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QUALITY FUNCTION DEPLOYMENT AND SENSITIVITY ANALYSIS OF REQUIREMENTS FOR FUTURE AIRCRAFT PROPULSION CRYOGENIC COOLING SYSTEMS

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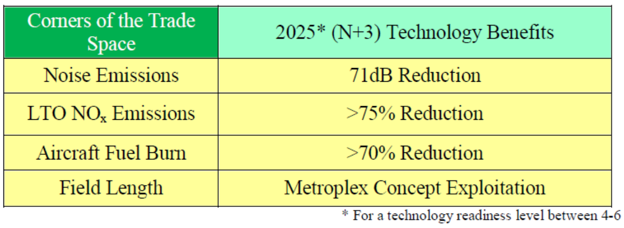
ABSTRACT

A number of novel future airframe and propulsion concepts are considered in order to meet aviation targets set by various aviation regulatory bodies including NASA and the Advisory Council for Aeronautics Research in Europe (ACARE). The current NASA concept for long-range civil aircraft is the Blended-Wing Body (BWB) aircraft, coupled with turbo-electric distributed propulsion (TeDP), to enable a host of efficiency benefits over current designs. NASA has identified superconducting technology as a key enabler to deliver this airframe. Superconductors need to be cooled to cryogenic temperatures for normal operation. Using a sensitivity matrix, it was found that the Exchange Heat and Transport/Pump Cryogen functions are the most sensitive to input variation. The failure modes and effects analysis performed on the functional model show that the detection functions are critical during component failure. Quality Function Deployment (QFD) analysis shows the Exchange Heat and Transport/Pump Cryogen functions are also critical.

Keywords: Systems Engineering, Cryogenics, Distributed Propulsion.

1 INTRODUCTION

As global aviation popularity perpetuates itself and as hydrocarbon fuels become increasingly scarce, there is a fervent requirement for more efficient ways for aircraft to achieve similar or better performance compared to current designs. NASA has outlined a specific set of targets shown in Figure 1 with regards field length, fuel burn, and emissions including noise and NO_x (Kim, Brown, and Felder 2008). Many ways of achieving this are being considered in order to meet the specified N+3 targets, with the current best preferred method considered being turbo-electric distributed propulsion (TeDP) (Kim 2010).



Corners of the Trade Space	2025* (N+3) Technology Benefits
Noise Emissions	71dB Reduction
LTO NO_x Emissions	>75% Reduction
Aircraft Fuel Burn	>70% Reduction
Field Length	Metroplex Concept Exploitation

* For a technology readiness level between 4-6

Figure 1: NASA's ARMD N+3 Subsonic, Fixed Wing Targets (Kim 2010).

TeDP comprises of a gas turbine driven set of generators which distribute power to a set of electrically driven fans, typically spread across the trailing edge of any lifting surface. This potentially offers many benefits including boundary layer ingestion (BLI), higher lift-to-drag ratio, and a higher overall bypass ratio, meaning shorter field lengths and lower fuel consumption (Kim 2010). TeDP is made possible by recent advances in superconductivity and materials, whereby extremely high power densities can be achieved within superconducting electrical networks and machines where previously weight was too high for consideration. The technology however requires cooling to cryogenic temperatures which requires a plethora of heavy, bulky, and inefficient machinery by current cryogenic technological standards.

This paper follows previously generated research into the requirements and functions of the cryogenic cooling system using the baseline example of NASA's N3-X blended-wing body concept (Palmer, Shehab, and Husband 2012). During the research, a functional model at the holistic and generic functional first level of the cryogenic cooling system was generated and validated through repeated iteration and expert opinion. This paper analyses the functional model using a series of system techniques, providing insight into the critical functions within the model, and to suggest possible mitigations regarding possible failure modes. Finally the functional model is assessed against the overall, expert validated set of requirements to enable understanding of whether the model is suitable for ongoing research, and whether any modifications or omissions will need to be made. A brief assessment of current cryocooling technology and concepts will be given in Section 5.

2 SYSTEMS APPROACH METHOD

Integral to the process of this project is the 'Systems Engineering' method, whereby requirements take precedence over solutions, contrary to the usual 'Solution Engineering' method of design where solutions are suggested and analysed rather than requirements.

The first stage is to assess the relevant stakeholders in the project. The requirements of each stakeholder are then gathered, producing an overall set of generic requirements without specifying any solutions-dependant requirements. Each stage is validated through the stakeholders, allowing assessment of systems previously unknown in terms of how they are required to operate.

The next stage is to gather and model the functional requirements of the system, by separating the overall requirements from functional. This is then modelled using functional flow diagrams, whereby inputs and outputs of the system are considered, along with the system with which the cryogenic cooling system must interact.

Once the system is defined in terms of inputs and outputs, the individual functions the system must perform, although non-solution dependant, are considered by assessing what each input must provide to the system. This step is iterated until each input corresponds to each output, and there are no redundant or overloaded functions. The functional model generated is then assessed against the original requirements and potential failures or variables, providing insight into how the model must evolve and suggesting early design solutions to problems that become apparent.

3 FUNCTIONAL MODEL

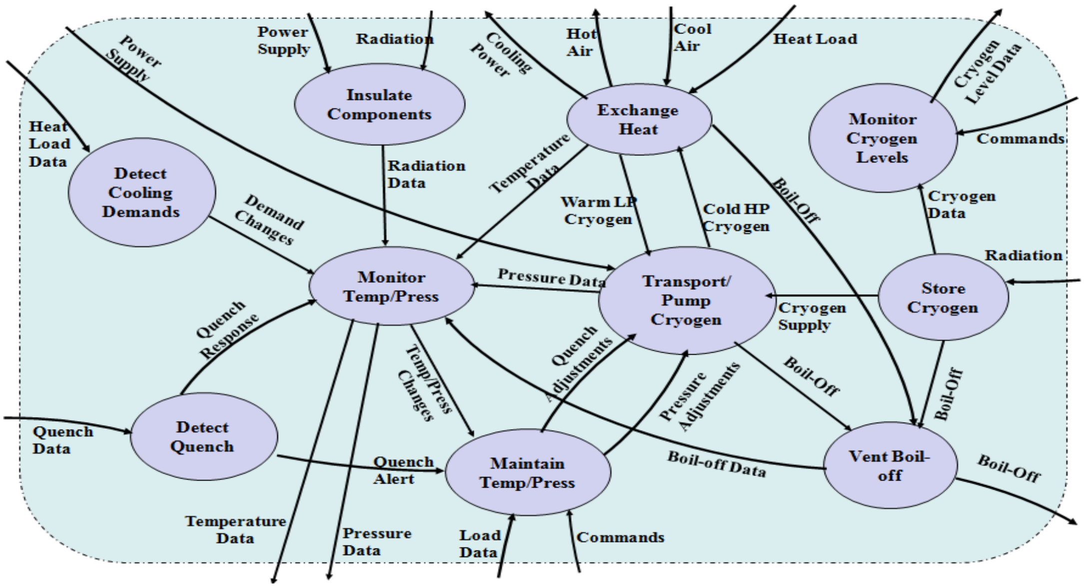


Figure 2: Cryogenic cooling system functional model (Palmer, Shehab and Husband 2012).

Figure 2 shows the functional model of the cryogenic cooling system previously generated. The model was validated by discussion with three groups of stakeholders, with two experts from each group included to minimise bias risk. The groups chosen were research aerospace, research electrical, and systems electrical. They were each chosen due to their stake in the project at this early stage; other stakeholders are yet to be involved, however at this level of technological maturity, it is preferable to maintain simplicity. The functional model shown was generated for one of five modes, the 'Maintain Temperature at Load' mode of operation. This was highlighted as most critical in operation due to the number of mission profile segments that fall within the mode (Palmer, Shehab and Husband 2012). As each mode is different in functional operation, each diagram is unique in terms of how it manages the inputs of the system. This model is used throughout the study, and although it is subject to further iteration, it can be assumed to be true for the current phase of analysis.

4 FUNCTIONAL MODEL ANALYSIS

4.1 Sensitivity Matrix

Figure 3 shows the sensitivity matrix for the model shown in Figure 2. The matrix shows that there are two areas of high sensitivity with a large number of affecting inputs and affected outputs. These are the 'Exchange Heat' and 'Transport/Pump Cryogen' functions. Although it may seem obvious from the diagram that this is the case given the number of inputs and outputs, their sensitivity to variation is not apparent. This is clearly evident by observing the 'Monitor Temp/Press' function, which is relatively insensitive despite a high number of inputs/outputs.

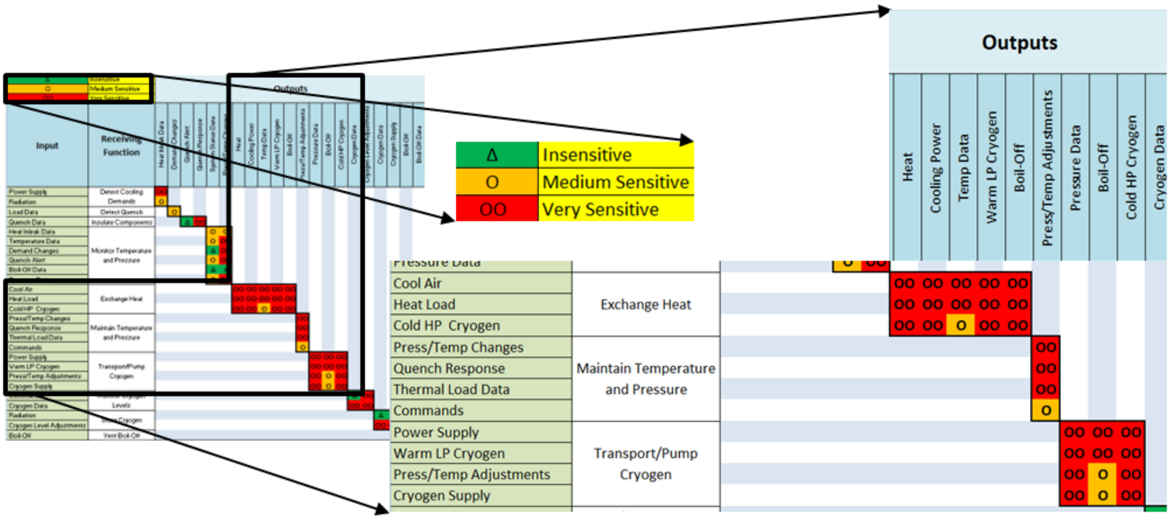
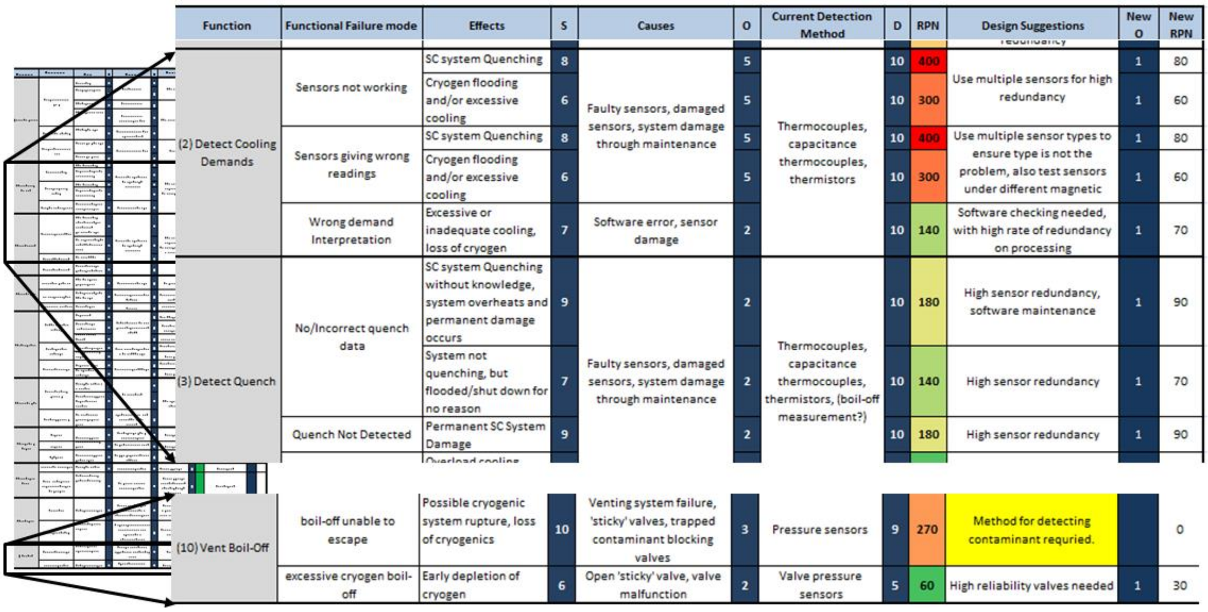


Figure 3: Flow sensitivity matrix for the 'Maintain Temperature at Load' mode.

There are other areas of sensitivity shown in the sensitivity matrix, mainly the 'Vent-Boil-Off' and 'Monitor Cryogen Levels' functions. These are both sensitive to variation, however as the 'Vent Boil-Off' function has only one input/output; it is not considered a major area of sensitivity at this stage. The 'Monitor Cryogen Levels' function can be considered sensitive due to the nature of the function; its function is to be sensitive to input variation, therefore its sensitivity is a desirable trait. Another area of variation affected in the same way as the 'Monitor Cryogen Levels' function is the 'Maintain Temperature and Pressure' function, whereby its purpose is to affect another function, and as a result appears sensitive, however as the function is designed to be, it can be assumed insignificant.

4.2 Failure Modes and Effects Analysis

Figure 4 shows the FMEA for the functional model. Three of the functions have been selected as of key interest, which are the 'Detect Cooling Demands', 'Detect Quench', and 'Vent Boil-Off' functions as each of these were recorded as high risk; however the reasons for this are varied. The two functions that enable detection are viewed as critical due to their functional nature; should the system not be able to 'detect' in the way they are designed, this would constitute not only a whole system failure, but possibly permanent damage to the cooling system and its dependant systems. The functions high risk (marked in red, Figure 4) can be explained by considering the functions themselves and the tasks they must perform; if a 'detect' function fails, then detection of that failure or any other problem becomes much more difficult.



Function	Functional Failure mode	Effects	S	Causes	O	Current Detection Method	D	RPN	Design Suggestions	New O	New RPN
(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	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
(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 requried.		0
	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

Figure 4: FMEA for the Functional Model.

Due to the temperatures involved, the failure rate or probability must be considered high as at this stage in cryogenics, reliable, robust sensors have not been developed. This is expected to change as technology and requirement for such sensors advances, which coupled with a high rate of redundancy, effectively manages the risk of a detection failure.

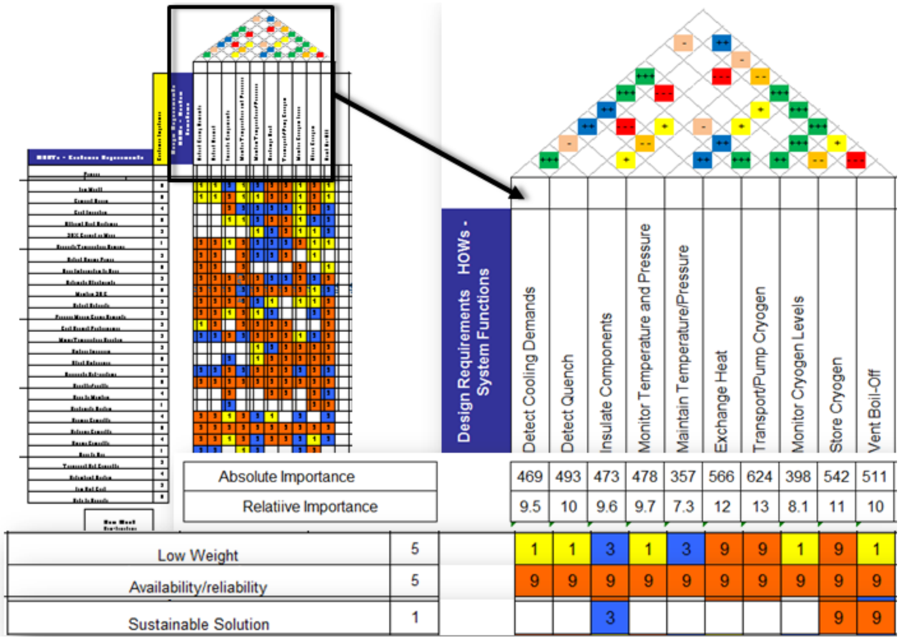
The 'Vent Boil-Off' function is also highlighted as a key area of interest due to its potential consequences and its difficulty of detection. The interest in this functional failure arises from its cause and detection; current cryogenic systems will not have to operate in varying environments, and as a result, contamination or foreign object presence probability is increased. Furthermore, there are no known methods for detection of such failures until damage has occurred; hence a need is identified for an active monitoring system for both the boil-off and vacuum systems necessary.

4.3 Quality Function Deployment

Figure 5 illustrates the QFD analysis 'House of Quality' (HoQ) diagram. Normally whilst performing a HoQ diagram, the customer requirements and functions have target performance values, however because of the very early stage of this type of concept, values are not known, hence they are omitted.

The first notable point of interest within the HoQ is the Low Weight requirement and its comparatively low overall importance score, despite having a customer importance factor of 5. Although highlighted by stakeholders as the overall key issue, it scores low due to its independency of the systems functional operation. If the system is lighter, it does not mean that the system necessarily performs the task better; however it will impact the aircrafts overall efficiency, hence the result can be adequately explained.

The highest scoring factor was the Availability/Reliability requirement, which was selected by all stakeholders involved as a key requirement. This shows that each function must perform its task reliably for the system as a whole to function as designed. This may mean however that the reliability requirement is too broad; future iterations of the HoQ could include subsections within reliability such as redundancy, low failure rates, and certification maturity.



Design Requirements HOWs - System Functions		Detect Cooling Demands	Detect Quench	Insulate Components	Monitor Temperature and Pressure	Maintain Temperature/Pressure	Exchange Heat	Transport/Pump Cryogen	Monitor Cryogen Levels	Store Cryogen	Vent Boil-Off
Absolute Importance		469	493	473	478	357	566	624	398	542	511
Relatiive Importance		9.5	10	9.6	9.7	7.3	12	13	8.1	11	10
Low Weight	5	1	1	3	1	3	9	9	1	9	1
Availability/reliability	5	9	9	9	9	9	9	9	9	9	9
Sustainable Solution	1			3						9	9

Figure 5: QFD House of Quality key points.

The final point of interest is the ‘Sustainable Solution’ requirement, which was selected as the most potentially needless requirement. Sustainability is important, although not selected as key at this stage; however the HoQ has shown it to bear little impact on the system functionality. This is similar in nature to the Low Weight function, whereby the functions of the system may not necessarily represent the overall requirement for a sustainable solution because it does not impact functional performance.

The absolute performance factors for the HoQ show that the most critical function is the ‘Transport/Pump Cryogen’ function, with the ‘Exchange Heat’, ‘Store Cryogen’, and ‘Vent Boil-Off’ functions also all scoring highly. This agrees with the sensitivity matrix, highlighting that the highest system criticality lies in less than half of the overall system functionality.

5 CRYOGENIC TECHNOLOGY

There are many possible options regarding the method of cryocooling for superconducting aircraft propulsion systems, however many of these are currently too heavy or bulky. Although some weight can be saved by replacement of industrial technology and materials for aerospace optimised versions, some technology is essentially never going to be sufficient for purpose. This likely will include any form of reciprocating compressor driven coolers, such as Gifford-McMahon (G-M) and Pulse Tube, due to their sizes and weights. Considering the N3-X concept machines are optimistically predicted to be 99.97% efficient, at an 80 MW full load this equates to 24 kW of cooling power at 25 K (Felder, Brown, and Kim 2009). Using the commercially available CryoMech AL325 G-M cold head with the CP1010 reciprocating scroll-type compressor, this would roughly mean an overall weight increase of 234 kg per 100 W of cooling power; roughly 60 tonnes of equipment (CryoMech Inc. 2013).

Assuming an 80% reduction in weight as optimisation (Palmer, Shehab and Husband 2012), we can assume the system could be delivered at 12 tonnes in a more compact design, however when also considering the required power input at 11.2 kW per compressor, the combined power required for operation of 2.68 MW returns an overall efficiency of 96.64%. As the cryocooler design is running at 9% of Carnot efficiency, even if NASA’s target of 30% of Carnot is achieved, this still represents an efficiency of 98.92%, over a 1% drop in overall efficiency. This is considerable as this cannot be sufficiently mitigated with aerospace technology to be viable, while also not considering the extensive incidental equipment required for operation. The cryogenic system weight of 12 tonnes adds 50% of the proposed weight of the electrical system in the best case theorised by NASA (Felder *et al.* 2011).

This brief analysis effectively rules out the use of reciprocating compressive technology for use within superconducting aerospace propulsion applications at this stage.

Currently preferred by NASA are reverse-Brayton cryocoolers, with some examples already in use for aerospace applications (Felder *et al.* 2011) (Hill *et al.* 2007). Options regarding cryogen cooling are also being considered, with liquid hydrogen possibly providing a tenable solution due to its convenient temperature range and high thermal capacity, both latent and specific heat.

6 CONCLUSIONS

From the analysis of the functional model it can be seen from both the sensitivity matrix and HoQ that the ‘Exchange Heat’ and ‘Transport/Pump Cryogen’ functions are most critical, with both exhibiting high sensitivity and strong relationships with the overall requirements outlined by stakeholders. This is in accordance with Pareto’s 80:20 principle, whereby in this case around 80% of the critical functionality comes from just 20% of the functions.

Use of the FMEA at this stage is confirmed as significant, due to the generic nature of the project and the FMEA’s nature of suggesting design mitigations for functions despite the need to maintain independence from solutions; however the approach serves some purpose in highlighting the detection functions as those requiring high redundancy.

Cryocoolers must undergo a revolution if they are ever to make their way onto aircraft for cooling of superconducting propulsion systems, as they are still too bulky, heavy, and inefficient. There are methods of mitigating their efficiency, for example by the addition of heat sinks with cryogen cooling, however further analysis on the effect of compound systems must be performed in order to confirm this. This does not mean reciprocating compressors may get a new lease of life; they will likely be superseded by rotary versions of higher power density, in much the same way and for similar reasons that the internal combustion engine was replaced by the jet engine.

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