Chapter 1
Principles of Cryostat Design

J.G. Weisend II

Abstract This chapter provides an introduction to the engineering and design of cryostats. It reviews cryostat requirements and provides detailed technical information on topics relevant to cryostats. These topics include: materials, heat transfer and thermal insulation systems, structural supports, safety, instrumentation, seals and connections, transfer lines and thermoacoustic oscillations. The role of prototyping and series testing in cryostat development is also discussed. Numerous tables, figures and equations provide useful information for the cryostat designer.

1.1 Cryostat Requirements

Successful engineering design depends upon a thorough understanding of the requirements of the component being designed. Rushing into design before fully understanding the requirements can lead to poorly optimized designs and a loss of time and resources.

Cryostats typically have a set of common requirements, not all of which can be simultaneously met to the same degree. Explicitly determining the requirements of a cryostat and determining which ones are most important is the key first step to a successful cryostat design. The following are requirements that should be considered in cryostat design.

1. Operating Temperatures and Allowable Heat Load

Since the purpose of a cryostat is to maintain systems at cryogenic temperatures, the definition of the operating temperatures and the allowed heat load at those temperatures are generally some of the first requirements defined. These requirements drive a number of aspects of the resulting design including: material selection, design of the thermal insulation system, cost, complexity and size. There are a

J.G. Weisend II (✉)
European Spallation Source ERIC, Lund University,
P.O. Box 176, 22100 Lund, Sweden
e-mail: john.weisend@esss.se

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number of subtleties in these requirements. An important distinction is that between static heat leak and dynamic heat load. Static heat leak refers to heat entering the cryostat from the outside environment. In many cryostats, this is the sole or principal source of heat deposited at cryogenic temperatures. However, in other cryostats there may be an additional heat load to cryogenic temperatures that stems from the operation of the cryogenic equipment itself. Such heat loads typically vary with time and are thus dynamic. Examples of such heat loads include heating of the cavity walls in superconducting radiofrequency systems and heat deposited by particle beams in accelerator or target cryostats. Dynamic heat loads can be the dominant heat loads to the cryostat, which may affect the design choices made in the cryostat's thermal insulation system.

The temperatures at which heat is deposited in the cryostat are determined by a number of factors. The required operating temperature of the cryogenic equipment is one requirement but temperatures of intermediate shields or heat sinks may be driven by the optimal performance of small cryocoolers or large cryogenic refrigeration plants.

Cryostats are frequently part of a larger cryogenic system. Allowable heat loads and operating temperatures must be consistent with the larger system needs and overall system optimization may be possible [1]. The allowable heat loads in a cryostat may also be related to the number of cryostats in the system. A system with a large number of cryostats, such as LHC or International Linear Collider (ILC) may require a smaller heat load per cryostat to keep the overall cryogenic system a reasonable size. Such systems put additional effort into reducing the heat load of each cryostat (see case studies in the following chapters).

2. Alignment and Vibration

Depending on the application, some cryostats have requirements on the alignment of the cryogenic equipment they contain or have limits on their allowable vibrations. Issues to consider when responding to these requirements are the impact of repeated thermal cycling on the alignment and the need, if any, to adjust the alignment while the cryostat is cold or under vacuum Alignment requirements can be quite tight. In the case of the TESLA cryomodules [2] the magnets had to maintain an alignment to ± 0.25 mm relative to an ideal reference.

3. Safety

Safety requirements including maximum credible accidents should be determined at the start of the design and any design implications factored in from the beginning. Retrofitting a design to meet safety requirements can be very expensive and time consuming. In particular, issues due to overpressure and venting as a result of vacuum or pipe failures can require significant design effort [3].

4. Allowable Size and Weight

These are particularly important for space borne cryostats but are also relevant for cryostats that must be transported.

5. Amount and Type of Required Instrumentation

This may well vary between prototype and mass produced cryostats.

6. Number of Feedthroughs for Instrumentation, Power, External Manipulators, Optical Windows and Cryogenic Lines.
7. Ease of Access to Cryostat Components
8. Existence of Ionizing Radiation or Magnetic Fields

This will influence material and instrumentation choices. The performance of superconducting RF cavities, for example, is strongly affected by local magnetic fields. This results in a need for supplemental magnetic shielding in the cryostat as well as a limit on magnetic material near the cavities.

9. Additional Material Requirements

Some cryostats have additional unique material requirements. For example the Cryogenic Dark Matter Search cryostat (Chap. 8) requires the use of materials with no radioactivity to avoid false signals. This severely constrains the material choices.

10. Existing Regulatory Code Requirements

These might include pressure vessels codes or codes associated with flammable materials.

11. Expected Lifetime of the Cryostat
12. Number of Cryostats Required

Is this a single unique cryostat or will it be mass-produced? Different design choices may be made in either case.

13. Cost and Schedule Limits

These should be known and considered at the beginning of the design.

All designs involve compromise and it's extremely unlikely that all cryostat requirements can be met equally. The trick is to properly prioritize the requirements in order to create an optimal design. Figure 1.1 shows an example of this approach. The figure shows the E158 liquid hydrogen target cryostat operated at the SLAC National Accelerator Lab [4]. This cryostat contained a loop of circulating LH_2 operating at 20 K. A high energy electron beam was scattered by the LH_2 as part of a fundamental physics experiment. The presence of the beam had two important effects: the cryostat was exposed to a extremely high ionizing radiation environment and the beam deposited roughly 900 W of heat into the 20 K LH_2. This resulted in two important design choices. First, materials such as kapton based multilayer insulation and ceramic based electrical insulation that survive high radiation doses were chosen for the cryostat. Second, given the high dynamic heat loads from the beam, expensive techniques to reduce the static heat load, such as actively cooled thermal radiation shields were not used.

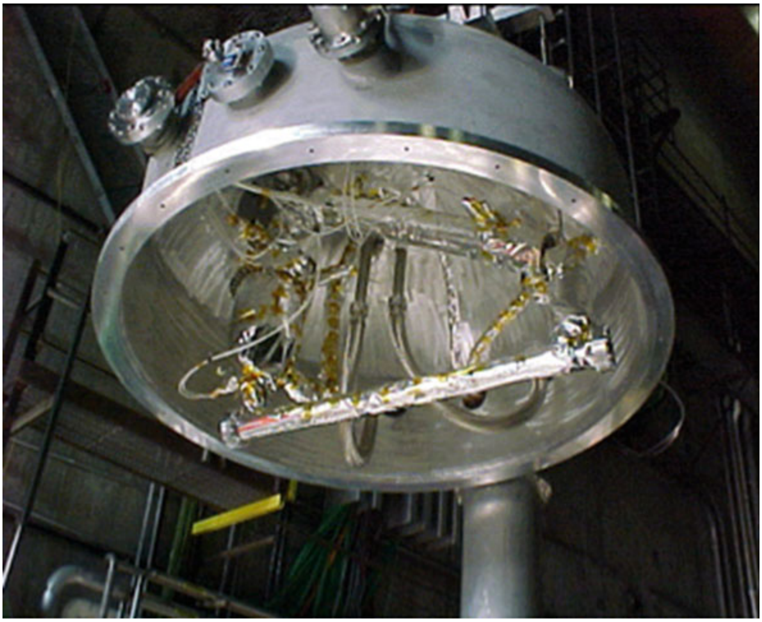


Fig. 1.1 View of the upper portion of the SLAC E158 liquid hydrogen target cryostat [4]

1.2 Cryogenic Properties of Materials

Selection of the proper materials is an important aspect of cryostat design. Many materials are unsuitable for use at cryogenic temperatures and the properties of materials can change greatly between room temperature and cryogenic temperatures. Failures in cryostats can frequently be traced to the use of inappropriate materials or to not accounting for the change in material properties as a function of temperature.

The following materials are suitable for use at cryogenic temperatures:

- Austenitic stainless steels e.g. 304, 304L, 316, 321
- Aluminum alloys e.g. 6061, 6063, 1100
- Copper e.g. OFHC, ETP and phosphorous deoxidized
- Brass
- Fiber reinforced plastics such as G-10 and G-11
- Teflon (depending on the application)
- Niobium and Titanium (frequently used in superconducting RF systems)
- Invar (Ni/Fe alloy) useful in making washers due to its lower coefficient of expansion
- Indium (used as an O ring material)
- Kapton and Mylar (used in Multilayer Insulation and as electrical insulation
- Quartz (used in windows)

Some materials unsuitable for use at cryogenic temperatures include:

- Martensitic stainless steels—undergoes ductile to brittle transition when cooled down.
- Cast Iron—also becomes brittle
- Carbon steels—also becomes brittle. Sometimes used in 300 K vacuum vessels but care must be taken that breaks in cryogenic lines do not cause the vacuum vessels to cool down and fail.
- Rubber and most plastics.

One should never use materials in cryostats unless their suitability for use at cryogenic temperatures is verified and their behavior as a function of temperature is well understood. Given the large, and frequently nonlinear, changes in material properties as a function of temperature, simple extrapolation of room temperature properties to cryogenic temperatures should never be done. References [5–9] are good starting points for finding the cryogenic properties of materials. Searching in the proceedings of the International Cryogenics Materials Conference series may also be useful. There are also commercially available computer codes that produce material properties at cryogenic temperature [10, 11]. Aspects of some key cryogenic properties of materials are given below.

1.2.1 Thermal Contraction

Almost all materials change size (most shrink) when cooled to cryogenic temperatures. This effect can be significant and can cause a number of issues in cryostats including the development of interferences or gaps between adjacent parts upon cooling, adverse impact on alignment and possible failure upon cool down in over constrained components or wires.

Thermal contraction should always be considered in cryostat design. Guidelines for design include:

- Allow components room to contract through the use of sliding joints, bellows or only fixing at a single point
- Install sufficient slack into wire and cable assemblies to allow for contraction
- Overlap thermal shields and multilayer insulation to avoid gaps upon cool down and contraction
- Analyze the effect of thermal contraction on system alignment and on the possibility of interferences between developing between adjacent components
- Play particular attention to the impact of thermal contraction on different materials connected to or adjacent to each other

Thermal contraction is generally described by the property of thermal expansivity [12] which is the change in volume or length of a material with temperature. This property, which itself is a function of temperature, is of limited use in cryostat

Table 1.1 Integrated thermal contraction for practical engineering materials between 300 and 100 K and between 100 and 4 K

Material	ΔL/L (300–100 K)	ΔL/L (100–4 K)
Stainless steel	296×10^{-5}	35×10^{-5}
Copper	326×10^{-5}	44×10^{-5}
Aluminum	415×10^{-5}	47×10^{-5}
Iron	198×10^{-5}	18×10^{-5}
Invar	40×10^{-5}	–
Brass	340×10^{-5}	57×10^{-5}
Epoxy/fiberglass	279×10^{-5}	47×10^{-5}
Titanium	134×10^{-5}	17×10^{-5}

design. More useful is the integrated change in length of a material between two end temperatures. This is shown in Table 1.1 for a number of practical engineering materials.

In order to find the change in length per unit length from 300 to 4 K, simply add the two columns together. Thus, on average, a 1 m length of stainless steel will contract 331×10^{-5} m or 3.3 mm. Notice that Invar, a Iron–Nickel alloy contracts very little as a function of temperature. Invar has been used in cryostats (see Chap. 5) where very little length contraction is desired.

1.2.2 *Thermal Conductivity*

The thermal conductivity of materials, particularly metals, varies strongly with temperature between 300 and 0 K. This variability must always be taken into account in cryostat design. Figure 1.2 shows the thermal conductivity of a number of materials as a function of temperature. In many cases, the analysis may be simplified by the use of thermal conductivity integrals [8]. In this approach, the conduction heat transfer in one dimension is given by:

$$Q = -G(\theta_1 - \theta_2) \tag{1.1}$$

where Q is the total heat transferred by conduction and the Geometry Factor (G) is given by:

$$G = \frac{1}{\int_{x_1}^{x_2} \frac{dx}{A(x)}} \tag{1.2}$$

Here x is the position along the conduction path and A is the cross sectional area. Note that in the case of a component with length L and constant cross sectional area A, Eq. 1.2 becomes simply A/L.

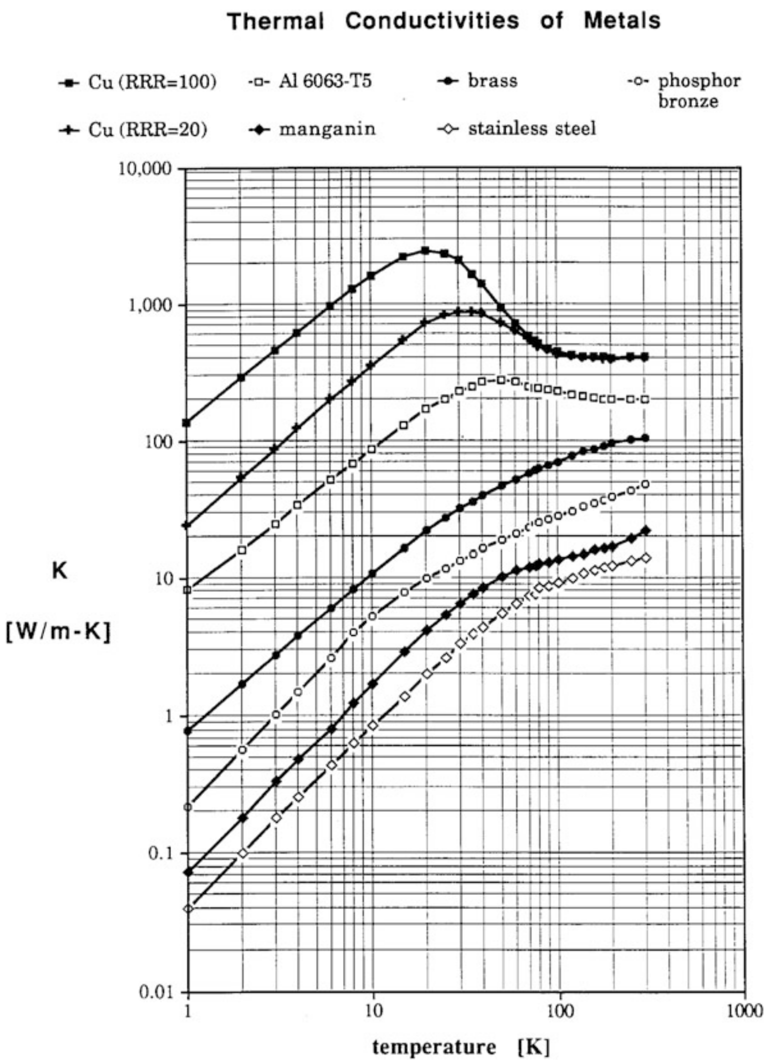


Fig. 1.2 Thermal conductivity as a function of temperature for a variety of engineering materials [8]

The thermal conductivity integral θ_i is given by:

$$\theta_i = \int_0^{T_i} k(T)dT \tag{1.3}$$

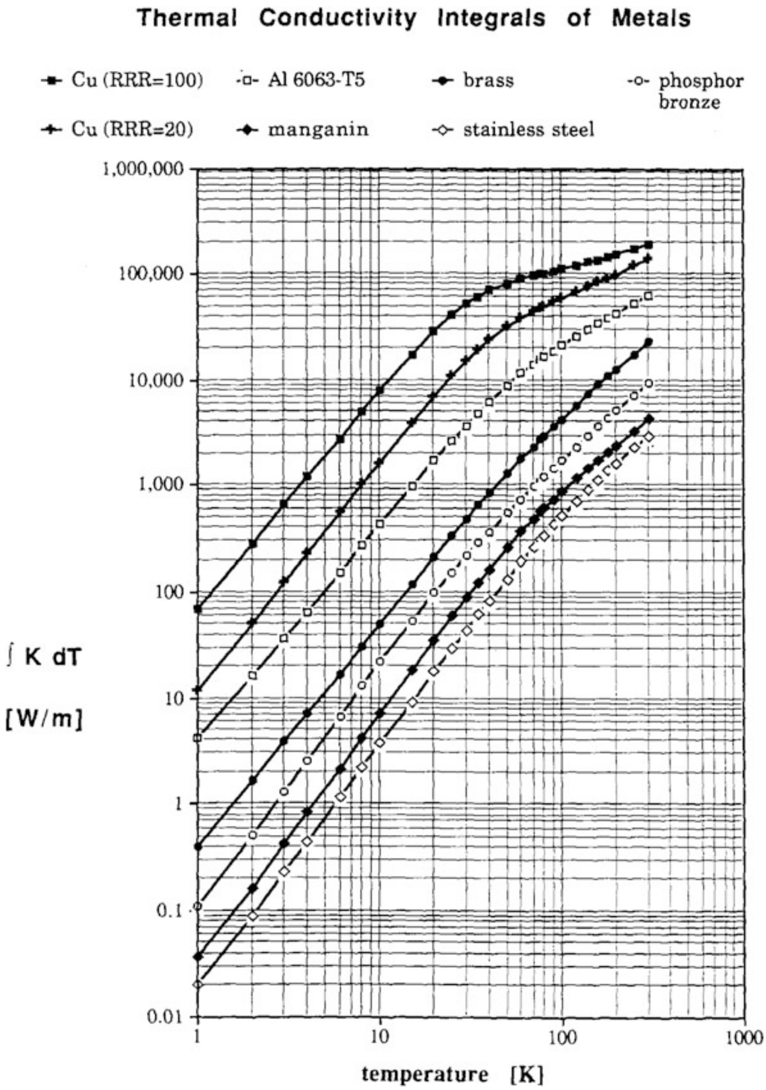


Fig. 1.3 Thermal conductivity integrals of a variety of engineering materials [8]

where T is the temperature and k is the thermal conductivity. Knowing the appropriate thermal conductivity integral for a given material and temperature allows quick calculation of the heat transfer between known temperatures while still taking into account the variation of thermal conductivity with temperature. Figures 1.3 and 1.4 show thermal conductivity integrals for a range of materials.

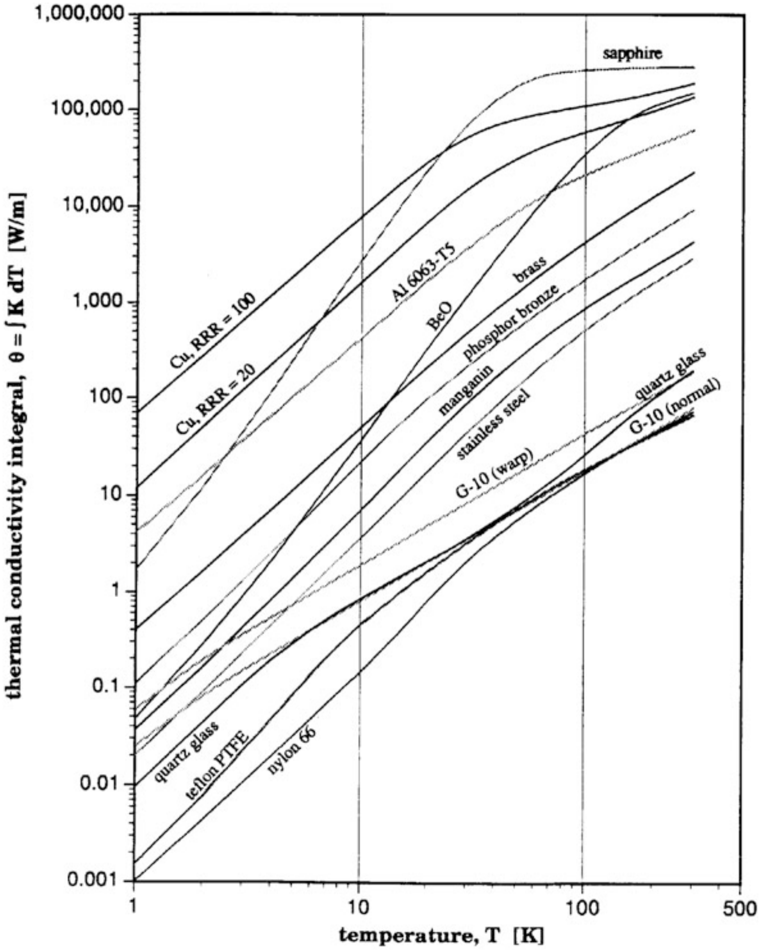


Fig. 1.4 Thermal conductivity integrals of a variety of engineering materials—Courtesy of Lakeshore Cryotronics

1.2.3 Heat Capacity

The heat capacity or specific heat of materials generally decreases as a function of temperature. This has two principal effects in cryostats. First, for a constant rate of cooling, the drop in temperature over time increases as the cryostat becomes colder. This effect is easily seen in larger systems which cool down more rapidly at lower temperatures. Second, at cryogenic temperatures, the lower heat capacity means that small heat leaks can cause significant temperature rises. This can be particularly important for system operating below 1 K. Figure 1.5 shows the specific heat as a function of temperature for a number of engineering materials.

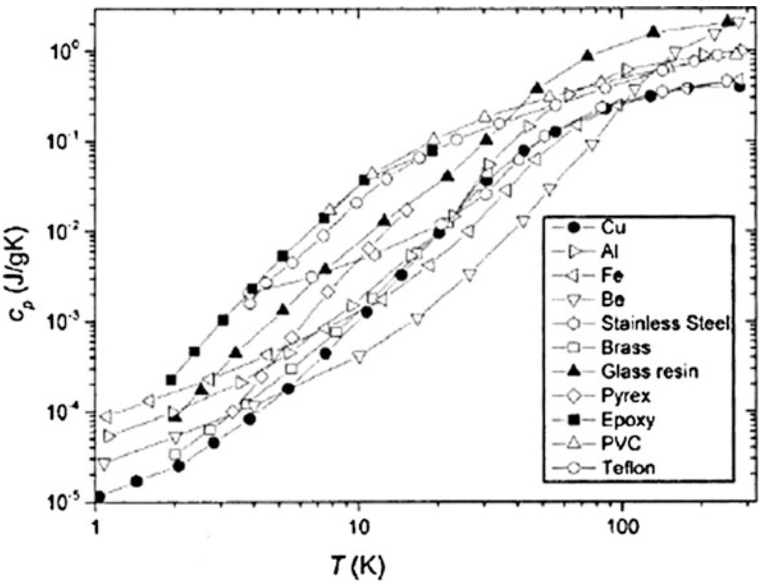


Fig. 1.5 Specific heat as a function of temperature for a variety of engineering materials [9]

1.2.4 Material Strength

Material strength properties such as yield strength and ultimate tensile strength also change with temperature. In many metals, those that don't become brittle, the strength actually increases with decreasing temperatures. However in this case, most cryostats are designed using the lower, more conservative values at 300 K. The reason for this is two-fold. First, all cryostats start out at room temperature and second, due to operational issues even a cold cryostat may return suddenly to room temperature.

There are some cases in which the higher values at lower temperatures may be taken into account. In the case of Superconducting RF cavities made from niobium, the increased strength of the niobium at cryogenic temperatures may be used when analyzing the response of the cavity to accidents that only occur when the cavity is at cryogenic temperatures. An example of such an accident is the loss of beam tube vacuum and the subsequent condensation of air on the surface of the cavity. This condensation deposits heat and rapidly boils away the helium surrounding the cavity causing large pressure rises in the helium space. Such a scenario can't occur if the cavity is at room temperature and thus the cavity's stronger, lower temperature strength properties can be used in determining the cavity's response to the sudden pressure rise.

As always, the material strength properties should always be checked at the temperatures of interest to the cryostat being designed.

1.3 Thermal Insulation and Heat Transfer

A primary function of a cryostat, of course, is to maintain the equipment inside at cryogenic temperatures. This is accomplished by developing thermal insulation systems that block heat from the outside environment from reaching the cryogenic equipment. While a perfect insulation system doesn't exist, properly designed cryostats can reduce the heat leak to very low, even μW, levels. This is accomplished by interrupting the three mechanisms of heat transfer within the cryostat: conduction, convention and radiation.

1.3.1 Reducing Conduction Heat Transfer

The Fourier heat conduction equation (Eq. 1.1) shows that the heat transferred by conduction is proportional to the temperature difference, the thermal conductivity and the cross sectional area of the conduction path and is inversely proportional to the length of the conduction path. Thus, the conduction heat leak can be reduced by using low thermal conductivity materials, reducing the cross sectional area of the conduction path and increasing the length of the conduction path. As you read through the case studies later in this book, you will notice again and again, the presence of long, thin conduction paths made from low conductivity material. Another way to reduce the conduction heat leak to the lowest temperature is to intercept the heat at an intermediate temperature. This reduces the temperature difference and thus the heat to the lowest temperature point. The heat conducted from higher temperatures to the intermediate heat sink still has to be removed but it is thermodynamically more efficient to remove the heat at a higher temperature. Chapter 7 gives an example of the optimization of such heat sinks.

Figure 1.6 shows the support post first developed for the SSC magnet cryostat and shown here for use on the TESLA (now ILC) cryomodule [13]. The design of this post reduces the conduction heat leak via the principles described above. The conduction path in the post is made from low conductivity G-10 cylinders with a small cross sectional area. In addition, active heat sinks are installed at the 77 K and 4 K levels. As a result, the post transfers only 0.03 W of heat between room temperature and 2 K over a distance of 140 mm while still being able to support a load of 50 kN.

1.3.2 Reducing Convection Heat Transfer

Convection heat transfer is that caused by a moving fluid. In many cryostats, this mode of heat transfer is eliminated by using a vacuum space to separate the cold and warm portions of the cryostat. This removes any fluid that can transfer heat via

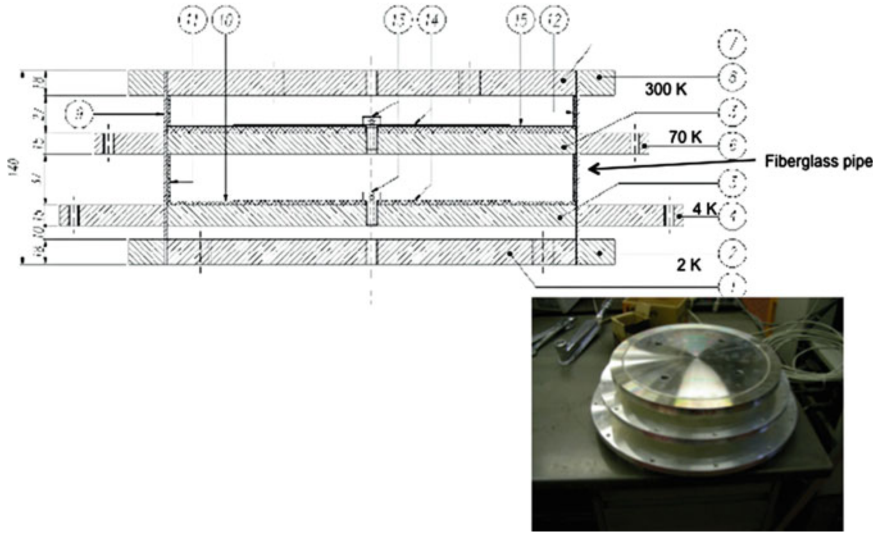


Fig. 1.6 The support post for the ILC cryomodule—Courtesy of Nicol [13]

convection. The use of such an isolation vacuum was a key feature of James Dewar's original liquid hydrogen cryostat.

In general, a pressure of 10^{-6} millibar or less is sufficient vacuum to eliminate all convective heat transfer. The cold wall of the vacuum space acts as a cryopump for residual gases. Cryostats, particularly those operating below 77 K may have isolation vacuums of 10^{-8} millibar or less when cold. It is not good practice to depend upon cryopumping only but rather to use mechanical pumps to reduce the pressure to near 10^{-6} millibar prior to cooling the cryostat down. In some cases, the use of isolation vacuum spaces is not possible or practical and other techniques such as foam insulation are used; see Sect. 1.3.4.

1.3.3 Reducing Radiation Heat Transfer

All surfaces emit heat via electromagnetic radiation. This thermal radiation is frequently the largest source of heat leak into a cryostat. There are a number of techniques for reducing the radiation heat leak into a cryostat. These techniques are driven by the applicable governing equation for idealized (infinite parallel plates, surface emissivities equal and ≪1) radiation heat transfer [8]:

$$q = \frac{\epsilon}{(N+1)*2}\sigma\left(T_H^4 - T_L^4\right) \tag{1.4}$$

where q is the heat transferred in W/m^2, ε is the emissivity of the surfaces, σ is the Stefan-Boltzmann constant (5.67×10^{-8} $W/(K^4m^2)$) and N is the number of uncooled radiation shields between the high temperature surface (T_H) and the low temperature surface (T_L). Equation 1.4 can also be shown to apply for the case of long concentric cylinders where the gap between the cylinders is small compared to the diameter of the inner cylinder [14]. Based on Eq. 1.4, the heat leak can be reduced by decreasing the emissivity of the surface, adding uncooled radiation shields between the high temperature and low temperature surfaces and reducing the temperature of the high temperature surface.

The temperature of the high temperature surface can be reduced by inserting a lower temperature actively cooled radiation shield between the room temperature (300 K) surface and the lowest temperature surface. The effect of this can be significant. If we use Eq. 1.4 assuming an emissivity of 0.2 and no uncooled shields (N = 0), the heat leak between a 300 and 4.2 K surface is 46 W/m^2. If the warmest surface facing the 4.2 K surface is now 77 K then the heat leak is reduced to 0.2 W/m^2. The use of actively cooled thermal radiation shields is very common and is seen in most of the case studies that follow.

Actively cooled shields may cooled by cold vapor boiling off from a cryogenic reservoir, cooling flows from a cryogenic refrigeration plant and conductive cooling from a small cryocooler attached to the shield. In many laboratory dewars, a liquid nitrogen bath serves as the thermal radiation shield for the inner liquid helium space.

Figure 1.7 shows emissivities of typical material used in cryostats. When calculating radiation heat leak take care not to underestimate the value of the emissivity; allow for the possibility of tarnishing or oxidizing of the surface that might result in a higher emissivity. Silver plating a surface or coating the surface with highly reflective tape will help reduce the emissivity but can be costly and is generally done only where the absolute minimum radiation heat leak is desired [15] or where there is no room for multilayer insulation.

The reduction of thermal radiation heat leak by the use of uncooled shields to block the line of sight between the cold and warm surfaces can be significant. Multilayer insulation (MLI) also sometimes called superinsulation is the logical extension of this approach. MLI consists of many layers of thin aluminized Mylar or sometimes aluminized Kapton placed into the vacuum space between the warm and cold surfaces. A design feature of MLI is to reduce or eliminate the thermal conduction between the successive layers. This is typically done by placing a nonconductive mesh or paper between the aluminized Mylar sheets or in some cases by only aluminizing only one side of the Mylar and then crinkling the sheets so there are only point contacts between them. Since MLI makes the term N in Eq. 1.4 large, its impact on the thermal radiation heat leak is impressive. As such, most of the case studies that follow employ MLI in their design. Figure 1.8 shows an example of the MLI from the Large Hadron Collider (LHC) magnet cryostat [16].

There are some cautions with the use of MLI. Care much be taken not to pack the MLI too tightly in the vacuum space. Doing so causes the conduction heat load

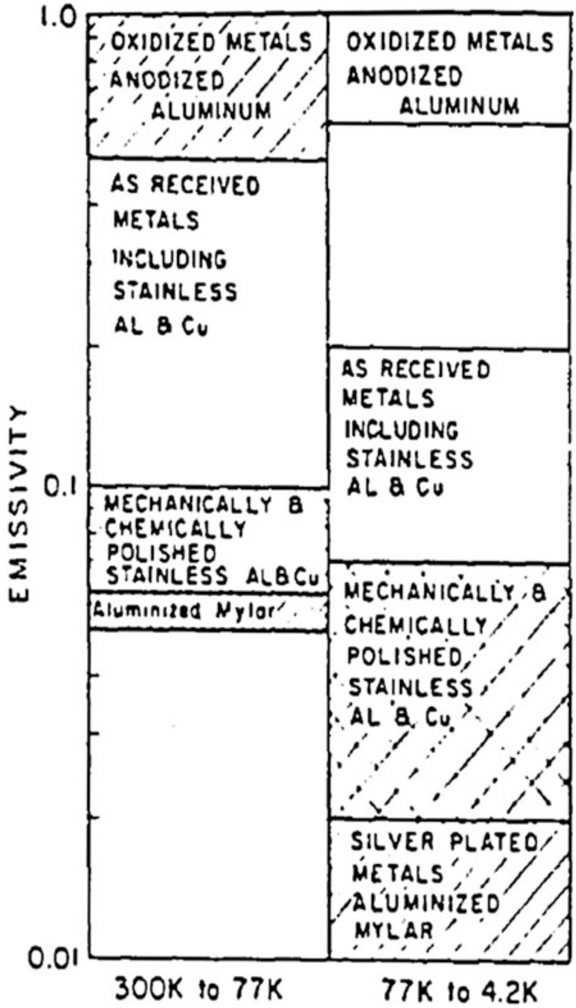


Fig. 1.7 Emissivities of typical cryostat materials [14]

Fig. 1.8 The MLI system for the large hadron collider (LHC) magnet cryostats. Reproduced with permission from Poncet and Parma [16]. Copyright 2008, AIP Publishing LLC

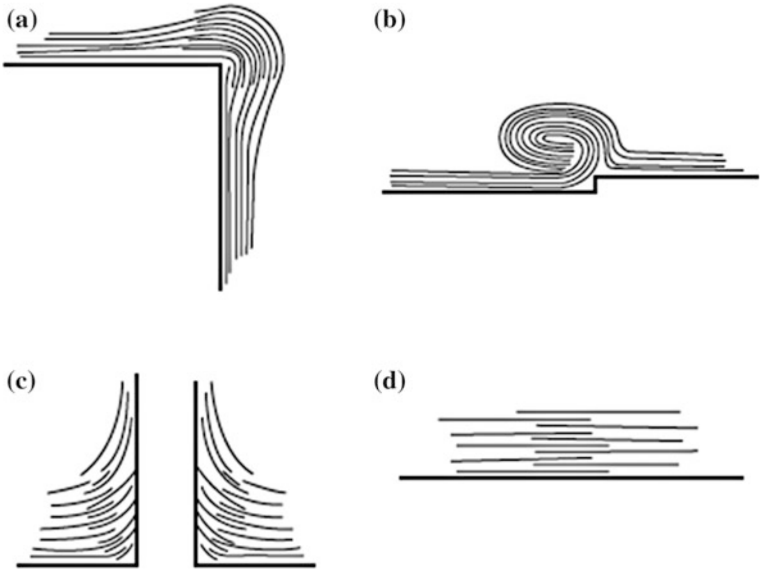


Fig. 1.9 Examples of the proper installation of MLI for corners (**a**), steps (**b**), penetrations (**c**) and overlaps (**d**) [18]

to increase, reducing the benefit of the MLI. This effect was seen in the SSC Collider Dipole thermal measurement model (see Chap. 2). A good guideline is to keep the density of the MLI in the vacuum space to around 0.5 layers per mm [14]. Another hazard with MLI is associated with seams, ends, penetrations and corners [17]. If these aspects of the installation are not handled properly, their effect can dominate the heat leak. The basic rule here is to avoid connecting the warmest outer layer of the MLI with one of the colder inner layers. This would, in effect, short circuit the MLI and reduces its effectiveness. It is also important to overlap the layers of the MLI at seams so that when the MLI shrinks during cool down, a gap does not open up that allows the warm surface to directly see the cold surface below the MLI. Figure 1.9 illustrates the proper way to address these issues. Detailed analysis and measurements have been made of specific MLI designs and additional information may be found in Refs. [8, 18–20].

1.3.4 Other Insulation Approaches

The general approach of using vacuum insulated cryostats combined with actively cooled thermal shields and MLI in the vacuum space is not used in all cryostats. In some cases, such as cryogenic tanks for rocket propellants, the weight penalty caused by the presence of a second wall is too high. In other systems, the cost or complexity of vacuum spaces, MLI and thermal shields out weighs the benefit of a reduced heat leak. This is frequently seen in large storage and transport tanks, particularly for those operating at or above liquid nitrogen temperatures.

One alternative is to remove the vacuum space entirely and coat the cryogenic surface with insulating foam, typically a closed cell foam. This approach was taken with the cryogenic propellant tanks used in the Saturn 5, Space Shuttle and Ariane 5 launchers. This approach is also seen in vent lines and intermittently used liquid nitrogen fill lines mainly to avoid condensing water or air on the cold line surfaces. In the more high performance applications of cryogenic propellant tank insulation, the foam systems can be quite sophisticated, employing water proof barriers and helium gas purging to prevent condensation of water or air. Figure 1.10 shows the foam system for the Saturn 5 s stage liquid hydrogen tank [21]. The overall heat transfer from this insulation system (including conduction, convection and radiation) was 0.86–1.1 mW/(cm K) at an average temperature of 144 K.

Alternative insulation approaches also include: using glass microspheres [22] or Perlite powder in a annular space (either filled with inert gas or vacuum) surrounding the cryogenic vessel. Opacified powder in which metallic flakes are mixed with the insulating powder can provide higher performance due to its ability to reflect back more of the thermal radiation. Recent advances in aerogel [23, 24] have led to its use in thermal blankets for cryogenic systems.

A nice comparison for scaling purposes of various insulation systems is given in Table 1.2 [25]. The heat flux in all cases includes conduction, convection and radiation. Notice that between 300 and 77 K the use of Perlite powder in a vacuum is more effective than just a high vacuum space. This results from the Perlite intercepting some of the thermal radiation heat leak. References [21, 25] provide detailed descriptions of many of these alternative insulation system.

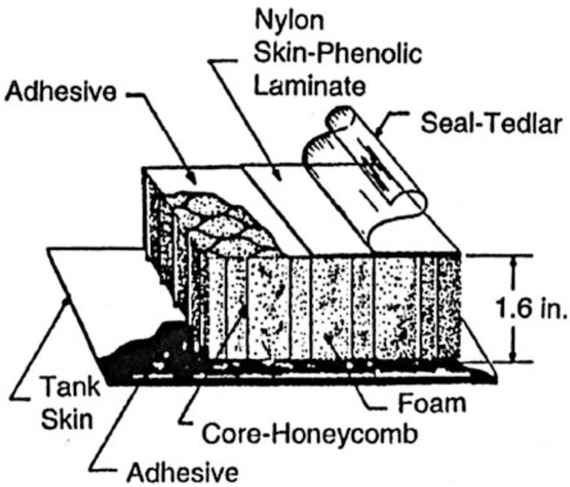


Fig. 1.10 The foam insulation system of the Saturn 5 s stage LH_2 tank [21]

Table 1.2 Comparison of thermal insulation approaches (6 in. thick insulation in all cases)

Type of insulation	Total heat flux (W/m^2)	
	300–77 K	77–20 K
Polystyrene foam	48.3	5.6
Gas filled Perlite powder (5–6 lb/ft^3 filled with He)	184.3	21.8
Perlite powder in vacuum (5–6 lb/ft^3)	1.6	0.07
High vacuum (10^{-6} torr, ε = 0.02)	9	0.04
Opaciated powder (Cu flakes in Santocel)	0.3	–
MLI	0.03	0.007

Reference [25]

1.4 Structural Supports for Cryostats

Structural supports for cryostats serve many purposes. An example is the stand or frame that connects the room temperature outer wall of the cryostat to the outside environment (floor, ceiling etc.). Since these devices connect two room temperature components, they are designed using standard structural engineering techniques. Cryostat stands aren't trivial, they may have to support very large loads or react against strong forces (for example from unbalanced pressure loads or magnetic fields) they may need to allow precision movement or alignment of the cryostats.

More interesting for this book are the supports that connect the cryogenic parts of the cryostat with its room temperature outer wall. There are a number of challenges for these supports.

1. They must support the weight of the components plus any applied loads (e.g. pressure, magnetic field, transport, space launch) while at the same time minimizing the conduction heat leak (see Sect. 1.3.1).
2. They must allow for thermal shrinkage of both the components and the supports during cool down.
3. If required, they must achieve the proper alignment of the cryogenic components upon cool down.
4. The supports and the cryogenic components that are attached must be designed to avoid any unwanted resonant frequencies.

The structural supports in the case studies that follow are designed to meet these challenges.

This section first addresses the issue of alignment and then discusses various design solutions for cryostat structures.

1.4.1 Alignment Approaches

Some cryostats have little to no alignment requirements. Examples of these include many small laboratory systems, cold boxes for refrigeration plants, transport and liquid storage Dewars. In these cases, the support system must allow the components to shrink and move without causing damage. As mentioned in Sect. 1.2.1 not just supports but all components such as pipes and wiring must be designed to allow for thermal contraction. Over constraining a component by rigidly fixing it so that it can not move may well lead to failure upon cool down.

Many other cryostats do have tight alignment requirements. In these cases, the position of certain components must be in the correct location once at cryogenic temperatures. Examples of these cryostats include: superconducting magnets, superconducting cavities and other components used in particle accelerator beam lines, telescopes and other optical systems and space based systems. As will be seen in the case studies, the alignment requirements can be quite strict with allowable tolerances as small as a fraction of a millimeter. There are three general approaches to meeting alignment requirements.

Maintain the alignment upon cool down. In this approach, the structure is designed so that the cool down is symmetric. Those components with tight alignment requirements are properly aligned while warm and keep this alignment when cooled down. In some cases the alignment of the components changes but stays within the allowable alignment tolerance. Examples of this approach include the ESS cryomodules [26].

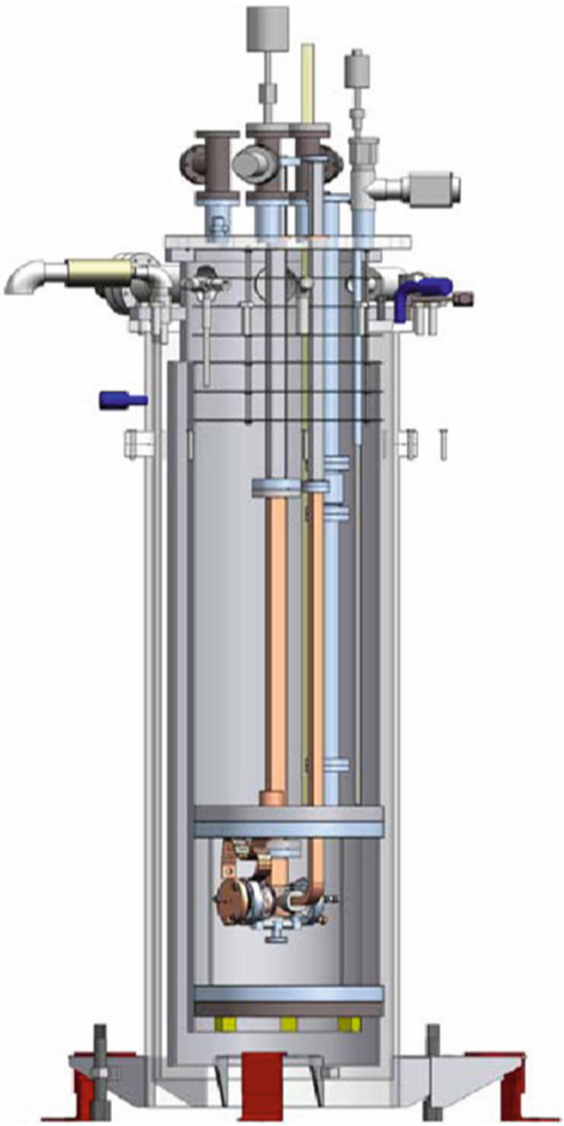
Allow the alignment to change in a predictable way. Here the components are allowed to change position during cool down, but do so in a predictable way that is repeated in each cool down. With these designs, the component is installed so that its out of alignment while at room temperature but moves into alignment when cooled. An example of this is the ILC cryomodule (Chap. 5). In this design, it was calculated that the center of the cavity beam tube would shrink upwards by 1.8 mm upon cool down. The cryomodules were aligned into the accelerator beam line so that the center of the beam tube was 1.8 mm lower than the ideal beam line. Upon cool down, the cavity beam tube was properly aligned with the rest of the system.

Allow realignment once cold. In this approach, components with tight alignment tolerances are realigned into the proper position after they have reached their final cryogenic temperature. This can be accomplished via screws or rods that can adjust the position of the cryogenic components from room temperature or by the use of remotely controlled positioners or motors within the cryostat. However, there are a number of disadvantages with this choice. The screws, rods, motors or positioners may add heat leak, may be expensive and may reduce system reliability. While cryostats have been designed in this way, it's generally best to use approach as the last resort or as a back up to the other two approaches.

1.4.2 Suspension of Components from a Room Temperature Top Flange

This is a very common choice and is used in many laboratory cryostats as well in liquid storage Dewars and refrigerator cold boxes. An example of this approach is shown in Fig. 1.11. All the components inside the innermost part of the cryostat are suspended from the room temperature top flange and not fixed anywhere else. As

Fig. 1.11 Cutaway view of a vertical test cryostat at the SLAC National Acceleratory Laboratory



the system is cooled down, the components are allowed to shrink upwards towards the top flange. This design choice does not tend to guarantee the alignment of components and functions best where alignment tolerances are very loose or nonexistent. The suspension of the components also means that changes in the cryostat's orientation or motion during transport or operation may cause the components to oscillate and become damaged. The use of stops to limit the motion or shipping restraints may be required. This approach has the virtues of being simple, low cost and may result in low conduction heat leaks to the cryogenic components. Figure 1.12 shows this design applied to two different refrigerator cold boxes.

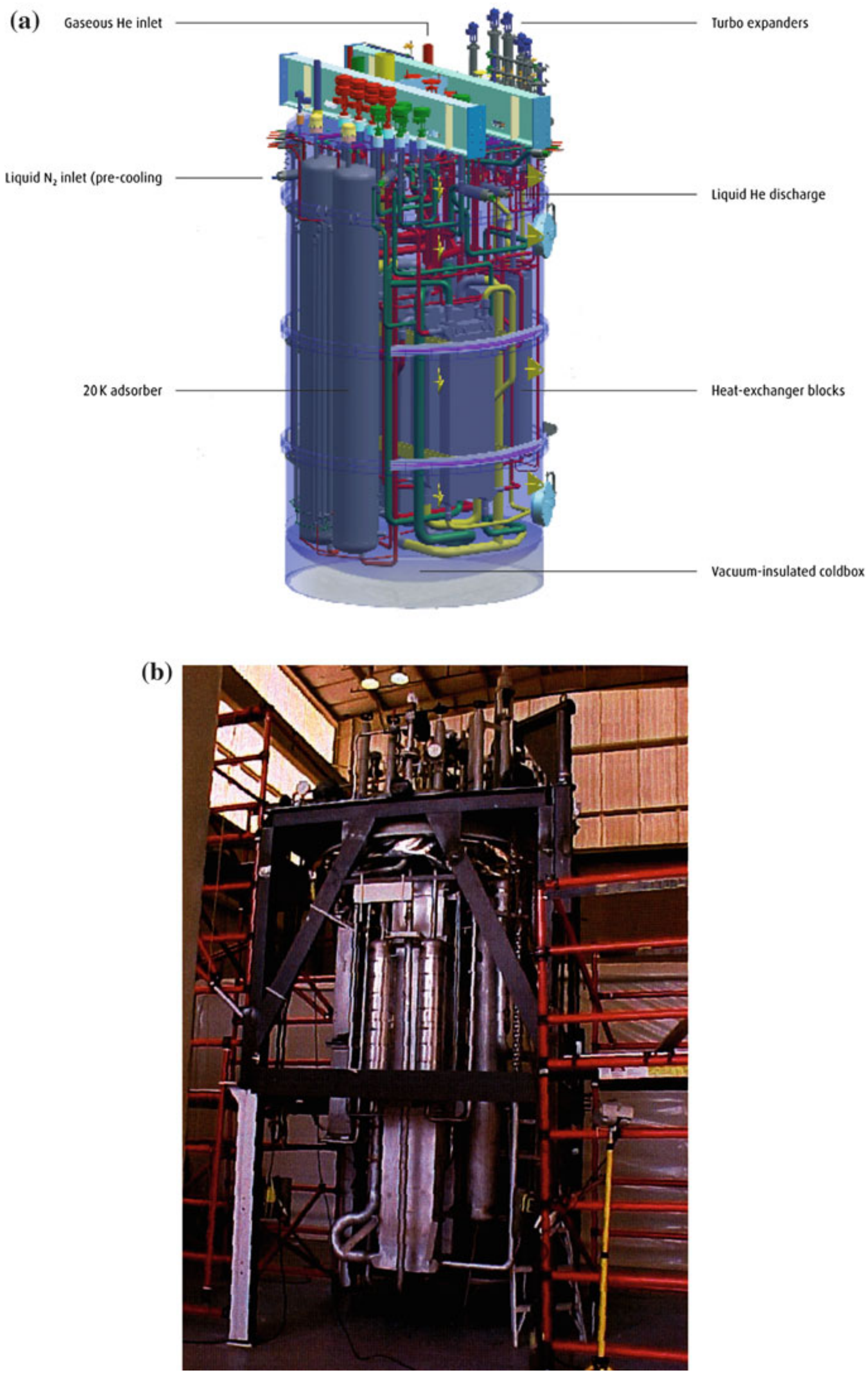
When applied to liquid storage Dewars, this design choice results in everything, including the inner vessel and thermal shields, being suspended from the neck of the Dewar. Again, stops or shipping restraints may be required.

This approach can also be taken with accelerator beam line components if the alignment requirements aren't too stringent. Figure 1.13 shows the inner components of the ATLAS Upgrade cryomodule built at Argonne National Laboratory [27]. The Superconducting cavities, magnets, shields and cryogenic lines are all fixed to the upper flange. The movement of the components up as they cool down is within the alignment tolerances.

1.4.3 Space Frames

In this approach, the cryogenic components are attached to a, typically cylindrical, frame that is thermally and structurally attached to the inside of the room temperature vacuum vessel of the cryostat. The frame itself is kept at or near to 300 K and the cryogenic components are connected by long low conductivity metal rods made from stainless steel, titanium etc.

Figures 1.14 and 1.15 show views of the design of the European Spallation Source (ESS) Elliptical Cavity Cryomodule [26]. Note the use of the hanging rods that attach the cavity string, thermal shields and cryogenic pipes to the space frame. The components can all be assembled onto the space frame and then the entire complete assembly can be inserted into the vacuum vessel, aligned properly and then locked into place. The long cylindrical axis of such systems results in all the components cooling symmetrically towards the center with the result that the cavities maintain their original room temperature alignment at cryogenic temperatures. Space frames are very popular in Superconducting Radiofrequency cryomodules and have also been used in the Spallation Neutron Source and the Jefferson Lab 12 GeV Upgrade projects among others (see Chap. 6).


(a)
Gaseous He inlet
Turbo expanders
Liquid N_2 inlet (pre-cooling
Liquid He discharge
20 K adsorber
Heat-exchanger blocks
Vacuum-insulated coldbox
(b)

◀ **Fig. 1.12** Views of two cryogenic refrigerator cold boxes showing components suspended from a top plate. **a** Courtesy by Linde Kryotechnik AG and **b** the CTI-4000 cold box at the SLAC National Accelerator Laboratory

Fig. 1.13 Components suspended from the upper plate of the ALTAS upgrade cryomodule [27]

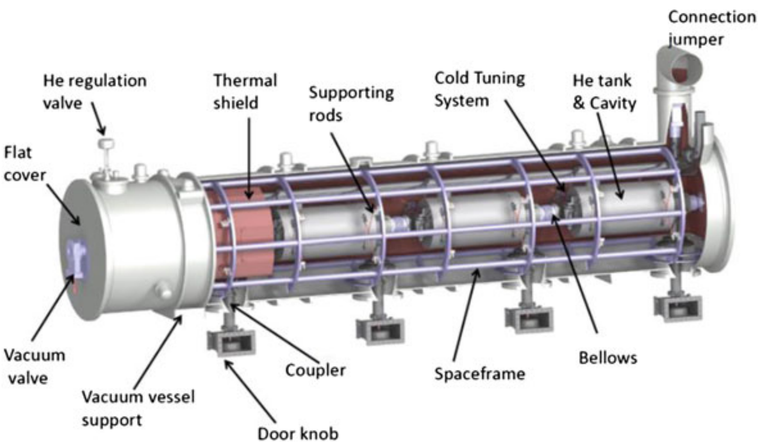


Fig. 1.14 Cut away view of the ESS elliptical cavity cryomodule. Courtesy of Gilles Olivier (CNRS-IPN Orsay)

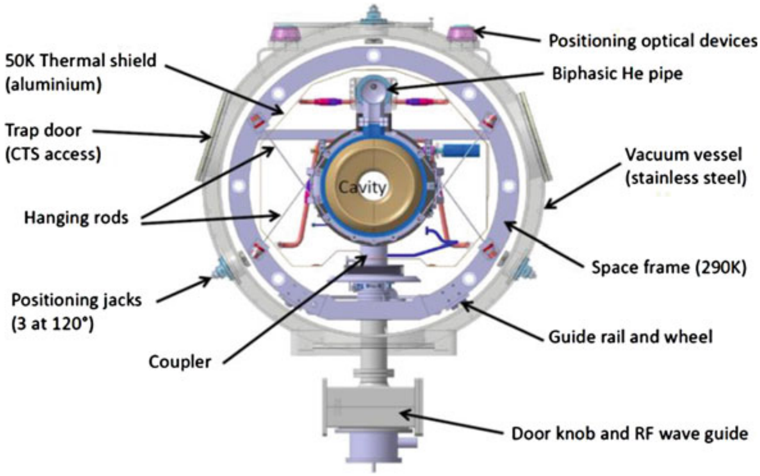


Fig. 1.15 Cross sectional view of the ESS elliptical cavity cryomodule. Courtesy of Gilles Olivier (CNRS-IPN Orsay)

1.4.4 Support Posts

Cryogenic components can also be connected to the 300 K vacuum vessel via support posts. The components can either sit on top of the support posts or be suspended from the support posts. The posts themselves are designed to minimize the heat transfer between 300 K and cryogenic temperatures (see Sect. 1.3.1). An advantage of this approach is that the posts can be designed to support very large loads and are thus frequently used in magnet systems. Since the cryogenic components are not supported in a symmetric manner the position of the components will change during cool down and this effect must be allowed for in the design. Examples of cryostats using support posts include: the LHC magnet cryostat (Chap. 3), the ILC cryostat (Chap. 5) and the SSC magnet cryostat (Chap. 2).

1.4.5 Supports in Space Cryogenics

Space cryogenic systems have additional challenges in cryostat supports. Not only must they minimize heat lead leak via the supports but the large forces that develop during the rocket launch require (at least temporarily) strong supports. Creative approaches have been developed to solve this problem.

Since the orientation of the launch loads is well known, one approach is to optimize the design by making the supports which resist the launch loads stronger while minimizing the strength of the supports in other orientations. This approach was taken with the AXAF cryostat [15].

Another technique is the use of Passive Orbital Disconnect Struts (PODS). These supports are designed in such a way that during orbit or while stationary on Earth, the cryogenic components are supported on thin wall, low heat leak tubes. However, during launch, the forces are taken up by much stronger, thick wall tubes that are parallel to the thin wall tubes. Once the spacecraft is in orbit, the thick wall tubes passively disconnect and the lower heat leak thin wall tubes again provide the support. One advantage of this approach is that the use of the thin wall tubes while on Earth reduces the heat load during any long launch delays and permits verification of the expected heat load in space. These devices have gone through a number of generations and have been extensively tested and studied [28]. They were a key component of the Gravity Probe B cryostat [29].

1.5 Instrumentation

The correct measurement of properties such as temperature, pressure, flow, level and vacuum in cryostats is a key factor in the success of the cryostats. Measurements allow us to understand if our cryogenic components are working properly, enable us to control them and permit the collection of scientific data. There are many subtleties in the selection and installation of cryogenic instrumentation. Poor sensor selection and installation can result in wildly inaccurate readings or sensor failure.

A frequent mistake is to fix one's attention only on the sensor making the measurement itself. By far, the better approach is to think of each measuring point as a complete system including: the sensor, sensor calibration, wiring, feed through, data acquisition hardware and software. The cost of such a complete system can easily exceed $1000 per measurement point. Additional material on cryogenic instrumentation may be found in [8, 30].

1.5.1 Temperature Measurement

Temperature in cryogenics is determined by measuring a physical quantity such as voltage, resistance or pressure that changes in a known repeatable way with temperature. A wide range of options for temperature measurement exists for cryogenics. The existence of reliable commercially available temperature sensors for use in cryogenics has been a major advance in the field. The need to use home made temperature sensors has almost been completely eliminated. The use of home made temperature sensors should be avoided in lieu of commercial devices that are repeatable, reliable, accurate and whose behavior is well understood. The performance of temperature sensors depends on the operating temperature. Some devices, such a silicon diodes, are responsive (though with varying sensitivity) from room temperature all the way down to 1 K. Others, such as platinum resistors, become

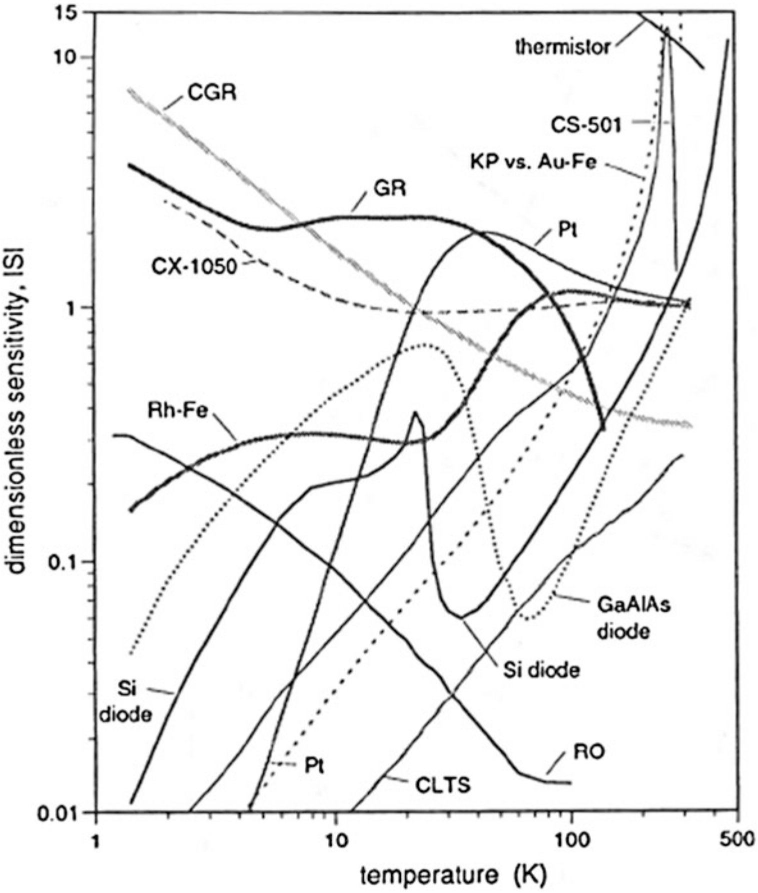


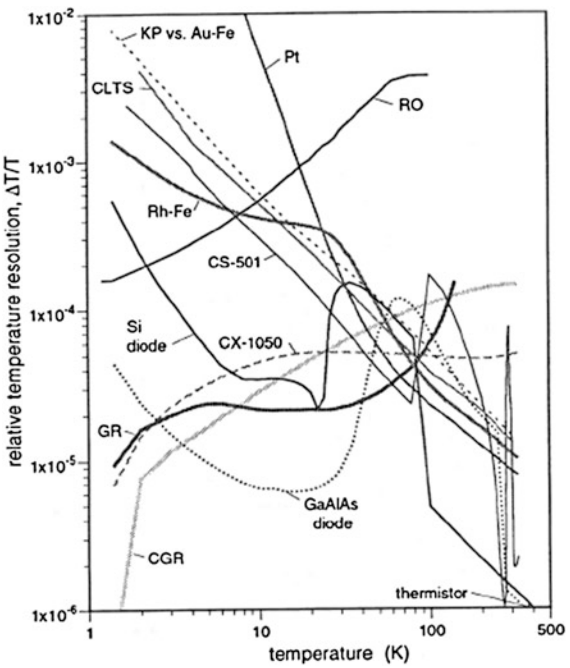
Fig. 1.16 Dimensionless sensitivity of cryogenic temperature sensors [8]

essentially unresponsive below a given temperature (typically 30 K). Choosing the correct temperature sensor for the temperature range of interest is key. In some cases, a combination of sensors will be required. Figures 1.16 and 1.17 show the sensitivity and temperature resolution of a wide range of temperature sensors.

Self Heating. An issue with temperature sensors, particularly those operating in a vacuum space is that the excitation current applied to the sensor can cause the sensor itself to heat up and thus provide a false measurement. This problem is avoided by always following the manufacturer's recommendations regarding excitation.

Environmental Conditions. The performance of temperature sensors is greatly influenced by the environment in which they operate. Some sensors such as, silicon diodes or germanium resistors perform poorly in magnetic fields or ionizing radiation environments while others such as carbon glass or Cernox sensors work well

Fig. 1.17 Relative temperature resolution of cryogenic temperature sensors [8]



under these conditions. Care must be taken to choose the correct sensor for the expected operating conditions. Table 1.3 shows the impact of magnetic and ionizing radiation on common cryogenic temperature sensors. More details may be found in [8].

Calibration. Some types of temperature sensors, such as platinum resistors or silicon diodes have general calibration curves that apply for all sensors of a given type. Others such as cernox or germanium need to be individually calibrated for

Table 1.3 Impact of magnetic field and ionizing radiation on common cryogenic temperature sensors

Sensor type	Suitability for use in magnetic fields	Suitability for use in ionizing radiation
Silicon diode	Poor	Poor
Platinum resistor	Poor	Good
Germainium resistor	Poor	Poor
Carbon glass resistor	Fair	Good
Ruthenium oxide	Good	Good
Cernox	Good	Good
Thermocouple	Good	TBD
Cryogenic linear temperature sensors	TBD	Good

Data from Ref. [8]

best accuracy. In addition, the calibrations of some sensors will drift over time and manufacturers will have recommendations on the need for periodic recalibration of their sensors. In many cases, the calibration drift is not significant, but in situations requiring high accuracy, the cryostat has to be designed to either allow in situ recalibration of the sensors or removal of the sensors for recalibration.

Redundancy. Even the best installed sensors can fail. Once installed inside of cryostats, temperature sensors can be very difficult to remove. In situations where proper temperature measurement is vital to the success of the cryostat, either redundant sensors should be installed at each measuring point or the sensors should be installed in such a way that they can be replaced. This can be accomplished by placing the sensors on removable probes or by installing access ports near the sensors to allow their replacement in the case of in accessible cryostats such as space cryostats, redundant sensors are the answer.

1.5.2 Pressure Measurement

Pressure measurements in cryogenic systems are generally carried out by room temperature pressure sensors. There are a variety of high precision room temperature pressure sensors commercially available. Room temperature pressure transducers have the advantage of being easily replaceable. They are connected to the measuring point via small capillary tubes. These tubes have some disadvantages. First, if improperly designed, they can lead to thermoacoustic oscillations (see Sect. 1.9) and experiments [31] have shown that the capillaries can damp out and delay high speed pressure signals. In those situations where either space requirements or the need for accurate high speed pressure signals exist, there are some pressure transducers that will operate at cryogenic temperatures. Another option is to use non-cryogenic pressure transducers but locate them near the point of measurement in an insulated and heated enclosure to maintain them at room temperature. An example of this approach is given in [32]. Many pressure transducers, both warm and cryogenic, are susceptible to damage from ionizing radiation. Such devices may need local shielding when operated in a radiation environment.

1.5.3 Flow Measurement

As in the case of pressure measurement, flow measurement in cryostat systems is best carried out at 300 K. This increases the amount of flow meters available and allows easier repair or replacement. In cases where flow measurement at cryogenic temperatures is required, many typical flow metering approaches e.g. Venturi meters, orifice plate meters, turbine flow meters etc. can be applied at cryogenic temperatures. Care must be taken to ensure that the meters are properly calibrated for the properties such as density, viscosity, pressure, temperature of the cryogenic fluids. Additional installation requirements such as a certain amount of straight pipe upstream and downstream of the meter must also be met. Many cryogenic flow meters function by measuring a pressure difference and thus the comments on pressure transducers also apply here. Additional information on cryogenic flow metering can be found in [8] with some specific examples given in [33, 34].

1.5.4 Level Measurement

Measuring the level of a cryogenic liquid bath is important for proper control and operation of cryogenic systems. There are a number of ways to accomplish this measurement. In liquid helium systems, the use of superconducting level gauges is common. In these devices a probe containing a superconductor is the placed into the bath. The superconducting probe is designed so that the wire is superconducting when in contact with liquid helium and normal conducting when in contact with the corresponding helium vapor. The total voltage drop across the wire can then related to the liquid level. Work [35, 36] has been done to extend this approach to warmer fluids such as hydrogen, nitrogen and oxygen using high temperature superconductors; but alternative methods such as capacitive or pressure differential techniques are more common for these fluids.

In the capacitive approach [37, 38], the differing dielectric constants between the liquid and vapor phases of the fluid are used to determine the fluid level. These are commercial devices and work with a number of cryogenic fluids. As they do not require superconductors to operate they are also useful for fluids warmer than liquid helium.

The differential pressure approach essentially measures the weight of the liquid level of the fluid from which the level can be calculated. Again, these don't require superconductivity.

A final technique, that provides discrete rather than continuous liquid level measurements is the use of Liquid Vapor Detectors (LVDs). These devices can either be discrete superconductors that function similarly to superconducting liquid level probes or more commonly temperature sensors that are powered so that they self heat and provide a very different response in the vapor phase than the liquid phase. Reference [39] provides an example of such devices. This technique was tested in the SHOOT Project (see Chap. 4).

1.5.5 Installation, Wiring, Heat Sinking and Feedthroughs

Cryogenic instrumentation systems can easily give inaccurate results if improperly installed. There are a number of issues to take into account.

Keep in mind that wires will generally contract significantly when cooled (see Sect. 1.2.1). If the instrumentation wires are installed with no slack or loops

Table 1.4 Required heat sinking lengths for wire to achieve a measurement within 1 mK of the actual value

			Heat sinking length (mm)			
Material	T_h[K]	T_l[K]	0.21 mm^2 (24 AWG)	0.032 mm^2 (32 AWG)	0.031 mm^2 (36 AWG)	0.005 mm^2 (40 AWG)
Copper	300	80	160	57	33	19
	300	4	688	233	138	80
Phosphor-Bronze	300	80	32	11	6	4
	300	4	38	13	7	4
Maganin	300	80	21	4	4	2
	300	4	20	7	4	2
304 SS	300	80	17	6	3	2
	300	4	14	5	3	2

Results assume that the wire and sensors are in vacuum and that the thermal conductivity of the adhesive is given by the fit to the thermal conductivity of GE 7031 varnish [8]

between fixed points; upon cool down the wires will shrink and may break or come loose from a solder connection. Always allow sufficient slack in wire installation to allow for this shrinkage.

Instrumentation wires provide a thermal conduction path and thus heat leak between room and cryogenic temperatures. Thus, the number and diameter of the wires along with the type of material in the wires should be chosen to reduce this heat leak. Experience with an early prototype of the ILC Cryomodule (see Chap. 5) illustrates what can happen if this conduction path is not properly considered. Heat sinking the wires at intermediate temperatures (again allowing for shrinkage) will also reduce the heat leak.

An important aspect of heat sinking comes in when using cryogenic temperature sensors in a vacuum space. This is a common installation in which temperature sensors are attached to the outside of a pipe or vessel containing cryogenic fluid. The sensor itself while attached to the cold surface sits inside a vacuum space. Heat leak down the wires, even from an intermediate temperature heat sink can cause the temperature sensor to read an erroneously high temperature despite itself being in good thermal contact with the pipe or vessel. The solution is to always heat sink the wire to the measurement point immediately adjacent to the sensor. Table 1.4 shows the length of wire required to be heat sunk adjacent to the sensor to result in a temperature measurement of within 1 mK of the actual value. As can be seen, the impact of wire choice can be quite impressive. If one were to use 36 gauge Phosphor-Bronze wire, a common choice in cryostat systems, only 7 mm of wire would need to be heat sunk near a sensor operating at a 4 K surface. However, if one were to use 24 gauge copper wire in the same scenario, more than half a meter of wire would need to be heat sunk near the sensor to get a proper reading.

A final installation comment involves the use of feed throughs. If a sensor is immersed in a cryogenic fluid there are basically two options for connecting the sensor via wires to the outside environment. The most common and by far preferable option is to feed the wire through a tube that links the cryogenic fluid environment to the room temperature environment. The room temperature side of the tube is topped with a room temperature electrical feed through that passes the signals to the outside world while maintaining a barrier between the cryogenic space and the outside environment. There are some disadvantages to this approach. The required tube can be hard to route between the two spaces and provides a parallel thermal path from 300 K to the cryogenic space. Such a tube may also be susceptible to thermoacoustic oscillations (see Sect. 1.9).

The second approach, which can be tempting, is to use a cryogenic feed through that connects the cryogenic space to the vacuum space and then run just wires in the vacuum space up to a room temperature connector. This eliminates the tube and along with it, the possibility for thermoacoustic oscillations and the parallel conduction path. It also allows greater flexibility in routing the wires out of the cryostat. Despite its apparent advantages, the use of cold electrical feedthroughs should be avoided if at all possible. The reason is that these cold feedthroughs tend to have poor reliability and can leak. If a leak occurs then there is a leak directly between the cryogenic fluid and the cryostat vacuum space. Such a leak may well spoil the vacuum and stop operation of the cryostat until fixed. Such a repair can be quite time consuming. It's better to use a warm feed through approach. In some cases, such as the SHOOT Helium Dewars (Chap. 4), the use of cold feed throughs is necessary but in theses case extensive testing and prototyping is required to ensure high reliability.

1.5.6 Commercial Availability of Instrumentation Systems

During the past 25 years, the commercial availability of sensors and related instrumentation systems suitable for cryostats and cryogenic systems has significantly increased. This is particularly true for temperature sensors but also applies for other measuring systems. Whenever possible, the best practice is to use commercial solutions. This allows the cryostat designer to benefit from the extensive research, development and testing that have gone into these devices and to take advantage of the customer support provided by these companies. A good source for finding cryogenic instrumentation is the Cryogenic Society of America's annual Buyers Guide [40].

Some instrumentation problems can not be solved by existing devices and research into cryogenic instrumentation continues. Good resources for recent research in cryogenic instrumentation include Advances in Cryogenic Engineering [41], *Proceedings of the International Cryogenic Engineering Conference* [42] and the journal *Cryogenics* [43].

1.5.7 Best Practices for Cryostat Instrumentation

Summing up this section, when considering instrumentation in cryostat design, one should keep in mind:

1. Treat instrumentation as a complete system: sensor, wiring, feed through, calibration and data acquisition hardware and software.
2. Don't use more accuracy and precision than required.
3. Use commercially produced sensors whenever possible—there is a lot available.
4. When possible, mount sensors outside cryostat at 300 K (e.g. pressure transducers, flow meters).
5. Play close attention to the installation of wiring and to the proper heat sinking of both wiring and sensors.
6. Consider the possibility of thermoacoustic oscillations. See Sect. 1.9 of this chapter.
7. For critical devices inside of cryostats, install redundant sensors whenever feasible.
8. Be sure to consider how to recalibrate sensors.
9. If at all possible avoid, cold instrumentation feedthroughs.
10. Once prototyping is complete, minimize number of sensors in series production of cryostats.

1.6 Seals and Connections

A common feature of cryostats is the need to connect together components such as pipes, vessels, flanges and feedthroughs. In many cases, these connection have to provide vacuum tight seals at cryogenic temperatures; separating a cryogenic fluid from a vacuum space.

Whether the connection will operate at room temperature or cryogenic temperature, the most reliable approach is to weld the components together. Good quality welds, particularly in stainless steel, are the simplest way to create reliable, vacuum leak tight connections. A common temptation is to include many demountable joints, such as flanged connections, in the cryostat design to allow easy assembly and disassembly. This temptation should be avoided. While reliable, demountable, connections do exist; the difficulty in finding and fixing leaks in cryogenic systems is so large that welding and then later cutting systems apart is the better approach. This is particularly true in cryostats that are produced in large numbers such those for the LHC and SSC magnets (Chaps. 2 and 3) or those for the ILC cryomodules (Chap. 5).

Other metal joining techniques include brazing (sometime used in copper systems) and soldering. Soldering of tubes and pipes should be avoided, except

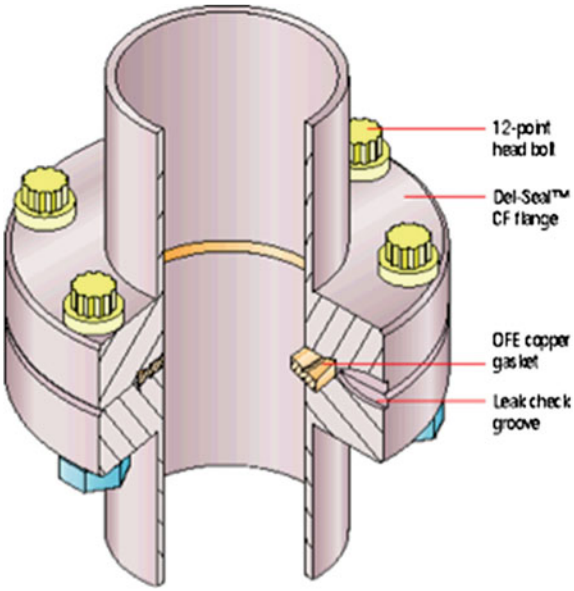


Fig. 1.18 Example of a ConFlat flange using a soft copper gasket—Courtesy MDC Vacuum Products, LLC

possibly in the case of small laboratory experiments where reliability is less important than the ability to make quick changes. Even in this case, flanged connections are superior if space permits.

When welding dissimilar metals such as aluminum, stainless steel and niobium, transition joints are needed. Reliable transition joints based on brazing, explosive welding or diffusion bonding of the dissimilar metals together have been developed for use at cryogenic temperatures [44, 45] and are available commercially [46].

There are situations where demountable cryogenic connections are required. Two common approaches for this problem are flanged assemblies and bayonets.

Flanged assemblies require a gasket or O-ring to create the final seal between the mating surfaces. At cryogenic temperatures, polymer or rubber O-rings will become brittle and won't work. However, soft metal gaskets (such as copper) will work at cryogenic temperatures. Figure 1.18 illustrates such a system. These devices are reliable and can be obtained commercially [47]. Another flanged option is the use of indium wire for the O-ring. This approach is illustrated in Fig. 1.19. Note the relative areas of the indium wire and Vee grove indicated in the figure. Indium O-ring flanges are generally made in house as opposed to purchased commercially. Flanged connection can be used in all orientations and can separate vacuum spaces, fluids from vacuum and fluids from each other. Care must be taken in flanged connections that differential thermal contraction upon cooling does not result in the bolts holding the flanges together shrinking less than the flanges themselves. This may result in a lessening of the force holding the flanges together resulting in a leaky joint. One solution to this problem is to use Invar washers in the bolt assembly. Invar (see Table 1.1) contracts very little between 300 and 4 K. Properly designed into a

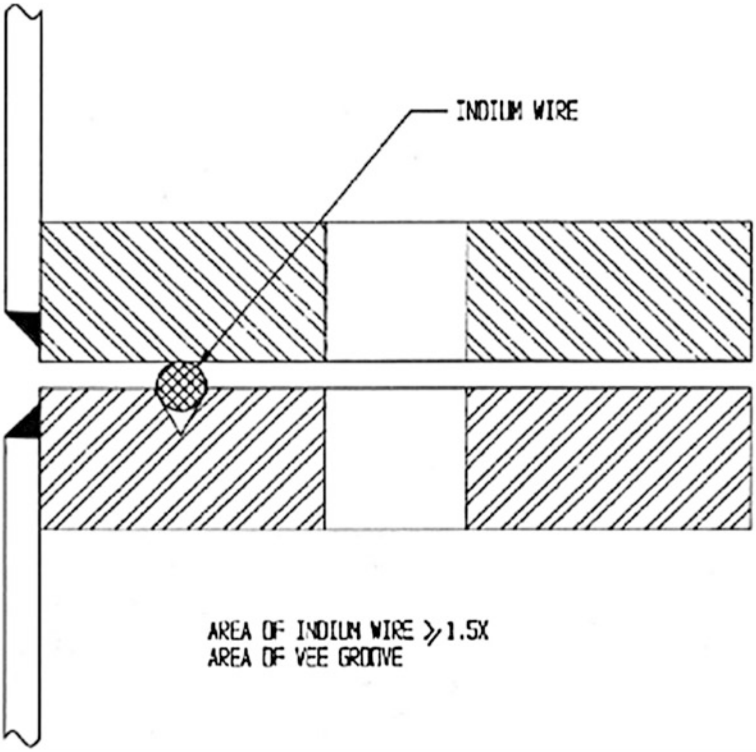


Fig. 1.19 View of an Indium O-Ring flange [48]

flanged assembly, these washers can serve to keep or increase the force on the flange joint during cool down, preventing leaks. Figure 1.20 and Eq. 1.5, both from Ref. [48] show how to design such a joint assembly using Invar washers.

$$X = [L_A(\alpha_A - \alpha_S) + \varepsilon(L_A + L_S)]/(\alpha_S - \varepsilon - \alpha_I) \quad (1.5)$$

where

X required thickness of the Invar washer
α_A temperature expansion coefficient for aluminum
α_S temperature expansion coefficient for stainless steel
α_I temperature expansion coefficient for Invar
L_A thickness of aluminum flange
L_S thickness of stainless steel flange
ε unit strain of bolts due to cool down (m/m).

Another common approach to making demountable cryogenic piping connections is to employ bayonets. Bayonets are a set of nested pipes (one "male" and one "female") connected together by a room temperature seal. Figure 1.21 illustrates a typical bayonet pair. Note that the bayonets employ some of the thermal insulation techniques described above; for example, long thin walls connect the room

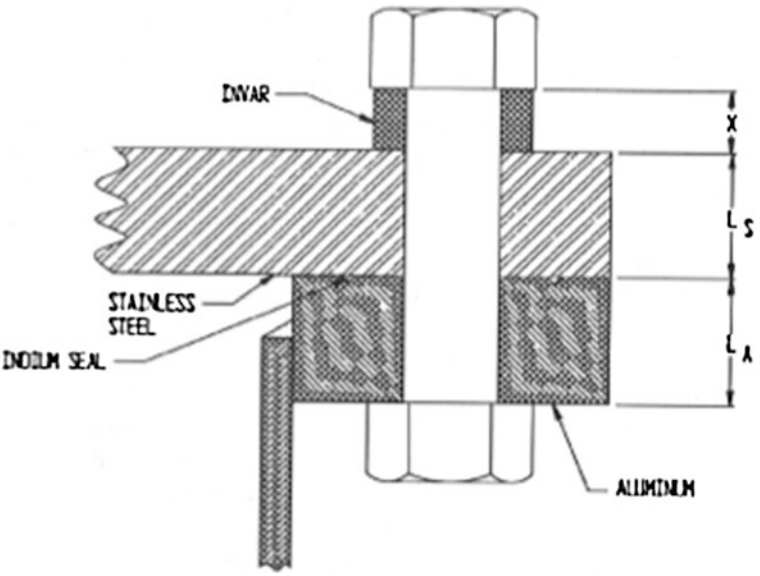


Fig. 1.20 Flange assembly using Ivar washers [48]

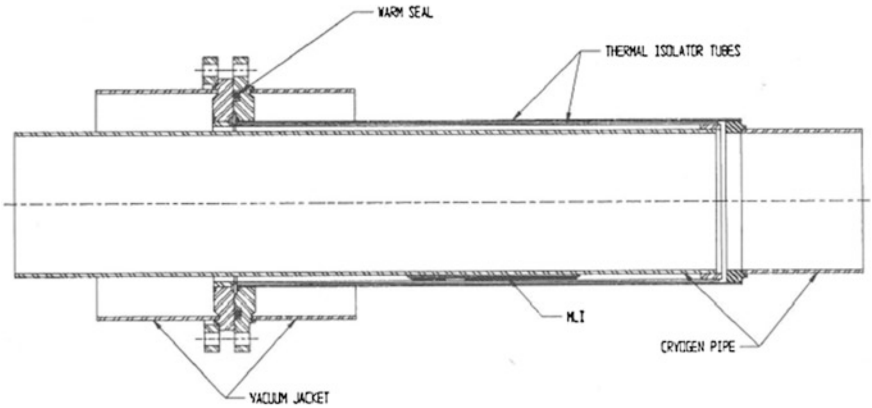


Fig. 1.21 Example of a cryogenic bayonet pair [48]

temperature and cryogenic portions of the bayonets. The small gap between the female and male bayonets is designed to impede the development of convective heat transfer cells between the cryogenic and room temperature portions thus further reducing heat leak.

Bayonets have a number of advantages, they are commercially available, reliable and can be easily disconnected to decouple different cryogenic components. There are disadvantages as well to bayonets; they are expensive, add additional heat leak

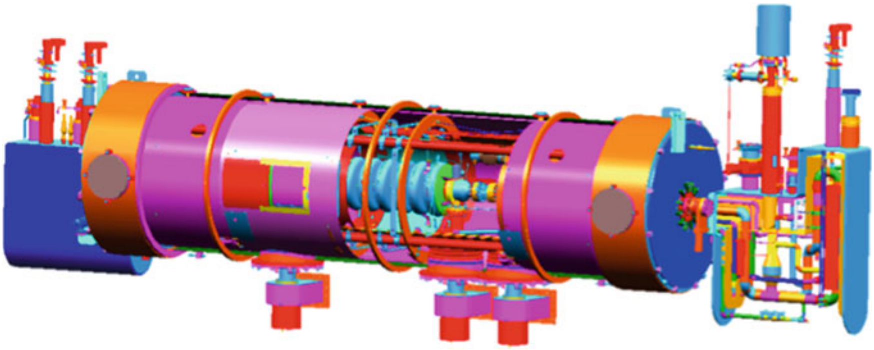


Fig. 1.22 Cutaway view of the SNS medium beta cryomodule—Courtesy E. Daly-Jefferson Lab, see Chap. 6). Connection to the cryogenic system are done via bayonets on the end boxes

to the system, are not as reliable as welded assemblies and can be hard to disconnect if the pipe diameter becomes too large. Additionally, unlike welds and flanged assemblies, bayonets can only be used in vertical or near vertical orientations. That is, the warm end of the bayonet must be above the cold end. If this is not done, then there is the possibility that the cryogenic fluid will flow into the annual space between the bayonets causing significant heat leak and cooling and possible failure of the room temperature seal.

Bayonets are a valuable tool in cryostat design but are best used only in situations where the regular disconnection of cryogenic components is expected. Bayonet connections are common in segmented cryomodule designs (Chap. 6) where they allow rapid disconnection of individual cryomodules. Figure 1.22 shows an example of bayonets used in a cryomodule design.

1.7 Transfer Lines

In large scale systems, cryostats are typically connected to each other, to cryogenic refrigeration plants or to other equipment via insulated transfer lines. These transfer lines move cryogenic fluids between the various components. Transfer lines can be quite complicated and their proper design is an important aspect of a successful cryogenic system. Complicated transfer line systems are also referred to as cryogenic distribution systems. In effect, transfer lines are simply another type of cryostat. Chapter 9 presents more details and examples of cryogenic transfer lines.

Figure 1.23 [49] shows the cross section of a typical multiple line cryogenic transfer line. Notice that it follows the basic principles of thermal insulation. The internal cryogenic pipes are enclosed within an outer vacuum jacket and surrounded by both a actively cooled radiation and an MLI blanket. A low conductivity support separates the pipes and shield and connects them to the outer vacuum jacket.

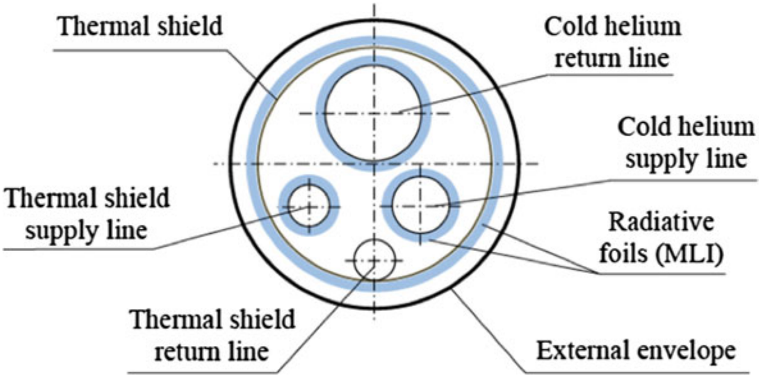


Fig. 1.23 Cross section of a typical multiline cryogenic transfer line—Courtesy J. Fydrych, ESS (see Chap. 9)

Transfer lines have particular requirements based on their typical geometry. Due to their length, there is significant thermal contraction of the lines during cool down. This contraction has to be dealt with on the design. The common approach is to have some of the internal supports fixed to both the internal pipes and to the outer vacuum jacket with the remainder of the internal supports allowing relative movement between the pipes and the outer vacuum jacket. Bellows are then installed on the pipes between the fixed supports to allow relative contraction of the pipes. An example of this approach is shown in Fig. 1.24 [50]. Note the fixed support and the support that can move relative to the outer vacuum jacket. An alternative approach is to fix all the supports to the vacuum jacket but design some of them so that the pipes can move freely through them upon cool down.

There are other possibilities rather than the use of bellows in the design of transfer lines to allow for thermal contraction. If the transfer line contains enough bends or elbows of sufficiently large bend radius then the motion of the pipes with in the bends relative to the vacuum jacket may be enough to compensate for thermal contraction. Another option is to construct the cryogenic pipes from Invar. As shown in Sect. 1.2.1, this material contracts very little upon cool down. Constructing pipes from Invar greatly reduces the amount of thermal contract that needs to be allowed for in the design, potentially simplifying the design. This approach is described in Refs. [51, 52].

A final issue that must be allowed for in transfer lines is the effect of the line pressure on closed ends of the line. Given the size of many cryogenic pipes, this pressure can result in a very large unbalanced force that must be transferred to the vacuum jacket and from the jacket via support structures to the building or earth. Improper allowance of this effect can result in damage, motion or loss of alignment of the transfer line.

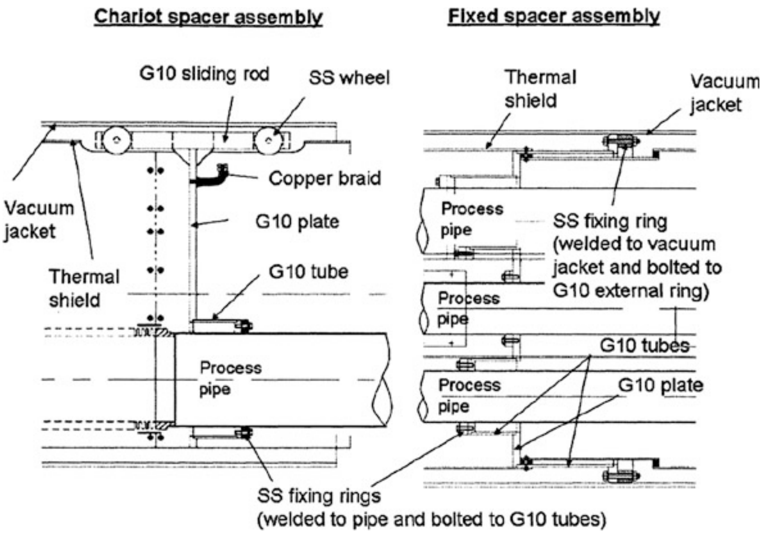


Fig. 1.24 Example of fixed and moving spacers in a cryogenic transfer design. Reproduced with permission from Parente et al. [50]. Copyright 2006, AIP Publishing LLC

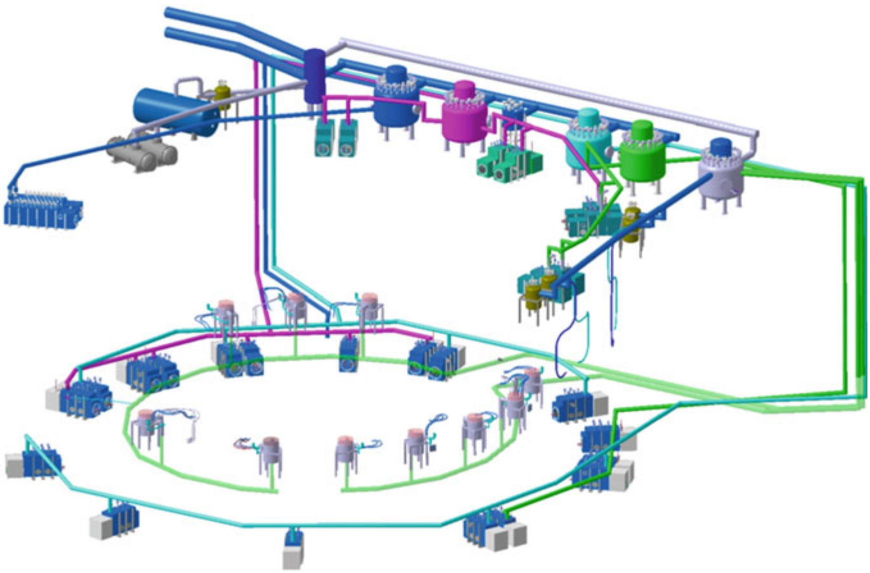


Fig. 1.25 The ITER cryodistribution system. Reproduced with permission from Serio [53]. Copyright 2010, AIP Publishing LLC

Figure 1.25 [53] is an example of a complex transfer line or distribution system. While most transfer line are custom made, there exist commercial options for simpler systems [54].

1.8 Safety

Safety is a broad topic throughout the field of cryogenics. References [55–60] provide a good overview of cryogenic safety. There are safety issues specific to cryostats and these issues should be planned for at the very earliest stage of the design. Altering the design later to remove safety issues can be very time consuming and expensive.

One of the most common mistakes in cryostat design that lead to safety hazards is the use of inappropriate materials. Materials (see Sect. 1.2) that are inappropriate for cryogenic use can become brittle and suddenly fail. The solution here is to always use materials proven for cryogenic service or conduct tests of the material to show that it is suitable for cryogenic temperatures. One should always keep in mind that materials nominally expected to operate at room temperature, may though some other failure, become cooled to cryogenic temperatures and then themselves fail. Such scenarios should be considered in the design of the cryostat.

A hazard that always has to be addressed in cryostat design is over pressurization. This hazard stems from the very large volume difference between a cryogenic liquid at its normal boiling point, i.e. at 1 Bar and the gas phase at room temperature and pressure. Table 1.5 shows this volume ratio for number of cryogenic fluids.

As can be seen, the ratios are very high. Thus, if a cryogenic liquid is in a closed volume and converted to a warmer gas, very high pressures will result. These pressures can easily result in explosive failure of the closed volume causing death, injury and property damage.

The design solution to this problem is to always install properly sized relief valves in any cryostat so that pressures never go above those for which the cryostat is designed.

The details of properly sizing relief valves depend on local requirements, including the applicability of pressure vessel codes. In most locations, it is a requirement that pressure vessels be designed, built and certified in accordance with these codes such as the AMSE Pressure Vessel Code [61] or the European Pressure Directive [62]. Since pressure vessels are frequently defined as vessels in which the maximum allowable working pressure is greater than 1.5 Bar (absolute) then many cryostat vessels fall under these codes. In some cases, such as cryostats for space

Table 1.5 Volume ratios between cryogenic fluids at their normal boiling point and at 300 K and 1 Bar

Fluid	V_{gas}/V_{Liquid}
Helium	701
Parahydrogen	788
Neon	1341
Nitrogen	646
Argon	779
CO_2	762
Oxygen	797

applications, weight restrictions prevent full implementations of pressure vessel codes. In this case local authorities generally required demonstration of an equivalent level of safety.

While details on pressure vessel requirements and relief valve sizing vary between localities, general guidelines for pressure safety in cryostats include:

1. Always use relief valves that are certified under the applicable pressure code.
2. Never place a shut off valve between the relief valve and the space it is protecting.
3. Consider how any recalibration requirements of the relief valves will be met.
4. Perform a risk analysis of the system. Ask "what if" questions and then install relief valves to cope with resulting hazards. In particular, look for volumes that may not be pressure relieved under certain conditions. Keep in mind that process valves may be operated incorrectly or may leak; that cryogenic systems may warm up suddenly and that vacuum insulation systems may fail.
5. While isolation vacuum jackets typically don't see pressure, they will if the cryogenic system they contain leak. Allow for this eventuality by always installing appropriately sized pressure relief devices on vacuum jackets.
6. Never disable or remove pressure relief devices and never introduce cryogenic fluids into systems without suitable pressure reliefs.
7. Have the cryostat's pressure relief system reviewed by in-house or external experts.

When considering possible failure modes for sizing relief valves, a frequently used worse case scenario is the sudden loss of insulation vacuum. It key to remember here that the issue here is not the sudden appearance of convective heat transfer (Sect. 1.3.2) but rather that the in rush of air will condense on the cryogenic surfaces depositing large amounts of heat and boiling off the cryogenic fluids contained in the vessels and piping. This effect is much more significant than heat deposited by convective heat transfer. The addition of multilayer insulation wrapped around the surface of the cryogenic vessel or pipes helps reduce this effect. Further information is given in [63]. In the case of accelerators with superconducting magnets or superconducting RF cavities, the same effect is seen in the sudden loss of beam tube vacuum [32].

Additional details of pressure rises in magnet cryostats are provided in Chap. 7 of this book. A useful reference for the sizing of relief valves is found in [64].

Cryostats containing oxygen or flammable liquids like hydrogen and LNG have additional unique hazards; always involve experts in these areas when working with such fluids.

As mentioned at the start of this section, safety in cryogenics extends beyond issues associated solely with cryostats. Significant hazards including Oxygen Deficiency Hazards need to be considered. References [55–60] should be consulted for the broader issue of cryogenic safety.

1.9 Thermoacoustic Oscillations

Thermoacoustic oscillations (TAOs) are spontaneously occurring pressure oscillations that are frequently seen in cryogenic systems. They generally occur in geometries in which a tube connects room temperature with a cryogenic fluid and is closed at the 300 K end. The tube thus has a strong temperature gradient between the warm and cold ends. Unfortunately, this geometry describes many common cryostat design solutions including: tubes connecting instrumentation wires to room temperature feed throughs, a capillary tubes connecting a cryogenic bath to a room temperature pressure transducer, pressure relief lines and a closed bayonet connections.

"TAOs begin when the temperature gradient causes cold gas in the tube to warm and expand, thus increasing in pressure. This increased pressure then pushes the gas into the colder end of the tube, causing the pressure in the warmer end to fall. The gas then moves back to the warmer end to occupy this now lower pressure space. Under the proper conditions of tube size and temperature gradient, sustained pressure oscillations can be set up" [65]. Thermoacoustic oscillations can result is large pressure swings which can damage equipment and also are very efficient at moving heat between the warm and cold ends of the tube greatly increasing the heat load to the cryogenic fluid.

Ideally, one would like to design systems to avoid TAOs. While this is not completely possible, there have been studies on idealized systems that provide some guidance. The physics behind TAOS indicate that there should be two zones of stability where TAOS won't occur. If the tube is small enough, then the friction of the oscillating gas on the tube wall will damp out the oscillations preventing the TAOS from starting. This is known as viscous damping. The other area of stability occurs in large tubes or vessels where the mass of the fluid is too big for the fluid to be moved significantly by the heat being transferred form the warm tube wall and thus oscillations will not start. This is know as inertial damping.

Experimental studies by Gu [66] on the idealized case of tubes with linear temperature gradients have shown exactly these regions of stability. Figure 1.26 shows these results. For each set of parameters, the left hand region of stability represents the viscous damping while the right hand region of stability represents the viscous damping. While idealized these curves can at least give some guidance. The parameters on the plots are defined as:

$$\alpha = \frac{T_H}{T_C} \tag{1.6}$$

$$\xi = \frac{L_H}{L_C} \tag{1.7}$$

where

T_H the warm temperature

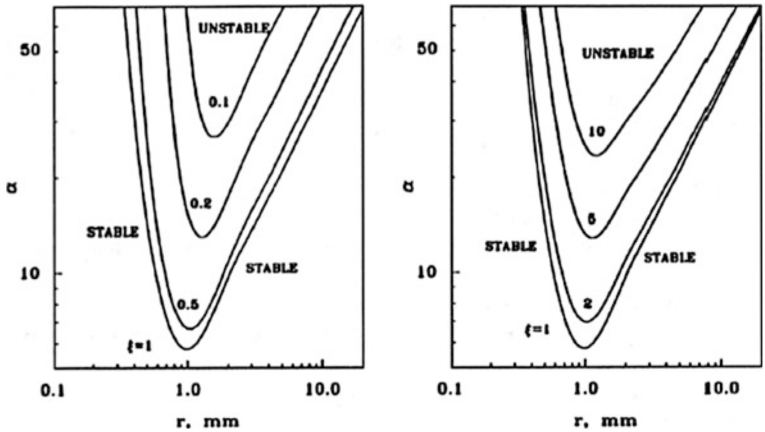


Fig. 1.26 Stability maps for thermoacoustic oscillations [67]

T_C the cold end temperature
L_H the warm section length
L_C the cold section length

The limit between the cold and warm lengths of the tube is defined as the point in the linear temperature gradient where

$$T = (T_H + T_C)/2 \quad (1.8)$$

The studies were done with a 1 m long tube. In order to apply the results to other geometries, use the reduced radius r′ defined as:

$$r' = r/\sqrt{L} \quad (1.9)$$

The studies described above used a very ideal case and thus even if you are in the stable regions you may find TAOs occurring. There are mitigations that can be taken in the event that TAOs are present. These include:

- Add volume to the warm end or design the warm end with fixtures to allow the addition of this volume
- Install a check valve between the warm and cold end (near boundary between the two)—this converts the problem to a closed cold tube with no TAOs
- Heat sink the closed end (thus changing T_H/T_C)
- Allow flow through the warm end.

Further details on TAOs may be found in Refs. [67–70].

1.10 Prototyping and Series Testing

A common aspect in the creation of successful cryostats is the building and testing of a prototype. This process allows the performance of the design to be tested and compared against requirements. It is not uncommon for the results of the prototype testing to lead to changes, sometimes major changes, in the final cryostat design. Prototyping is found in almost all of the case studies that follow in this book. Full scale prototypes, tested under the expected final operating conditions provide the most value but in some cases, testing of prototype subassemblies is sufficient.

For systems in which a number of identical cryostats are required, series testing of the final production cryostats is also recommended. Testing the performance of completed cryostats under their final operating conditions provides the best evidence that the cryostats are being properly manufactured. Due to the complexity of many cryostats, small changes in the manufacturing process can lead to significant problems such as vacuum leaks, electrical shorts or higher than designed heat loads. Series testing of the completed cryostats as they are produced can identify these problems in time to correct them in the remaining cryostats under production. Series testing was carried out for the LHC magnet cryostats [71], the SRF cryomodules for XFEL [72] and 12 GeV Upgrade [73]. Such testing is also planned for the LCLS II [74] and ESS [75] cryomodules.

The cost and schedule impact of both prototyping and series testing can be significant; requiring expensive test stands and months of additional time. There is always a temptation to skip these steps and move directly to a test of the final integrated system that uses the cryostats. Doing so, however, leads to a significant risk that the original design may not meet specifications or that manufacturing errors have resulted in poor performance. If this occurs, the cost and schedule impact of repairing the cryostats can easily be more than the initial impact of any forgone prototyping and series testing. Generally speaking, it is advisable to allow for prototyping and series testing in the initial cryostat project plan.

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