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Non-functional superconducting system requirements in a marine environment

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Abstract. The Office of Naval Research and the Naval Sea Systems Command have worked towards developing applications of superconducting and cryogenic technology including motors, generators, cables, and magnets. When designing such complex systems, a set of specifications and requirements are the basis for meeting performance metrics. Quantifiable requirements may be considered as functional since they are necessary to meet a goal. Non-functional requirements are also important when designing superconducting systems for use in the US Navy's marine environment. These non-functional requirements may include quality attributes of affordability, availability, reliability, sustainability, and resiliency. As the US Navy starts to adopt superconducting and cryogenic technology these non-functional requirements become more important to ensure continuous operation of its ships and the safety of its sailors. It is the responsibility of the engineers and researchers working on new applications to ensure these aspects of a system are considered along the way. The goal of presenting these concepts is to raise the awareness of these non-functional requirements that must be included for the US Navy to embrace the technology. This paper has been approved for approved for public release; distribution is unlimited, reference number NSWCPD-002865.

1. Introduction

The US Navy has been investing in superconducting and cryogenic technology since the 1940's when the Navy Research Lab published its first scientific article on the subject [1]. Over the past eight decades of development a great deal of money has been spent to advance the technology. The United States Department of Defense (DoD) invests in various levels of research and development from basic science through operational system development. These activities are assigned budget activity codes from 6.1 - 6.8. Research in areas 6.1 – 6.3 are considered Science and Technology (S&T) developments in the form of Basic Research, Applied Research, and Advanced Technology Development. While research in areas 6.4, 6.5, and 6.7 are considered the application of the S&T developments to the operational need in the form of Advanced Component Development and Prototypes, System Development and Demonstration, and Operational Systems Development.

A majority of investments in DoD research falls under Title IV of the Defense Appropriations Act passed by US Congress. Title IV appropriations fund the US military services' Research, Development, Testing and Evaluation (RDT&E) programs. The total approved budget for RDT&E programs under Title IV in fiscal year (FY) 2024 was $148.5 billion US dollars [2]. The breakdown of funding by the budget activities mentioned above and by DoD component is seen in Figure 1.

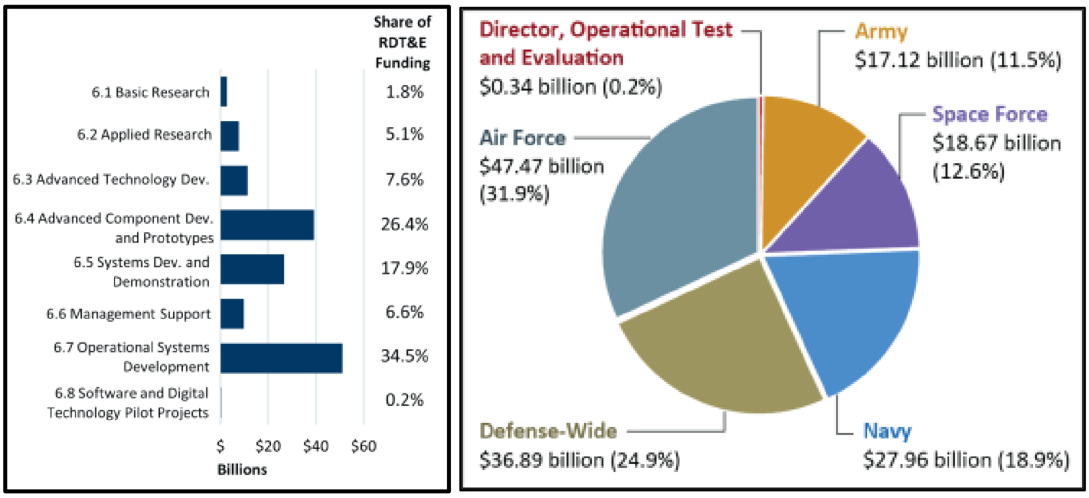

Figure 1. Breakdown of RDT&E funding by budget activity and DoD component under Title IV of the Defense Appropriation Act for fiscal year 2024 [2]. "The appearance of U.S. Department of Defense (DoD) visual information does not imply or constitute DoD endorsement."

As one can see from the graphic on the left side of Figure 1, less than 7% of the RDT&E budget is dedicated to basic and applied research. Transposing this budgetary breakdown onto individual DoD organization RDT&E budgets, the Navy's budget for basic and applied research was $1.9 billion US dollars in FY2024. With such a limited budget for the early phases of R&D it is imperative to reduce as much risk as possible to the transition of these new technologies to the Fleet. Part of risk reduction is to understand the operational environment and the requirements for the technology to meet the operational need.

The Navy's operating area is harsh and unforgiving. Foul weather, high sea states, humidity, corrosive salt air, sea water, and temperature fluctuations are all experienced by systems that the US Navy deploys on their ships. This is a much different environment than the places early R&D is conducted. Basic research may be conducted in clean rooms, while applied research is conducted in larger laboratories. These locations are in a stationary building, and most likely have a temperature and humidity-controlled atmosphere. The cryogenic environment of a superconductor will be definitely affected by the operational environment.

Requirements for the systems operating in the marine environment come in many forms. Engineers typically think in terms of technical requirements for a system. Quantifiable aspects of a technology or system that can be used for evaluation. These are also considered as "functional" requirements. It's the un-quantifiable, or quality based attributes that are often not considered during the basic and applied research phases of technology development. These requirements are considered "non-functional".

Although the operational environment and non-functional requirements may not be the focus during discovery and invention phases during basic research, an understanding of these aspects will save valuable time, money, and resources. Considering these two aspects will help avoid the technology transition "valley of death". The "valley of death" is the gap between the S&T/R&D phase and the acquisition phase [3]. Our mission as engineers and scientists for the US Navy is to conduct research and development within the confines of fiscal responsibility and timelines set forth by the Fleet. The final goal is to transition these new technologies to the Fleet so they can complete their mission. Therefore, non-functional requirements in the operational environment must be considered while progressing from basic and applied research into technology transition, acquisition, and sustainment.

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2. Operational Environment

The US Navy's mission is to "defend freedom, preserve economic prosperity, and keep the seas open and free" in collaboration with its allies and partners [4]. They operate nearly 300 ships and thousands of aircraft across the globe, with 100 ships and submarines deployed overseas or sailing the oceans daily [4]. As seen in Figure 2, the US Navy's operating environment may be in a tropical, humid climate such as in South America (4th Fleet), or an arctic dry climate such as in the north Atlantic (6th Fleet). The seas can be calm and peaceful, or with waves crashing over the bow of the largest of vessels. Therefore, the systems that deploy with the Fleet must withstand the same conditions to support the ship, its crew, and their mission.

Figure 2. US Navy global operations [4]. "The appearance of U.S. Department of Defense (DoD) visual information does not imply or constitute DoD endorsement."

2.1 Sea State

One way of describing ocean conditions is by sea states. The US Joint Chiefs of Staff (JCS) define sea state as "a scale that categorizes the force of progressively higher seas by wave height" [5]. The US Naval Meteorology and Oceanography Command is an entire organization dedicated to the data collection and prediction of the weather and ocean conditions across the globe. The US also has the National Oceanic and Atmospheric Administration (NOAA) and the National Weather Service (NWS) that provides information on weather to commercial or private sailors and boaters.

There are three major scales which are frequently referenced when describing sea state. The first was developed by Royal Navy's Rear Admiral Sir Francis Beaufort in 1805 who started to develop a wind scale based on wind speed and observations of the resulting seas that he encountered while sailing [6]. The Beaufort Wind Scale was adopted by the Royal Navy in the 1830s and is still used by the NWS today. The second is the Pierson-Moskowitz Sea Spectrum, which uses modelling and data to provide a concise and sequential listing of both wind speed and wave heights. It is used by the JCS for Joint Logistics Over-the-Shore operations. Finally, the Douglas Sea Scale, which has been adopted by the World Metrological Organization (WMO) and the North American Treaty Organization (NATO). Table 1 is a simplified list of the wind speed and wave height associated with the three different scales. In this table, the sea states were grouped together by color according to the Douglas Sea Scale wave heights since this is what NATO uses and is taught to US Navy officers at the US Naval Academy for sea keeping.

Table 1. Comparison of the three major sea state scales used by mariners.

<table>
<tr><th colspan="3">Beaufort Wind Scale [7]</th><th colspan="3">Pierson-Moskowitz Sea Spectrum [5]</th><th colspan="3">Douglas Sea Scale [8]</th></tr>
<tr><th>Scale</th><th>Wind Speed (kts)</th><th>Wave Height (ft)</th><th>Scale</th><th>Wind Speed (kts)</th><th>Wave Height (ft)</th><th>Scale</th><th>Wind Speed (kts)</th><th>Wave Height (ft)</th></tr>
<tr><td>0</td><td>0</td><td>0</td><td>0</td><td>0-2.8</td><td>0-0.2</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>1</td><td>1-3</td><td><0.5</td><td rowspan="2">1</td><td rowspan="2">5.2-8</td><td rowspan="2">0.5-1.2</td><td>1</td><td>1-6</td><td>0-0.3</td></tr>
<tr><td>2</td><td>4-6</td><td>0.5-1</td><td>2</td><td>7-10</td><td>0.3-1.6</td></tr>
<tr><td>3</td><td>7-10</td><td>1-3</td><td>2</td><td>5-12.7</td><td>1.5-3</td><td rowspan="2">3</td><td rowspan="2">11-16</td><td rowspan="2">1.6-4.1</td></tr>
<tr><td>4</td><td>11-16</td><td>3-5</td><td>3</td><td>13.7-16.4</td><td>3.5-5</td></tr>
<tr><td>5</td><td>17-21</td><td>5-8</td><td>4</td><td>17.9-20</td><td>6-7.5</td><td>4</td><td>17-21</td><td>4.1-8.2</td></tr>
<tr><td>6</td><td>22-27</td><td>8-12</td><td>5</td><td>20.7-25.3</td><td>8-12</td><td>5</td><td>22-27</td><td>8.2-13.1</td></tr>
<tr><td>7</td><td>28-33</td><td>12-19</td><td rowspan="2">6</td><td rowspan="2">27.4-32.7</td><td rowspan="2">14-20</td><td>6</td><td>28-47</td><td>13.1-19.7</td></tr>
<tr><td>8</td><td>34-40</td><td>18- 25</td><td rowspan="2">7</td><td rowspan="2">48-55</td><td rowspan="2">19.7-29.5</td></tr>
<tr><td>9</td><td>41-47</td><td>23-32</td><td rowspan="2">7</td><td rowspan="2">36.6-46.2</td><td rowspan="2">25-40</td></tr>
<tr><td>10</td><td>48-55</td><td>29-41</td><td rowspan="2">8</td><td rowspan="2">56-63</td><td rowspan="2">29.5-45.9</td></tr>
<tr><td>11</td><td>55-63</td><td>37-52</td><td>8</td><td>49-56.6</td><td>45-60</td></tr>
<tr><td>12</td><td>>63</td><td>>45</td><td>9</td><td>61.2-73</td><td>70-100</td><td>9</td><td>>63</td><td>>45.9</td></tr>
</table>

[a] Wind speed and wave heights are rounded for comparison purposes.

As one can see, the different scales associate wind speed and wave height with different sea states but they are similar in terms of wave height. The description of the sea state ranges from "calm and glassy or ripples" at sea state 0-1, to "moderate and rough" a sea state 4-5, all the way up to "phenomenal" at sea state 9 where the wave heights are over 45 ft.

2.2 Environmental Conditions

Extreme environmental conditions which may damage military equipment can be defined under the following seven stresses thermal, humidity, precipitation, wind, penetration and abrasion, salt spray, and atmospheric pressure [9]. Each of these conditions will affect a technology differently depending on its use case, where it may be located within the ship, or its sensitivity to external factors. For example, a system on the deck of a ship will encounter wind, precipitation and salt spray; whereas a system that in the lower decks of the ship would not be subject to these conditions but will still have to deal with humidity and thermal stresses. Ultimately, it is up to the developer of new technologies to ensure the system will operate in these extreme conditions.

2.3 Shipboard Surroundings

The shipboard environment is very industrial. Upholding a US Navy ship's operational posture requires frequent maintenance, upgrades and cleaning from all the environmental effects mentioned prior. Figure 4 contains images of the operational environment showcasing plasma cutting metal, maintenance of a dirty vacuum pump system, and typical cleaning of passageways.

Figure 3. Plasma cutting, pump maintenance, and cleaning aboard US Navy ships showing the industrial environment new technology will be subjected to [10][11][12]. "The appearance of U.S. Department of Defense (DoD) visual information does not imply or constitute DoD endorsement."

Other factors in the shipboard environment are the effect of systems on other systems. This could be from electromagnetic interference (EMI) radiating from or to co-located hardware, chilled water pressure drops between heat exchangers, or human interfaces and safety. All these aspects of the ship will add complexity to integrating new technology.

3. Requirements

The US Navy's mission relies on the capabilities it possesses. These capabilities drive requirements of a ship, a system, a material property, or even a human. New capabilities being developed will have many different types of requirements. They start with primary requirements which are identified in an original statement. Primary requirements drive secondary requirements, which are then divided into functional requirements that the system is required to perform, performance requirements for how well the system functions, and non-functional requirements as attributes of constraints for which the system will operate [13][14]. These three requirement sets can further be defined as mandatory vs. non-mandatory, and explicit vs. implicit.

The US Navy uses a top-level requirement (TLR) process to "provide sharply focused and effective warfighting capabilities to the Fleet and Joint Warfighter", as outlined in the Chief of Naval Operations Instruction 5420.119 (OPNAVINST 5420.119) [15]. Top-level requirements can be considered as primary or even secondary requirements. Top-level requirement documentation contains a mission statement and overall "requirements and characteristics" of the capability being developed. Based on the intent of TLRs and examples provided in OPNAVINST 5420.119, requirements could be considered as technical requirements or functional requirements, and characteristics could be considered as qualitative requirements or non-functional requirements.

3.1 Functional Requirements

Functional requirements of a system are generally easier to define. They are quantifiable through experimentation, demonstration, testing and evaluation. Size, weight, and Power (SWaP) are simple examples of functional requirements. The US military has identified a specific set of functional requirements commonly referred to as Military Standards (MIL-STDs), Military Specifications (MIL-SPECs), or Military Detailed Specifications (MIL-DTLs). Table 2 has a listing of documents usually included as requirements for integrating new technology into applications for the military, specifically the Navy. In addition to the typical military requirements, there are obviously technical requirements associated with systems being developed for the Navy.

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Table 2. A list of US Department of Defense military standards typically applied to the development of US Naval ships, submarines, and shipboard systems.

Designation	Title and Purpose
MIL-STD-1399C	Interface Standard for Shipboard Systems: To define standard interface characteristics and constraints applicable to the design of ships and shipboard equipment to ensure interface compatibility within the shipboard environment [16].
MIL-DTL-901E	Requirements for Shock Tests, High-Impact Shipboard Machinery, Equipment, and Systems: To verify the ability of shipboard installations to withstand shock loadings due to the effects of nuclear or conventional weapons or environmental mechanical shock during operation [17].
MIL-STD-167-1A	Mechanical Vibrations of Shipboard Equipment (Type I – Environmental and Type II – Internally Excited): To specify procedures and establish requirements for environmental and internally excited vibration testing of Naval shipboard equipment installed on ships with conventionally shafted propulsion [18].
MIL-STD-461G	Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment: To establish interface and associated verification requirements for the control of the electromagnetic interference (EMI) emission and susceptibility characteristics of electronic, electrical, and electromechanical equipment and subsystems designed or procured for use by activities and agencies of the Department of Defense (DoD) [19].
MIL-STD-810H	Environmental Engineering Considerations and Laboratory Tests: To Describe the environmental tailoring process that results in realistic materiel designs and test methods based on materiel system performance requirements [20].

3.2 Non-Functional Requirements

Non-functional requirements are harder to define and are not easily measured. A systems engineering approach to new technology development helps outline the non-functional requirements of a technology. In 2022 the US Navy approved its latest revision of its Systems Engineering Guidebook. Outlined in the guidance are best practices and process for defense acquisition programs [21]. The process for defining, deriving, and refining requirements includes analysing the end user need, translation into basic functions with quantifiable, qualitative (non-functional), and quantitative (functional) requirements. During the basic and applied research phases of technology development the qualitative aspects of a system are usually not considered.

Non-functional requirements are often referred to as "-ilities" since many end in "-ility", which in the English language, convert a verb into a noun. For example, the definition of maintain is, *to keep in an existing state*. This is a verb, describing an action. While the definition of maintainability is, *the ease of which maintenance can occur*. This is a noun, describing a thing, i.e. the system has maintainability (it can be done), versus, the system has been maintained (it was physically completed).

Table 3 is a list of typical non-functional requirements describing attributes of a system. As one can see from the definitions of these non-functional requirements all but one contain the word "ability". This is what makes it difficult to account for when developing new technology. The -ilities above the bold line are general non-functional requirements that many commercial systems might consider. Whereas the -ilities below the line are more essential to military applications.

Table 3. A listing of typical non-functional requirements or "-ilities" [21][22][23].

-ilities	**Definition**
Adaptability	The ability of a system to be changed by a system-internal change agent.
Agility	The ability to change in a timely fashion.
Changeability	The ability of a system to alter its form, and consequently possibly its function, at an acceptable level of resource expenditure.
Extensibility	The ability to accommodate new features after design.
Flexibility	The ability of a system to be changed by a system-external change agent.
Quality	The ability to deliver requirements at a 'high' level, as perceived by people relative to other alternatives that deliver the same requirements.
Versatility	The ability of a system to satisfy diverse expectations on the system without the need for changing form.
Maintainability	The ability to perform maintenance on a system to prevent a potential future failure.
Reliability	The probability that a system or component will satisfy its requirements over a given period and under given conditions.
Repairability	The ability to be returned to the original state of function when some function is lost.
Resiliency	The ability of a system to adapt affordably and perform effectively across a wide range of operational contexts, where context is defined by mission, environment, threat, and force disposition.
Robustness	The ability of a system to maintain its level and set of specification parameters in the context of changing system external and internal forces.
Supportability	The ability to provide logistical support with manning, materiel (spares), or training.
Interoperability	The ability to effectively interact with other systems.
Affordability	The ability to allocate resources out of a future total budget projection to individual activities.
Survivability	The ability of a system and its crew to avoid or withstand a hostile environment without losing the capability to accomplish its designated mission.
Operational Availability	The ability of a system to be ready to perform its operation in support of the mission.

Based on experience, the single most important non-functional requirement for the Navy is a systems operational availability, commonly expresses as "A-sub-o" or Ao. This is so important to the Navy that the Deputy to the Chief of Naval Operations signed an instruction addressing Operational Availability of Equipment and Weapons Systems [24]. The Ao is the most important non-functional requirement since it is an indication of a systems readiness to be deployed. Ao is expressed as a percentage. It is derived from dividing a systems uptime, (when the system is usable), by the total time, which is uptime plus downtime, (when the system is unusable) [25].

Even though the Ao of a military system is the most important non-functional requirement there are several other important non-functional requirements. Reliability of a system will increase the Ao as well as make it more affordable when considering the total ownership cost to maintain a system. Repairability, maintainability, and supportability are important to ensure that the Navy's sailors and marines can perform these actions on hardware or software while deployed. These will also affect the affordability of a system over time. Interoperability may be on a microscale level for interactions of one system to another, or macroscale level of interactions between allied Navy ships and submarines. Finally, affordability is a very difficult non-functional requirement to design for, but as expressed earlier, there are limited resources available and the more affordable a technology is the easier it is to transition it to the Fleet.

4. Superconducting and Cryogenic Applications

4.1 Operational Environment Effect

Since cryocoolers typically reject heat to air or water the condition of the atmosphere and hydrosphere will greatly affect their performance. The thermal stresses will also affect the application the cryocoolers are removing heat from. An example of solar radiation's effect on a cryogenic system was observed during testing of a prototype superconducting system developed by the Naval Surface Warfare Center, Philadelphia Division. The system was installed in San Diego, CA on the deck of a Navy vessel. During the evenings the cryogenic temperature in the system would decrease, and during the day when the sun was radiating heat onto the stainless-steel cryostat the temperature would increase. It was a negligible change; however, it was noticed when reviewing thermal data as is shown in Figure 3.

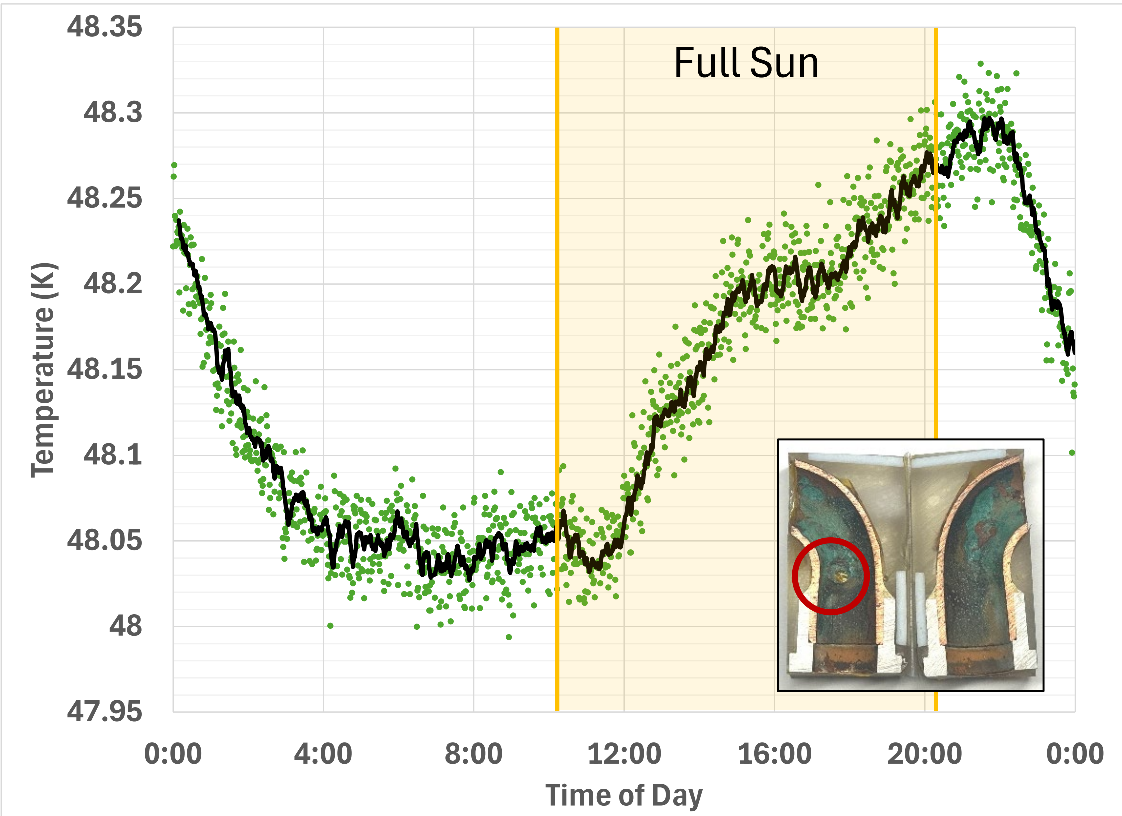

Figure 4. Thermal data of superconducting system over a twenty-four-hour period showing the effect of solar radiation and a piece of heat exchanger tubing corroded by sea water causing pin hole erosion.

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Figure 3 also shows another example of the environment affecting the cryogenic system during the same at-sea demonstration. The superconducting system was cryogenically cooled by a Gifford-McMahon cryorefrigerator being driven with a water-cooled helium compressor. The decision was made to use sea water to cool the compressor since the demonstration was only supposed to be for a week, and the heat exchanger was designed for the sea water temperature extremes. This proved to be a poor decision. Although the heat exchanger was designed for the temperatures of the sea water it was not constructed with materials compatible with sea water. Within a few days the sea water eroded the copper tubing in the heat exchanger causing helium leak into the sea water space and finally created a hole which caused a leak into the compressor cabinet.

4.2 Cryogenic Requirements

Several key performance parameters drive new cryocooler developments. Typical functional requirements posed on these machines are SWaP, air- or water-cooled heat exchange, Carnot efficiency, and most importantly, heat lift at a specific temperature. Commercial cryorefrigerator manufacturers provide specifications of their products on data sheets which may satisfy the functional requirements of a system under development. Often, the specification of commercially available cryocoolers will not meet the Navy's need for its applications. When the Navy is developing new applications for superconducting systems, cryorefrigerator functional requirements are prioritized along with non-functional requirements, and new or modified cryocooling technology may need to be developed.

Non-functional requirements in cryogenic systems may not be as important in the commercial sector; however, when designing systems for the Navy they are almost as important as the technical requirements. Over the past four decades the US Navy has been investing in cryocooler developments. In the past, Gifford-McMahon systems were studied extensively. Recent investments have been developing free-piston Stirling and reverse-turbo Brayton cryocoolers. Among the technical requirements for these systems, the Navy sought lower-cost options, options with better reliability and lower maintenance schedules, more survivable systems operating in the environments described above, and ultimately systems that provide a high Ao. For the Navy to complete its mission these non-functional requirements as well as others not listed are imperative to the operation of its ships, submarines, aircraft, and every system aboard these assets.

5. Conclusion

There are many research and development programs advancing cryogenic technology and materials. During the initial basic and applied research phases of development the focus is on technical or functional requirements of the materials or systems. However, it is also imperative to consider the non-functional requirements. Taking non-functional requirements into consideration early on will increase the ability to transition a technology from the laboratory the US Navy Fleet.

Aspects of the operational environment will greatly affect a systems operation and performance. Waiting till the transition phase of a research program to address the operational environment may cause the technology to be disregarded as a capability the Navy can use to meet its mission. In a resource limited atmosphere, the operational environment and non-functional requirements should be addressed as early as possible. This will increase success in transitioning new cryogenic technologies into the Fleet by avoiding the transition "valley of death".

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