General Safety Considerations for the Installation and Operation of Superconducting Magnet Systems

Revision 1.1.
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1. Introduction

1.1 Read this first!

Please read it carefully and make it accessible to everybody working with the magnet system.

- A superconducting NMR Magnet System can be operated easily and safely provided the correct procedures are obeyed and certain precautions observed.
- These notes must be read and understood by everyone who comes into contact with a superconducting NMR Magnet System. They are not for the sole information of senior or specialist staff.
- Proper training procedures must be undertaken to educate effectively all people concerned with such equipment with these requirements.
- Since the field of the NMR magnet system is three dimensional, consideration must be given to floors above and below the magnet as well as to the surrounding space at the same level

1.2 Warning areas

The installation and operation of a superconducting NMR magnet system presents a number of hazards of which all personnel must be aware. **It is essential that:**

- Areas, in which NMR magnet systems are to be installed and operated, are planned with full consideration for safety.
- Such premises and installations are operated in a safe manner and in accordance with proper procedures.
- Adequate training is given to personnel.
- Clear notices are placed and maintained to effectively warn people that they are entering a hazardous area.
- All health and safety procedures are observed.

These notes outline aspects of operation and installation which are of particular importance. However, the recommendations given cannot cover every eventuality and if any doubt arises during the operation of the system the user is strongly advised to contact the supplier.

2. Magnetic Field

2.1 Overview

Superconducting NMR magnets pose numerous hazards related to the forces caused by the strong magnetic fields associated to these magnets. Precautions must be taken to ensure that hazards will not occur due to the effects of a magnetic field on magnetic materials, or on surgical implants. Such effects include, but are not limited to:

- Large attractive forces may be exerted on equipment in the proximity of the NMR magnet system. The force may become large enough to move the equipment uncontrollably towards the NMR magnet system. Small pieces of equipment may therefore become projectiles.
- Large equipment (e.g. gas bottles, power supplies) could cause bodies or limbs to become trapped between the equipment and the magnet.
- The closer a ferromagnetic object gets to the magnet, the larger the force. Also, the larger the equipment mass, the larger the force.

2.2 Shielding

Most of the newer NMR magnet systems are actively shielded. The following must be understood when installing or working with such a shielded magnet:

- The active shielding of the superconducting coil reduces the stray magnetic fields, and therefore its effects.
- Nevertheless, the magnetic field gradient is much stronger compared to non-shielded magnets, hence the distance interval between various stray field contour lines (for instance distance between 5G and 50G) is much smaller, and caution must be taken to avoid bringing ferromagnetic objects close to the magnet.
- In spite of the active shielding, the stray magnetic field directly above and directly below the magnet is very high and the attractive forces on ferromagnetic objects are very strong!

2.3 Electronic, electrical and mechanical medical implants

The following must be understood concerning the effects on electronic, electrical and mechanical medical implants and devices:

- The operation of electronic, electrical or mechanical medical implants, such as cardiac pacemakers, biostimulators, and neurostimulators may be affected or even stopped in the presence of either static or changing magnetic fields.
- Not all pacemakers respond in the same way or at the same field strength if exposed to fields above 5 gauss.

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2.4. Surgical implants and prosthetic devices

The following must be understood concerning the effects on surgical implants and prosthetic devices:

- Besides electronic, electrical, and mechanical medical implants, other medical surgical implants such as aneurysm clips, surgical clips or prostheses, may contain ferromagnetic materials and therefore would be subject to strong attractive forces near to the NMR magnet system. This could result in injury or death.
- Additionally, in the vicinity of rapidly changing fields (e.g. pulsed gradient fields) eddy currents may be induced in the implant, hence resulting in heat generation and possibly create a life-threatening situation.

2.5 Operation of equipment

The operation of equipment may be directly affected by the presence of strong magnetic fields.

- Items such as watches, tape recorders and cameras may be magnetized and irreparably damaged if exposed to fields above 10 gauss.
- Information encoded magnetically on credit cards and magnetic tapes may be irreversibly corrupted.
- Electrical transformers may become magnetically saturated in fields above 50 gauss. The safety characteristics of equipment may also be affected.

2.6 Before ramping the magnet to field

Prior to start energizing the magnet system, one must:

- Ensure all loose ferromagnetic objects are removed from within 5 gauss field of the NMR magnet system.
- Display magnet warning signs at all points of access to the magnet room.
- Display warning signs giving notice of the possible presence of magnetic fields and of the potential hazards in all areas where the field may exceed 5 gauss.

2.7 After ramping the magnet to field

After energizing the magnet to field, one must:

- Not bring ferromagnetic objects into the magnet room.
- Use only nonmagnetic cylinders and dewars for storage and transfer of compressed gas or cryogenic liquids.
- Use only non-magnetic equipment to transport cylinders and dewars

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2.8 General safety precautions

To prevent situations as described above to occur, the following precautions are provided as guidelines, and they should be regarded as minimum requirements.

- Every magnet site location should be reviewed individually to determine the precautions needed to be taken against these hazards.
- Consideration must be given to floors above and below the magnet as well as the surrounding space at the same level, since the magnetic field produced by the NMR magnets is three dimensional.

3. Magnet Zones

3.1 Introduction

The FDA requires that the hazards listed above are prevented by establishing two secure and clearly marked zones, as follows:

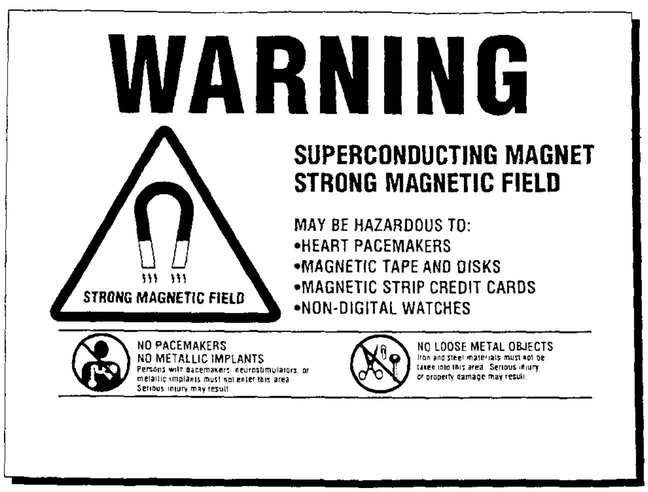
- The exclusion zone, and
- The security zone.

3.2 Exclusion Zone

The following must be understood concerning the exclusion zone:

- **Definition**: The exclusion zone comprises the area (rooms, hallways and so on) inside the magnets 5-gauss line. Individuals with cardiac or other mechanically active implants must be prevented from entering this area.
- **Extension of magnetic field**: The magnetic field surrounds the magnet in a three dimensional fashion. Access must be limited and warning given to individuals who are potentially at risk, not only at the same floor as the magnet, but also at the levels above and below the magnet.
- **Warning signs**: The exclusion zone must be enforced with a combination of warning signs and physical barriers. Figure 1 shows the recommended layout of the warning sign

Figure 1 Warning Sign



3.3 Security Zone

The security zone is usually confined to the room that houses the magnet. The security zone is established to prevent ferromagnetic objects from becoming projectiles. ***Ferromagnetic objects shall not be allowed inside the security zone.***

4. Safe Handling of Cryogenic Substances

4.1 Overview

A superconducting magnet uses two types of cyrogens, liquid helium and liquid nitrogen. Cryogenic liquids can be handled easily and safely provided certain precautions are obeyed.

The recommendations in this section are by no means exhaustive, and when in doubt the user is advised to consult the supplier.

- **<u>Types of substances</u>**: The substances referred to in these recommendations are nitrogen, helium and air. Contact your cryogen supplier for the appropriate MSDS sheets for these cryogens.
  - **<u>Helium</u>**: This is a naturally occurring, inert gas that becomes a liquid at approximately 4K. It is colorless, odorless, non-flammable and non-toxic. In order to remain in a superconducting state the magnet is immersed in a bath of liquid helium.
  - **<u>Nitrogen</u>**: This is a naturally occurring gas that becomes liquid at approximately 77K. It is also colorless, odorless, non-flammable and non-toxic. It is used to cool the shields, which surround the liquid helium reservoir.
- **<u>Cryogen transport dewars</u>**: During normal operation, liquid cryogens evaporate and will require replenishment on a regular basis. The cryogens will be delivered to site in transport dewars. I***t is essential that these cryogen transport dewars are non-magnetic***.
- **<u>Physical properties</u>**: Safe handling of cryogenic liquids requires some knowledge of the physical properties of these liquids, common sense and sufficient understanding to predict the reactions of such liquids under certain physical conditions.

4.2 General safety rules

General safety rules for handling cryogenic substances include, but are not limited to:

- Cryogenic liquids remain at a constant temperature by their respective boiling points and will gradually evaporate, even when kept in insulated storage vessels (dewars)
- Cryogenic liquids must be handled and stored in well ventilated areas.
- Passengers should never accompany cryogens in an elevator. There is a risk of asphyxiation.
- The very large increase in volume accompanying the vaporization of the liquid into gas and the subsequent process of warming up is approximately 740:1 for helium and 680:1 for nitrogen.

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4.3 Cryogen transport dewars

The rules concerning the cryogen dewars used to transport cryogenic liquids include, but are not limited to:

- All cryogen dewars transporting cryogenic liquids must not be closed completely as this would result in a large build up of pressure. This will present an explosion hazard and may lead to large product losses!
- All cryogen transport dewars must be constructed of non-magnetic materials.

4.4 Health hazards

Main health hazard related rules include, but are not limited to:

- Evacuate the area immediately in the event of a large spillage
- Provide adequate ventilation in the room to avoid oxygen depletion. Helium can displace air in the upper area of a room and cold nitrogen can displace air in the lower area. Please see the "Ventilation" section for detailed information.
- Do not come in direct contact with cryogenic substances in liquid or vapor form (or as low temperature gases), since they will produce "cold burns" on the skin similar to burns.
- Do not allow insufficiently protected parts of the body to come in contact with non-insulated venting pipes or vessels (see "Ventilation" section), since the body parts will immediately stick to them. This will cause the flesh be torn if the affected body part is removed.

4.5 First aid

First aid rules include, but are not limited to:

- If any of the cryogenic liquids come into contact with eyes or skin, immediately flood the affected area with large quantities of cold or tepid water and then apply cold compresses.
- Never use hot water or dry heat.
- Medical advice should be sought immediately!

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4.6 Protective clothing

Protective clothing rules include, but are not limited to:

- Protective clothing must be worn mainly to avoid cold burns. Therefore dry leather or cryogenic gloves must be worn when handling or working with cryogenic liquids.
- Gloves must be loose fitting so that they can be removed easily in case of liquid spillage.
- Goggles must be worn to protect the eyes.
- Any metallic objects (e.g. jewelry) should **not** be worn on those parts of the body, which may come into contact with the liquid.

4.7 Others

Other rules of handling cryogens include, but are not limited to:

- Handle the liquids carefully at all times. Boiling and splashing will always occur when filling a warm container.
- Beware of liquid splashing and rapid flash off of cryogens when immersing equipment at ambient temperature into the liquid cryogens. This operation must be carried out very slowly.
- When inserting open ended pipes into the liquid, never allow open ended pipes to point directly towards any person
- Use only metal or Teflon tubing connected by flexible metal or Teflon hose for transferring liquid nitrogen. Use only gum rubber or Teflon tubing.
- Do not use tygon or plastic tubing. They may split or shatter when cooled by the liquid flowing through it and could cause injury to personnel.

4.8 Smoking

Please obey the following basic rules concerning smoking:

- Do not smoke in any rooms in which cryogenic liquids are being handled
- Designate all rooms in which cryogenic liquids are being handled as “No Smoking” areas, using appropriate signs

Additional facts and precautions:

- While nitrogen and helium do not support combustion, their extreme cold dewar causes oxygen from the air to condense on the dewar surfaces, which may increase the oxygen concentration locally.
- There is a particular fire danger if the cold surfaces are covered with oil or grease, which are combustible. **Self-ignition could occur!**

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4. Safe Handling of Cryogenic Substances, Continued

4.9 Properties of cryogenic substances

Properties	**Nitrogen**	**Helium**
Molecular weight	28	4
Normal boiling point [^oC] [^oK]	-196 77	-269 4.2
Approximate expansion ration (volume of gas at 15'C and atmospheric pressure produced by unit volume of liquid at normal boiling point).	680	740
Density of liquid at normal boiling point [kg m^{-3}]	810	125
Color (liquid)	none	none
Color (gas)	none	none
Odor (gas)	none	none
Toxicity	very low	very low
Explosion hazard with combustible material	no	no
Pressure rupture if liquid or cold gas is trapped.	yes	yes
Fire hazard: combustible	no	no
Fire hazard: promotes ignition directly	no	no
Fire hazard: liquefies oxygen and promotes ignition	no	no

5. Refill of Liquid Nitrogen

5.1 Read this first!

Please read this carefully and make it accessible to anybody working with the magnet system.

- A shielded superconducting NMR Magnet System can be operated easily and safely provided the correct procedures are obeyed and certain precautions observed.
- The recommendations in this section cannot cover every eventuality and if any doubt arises during the operation of the system, the user is strongly advised to contact the supplier.

5.2 Condensing oxygen

Minimize contact with air. Be aware of the following facts and precautions, contact with air occurs:

- Since liquid nitrogen is colder than liquid oxygen, the oxygen in the air will condense out.
- If this happens for a period of time, the oxygen concentration in the liquid nitrogen may become so high that it becomes as dangerous as handling liquid oxygen. This applies particularly to wide necked dewars due to the large surface area.
- Therefore, ensure that contact with air is kept to a minimum.

5.3 Nitrogen flow system

A pressure relief valve is provided for the nitrogen vessel to ensure that at least the rear neck tube cannot be blocked by the ingress of air or moisture. **This valve shall be mounted at all times even when the vessel is being refilled.**

5.4 Refill of liquid nitrogen

Other general rules include, but are not limited to:

- Do not allow liquid nitrogen to spill onto the room temperature bore closure flanges when the refilling the nitrogen vessel
- Place gum rubber tubes or Teflon tubes on the nitrogen neck tubes during refill!
- **Stop the transfer immediately when the vessel is full.** Failure to observe this can lead to the freezing of the o-rings and a subsequent vacuum loss of the magnet cryostat.

6. Refill of Liquid Helium

6.1 Read this first!

Please read this carefully and make it accessible to anybody working with the magnet system.

- A shielded superconducting NMR Magnet System can be operated easily and safely provided the correct procedures are obeyed and certain precautions observed.

The recommendations in this section cannot cover every eventuality and if any doubt arises during the operation of the system, the user is strongly advised to contact the supplier.

6.2 General rules when handling liquid helium

Be aware of these general rules including, but not limited to:

- Liquid helium is the coldest of all cryogenic liquids.
- Liquid helium will condense and solidify any other gas (air) coming into contact with it.
- Liquid helium must be kept in specially designed storage or transport dewars.
- Dewars should have a one way valve fitted on the helium neck at all times, in order to avoid air entering the neck and plugging it with ice.
- Only vacuum insulated pipes should be used for liquid helium transfer. Breakdown of the insulation may give rise to the condensation of oxygen.

6.3 The helium vessel

The superconducting NMR magnets contain an inner vessel with liquid helium.

- The helium vessel should be checked weekly for boil-off and helium level.
- Use a helium flow meter or a helium gas counter!
- A one way valve is supplied to be mounted on the helium manifold to ensure that the helium neck tubes cannot be locked by the ingress of air or moisture. This valve should be mounted at all times except during a helium transfer

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6.4 Refill of liquid helium

Please follow the following instructions concerning the refill of NMR magnets with liquid helium:

- Refill the helium vessel within the specified hold time period and certainly before the level falls below the allowed **minimum** level listed in the magnet manual.
- **Important Note: Transfer of liquid helium can be done easily and safely, provided:**
  - the handling of the helium transfer line is correct,
  - the helium transfer line is not damaged, and
  - the transfer pressure does not exceed 2 psi.
- Never insert a warm helium transfer line into the cryostat, since the warm helium gas could lead to a quench of the magnet!
- Always allow the helium transfer line to cool down to helium temperature before inserting it into the right helium neck tube. You should see liquid helium leaving of the short end transfer lines for a few moments, before inserting it into the right helium neck tube.

6.5 Rapid Helium transfer

Do not remove the nitrogen security flow system during any transfer liquid helium!

During a rapid transfer of liquid helium, super cooling of the liquid nitrogen occurs. This can lead to the following:

- Decrease of static boil off to zero, and producing a negative pressure in the nitrogen vessel
- Transfer of air or moisture that can be sucked into the necks of the vessel, and which would solidify and create ice blockages.

7. Ventilation

7.1 General safety rules concerning ventilation

General safety rules concerning ventilation include, but are no limited to:

- Cryogenic liquids, even when kept in insulated storage dewars, remain at a constant temperature by their respective boiling points and will gradually evaporate. These dewars must always be allowed to vent or dangerous pressure buildup will occur.
- Cryogenic liquids must be handled and stored in well ventilated areas.
- The very large increase in volume accompanying the vaporization of the liquid into gas and the subsequent process of warming up is approximately 740:1 for helium and 680:1 for nitrogen.

7.2 Ventilation during normal operation

Superconducting magnets use liquid nitrogen and liquid helium as cooling agents, and a boil-off of liquid cryogens is expected during the normal operation of the magnet system, as follows:

- Normal boil-off of liquids contained in the magnet based on the given boil-off specifications
- Boil-off of cryogens during the regular refills with liquid nitrogen and liquid helium.

The gases are nontoxic and completely harmless as long as adequate ventilation is provided to avoid suffocation. Rules for ventilation during normal operation include but are not limited to:

- The NMR magnet system should never be in an airtight room. The magnet location should be selected such that the door and the ventilation can be easily reached from all places in the room.
- Room layout, ceiling clearance and magnet height should be such that an easy transfer of liquid nitrogen and helium is possible. This will considerably reduce the risk of accidents.

7.3 Emergency Ventilation during a quench and during magnet installation

A separate emergency ventilation system should be provided to prevent oxygen depletion in case of a quench or during the magnet installation.

During a quench, an extremely large quantity of helium gas (i.e. 1,500 to 21,000 ft^3 depending on the magnet type) are produced within a short time

During the installation and cooling of superconducting magnets, under certain conditions, large volumes of nitrogen or helium gases may be generated.

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7.3 Emergency Ventilation during a quench and during magnet installation (continued)

Although these gases are inert, if generated in large enough quantities, they can create dangerous circumstances if they displace the oxygen in the room. The table below illustrates this with examples.

Notes:

- The values below are approximate may not reflect actual conditions. They are to be used for example only.
- Pre-cool times vary.
- Quench times are generally longer.
- Please consult with Bruker BioSpin for values associated to your NMR magnet system

Magnet type	N2 gas liberated during pre-cool	Time to liberate N2 gas during pre-cool	He gas liberated during Cooling and filling	Time to evolve He gas during cooling and filling	He gas liberated during a "quench"	Time to liberate He gas during a "quench"
UltraShield 300/54	3,600 ft^3	4 hours	5,300 ft^3	3 hours	1,400 ft^3	0.5 minute
UltraShield 700/54	31,500 ft^3	24 hours	30,000 ft^3	6 hours	11,800 ft^3	1 minute

7.4 Emergency exhaust

There are various types of emergency exhaust that can be implemented to avoid oxygen depletion during a quench or during the installation of the magnet system. These include, but are not limited to:

- **Active exhaust**: This solution is based on a motorized fan, vents, and exhaust duct pipe that is not connected to the magnet itself. The exhaust should be activated both automatically by an O2 sensor, as well as manually by a switch in the room. The latter is needed during magnet installation and regular refills to prevent cryogen build-up in the room by evacuating them faster than the regular HVAC system.
- **Passive exhaust**: This solution is based on louvers in the ceiling that open by the gas due to the overpressure of helium gas during a quench.

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7. Ventilation, Continued

7.4 Emergency exhaust (continued)

- **Quench pipe**: This solution is based on a pipe connected directly to the magnet, which is then routed to the outside of the building. It is important to note the following:
  - Ideally, the helium exhaust from the magnet should be vented directly to the outside of the building in case a quench occurs.
  - The ducting to the outside of the building should be of large enough diameter to avoid excessive pressure build up due to the flow impedance of the duct.
  - The location of the exit end of the exhaust duct must not allow unrestricted access to anyone other than service personnel; in addition the exit opening should be protected from the ingress of rain, snow or any debris which could block the system.
  - It is also essential to ensure that any gas which vents from the exhaust duct cannot be drawn in to any air conditioning or ventilation system intakes. The location of duct's exit should be carefully sited to prevent this from happening in all atmospheric conditions and winds.
  - Insulation of accessible exhaust piping should also be provided to prevent cold burns during a quench.
- **Exhaust for magnet pits**: Special attention to ventilation and emergency exhaust must be given when magnets are placed inside pits. Magnet pits are confined spaces with a possibility of increased risk of oxygen depletion if appropriate exhaust measures are not taken.
  - Nitrogen is heavier than the air and starts filling the pit from the bottom during the magnet pre-cool or regular nitrogen fills
  - It is essential to provide a low exhaust system down inside the pit to efficiently evacuate the nitrogen gas and prevent oxygen depletion

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7.5 Oxygen monitor and level sensors

An oxygen monitor is required inside the magnet room. The following sensors should be provided:

- **Above the magnet**: One oxygen level sensor above the magnet, to detect low oxygen levels due mainly to He gas
- **Close to floor**: One oxygen level sensor 1' off the floor of the magnet room
- **Down in the pit**: One additional oxygen level sensor 1' off the bottom of the pit, in case the magnet is located inside a pit.
