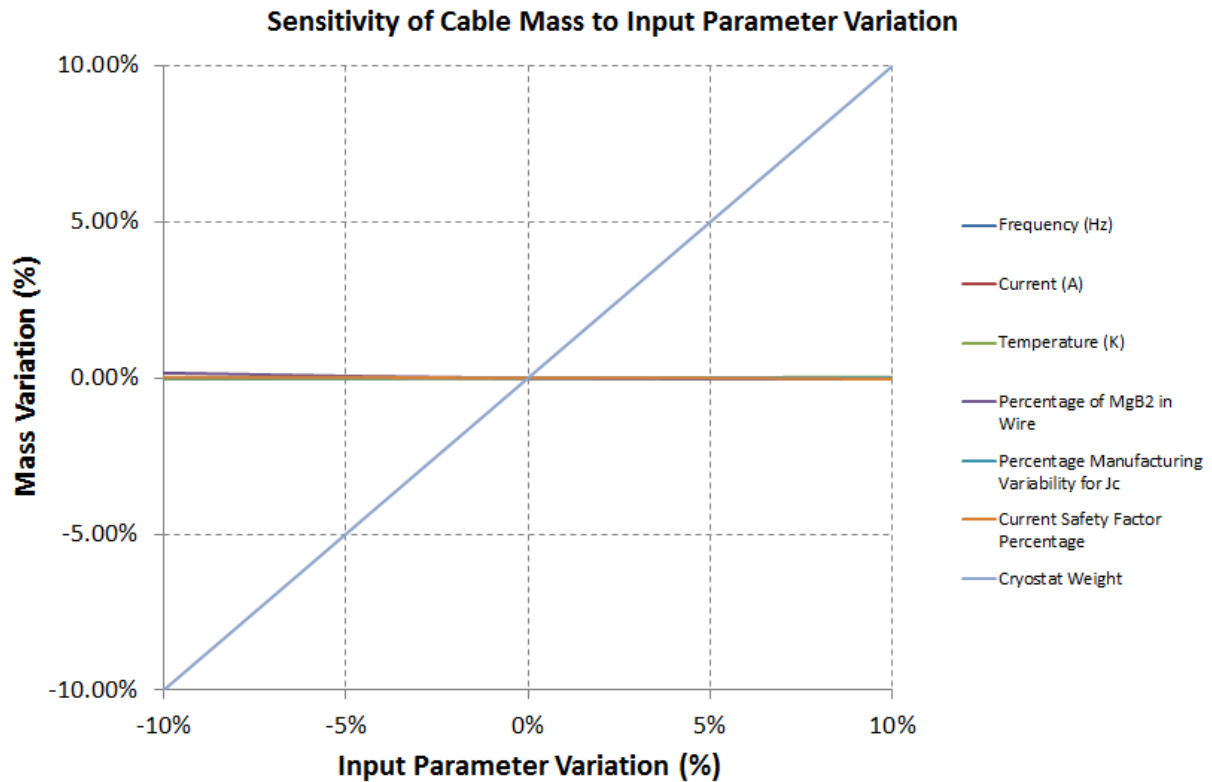


Figure 9-26 – Sensitivity graph showing the cable mass sensitivity with input variables

A more interesting picture is derived when considering the superconducting cable losses with variation in the same parameters. Table 9-5 and Figure 9-27 show the loss sensitivity to the model input parameters when input parameter are varied.

Table 9-5 – Cable loss sensitivity to percentage variations in input parameters

Parameters	Start Value	Loss Percentage Change				
		-10%	-5%	0%	5%	10%
Frequency (Hz)	500	-9.97%	-4.98%	0.00%	4.98%	10.03%
Current (A)	10000	-19.03%	-9.76%	0.00%	10.24%	21.04%
Temperature (K)	20	0.00%	0.00%	0.00%	0.00%	0.00%
Percentage of MgB2 in Wire	20	0.00%	0.00%	0.00%	0.00%	0.00%
Percentage Manufacturing Variability for Jc	20	0.00%	0.00%	0.00%	0.00%	0.00%
Current Safety Factor Percentage	50	-23.60%	-12.04%	0.00%	12.73%	26.09%
Cryostat Weight	3	0.00%	0.00%	0.00%	0.00%	0.00%

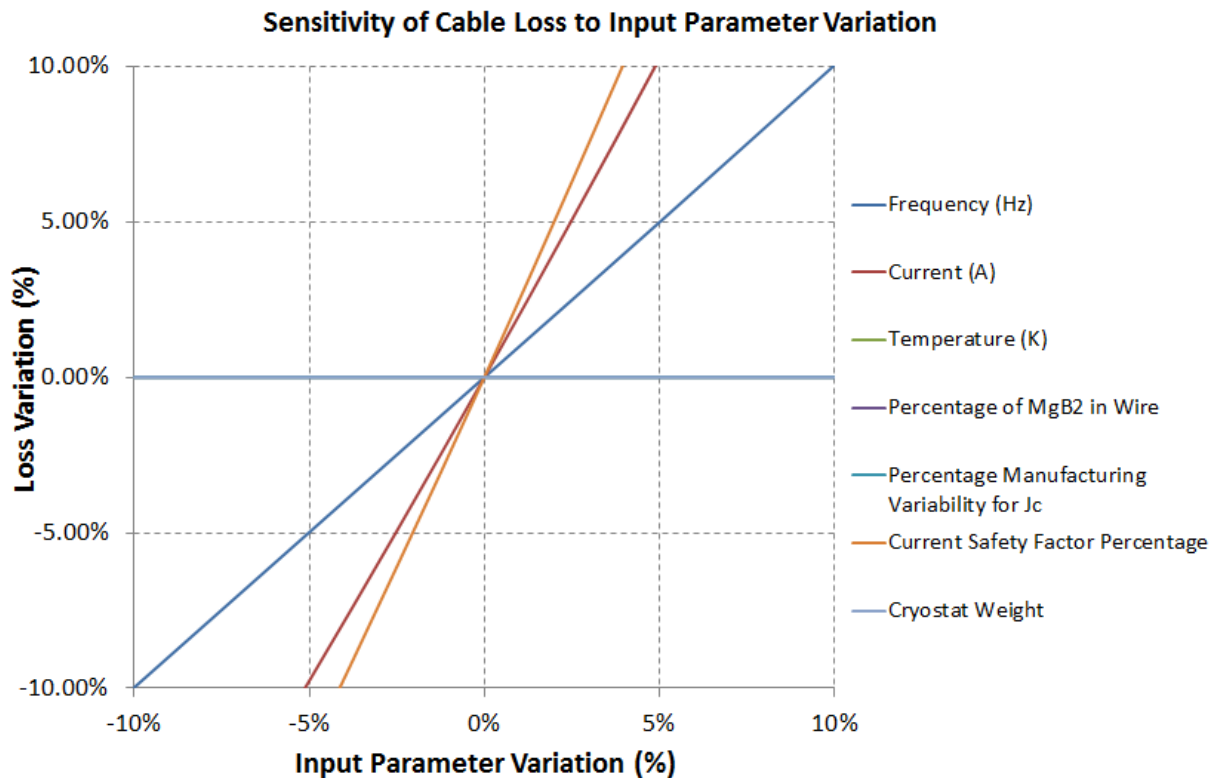


Figure 9-27 – Sensitivity graph showing the variation in cable loss to input parameters

Three input parameters are shown to exhibit sensitivity to loss, in all case the sensitivity is increase-proportional. The most sensitive input parameter is the current safety factor margin, which is a user-defined level of safety for reducing the possibility of a superconducting quench. Typical margins are set to 50%, whereby the peak current in a superconducting wire should not exceed 50% of the rated J_c for the superconductor at the operating temperature. The next largest influencing factor was the current, which coupled with the safety factor, affect the losses in a given cable significantly. Finally as expected the frequency also proportionally negatively affects the loss figures for cables. This would suggest that the ideal solution when considering both the machines and cables that a lower frequency network solution should be adopted for an AC-AC network configuration. For AC-DC-AC networks, the likelihood is that although DC transmission does not suffer similar AC cables losses to those of AC transmission, the power electronics necessary will prefer to operate at lower frequencies when considering efficiency (Rashid, 1993).

9.4. Discussion

The outcome of this chapter is a clear observation that the two-stage cryocooler design is more suitable in terms of viability and future performance improvements than the single stage design. Furthermore, the adaptive nature of the models generated has been demonstrated, by comparing results from different superconducting materials, heat sink options, and component level efficiencies and performance parameters.

The modelling results of this chapter are critical to understanding the cryogenic cooling system intricacies and the wider implications of the superconducting electrical network. The results in general show agreement between the systems engineering qualitative methods and the performance-centric modelling methods, that the most critical function of the cryogenic cooling system is transport/pump cryogen, and that the heat exchanger function must also not be ignored if performance targets are to be met.

From a qualitative perspective, the research has allowed the key critical functions of a performance nature to be identified early on. Once quantitative methods can be assessed, the results have clearly agreed with the quantitative, but placed more importance on the compression/pump side of the requirement than on the transport, as reflected in the first part of this chapter.

This observation leads to the first key observation and outcome of this research, that compressors and expanders/turbines will be critical to future concept success. If the compression ratios and compression efficiencies required of a given concept cannot be met in the future, then the overall system viability collapses. For any given concept studied at any temperature, improvements will need to be made if the aggressive goals set by NASA on percentage of Carnot and specific mass are ever to be met. New disruptive compressive technologies are unlikely to emerge, since compressors are already highly efficient within aerospace applications, however the application of aerospace technologies to the cryogenics industry is still in its infancy. Only small-scale satellite cryocoolers are making use of aerospace-grade materials and design methods, and with such high power applications required for superconducting aircraft propulsion, this must continue to progress. Aerospace

engine manufacturers are uniquely placed to enable this given the decades of design experience in materials and manufacturing methods.

In concept terms, significant knowledge of the reverse-Brayton design space has been gained. It is now known and understood as a direct result of this research which cryocooler concepts can be feasible and which are unlikely ever to meet the feasibility standards set previously by NASA.

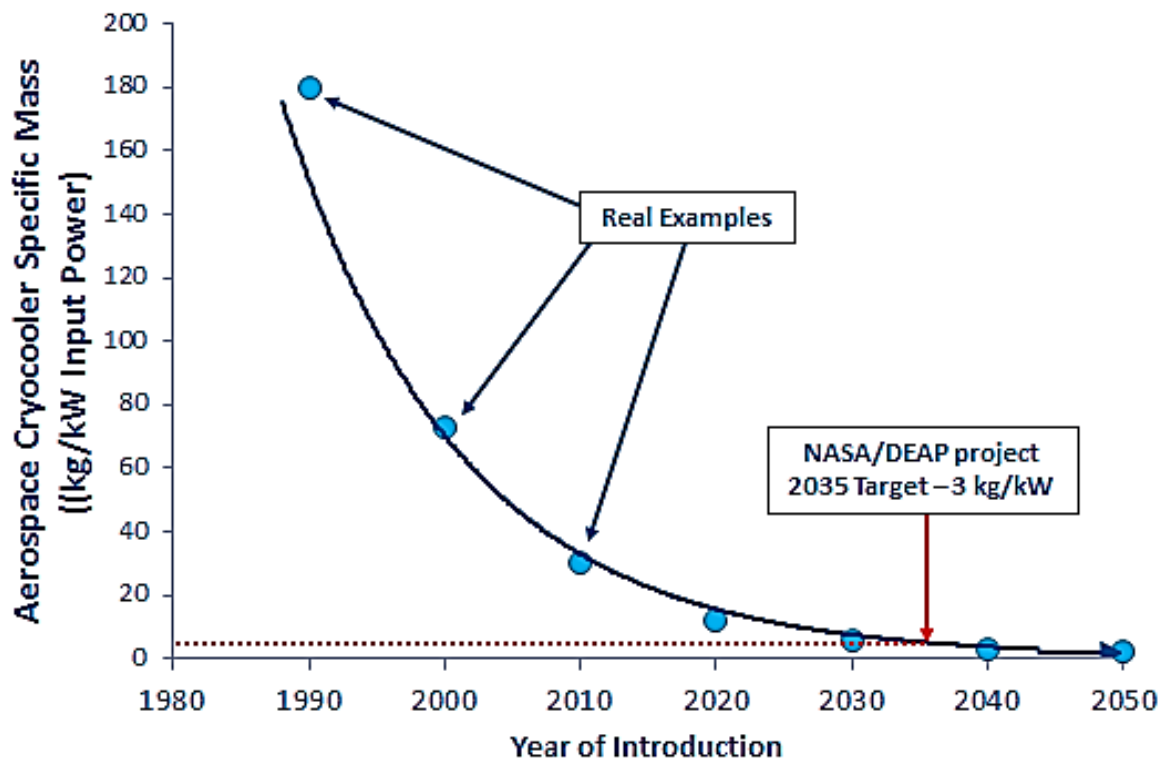


Figure 9-28 – Projected future development of reverse-Brayton cryocoolers (1990-2050)

Figure 9-29 shows how the future projected development of cryocoolers is predicted to progress. The graph was derived by first plotting the state-of-the-art reverse-Brayton cryocoolers of the past three decades. The trend is then extrapolated for the next four decades. Future development is likely to be driven by the increasing need to ever-larger aerospace cryocoolers for cooling avionics, particularly given the increasing electrical load present on many proposed civil and military aircraft. The confidence level on the graph is likely to be sufficiently accurate for the purposes of conceptual research, particularly as NASA's development goal for N3-X lies directly on the graph despite being independent of the data. The NASA target of 3 kg/kW

input power lies directly on the trend for the predicted time frame of 2035. This confirms the goal as reasonable for the projected time frame, as well as aggressive considering the necessary advancements in cryocooler technology to meet the target.

Table 9-6 shows the summary of the temperature results and their implications for future configuration options. The ambient air concept has shown low feasibility regardless of the superconducting material used, with the MgB_2 air cooled concept being ruled out completely, even considering future cryocooler improvements. The LCH_4 cooled concept shows moderate feasibility in both superconducting material concepts, although the MgB_2 concept will need significant cryocooler technology development to become feasible. The LH_2 cooled concept could feasibly be developed from technology available in much shorter time frames. However as previously discussed with LH_2 , the key challenge isn't with the performance aspects; rather it lies with the development of a suitable infrastructure to handle its synthesis and liquefaction at airports.

Table 9-6 – Feasibility of cryocooler concepts at different temperature configurations

	MgB_2 Superconductor (10-20 K)	BSCCO Superconductor (55-65 K)
LH_2 Cooled Heat Sink (21K)	Single Stage Reverse-Brayton – High Feasibility	Not Applicable
LCH_4 Cooled Heat Sink (110 K)	Two-Stage Reverse-Brayton - Moderate Feasibility	Two-Stage Reverse-Brayton – Moderate-to-High Feasibility
Ambient Air Cooled Heat Sink (300 K)	Not Feasible	Two-Stage Reverse-Brayton – Low Feasibility

The outcome of this chapter has proven invaluable; not only has the research carried out identified that the reverse-Brayton cryocooler (RBC) is the most suitable concept, the modelling work carried out has allowed decisions to be made on which configuration the RBC should be used in when considering high-level design decisions, such as choice of heat sink and superconducting material used. Furthermore, future research has been supplied with direction regarding development of cryocoolers; with the compressor and turbines in a given concept proving most critical to performance targets. These aspects of this chapter have neatly converged into a future recommendation and final conclusion.

Chapter 10. Discussion and Conclusions

10.1. Introduction

This research has been carried out while the main focus, electrical propulsion, has been highly topical. Many studies have been launched during and after this research has taken place, whereas beforehand the notion of distributed propulsion using superconducting electrical networks was essentially unheard of. Since this project began, significant advancement has been made on the aspects of superconducting electrical propulsion; however the cryogenics aspects are still relatively unknown. NASA's N3-X has provided an excellent starting point for the project as a guide and as a concept that highlights some of the many potential options. Project DEAP (Wright *et al*, 2015), a close collaboration between Airbus Group Innovations, Rolls-Royce, and Cranfield University, then proved invaluable in developing the models for this report. Previous chapters have had discussion sections that go into more detail about specific aspects of this research; however this chapter aims to give a high-level perspective and to look retrospectively upon the thesis objectives, giving commentary as to the success of the project.

This conclusions section is divided into five sections, which all provide commentary on the various conclusions and outcomes of each part of this thesis. The final two sections present the overall high-level conclusions and findings, as well as the authors' opinions on where future research should be concentrated. Finally, the author will give final recommendations as to which concept is most likely to win overall, should electrical propulsions ever be adopted using superconducting technology.

10.2. Methodology and Systems Process

Adopting the Rolls-Royce systems engineering process has proven invaluable given the scale and complexity of this research. Before undertaking the research, many aspects of cryogenics for high-power aerospace propulsion were complete unknowns, particularly given that the superconducting system intended for support was also unknown. Managing the complexity has been challenging, however a number of conclusions can be drawn from the methodology used and the Rolls-Royce system process in general.

Firstly, the method itself is highly useful in complex, unknown engineering challenges. Gathering requirements and understanding the functionality of a system should be paramount in any complex system involving multiple variables. The caveat however is available time. If the Rolls-Royce systems process had been followed in its entirety, the research could not have been conducted in a timely manner. This highlights the first trade-off in this conclusion chapter, which is whether to use the full Rolls-Royce systems engineering approach or a more traditional solutions engineering approach.

Systems engineering versus solutions engineering is an ongoing battle fought within industry and academia. The advantages of systems engineering (robust, repeatable design, more likely to be the optimum solution) versus the main disadvantage of time constraints mean that systems engineering is often used but not completed, particularly within Rolls-Royce. Solutions engineering has long been the bastion of engineering and research, however often mistakes are made, and research is often partly or even wholly rendered moot as a result. This would have easily been the case with this research, given its complexity. This project has both complexity and time constraints, which are highly evident in this thesis. The method to overcome this was to adapt and simplify the Rolls-Royce systems process and merge the systems process with the solutions process.

By taking the unmodified Rolls-Royce systems process first to identify the problem and corresponding solution, numerical modelling and solutions engineering can take place. Stakeholder requirements and functional modelling were crucial to understand what a given solution must look like. However since the cryogenic cooling system of an as-of-yet (at the time) undefined superconducting electrical network was unknown in both concept and scale, this presented a challenge. The solution was to simplify the methods but not the overall process.

Modifying the House of Quality and QFD process was crucial to hastening the Rolls-Royce systems process. The decision not to return to the stakeholders and functionality as is normally typical for second or even third passes was also taken. The reason behind that decision was that this early, conceptual level study is not intended to be a detailed design effort. Therefore, if a single pass can capture

around 80% of the functionality or more, this is sufficient to base high-level design decisions on.

The method of stakeholder engagement was carefully considered, due to the complexity and high level of unknowns. Elimination of positional or technical biases whether from senior or junior engineers from different fundamental engineering disciplines was essential to maintaining impartiality. This method generated some interesting minor differences; however the majority tended to agree with each other on both general and key requirements. This gives the research confidence that the requirements set is sufficiently complete to proceed with the project.

Functional analysis was performed once key requirements were known and understood. The generation of functional models was critical to concept selection, hence it could not be skipped and the method was also simplified. Two tiers of functional models were generated; the system-level and the sub-system level. Typically during the Rolls-Royce systems process, even sub-system level functions are then functionally mapped. However for the purpose of impartiality, and since a concept had not yet been defined, the lower tier functional flow diagrams were not generated. In doing so, the functional flow diagrams remained unbiased toward potential concepts.

Once sensitivity analyses and critical functions were identified, concept selection and modelling took place. This method of combining systems techniques with numerical modelling proved crucial. Qualitative and quantitative metrics are often difficult to compare, since they rely on fundamentally different principles. It is often difficult to quantify a quality, and similarly it is difficult to assess the qualitative effects of a known quantity. This research attempted to circumvent this by keeping the two separate but in competitive comparison. By first defining the critical functions and then modelling the preferred system concept through modelling, the final outcomes can be compared. The overall outcome for the adapted Rolls-Royce systems engineering method has been successful with some caveats. The success is that both the qualitative and quantitative methods agree on key requirements and where future focus lies; the caveats are that the systems process identified moot functions that need reassessment, and the modelling work has been limited by the number of unknowns still present.

10.3. Concept Selection and Modelling

The concept selection part of this research was also largely successful, because it identified where efforts must be concentrated and where knowledge is lacking in the scientific community. The details of the available different cryocoolers had to be understood and the advantages and disadvantages from a qualitative perspective considered in a robust manner. Using the functions means analysis (FMA) method proved invaluable. The less important functions from a performance perspective were identified, particularly the detect functions, through rationalising how they affect the quantitative performance. This method of function neglect is not recommended as a method for other projects however; it was simply necessary given the complexity of the challenge, and the time scales that constrain the research.

The concept selected was the reverse-Brayton cryocooler. This concept showed the most qualitative and quantitative potential, given its high reliability, use of cryogen instead of conduction heat transfer, and its superior power-to-mass ratio. Although the results of this study agree with the conclusions drawn from the N3-X NASA study regarding cryocooler selection, the methods of selection were entirely different and independent. NASA used Creare Inc., an engineering research and development company that have a history regarding the design of cryocoolers to propose a design of cryocooler in the 55 K Bismuth Strontium Calcium Copper Oxide (BSCCO) case (Felder *et al*, 2011). It is the author's opinion that this decision was based on the choice of ambient air as the heat sink. With its much lower T_c of 39 K, and even lower likely operating temperature of <25 K, MgB_2 would have certainly been ruled out quickly. The rigorous approach taken to design and modelling in this thesis also confirms that decision as correct, given the feasibility of design for two-stage reverse-Brayton cryocoolers at MgB_2 and ambient air cold and hot temperatures.

Other cryocoolers were considered; the impact of increasing efficiency of external compressors in the case of pulse tubes, Gifford-McMahon, and Stirling cycle cryocoolers cannot be ignored. If it is assumed that the compressor portion of the cryocooler no longer constitutes the largest aspect, but instead is in line with those assumed in the reverse-Brayton cryocoolers, the mass drops considerably. However, due to the reciprocal nature of the PT, GM, and SC type cryocoolers, the efficiency can never fully be equalled because of reverse-momentum losses per

cycle of the fluid. The fluid frequency is also a limiting factor. The higher the frequency, the higher the theoretical efficiency, however the higher the frequency is pushed, the larger the regenerative material in the system needs to be, therefore the size increases significantly.

Furthermore, these systems will all require secondary thermal transfer loops and cannot be used alone. Since they are all effectively conduction-heat transfer type refrigerators, they will either require a series of complex conduction carriers leading to the target cooled parts, or a secondary fluid loop that carries the cold fluid. In either case, this presents significant design challenges. Conduction carriers are typically copper, and are as a result, heavy. Furthermore, should there be a sudden quench or break in cooling within the conductor (hotspots can cause this), the hot spot or quench must first be cooled before cooling can reach beyond it. This can be mitigated by parallel thermal conductors; however this again significantly increases the mass of the concept. Secondary fluid loops can be used, however once again this is at significant additional mass penalty (heat exchangers, transfer tubes) compounded with the added losses in the required pumping system to drive the fluid around. Since the reverse-Brayton cryocooler (RBC) already uses a fluid loop, the conduction issue is avoided entirely. It requires no additional mass, the heat exchange masses can be reduced through integrated design of components and heat sinks, and the fluid cooling reliability is much higher than that of conduction cooling. When coupled with the clear power-to-mass superiority that RBC has over any other type of cryocooler, this makes it the obvious choice.

Liquid hydrogen (LH₂) has largely been ignored within this study, despite being a critical consideration within the NASA N3-X study. The reason for omission is two-fold; firstly the omission is down to wider issues present with LH₂. Although LH₂ is attractive from a performance perspective (large specific and latent heats, high energy of combustion, ideal boiling point at atmospheric pressure for MgB₂), the issues with handling, production, transportation, and availability are too great. For the concept to prove a reality, aviation safety would need significant update due to the properties of hydrogen, particularly the ability of hydrogen to diffuse and cause embrittlement to most metals.

The production of LH_2 is also highly inefficient. Typical efficiencies in LH_2 production to useful energy is around 70% at present-day liquefaction and cooling technology (Schwartz, 2008), which when considering the inefficiency of combustion (between 40-60%) leads to an overall loss of up to 75%. For this kind of energy loss to be acceptable, large-scale renewable energy will need implementing along with cheap nuclear reactors. Even if that becomes a reality, it is likely that a 25% round-trip efficiency is too large of a loss to accept.

Arguably the largest single issue is with the public image of hydrogen. Wider political issues have long hampered widespread hydrogen economy, particularly the advent of the thermonuclear age and the highly-publicised Hindenburg airship disaster. This political and propagandist attention has significantly hampered efforts to promote hydrogen as a safe alternative to hydrocarbon fuel. Despite the negative connotations of the term 'H-bomb', many members of the general public would likely be shocked to learn that thermonuclear weapons also heavily rely on lithium to facilitate fusion, a key component in every smartphone battery today. This shows the power of propaganda, and this issue will be toughest to overcome if hydrogen is ever to become a fuel of the future.

The modelling work during this thesis has been largely successful, but not without difficulties. The problem that quickly became apparent at the start of the project was the number of unknown quantities. Unknown quantities can be considered in two categories; known-unknowns, and unknown-unknowns. In the former, the quantity may be unknown, but the metric may be known, for example the cooling power required to operate a cryogenic cooling system is a known unknown. Unknown-unknowns however are more difficult to assess; the current sharing properties of multi-cabled superconducting networks is an example of an unknown-unknown, since the physical principles of the formula $V = IR$ are no longer applicable due to the zero DC resistance property of superconductors. In order to manage this difficult and complex problem, a two-tiered approach was taken to modelling; simplification, and investigation through expert liaison. Using simplified analogies such as basic thermodynamic principles and relationships and gathering best-knowledge in the form of expert opinions on modelling techniques was how the majority of the electrical models were derived. By doing this, models were able to be built in a step-

by-step methodical manner that resulted in the four-stage validation process. The four stage process of validation at the knowledge capture, model design, model test results, and overall model performance proved highly effective in producing results that were deemed reliable by numerous subject experts. The process undertaken ensured that the models generated could be deemed valid despite the many assumptions and simplifications made.

The purpose of the models (both electrical and cryogenic) was to understand the relationships and sensitivities rather than to give definitive accuracies regarding weight or efficiency. It was well understood throughout the project that reliable absolute numerical figures would be near-impossible to achieve due to the novel and highly conceptual future-based nature of the research. The sensitivity and scalability of each input and output however is accurate; particularly concerning the inputs that influence key outputs, such as required input power and weight. The method used to determine the weight is approximate and will require significant further work to fully understand, however the sensitivity observed is highly useful in understanding future systems. Furthermore, the method allowed the generation of future targets, the validation of the NASA cryocooler specific mass targets, and the effective confirmation of the necessary roadmap to realisation that cryogenic cooling systems must adhere to in order to become viable. Confirmation of the overall targets validity serves as validation of this research through mutual, independent agreement, with the NASA goals appearing realistic but aggressive; typical for NASA future targets.

The assumptions for each model were again generated using expert opinions on performance targets. This again followed a rigorous validation approach, ensuring that no single expert had agreed on any single assumption; for acceptance as a value or range of values to test, there must be agreement between all experts that the values are sensible and practical. This proved more difficult than anticipated; many experts found it difficult to estimate values of machine and cryogenic cooling properties when considering none of either had ever been built and tested.

Overall the concept selection and modelling has proven a valuable exercise and learning experience. Dealing with extreme ambiguity regarding finite-quantity numerical models is highly challenging. By taking the rigorous validation methodology in this research and by simplifying the systems process and concept

selection methods, a robust solution was found and exploited to produce results, leading to the conclusion that this section is successful in both aim and approach.

10.4. Discussion of Results, Analysis, and Concepts

The results derived from the modelling show the highly sensitive nature of both the electrical system and the cryogenic cooling system. The reverse-Brayton cryocooler can be configured in numerous ways as shown previously, however the results suggest that only two-stage designs are feasible when minimising the temperature differential between the cold and hot parts of the cryocooler. The single stage design can only be feasible when considering current or future specific mass targets when using liquid hydrogen as a heat sink. Two-stage designs, although heavier than single stage concepts, show much higher feasibility when the component level targets are considered. By taking into account the required compression ratios, feasibility limits were established for both concepts. In doing so, the NASA target for specific mass of 3 kg/kW can be met with future improvements in compressor design. Compressors for cryogenic cooling systems typically occupy the 75-85% region of efficiency, however when considering Rolls-Royce's compressor design expertise, it is not beyond reason that the upper limits of aerospace air compressors seen in modern turbofan engines (>90% polytropic) could be achieved, paving the way for lightweight, aerospace-grade high power cryogenic cooling systems.

Specific mass targets for each concept were also derived, making future improvements easier to understand in terms of their implications for wider implementation. It was found that the NASA targets are aggressive, however considering the likely time scales of 20+ year's development, they are not unsurmountable. It is the authors opinion based on this research however that to enable superconducting electrical propulsion for aerospace, the priority should be to reduce overall electrical system losses. The loss incurred within the superconducting network has by far the largest impact on cryocooler weight and input power, exhibiting a cumulative effect as electrical efficiency drops. When considering the likely overall cryocooler efficiency of between 1-8%, for every Watt dissipated within the electrical system due to inefficiency, the cryocooler requires between 12-100 W of input power. Therefore future work must address this loss.

The highly interdependent nature of the system can bring advantages however. The target specific mass graphs for the two-stage design means that as incremental improvements occur in compressor design, the concept rapidly becomes feasible under the right conditions. It is the author opinion that this is a major outcome of this research; the feasibility of the two-stage design is far more likely to come to fruition than that of the single-stage design, leading to the final conclusion that single-stage concepts are flawed in all cases except that of liquid hydrogen fuelled concepts. Liquid methane/liquid natural gas concepts show more attractive near-term prospects. Since oil prices are likely to continue to rise, and as the world moves to a reduced carbon economy, liquid methane, a potent greenhouse gas, is widely considered a clean alternative fuel. Furthermore, it is already transported worldwide in its liquid state; the energy deficit necessary to provide cooling is already inherent in its use. Ambient air as a heat sink is shown to be unfeasible in all cases where magnesium diboride is used as the active superconducting material due to its low temperature requirements. This again seems to support the NASA conclusions that for BSCCO-based electrical networks, air could one day be viable with advancements in cryocooler technology. However, since NASA has not produced a concept detailing liquid methane as an option for cooling, the MgB_2 concept is ruled out unless using liquid hydrogen. The author of this research would like to suggest a third alternative concept; the liquid methane-cooled, MgB_2 concept. This concept would provide an attractive step between using liquid hydrogen, and using ambient air but an unfavourable superconducting material.

10.5. Fulfilment of Research Objectives

The thesis objectives have all been met during the course of the research. This section explains how each was met and briefly comments on the level of success for each objective.

Objective 1: Capture and structure knowledge on current cryogenic cooling systems and evaluate standard industry practice.

This objective was met through intensive literature searching and discussions with experts. Many facets of knowledge in this thesis meant that a broad literature search was necessary, with many topics covered and evaluated. Structuring the knowledge came in the form of concept selection in Chapter 6, where function means analysis

was used to qualitatively select a high-level concept cryocooler design. Standard industry practice for high-power aerospace cryogenics does not yet exist, however the interview undertaken with Manchester University (Appendix A) shows how small-scale laboratory cryogenics standard practice is implemented.

Objective 2: Establish requirements for the design of the AETA electrical systems and the cooling subsystem.

Chapters 4 and 5 both centre heavily on the cryogenic cooling system requirements from a generic and functional perspective respectively. The electrical systems had to be modelled in later chapters, however given that the network configuration is still highly variable, this thesis had to limit involvement with the electrical systems. Modelling the electrical components was crucial to understanding of qualitative and quantitative requirements of the cryogenic cooling system; hence the requirements of the electrical system were gathered through analysis carried out in Chapter 7.

Objective 3: Identify the functions to be satisfied by the AETA cooling systems and represent relationships among the different subsystems of the AETA systems that are directly linked to the cooling system.

Functional analysis was carried out during Chapter 5 whereby the functions of the cryogenic cooling system in its most generic form were generated and analysed. The subsystems of the cryogenic cooling system were identified through functional flow diagrams and the most critical functions identified through sensitivity analysis, failure mode analysis, and the house of quality tool. This qualitative analysis formed the basis for later validation used in conjunction with numerical modelling, which confirmed the validity of the final solution and results.

Objective 4: Generate options regarding the cryogenic cooling system and assess and validate them through the use of models.

The options regarding the cryogenic cooling system were first reduced through qualitative analysis carried out during Chapter 6, whereby the reverse-Brayton concept was preferred. Chapter 8 then focused on the modelling of reverse-Brayton cryocoolers, with two key options considered, single-stage and two-stage cryocoolers. The models validated the previously predicted critical functions, in

particular the 'Transport/Pump Cryogen' function which relates to the most sensitive component, the compressors and turbines, within the cryocooler models.

Objective 5: Consider future technology enablers and how they may impact the models and outcomes of the project.

Future technology enablers were assessed within Chapter 8 where variations on the reverse-Brayton cycle design were considered. Although these were not modelled, the impact of intercooling, recuperation, and additional techniques such as Joule-Thompson valves was briefly commented on. The rationale behind omitting these for modelling was that the high-level choice of number of stages and heat sink fluid was deemed more critical. The number of variations within each type of cryocooler led to the decision that to gain the most relevance to Rolls-Royce and future projects, the design choice as to whether to use a single-stage or two stage cryocooler should be given priority. The results of the modelling confirmed that a broad range of solutions are feasible dependant on the high-level design decisions taken, therefore the modelling work performed during this thesis remains most relevant. The risk of developing detailed models for either the single-stage or two-stage designs at this early conceptual stage would have been potential irrelevance in certain design conditions. By assessing the future design decisions such as heat sink choice, which will likely be a decision made at the airframe level, future designers can quickly determine which models to focus on without worrying about whether a high-level design choice might negate modelling efforts.

10.6. Contribution to Knowledge

The contributions to knowledge of the project can be summarised as follows:

- Development of the world's first functional modelling and analysis of a high-power cryogenic cooling system for aerospace propulsion purposes.
- Independent selection and verification of the reverse-Brayton cycle as the most likely plausible candidate for high-power aviation superconducting propulsion networks.
- Development and testing of the world's first superconducting component sizing tools for system-level and super-system level analysis of the electrical propulsion network design space.

- Identification of the most suitable configuration of reverse-Brayton cycle and the most critical components within the cryocooler.
- Collaborative buy-off from world experts in electrical, cryogenic, aerospace and systems engineering, including validation from experts in Cranfield University, Rolls-Royce plc, Airbus Group Innovations, and Manchester University.

These knowledge contributions lead to the conclusion that the research undertaken in this thesis is novel. By developing some of the world's first models and by following an adapted version of the Rolls-Royce systems process that is optimised for early-stage highly conceptual problems, rapid iteration capability has been developed that is capable of assessing future concepts as well as making design decisions where knowledge was previously sparse.

10.7. Overall Conclusions

The research undertaken in this thesis has been successful at identifying the process required to determine a conceptual design of cryocooler for high power aviation use. Furthermore, the cryocooler design space has been assessed and quantified, as well as a thorough qualitative survey carried out. It is both justifiable and defensible to state that this research has been a success. The position at the start of research was a compound unknown, where a cryogenic cooling system must be selected and modelled with unknown inputs, unknown cooling targets, and unknown design and feasibility definition. Furthermore to these challenges, the electrical system was also unknown, often at the fundamental physics level, particularly when concerning superconducting material electrical properties. The outcome is a defined concept and robust methodology, produced in a repeatable manner, and the development of a toolset that allows rapid iteration and comparison of multiple cryocooler design topologies. The research has not been without its difficulties however.

Due to the interdisciplinary nature of the research, the literature reviewed was extensive, covering topics ranging from thermodynamics, aerospace engineering, electrical components, physics, materials, superconductivity, and more. The project is truly a multi-disciplined approach, with the author taking inputs from a wide range

of sources and experts, to build up a picture of clarity which highlights the feasibility of cryogenics for high-powered aerospace applications in a range of configurations. The key high level conclusions for the thesis are as follows:

- The world's first functional mapping of a superconducting network cryogenic cooling system, yielding results that show the "Transport/Pump Cryogen" function is the most critical moving forward.
- The development of the world's first expert-validated conceptual superconducting machine sizing tool, and contribution towards a similar superconducting cable tool. This allowed sensitivity relationships to be understood, and led to numerous design-level conclusions and relationships that will influence future design work.
- Development of a set of two conceptual cryogenic cooling system models for the reverse-Brayton cycle cryocooler that enabled the testing and validation of both the system process conclusions along with the ability to assess component level and high-level design decisions made in future work.
- Clear observation that the two-stage cryocooler design is more suitable in terms of viability and future performance improvements than the single stage design, and the conclusion that the modified system process is valid and correct through agreement between both the qualitative and quantitative methods used that the "Transport/Pump Cryogen" function was indeed the most critical.

10.8. Recommendations for Future Work

Recommendations can be summarised by the section of each research and concept. The recommendations are easily derived from results obtained. Section 9.4 shows the cryocooler concept feasibility at different temperature configurations, and reflects author opinion on the most suitable concepts and their feasibility. Further to this, compressor technology must be considered critical to the success of any future concept. By building demonstrator projects and using in-house specialist knowledge and tools within Rolls-Royce, the author is confident that a viable helium compressor design that meets design and feasibility targets can be both designed and manufactured. The turbine must also be considered critical to success. The ability to

extract the inevitable large amounts of energy required for compression will be vital to keeping the required input power to a minimum.

Heat exchanger designs must also be considered a priority. Although the pressure drop was shown to be insensitive, the weight of heat exchangers typically scales with the rejection power at the peak condition. This implies that for a large system, the heat exchanger mass is likely to increase beyond the weight estimation capability of the models derived. Since the largest type of cryocooler surveyed had an input power of 1 MW, the likely weight of concepts beyond that size is difficult to estimate.

Weight estimation accuracy must also increase. Despite the cryocooler weight being of secondary concern to the cryocooler efficiency when considering the whole-aircraft system, the method of estimation must increase in fidelity to ensure viable concepts are not being ruled out at this early stage. This can be achieved by considering the component-level weights and then producing a sum-of-parts weight estimation based on the component inventory in any given concept. This would be an ideal topic of interest for future research projects, since it is both challenging and feasible given the time frame; and it is of critical concern moving forward should the research climate favour further investigation into this area.

The adapted Rolls-Royce systems engineering process used throughout this thesis should be investigated further as a possible alternative to the typically long and often unpopular traditional Rolls-Royce systems process. Further research to assess the validity of the adapted process may lead to new process applications within Rolls-Royce which can benefit from the rapid methodology. The shortened process used for this thesis is tailored to early stage complex systems with multiple unknowns. As technology progresses through the current incremental evolutionary improvements, the need for radical technology and multidisciplinary collaboration will increase. This will lead to the need for new validated techniques that can reduce the time required to perform conceptual level research which helps to maintain competitiveness within an industrial setting. Furthermore, the interdisciplinary nature of this thesis meant that solutions to problems were not biased in any way toward any single engineering discipline. Research in the future should focus on how interdisciplinary studies could lead to whole-system optimisation, which often yields benefits through non-obvious means. An example of this is superconducting electrical aircraft propulsion concepts;

the primary system is the superconducting electrical network. By optimising the mass of the superconducting network, the first-order loss mechanism for fuel burn is satisfied as far as the electrical network boundary. However the cryogenic cooling system may suffer as a direct result, and make the entire system-level concept unviable due to the single-system optimisation. The need for closer collaboration and even merged studies with interdisciplinary projects is highly apparent from this example.

The final future recommendation for this thesis is to undertake a study on thermodynamic cycles and cycle optimisation. This would also make a suitable research project, and requires extensive research into options and their variability. Since numerous assumptions would need to be made, this research serves as the ideal pre-cursor to the potential project, where assumptions can be carried over from the numerous experts. By understanding the ideal version of the reverse-Brayton cycle to use, future projects will be able to define the design space in more detail, leading to a more defined technological roadmap to realisation.

References

ACARE European Commission Directorate-General for Research and Innovation, (2011), "Flightpath 2050: Europe's goal for aviation", ISBN 978-92-79-19724-6, doi: 10.2777/50266

Aguayo, E., Fast, J. E., and Reid, D. J., (2011), "Design of a Thermosiphon for Cooling Low-Background HPGe Arrays", Presented at the Cryogenic Engineering Conference and International Cryogenic Materials Conference, Paper ID PNNL-SA-77076

Andres, M. J, (2008), "In-Shaft Reverse Brayton Cycle Cryocooler", US Patent Application No. US 2008/0238222 A1, Filed by Hamilton Sundstrad Corporation

Armstrong, M. J., Ross, C. A. H., Blackwelder, M. J., Rajashekara, K., (2012), "Propulsion System Component Considerations for NASA N3-X Turboelectric Distributed Propulsion System", 2012, SAE Int. J. Aerosp. 5(2):2012, doi: 10.4271/2012-01-2165

Armstrong, M., Ross, C., Blackwelder, M. and Rajashekara, K., (2012), "Trade Studies for NASA N3-X Turboelectric Distributed Propulsion System Electrical Power System Architecture," SAE Int. J. Aerosp. 5(2):, doi: 10.4271/2012-01-2163

ATI, (2013), "Lifting Off – Implementing the Strategic Vision for UK Aerospace", Published by the Aerospace Growth Partnership on behalf of HM Government, Available at <https://www.gov.uk/government/publications/lifting-off-implementing-the-strategic-vision-for-uk-aerospace>

Barrett, M. J., Johnson, P. K., (2005), "Performance and Mass Modelling Subtleties in Closed-Brayton-Cycle Space Power Systems", The 3rd International Energy Conversion Engineering Conference, 15th August 2005, ISBN: 978-1287240334, San Francisco, CA, pp. 16

Brake, H. J. M., and Wiegerinck, G. F. M, (2002), "Low-Power Cryocooler Survey", Elsevier, Cryogenics Vol. 42 pp. 705–718, doi: 10.1016/S0011-2275(02)00143-1

Breedlove, J.J., Magari, P.J., and Miller, G.W., (2008), "Cryocooler for Air Liquefaction Onboard Large Aircraft", Transactions of the Cryogenic Engineering Conference, Vol. 53, AIP Conf. Proc. 985, pp. 838 (2008); doi: 10.1063/1.2908678

Boeing, (2011), "Boeing 777 Specification Sheet", Commercial Product Specification Sheet at www.Boeing.com (accessed 18/12/2015)

Boles, C., (1998), "Thermodynamics: An Engineering Approach", Third Edition Published by McGraw-Hill College, pp 10-9, ISBN-10: 0072383321

Brewer, G. D. (1991), "Hydrogen Aircraft Technology", Lockheed California Co., CRC Press, pp. 343-357, ISBN 9780849358388

Brake, H. J. M., and Wiegerinck, G. F. M., (2002), "Low Power Cryocooler Survey", Published in Cryogenics 42, 705–718, doi: 10.1016/S0011-2275(02)00143-1

Brown, G. V., (2011), "Weights and Efficiencies of Electric Components of a Turboelectric Aircraft Propulsion System", Proceedings of the 49th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition, 4-7th January 2011, pp. 4-5, doi: 10.2514/6.2011-225

Buckel, W. and Kleiner, R., (2004), "Superconductivity: Fundamentals and Applications", 2nd Edition, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, pp. 11-62. ISBN: 3-527-40349-3

Bumby, J. R., (1983) "Superconducting Rotating Electrical Machines", Clarendon Press, Oxford University, p.25, ISBN: 978-0198593270

Cantos, F. M., (2010), "Knowledge-Based Functional Assessment for Electrical Power System Design of the All-Electric Aircraft", MSc thesis, Decision Engineering Centre, School of Applied Science, Cranfield University, UK.

Carnot, N. L. S., (1878), "Réflexions sua la Puissance Motrice Du Feu – Les Machine Propres A Dèvelopper Cette Puissance", Gauthier-Villars, Imprimeur-Libraire, Paris

CERN, (2015), "Powering CERN", Picture accessed 18/12/2015 at <http://home.cern/about/engineering/powering-cern>

CERN, (2006), Picture of superconducting-conventional 12,500 A comparison, Accessed 18/12/2015 taken courtesy of CERN Laboratories from www.newworldencyclopedia.org

Chow, L., Kapat, J., Chen, Q., Ham, C., Sundaram, K. B., Wu, T., Dhere, N., Arakere, N., Rini, D., Vaidya, J., Notardonato, B., and Haddad, G., (2005), "Reverse Turbo Brayton Cycle Cryocooler Development for Liquid Hydrogen Systems", Presentation given at the Florida Universities Hydrogen Review 2005, at www2.mmae.ucf.edu/~mini/private/Presentations-11-01-05/1.pdf (Accessed 18/12/2015)

Chow, L., Kapat, J., Chen, Q., An, L., Wu, T., Sundaram, K. B., Ham, C., and Dhere, N., (2007), "A Reliable, Efficient and Compact Reverse Turbo Brayton Cycle (RTBC) Cryocooler for Storage and Transport of Hydrogen in Spaceport and Space Vehicle Applications", Report produced for NASA by the University of Central Florida, Report Number NASA/CR—2009-215441

Collaudin, B., and Passvogel, T., (1999), "The FIRST and Planck "Carrier" missions: Description of the Cryogenic Systems", *Cryogenics* Vol. 39, Issue 2, p. 157-165, doi: 10.1016/S0011-2275(99)00012-0:

Crespi, P., (2012), Mass discussion held with Air Liquide Innovation and Technical Director on publication "Turbo-Brayton Cryogenic Systems", Accessed 18/12/2015 at www.airliquideadvancedtechnologies.com

Croft, J., (2010), "NASA, Boeing complete X-48B flight test campaign", Online article accessed 18/12/2015 at <https://www.flightglobal.com/news/articles/nasa-boeing-complete-x-48b-flight-test-campaign-340309/>

Davis, T., and Abhyankar, N., (2004), "Long Life Cryocooler for Space Applications: A Database Update", *Cryocoolers* 13, p. 599-605, doi: 10.1007/0-387-27533-9_75

Dorrell, D. G., Hsieh, M. F., Popescu, M., Evans, L., Staton, D. A., and Grout, V., (2011), "A Review of the Design Issues and Techniques for Radial-Flux Brushless Surface and Internal Rare-Earth Permanent-Magnet Motors", *IEEE Transactions on Industrial Electronics*, Vol. 58, No. 9, p. 3742, doi: 10.1109/TIE.2010.2089940

Ekin, J., (2006), "Experimental Techniques for Low-Temperature Measurements", Oxford University Press, ISBN: 978-0-19-857054-7

Faab, R. (2001), "Cryoplane", Final Report published by Airbus (EADS), Hamburg, December 2001, Available at www.ec.europa.eu/

Felder, J. L., Brown, G. V., Kim, H. D., Chu, J., (2011), "Turboelectric Distributed Propulsion in a Hybrid Wing Body Aircraft", Presented at the 20th International Society for Air-breathing Engines (ISABE 2011), 12-16 September 2011, pp. 1-19, doi: 10.2514/6.2009-1132

Fesmire, J. E. and Augustynowicz S. D, (2005), "Cryogenic Thermal Insulation Systems", Presented at the 16th annual Thermal and Fluids Analysis Workshop, Orlando, Florida, on behalf of the Cryogenics Test Laboratory, NASA Kennedy Space Centre

Gamble, B.B., Snitchler, G., Ige, S.O., (2006), "The Status of HTS Ship Propulsion Motor Developments", Published in the proceedings of the Power Engineering Society General Meeting, 2006. IEEE, doi: 10.1109/PES.2006.1709643

Gamble, B., Snitchler, G., MacDonald, T., (2011), "Full Power Test of a 36.5 MW HTS Propulsion Motor", IEEE Transactions on Superconductivity, vol. 21 No. 3, pp.1083-1088

Gohardani, A. S., Doulgeris, G., Singh, R., (2011), "Challenges of future aircraft propulsion: A review of distributed propulsion technology and its potential application for the all-electric commercial aircraft", Progress in Aerospace Sciences, 47, pp. 369-391, doi: 10.1016/j.paerosci.2010.09.001

Gomez, J. R., Garcia, R. F., Catoira, A. De-M., Gomez M. R., (2012), "Magnetocaloric Effect: A Review of the Thermodynamic Cycles in Magnetic Refrigeration", Renewable and Sustainable Energy Reviews, Vol. 17, January 2013, Pages 74–82, doi:10.1016/j.rser.2012.09.027

Holland, G. F., Stacy, A. M., (1988), "Physical properties of the quaternary yttrium barium copper oxide superconductor (YBa₂Cu₃O₇)", Acc. Chem. Res., 21 (1), pp 8–15, doi: 10.1021/ar00145a002

Jha, A. R., (2006), "Cryogenic Technology and Applications", Butterworth-Heinemann Publishing, p. 102, ISBN 0-75-067887-9

Johnson, W. L., (2010), "Thermal Performance of Cryogenic Multi-Layer Insulation at Various Layer Spacings", MSc Thesis published by the University of Central Florida, Orlando, USA, p. 45

Kacynski, K. J., and Hoffman, J. D., (1994), "The Prediction of Nozzle Performance and Heat Transfer In Hydrogen/Oxygen Rocket Engines with Transpiration Cooling, Film Cooling, and High Area Ratios", Presented at the 30th Joint Propulsion Conference, Indiana, USA, doi: 10.2514/6.1994-2757

Keller, K., Antonenko, J., and Weber, K. H., (1994), "High Temperature Insulations", Published by the European Space Agency, Accessed online 18/12/2015 at <http://www.esa.int/esapub/bulletin/bullet80/keller80.htm>

Kim, H. D., (2011), "Distributed Propulsion Vehicles", Proceedings of the 27th International Congress of the Aeronautical Sciences, Nice, France, 19-24th September 2011, pp. 9-10, ICAS 2010-1.1.3

Ladner, D. R., (2011), "Performance and Mass vs. Operating Temperature for Pulse Tube and Stirling Cryocoolers", Cryocoolers 16, International Cryocooler Conference and Cryogenic Engineering Conference, p. 638-640

London, F. and London, H., (1934), "The Electromagnetic Equations of the Supraconductor", Proceedings of the Royal Society London A134, 1934, pp 72-88

Luongo, C. A., Masson, P. J., Nam, T., Mavris, D., Kim, H. D., Brown, G. V., Waters, M., Hall, D., (2008), "Next Generation More-Electric Aircraft: A Potential Application for HTS Superconductors", IEEE/CSC & ESAS European Superconductivity News Forum (ESNF), No. 6, October 2008, doi: 10.1109/TASC.2009.2019021

Malkin, P., Pagonis, M., (2015), "Future Energy Solutions for Hybrid-Electric Powered Aircraft", Proceedings of the 22nd International Symposium on Air-Breathing Engines (ISABE), ISABE-2015-20028

Masson, P. J., and Luongo, C. A., (2005), "High Power Density Superconducting Motor for All-Electric Aircraft Propulsion", IEEE Transactions on Superconductivity, vol. 15, No. 2 p. 2226-2229

McAllister, W., and Crichton, G. C., (1987), "The Concept of Paschen's Law with Reference to SF₆", Journal of Physics D: Applied Physics, Vol. 20, No. 11, p. 1537, doi: 10.1088/0022-3727/20/11/027

McCarty, R. D., (1973), "Thermodynamic Properties of Helium-4 from 2-1500 K at pressures 10^8 Pa", Journal of Physics and Chemistry, Reference Data, Vol. 2, No. 4, doi: 10.1063/1.3253133

Meissner, W and Ochsenfeld, R, (1933), "A New Conception of Supraconductivity", Nature Physics, vol. 21, p-787 (single page)

Mueller, O. M., and Mueller, E. K., (2000), "Cryogenic Power Inverters for Magnetic Resonance Imaging (MRI) Systems", Advances in Cryogenic Engineering Vol. 45, p 1603, doi: 10.1007/978-1-4615-4215-5_83

Nagamatsu, J., Nakagawa, N., Muranaka, T., Zenitani, Y., Akimitsu, J., (2001), "Superconductivity at 39 K in magnesium diboride", Nature Issue 410, pp. 63-64, doi: 10.1038/35065039

Nakamura, T, Yamada, Y, Nishio, H, Kajikawa, K, Sugano, M, Amemiya, N, Wakuda, T, Takahashi, M, and Okada, M, (2011), "Development and Fundamental Study on Superconducting Induction/Synchronous Motor Incorporated with MgB₂ Cage Windings", Superconductor Science and Technology Journal, Institute of Physics, doi: 10.1088/0953-2048/25/1/014004

NASA, (2004), "Aerogel Photos", Accessed 18/12/2015 from the NASA Jet Propulsion Laboratory's website: <http://stardust.jpl.nasa.gov/photo/aerogel.html>

NASA, (2007), "NASA Systems Engineering Handbook", Accessed 18/12/2015 at ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080008301.pdf

NASA, (2010), "NASA Dryden Past Projects: X-48B Blended Wing Body", Accessed 18/12/2015 at <http://www.nasa.gov/centers/dryden/research/X-48B/>

Nexans, (2012), "Nexans Superconducting Cable Systems", Document accessed 18/12/2015 at http://www.nexans.de/eservice/Germany-de_DE/fileLibrary/Download_540144810/Germany/files/Nexans_Superconducting_cable_systems.pdf.

Oberly, C. E, (1977), "Air Force Applications for Superconducting Lightweight Machinery", IEEE Transactions on Magnetism, vol. 13, No. 1, p. 261-267, doi: 10.1109/TMAG.1977.1059255

Oomen, M. P., (2000), “AC Loss in Superconducting Tapes and Cables”, PhD Thesis submitted to Univeristy of Twente, Netherlands, pp. 22, ISBN 90-365-1444-4

Palmer, J., Shehab, E., Husband, M., (2012), “Cryogenic Systems Study for Turbo-electric Distributed Propulsion Aircraft Solution”, The More Electric Aircraft Conference on 20th November 2012, Bordeaux, France, pp. 6

Parker, R. J., (2013), “Propulsion & Power Systems for the Future”, Presented at the 49th Joint Propulsion Conference, American Institute for Aeronautics and Astronautics, 15–17 July, San Jose, California, USA

Pei, X., Smith, A. C., Zeng, X., Husband, M., and Rindfleisch, M., (2013), “Design, Build and Test of an MgB_2 AC Coil Using Wire for Use in a Superconducting Machine”, Applied Superconductivity, IEEE Transactions, Vol. 23, Issue 3, doi: 10.1109/TASC.2013.2245715

Pei, X., Smith, A. C., and Barnes, M., (2015), “Superconducting Fault Current Limiters for HVDC Systems”, Energy Procedia, Vol. 80, Pages 47–55, doi:10.1016/j.egypro.2015.11.405

Perez, B., Alvarez, A., Suarez, D., Caceres, D., Ceballos, J. M., Obradors, X., Granados, X., and Bosch, R., (2003), “AC Losses in a Toroidal Superconducting Transformer”, IEEE Transactions on Applied Superconductivity, Vol. 13, No. 2, doi: 10.1109/TASC.2003.813122

Prestemon, S., Ferracin, P., and Todesco, E., (2007), “AC Losses in Superconductors”, Presentation given at the United States Particle Accelerator School meeting in June 2007, Copyright CERN Laboratories, Available at <https://www.bnl.gov/magnets/staff/gupta/Summer1968/0511.pdf>, (Accessed 18/01/2016)

Radebaugh, R., (2000), “Development of the Pulse Tube Refrigerator as an Efficient and Reliable Cryocooler”, The 20th International Cryogenic Engineering Conference, London, UK, National Institute for Standards and Measurements Website, www.cryogenics.nist.gov/Papers/Institute_of_Refrig.pdf (Accessed 18/01/2016)

Radebaugh, R., (2009), "Cryocoolers: The State of the Art and Recent Developments", J. Phys.: Condens. Matter 21 164219, pp. 1, doi:10.1088/0953-8984/21/16/164219

Rashid, M., (1993), "Power Electronics: Circuits, Devices, and Applications", Second Edition, Pearson Education Inc., p. 53-55, ISBN 81-7808-730-8

Rodway, M., (2009), "The Vapour Compression Cycle", Fact sheet published by The Air Conditioning and Refrigeration Industry Board, accessed 18/12/2015 at www.acrib.org.uk

Rolls-Royce plc, (1986), "The Jet Engine", Rolls Royce Technical Publishing, Derby, DE24 8BJ, ISBN 0902121 235, pp.1

Rolls-Royce plc, (2012), "Systems Engineering Handbook", Published by Burgess-Hughes, Restricted Access

Rolls-Royce plc, (2016), "Civil Aerospace – Market Outlook", Website accessed 18/12/2015 at <http://www.rolls-royce.com/products-and-services/civil-aerospace/customer-focus/market-outlook.aspx>

Rolls-Royce plc, (2016), "Civil Aerospace – Trent XWB", Website accessed 18/12/2015, at <http://www.rolls-royce.com/products-and-services/civil-aerospace/products/civil-large-engines/trent-xwb/technology.aspx#technology>

Schlaich-Bergermann, (2006), Spanish Solar Array Picture taken courtesy of Schlaich-Bergermann und Partner, Accessed 18/12/2015 at www.sbp.de/en#sun/category/100-dish_stirling

Schwartz, J., (2008), "Advanced Hydrogen Liquefaction Process", Praxair Technology Inc., Project ID PDP-31, Accessed 18/12/2015 at www.hydrogen.energy.gov/pdfs/review11/pd018_schwartz_2011_p.pdf

Shi, D, (1995), "High-Temperature Superconducting Materials Science and Engineering", Elsevier Inc, Ergamon Publishing, p-441, ISBN: 978-0-08-042151-3

Smith, A. C., Malkin, D., and Pei, X., (2015), "TSB DEAP Superconducting Cable Model – Experimental Validation", Internal Technical Report, University of Manchester, Rolls-Royce University Technology Centre, RR/UM/WT4/TR/2015-001

SupTech (Superconductor Technologies Inc), (2013), "Conductus Superconducting Cables – Brochure", Brochure accessed 18/12/15 at http://www.suptech.com/Cables_Oct_10.pdf

Swift, W., (1993), "Preliminary Design for a Reverse-Brayton Cycle Cryogenic Cooler", Report produced for NASA Goddard Space Centre by Creare Inc., 1993, pp. 72-74

Swift, W. L., Zagarola, M. V., Nellis, G. F., McCormick, J. A., Sixsmith, H., and Gibbon J. A., (1999), "Developments in Turbo Brayton Technology for Low Temperature Applications", *Cryogenics* 39, p. 989-995, doi: 10.1016/S0011-2275(99)00117-4

UK Systems Eng Council, (2009), "Why Invest in Systems Engineering?", Information leaflet produced by the UK Systems Engineering Council, Accessed 18/12/2015 at www.incoseonline.org.uk/Documents/.../Z3_Why_invest_in_SE.pdf

Van der Laan, D. C, Schwartz, J, ten Haken, B, Dhallé, Van Eck, H. J. N, (2008), "Limits to the Critical Current in Bi₂Sr₂Ca₂Cu₃O_x Tape Superconductors: The Parallel Path Model", *Physical Review B*, Vol. 77, p. 104514-2, SSN 1098-0121

Walker, G., (1980), "Stirling Engines", Oxford Science Publications, Clarendon Press, 1980, pp. 2, ISBN 0198562098

Warwick University, (2000), "Meissner Effect of a HTS Material", Picture accessed 18/12/2015 courtesy of Warwick University Physics Department, www.warwick.ac.uk/fac/sci/physics/research/condensedmatt/supermag/research/superconductivity

Wright, J., Alderman, J., Berg, F., Raffaelli, L., Miller, P., Malkin, P., Pagone, E., (2015), "DEAP Final Technical Report", Internal Document from Airbus Group Innovations, Rolls-Royce plc, and Cranfield University, pp. 144,

Wu, M. K, Ashburn, J. R, Torng, C. J, Hor, P. H, Meng, R. L, Gao, L, Huang, Z. J, Wang, Y. Q, Chu, C. W, (1987), "Superconductivity at 93K in a New Mixed-Phase Y-Ba-Cu-O Compound System at Ambient Pressure", *Physical Review* Vol. 58, p. 908-910

Zagarola, M. V., Breedlove, J. J., Kirkconnell, C. S., Russo, J. T., Chiang, T., (2009), "Demonstration of a Two-Stage Turbo-Brayton Cryocooler for Space Applications", Cryocoolers 15, Proceedings of the International Cryocooler Conference, 2009, pp. 462

Appendix A

UAS/UAV Questionnaire – Bristol

Name: - Martin Johnson

Organization: - Rolls-Royce plc

Position: - Specialist Propulsion Systems

Years of Experience in Industry:- 20+

Research Areas: - Defence propulsion systems

1. Which aircraft (types/mission profile) can you see electrical systems buying their way onto, and why?

There are four main types of defence aircraft essentially, which are:

- Counter-air
- Non-persistent
- Persistent strike
- ISTAR (Intelligence, Surveillance, Target Acquisition, Reconnaissance)

UAV's tend to operate currently in the ISTAR and persistent types. For rapid deployment operations in high threat or rapidly changing situations manned aircraft are still required. On the other hand for long endurance surveillance operations or fixed target weapon deployment a UAV platform is preferred. The ultimate goal will be to create a total unmanned solution but for a number of missions such as counter-air operations these are currently too intricate for UAV's to deal with.

Non-persistent strikes are largely fulfilled by cruise missiles such as the Tomahawk and the Storm Shadow; hence UAV's are not required for these roles at present. The business value regarding UAV's can be seen from a military and civil perspective, as there are clearly overlaps between the requirements. An example of this is a surveillance UAV, carrying high-power monitoring equipment, that can be used for border control, agriculture monitoring, disaster relief, high voltage lines monitoring, harbour monitoring and high profile security at events like the Olympics. Other than

being able to carry and power the payload the key requirement for such UAV's is endurance. The ability to be operational for a long time reduces the number required to provide 24 -7 monitoring. There is also the drive to improve autonomy to reduce the number of operators required to support the UAV. Currently a team of about 100 people are required to maintain a 24-7 air capability. .

Rolls-Royce are currently a partner on the ASTRAEA project that is seeking to prove UAV technology suitable for un-segregated airspace, because at present the only places they are permitted to fly is Australia or conflict zones where air space laws are militarily controlled.

The specific types of UAV that exist now that would likely be able to utilize superconducting technology would be:

- Scavenger
- Reaper
- Global Hawk
- Mantis

UCAV applications would also be a worthy candidate, and perhaps the second step on the theoretical roadmap to market (to run parallel to the civil introduction of small UAV's) because of the time scales involved and the size of the aircraft (7-8 tonnes). As identified above the key requirement is efficiency of fuel burn. As endurance is a key requirement significant levels of fuel are required and thus the heaviest weight of the aircraft is fuel weight. This means that the preferred power solution would tend to be a more efficient generation and propulsion system even if is heavier than a conventional generation and propulsion system because it will save more weight in fuel for a given endurance. It was highlighted by Martin that all the potential payloads can be considered as requiring an electrical supply and this is another key reason why electrical systems are preferred. Certain required features of UCAV's such as stealth capability would mean significant advantages result from having a propulsion system that does not have a heat signature (or less of one). (PERSONAL FOOTNOTE: Cooling systems could also be utilized to cool down any exhaust gases to reduce heat signature much like the synergy theorized with regards compressor pre-cooling.) UCAV's are limited in altitude due to their platform and stealth aspects, and so usually are attributed to the 40,000-45,000ft range.

Mission profiles for UAV's are varied, and should be treated as such. Some types will be high altitude, long endurance (HALE) while others will be combat driven, with a range of different phases. Of particular interest is the cruise section of mission profiles, where generally the requirements for power are overestimated. This may perhaps suggest a benefit from having a hybrid electrical system, where the climb uses standard propulsion, and the cruise segment is facilitated by the electrical propulsion system. (Consideration has also been given to reusable power pods, similar to space missions that serve to launch the aircraft, get it to its cruise position before being ejected where it can be recovered). This could potentially save fuel burn, which as previously mentioned would increase the flight range of the aircraft.

2. Inversely, which type of aircraft do electrical systems clearly not buy their way onto, and why?

In terms of aircraft design, the diameter of the engine generally has implications on overall size of the aircraft. Due to the fixed nature of the platform required for stealthy operation, if an engine diameter can be reduced and thus the drag this causes then the size of the entire aircraft can then be reduced further reducing losses and fuel burn. The aircraft would benefit from these (SC/cryogenic) systems by allowing a smaller embedded GT engine, with a distributed propulsion system. Based on this it was highlighted that Martin believed the benefits of superconductivity would be more pronounced for larger aircraft. On the other hand small UAV's such as handheld or field operated types would not benefit from superconducting electrical systems, as the additional burden of the cooling system is highly likely to erode all the superconductivity advantages. As described above superconducting systems would more than likely be present on larger types of UAV such as being considered by the ASTRAEA project.

3. If cryogenic systems could enable significant weight/volume/efficiency benefits (or a combination of the above) on an electrical system, would you see this situation significantly changing?

Possibly, but for the reasons given in question 2, the systems that require superconducting technology (and therefore a cooling system) would be thought of first with respect to weight and volume. The minimum mass associated with cooling systems as previously mentioned would be the key barrier, however if the benefits

were numerous enough, then the cooling system would potentially buy its way on to smaller aircraft, where required.

4. Are you aware of any other customers and/or competitors who are investigating or see cryogenics on their future road-map?

NASA has certainly done a significant amount of research into these systems, however other than that, no. GE are likely to be doing work on this, however this is pure speculation.

5. What do you perceive to be the biggest risks associated with achieving aerospace compatible systems?

The potential risks could be from any number of sources; however the main risk at present (to civil use mainly) is political pressure. At the moment the public and governments opinion of automated aerial systems is fairly low, largely due to bad press and poor understanding of the systems themselves. This is largely what ASTRAEA hopes to dispel, however changing people's perceptions is not an easy thing to do, especially when you hear the word 'drone' associated with UAV systems. Technology will be another major hurdle to overcome, because if the technology isn't proven to be safe and compatible with the wider systems required (for example support networks, refuelling, and general UAS) then it will never make it into a civil application.

6. What would you see in the future is the highest value aerospace market?

Civil markets would be the largest application by far; however it would also be the hardest to break into regarding regulations, certification, and politics/public opinion. This is likely to be de-risked by developing the technology for the military market first. From this route to market commercial applications can follow that would more likely be smaller aircraft (UAV or manned [passenger or transport]) followed by larger commercial aircraft. The civil market is the highest value market.

7. What (in your view) would be a plausible route to market and why?

The first step would be to concentrate on military applications because they have more freedom regarding certification and airspace. This would allow the technology

to grow out of its infancy, promoting further research onto the technology, eventually leading to better, more reliable systems. The types of UAV's would be typical Reaper/Scavenger/Global Hawk ISTAR/persistent strike and future UCAV systems as well. Once UAV technology advances sufficiently, and ASTRAEA is seeking to de-risk the technology, then these military UAV's could be used for civil purposes, gradually building trust. This would then be the prerequisite to civil applications.

8. As this study moves forward and progress is made, would you be willing and interested to review my workings?

Yes, I would be very keen to know what your findings would be, and would appreciate further correspondence.

David Morgan – Chief of Research and Technology (ASTRAEA contact)

What is ASTRAEA?

ASTRAEA is an industrial consortium consisting of a number of large companies with the aim to prove UAS technology for use within un-segregated airspace. The consortium consists of BAE Systems, AOS, Rolls-Royce, Cassidian (EADS), Cobham, QinetiQ, and Thales. Each company is investigating a different aspect of the project, with Rolls-Royce handling the autonomy section. The aim is to generate a number of concepts to find out the requirements of future UAV systems, and what the wider implications will be. Systems engineering will play a major role in the project, with respect given to certification issues, feasibility, safety, and framework assessment. Autonomy however will not necessarily mean unmanned, it will simply mean that the systems are more autonomous, with most of the load and decision making being computer based. Human interaction will play a key part in the development roadmap to autonomy, so complete autonomy will not be considered until the first stage technology is tried and tested.

What technology would be the key enablers to the vision of autonomy according to Rolls-Royce?

EHM will be a key technology in enabling these systems, as the current situation means that to detect vibrations, bird strikes, etc. would require a multitude of sensors to understand where the problems cause lies. We take for granted being able to detect problems on-board aircraft with our senses, so bringing autonomy into aircraft such that their use is safe over populated areas means that complex and comprehensive systems must be in place for detection of faults.

Cryogenics Expert Questionnaire

- 1. Name:-** Stephen Harrison
- 2. Organization:-** Scientific Magnetics
- 3. Products Manufactured:** - Superconducting machines, cyclotrons, synchrotrons, cryostats, control systems, and consultancy.
- 4. Years of Experience in Industry:-** 20+ years
- 5. Research Areas:** - Cryogenics, space technology, superconducting magnetic machines, superfluid helium, particle acceleration.

1. How far do you see cryogenic technology developing in the next 20 years, in terms of packaging, reliability, and efficiency? Do you know of any publicly available references regarding future cryogenic developments?

I see smaller cryocoolers becoming more and more prevalent. There is a growing need for smaller cooling power as MRI scanners and mobile applications increase. For both floor-space and weight (civil engineering) requirements are becoming more important. Output power per kg should improve with time, with the advancements being made. These advances include compressor technology, heat exchanger technology and overall cooling strategy employed. On the later it was highlighted that given the increasing cost of helium many suppliers were now targeting indirect cooling methods. The main issue that is still a problem is the input power, though there is significant research on this being carried out globally. The overall efficiency of the cryocooler cycle is still poor and often limits the addressable mobile market because of the relatively high 3-phase input power requirement

Another major problem with current cryocoolers is that the majority of them are LHe₂ based. Helium only comes from a few places in the world as a by-product of natural gas extraction, with the US supplying most of the world's stocks seconded by Algeria and Qatar supplying much of the rest. The problem with Helium is that it tends to diffuse quite easily, and for major cryogenic boil-offs, the gas is released directly into the atmosphere. Because of the molecular density of helium, the gas will float to the top of the atmosphere and escape into space through solar wind, particle momentum, and ionization from the charged particles forming at the magnetic poles of the earth. Current predictions are that the US will run out of commercially available helium within the next 5 years, which will add to an increasingly short supply. As the cryogenics industry is the single largest industrial use of helium, this presents a major problem regarding low temperature cryogenics, especially MRI scanners. This is already leading to significant increases in the cost of helium but also ultimately means helium will eventually have to be phased out of commercial cryogenics, which may lead the way for research into using hydrogen as a cryogen.

For future technology references, I would refer you to conferences, as this is where the state-of-the-art and experts in the field tend to congregate.

2. Where do you see pulse tube technology evolving in the next 20 years? Could you recommend any references on this?

Pulse tubes are largely for applications that are particular sensitivity to vibrations, as the cryocoolers themselves have no moving parts. In his experience, they are less reliable, they are prone to contamination (from water or other type of molecule from inadequate purging), and also cannot be oriented in any other direction than upright. All of these facts limit the use of PTs to vibration sensitive applications only. He also highlighted that PT coolers are also less efficient and weigh more per kW input than GM coolers, so they are unlikely to ever be suitable for use within aviation. GM coolers have better potential, reliability can be improved with development and focus, and they can be used freely without restriction, as long as unit induced vibration is not a problem.

3. In your view, would existing cryocooler systems require significant modification to use hydrogen as a transfer fluid?

No significant modifications would be required. LH2 would behave almost identically to LHe2, with the exception of the boiling point and pressures required. These would only equate to minor adjustments in settings, rather than overhaul or modification in a physical sense.

4. What role do you see LH2 playing in future cryogenic systems, and what do you see as the key barriers to this? Do you recommend any sensible references on this topic?

Car manufacturers are already using LH2 as a fuel (BMW Hydrogen 7), however the limitations to this are the infrastructure needed to support it, and the energy required to produce it. Using the hydrogen as a high pressure gas cooling system from liquid presents the biggest potential for aviation, as it requires cooling only for storage, with the boil-off used to keep the superconducting systems cool. Hydrogen embrittlement shouldn't be a problem with standard cryogenic materials including stainless steel. The main barrier to hydrogen usage would be the safety aspects of storage and potential accidents, which would include persuading the public that it would be as safe as current types of transport. As part of this it needs to be recognized that Hydrogen also tends to burn in air with a blue, near invisible flame that rises vertical (i.e. does not spread), leading to differing HSE concerns relating to fires, in particular detection. There is a good reference available on hydrogen powered aircraft and their implications, by Lockheed and NASA as a joint project (ISBN: 0-8493-5838-8).

Cryogenics Questionnaire - Practical Knowledge Capture (Manchester University Rolls-Royce Technology Centre)

General

- 1. Name:-** Prof. Sandy Smith
- 2. Organization:-** Manchester University UTC
- 3. Research expertise:-** B.Sc. Hons (Aberdeen), PhD (Aberdeen), MA, C.Eng, SMIEEE, FIET
- 4. Years of experience:-** 32
- 5. Role:-** Professor of Electrical Machines

6. Current Projects:- Superconducting/low temperature machines, motor design, generator design, actuator applications and technology, computational electromagnetic methods, induction machines

Refrigerators/Coolers

7. a) What types of coolers are used, and what are the typical temperatures at which they operate?

Rationale: Basic information on the type of coolers used for database purposes

Gifford-McMahon single-stage cold head, air-cooled AL230 compressor with temperature range 20K-77K (for LN2 operation)

b) Basic specifications of the coolers

Rationale: Database purposes and clarification of typical performance parameters

Manufacturer: - Cryomech (Model AL230)

Approx. dimensions: - 0.55×0.55×1.2 metres (compressor), 0.5×0.3×0.2 metres (Cold Head)

Weight (total):- Cold head: 20kg; Compressor: 176kg

Cryogen: - LHe2 compressor, with LN2 transfer medium within test bed (LHe2 pressure: 21.5 bar out, 5 bar return)

Power consumption: - 8.5A, 380-420V (400V mean), 3-phase supply, 5888.8 W input power

Cooling capacity: - 20W at 20K, 100W at 77K, 50Hz power frequency

Cool-down time:- 4 to 8 hours cool-down, with a 4 to 5 hour ambient to evacuated shielding time

8. What are the practical/operational issues with the coolers within their specific applications?

Rationale: Regarding specific applications affected by parameters such as reliability, orientation, ease of maintenance, vibration, operating environment, etc. with respect to day-to-day operation

Cryostat: Not much maintenance, very reliable, must be upright. Inversion is a major problem due to the nitrogen bath transfer medium.

Compressor: Filter cleaning every 2000 hours (easily done with a vacuum cleaner in around 1 minute), reliable, air cooled (may need high air supply). Orientation effects unknown, although suspected that it would cause inoperability or major problems (more study required).

Cold Head: maintenance every 20,000 hours, reliable, free orientation (performance affected due to orientation, more study required).

Cryogenics

9. What cryogenics (if any) are you using to cool superconducting machinery?

Rationale: To establish whether non-conduction cooled SC machines are currently typical

LHe2 for compressor use, LN2 for cryostat transfer medium.

10. To your knowledge, has LH2 been practically used as a cryogen in either industry or research (NASA excluded)? If so, details?

Rationale: To gather knowledge on the industry and research opinion on LH2 as a cryogen, and to establish routes of contact/investigation into its current use

Power stations use hydrogen cooling for their turbo-generators. Fuel cells use gaseous hydrogen, however could be of some importance. Leak detection and safe venting is an issue (venting is a problem within aerospace due to the limited supply available). Storage can be problematic due to leakage and detection. Most UAV applications will be redundant, due to most types requirement to be high altitude, long endurance (HALE). UCAV's deemed to be the best application due to the weight of required systems.

11. How do current systems cope with sudden boil-off of a cryogen (especially if the cryogen cannot be vented to the outside atmosphere)?

Rationale: Knowledge capture on methods of venting, typical working pressures, causes and contingencies in the event of a boil off

The procedure is as follows for a minor boil off: The initial small pressure relief valve actuates, relieving pressure to the acceptable levels. During major boil off, the sudden pressure release cap will fly off, releasing large amounts of cryogen into the atmosphere. As the lab is inside, the area may need to be evacuated and ventilated during this event, should the boil-off be very large.

Cooling System

12. List the major practical and operational advantages/disadvantages of conduction cooling.

Rationale: Understanding of practical challenges and benefits of conduction cooling methods

Advantages: Leaks are impossible, hence higher reliability; 'to-and-from' transfer lines not required, so lower weight penalty; No cryogen, so no boil-off/pressure build up problems

Disadvantages: Slow recovery time for quenching/local heating; local heating can block cooling (i.e. if the transfer conductor has sudden heating that cuts off one side, that part must cool before the rest can continue; uneven cooling/heating)

13. List the major practical and operational advantages/disadvantages of fluid transfer cooling.

Rationale: as with question 11, except with fluid transfer

Advantages: More uniform cooling; good quench/local heating response; higher redundancy options; generally faster cooling; double function cryogen (can be burnt in GT as fuel supplement), this yields multiple advantages (open-loop LH2 system, lower SFC, plus more)

Disadvantages: Complicates structure and ergonomics; requires high insulation; boil-off can cause problems with system pressure; detection measures required; GT modification required.

14. What equipment is required to control the cooling system?

Rationale: Knowledge capture of the requirements within current cooling systems, and what is required for their safe operation

- Temperature controller
- Temperature probes
- Temperature monitor/display
- Compressor (including LHe2 transfer leads)
- Vacuum pump (turbo-molecular)
- Cryostat (Cold head, current leads, cryogen bath)
- Signal sockets (power)

Operation

15. Explain the start-up/shutdown procedure.

Rationale: Basic understanding of how SC machines need to operate to be used effectively and for consideration when looking at system requirements during the system design phase

Start:

- Turn on vacuum pump; check pressure ($<10^{-3}$ mbar)
- Pour LN2 transfer medium into cryostat bucket
- Turn on compressor; close lid on bucket
- Wait for temperature to reach desired level

Shutdown:

- Step the pressure down using controller (at 20K, drop down 20K each time, i.e. 20K, 40K, 60K, then 80K. Once above 77K, the compressor can be switched off)
- Once temperature is above boil (77K) the bucket lid can be opened
- Turn off vacuum pump

16. During operation, what happens if quenching occurs, what are the procedures for this event, and how long does it typically take to return to optimum state with current equipment?

Rationale: This question is to gain knowledge on the kind of real operational hazards associated with high power SC machinery and their thermodynamic characteristics during quenching

Quenching has two scenarios, which is recovery without load, and recovery with load. Tests so far have only covered recovery without load. The typical values are as follows; small quench, low ΔT , 2-3 minutes; Large quench, higher ΔT , >10 minutes. YBCO and MgB₂ conduct electrically at $T > T_c$, however it may cause damage to the material. Current design parameters for quenching are that the system is designed with a maximum operating condition factor of 1.6.

17. What are the current maintenance requirements of the equipment, and what is the expected lifespan of the system?

Rationale: Understanding of maintenance frequency and life cycle basics of cryogenic equipment

The system will last for more than 20 years if procedures are adhered to. Routine simple maintenance is required around every 10 weeks with constant operation, assuming 24 hour operation for each component.

Miscellaneous

18. How much does the cryogenic system cost in total?

Rationale: Practical information required for estimation and case building for a future experimental cryogenic test rig

Roughly £100,000; much of the cost is down to the custom design of the system. Off the shelf cost would probably be around £50,000; however those costs would be driven down if the market began to require more of these cryocoolers.

19. What laboratory requirements exist for cryogenic/superconducting machinery to operate?

Rationale: As with Question 18

3-Phase industrial power supply (32A, 420V), adequate venting/space for working within, without risk of asphyxiation from boil-off

20. What safety measures are in place within the laboratory?

Rationale: As with Question 18

PPE – Heat proof gloves, goggles, fan (for driving away boil off gas)

Risks – Electric shock, LN2 burns, asphyxiation, manual handling injuries

Note: Detectors in lab monitor O2 levels in the lab rather than N2 or He2.

Appendix B

Table B-1 – Superconducting machine model assumptions table

Machine Model Parameter	Parametric Model Assumption
Electric Loading (A/m)	400,000 – Electric loading figure predicted by experts
Magnetic Flux Density (T)	1.9 – Experts conservative estimate
Winding Factor	0.9
Pairs of Poles	1 – To minimise machine frequency
Efficiency (%)	99.9 - Experimental loss analysis in superconducting wires
Power Factor	1
L/D Ratio	1.2
Number of Turns	70 – Arbitrary number given by experts
Mean Stator Radius Factor	0.66 – Likely stator mean radius portion above the rotor radius; expressed as a ratio of the distance between outer stator radius minus the outer rotor radius
Active Density (kg/m ³)	4000 – Likely density of superconducting machines based on relative component densities and expert discussions
Cryostat Added Weight (%)	15 – Expert opinion based on aerospace technology and likely expenditure

Table B-2 – Superconducting cable model assumptions table

Cable Model Parameter	Parametric Model Assumption
Temperature (K)	20 – Proposed optimum MgB ₂ operation temperature
Percentage of MgB ₂ (%)	20 – Typical MgB ₂ cable manufacturer guideline
Manufacturing Variability in J _c (%)	20 – Typical MgB ₂ first generation manufacturing variability tolerance
Current Safety Factor (%)	50 – running at 50% of critical current to allow suitable cable quench protection
Number of Strands	30 – Typical multi-strand wire number
Cryostat Weight (kg/m)	3 – Present day cable cryostat weight per metre