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Thinking in solutions

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DEMACO DESIGN DOCUMENT

INVESTIGATION CRYOSTAT for the VIRGO EXPERIMENT

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1. Introduction.

DeMaCo has been contacted by NIKHEF to perform a cryogenic design check and a pressure design check of a cryostat.
DeMaCo has checked the design using the PED/CE and the design code AD2000, and has advised changes to the design and drawings on pressure and cryogenic issues, to achieve a safe and cryogenic sound detail design.
This report describes our advise and actions resulting from the design check.

Measures to reduce vibration are only described where these have a relation to pressure or cryogenic issues.

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2. Contents

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3. Scope of the project

The project P100331 consists of:

- Design check of the pressure design (PED/CE with design code AD2000). This is described in chapter 4-7 for the main assemblies:
    - Aluminium inner vessel
    - Stainless Steel outer vessel
    - Phase separator and filling system
    - Safety valves and degas system
- Operational modes of the Cryostat, described in chapter 8;
- Our set of definitive specifications. This is a description of all requirements that result out of PED/CE and AD2000. This is described in chapter 9.
- Proposal of testing. This is described in chapter 9 and appendix C.
- Planning. This is described in appendix D.
- Quotation for Full Scale Development of first prototype. This is described in appendix F.
- Concept design for the LN2 supply system. This is described in appendix E.

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4. Aluminium inner vessel

4.1 Pressure design acc to PED/CE

The Aluminium inner vessel has been designed by NIKHEF based on FEA analysis (Ideas) and checked by CODAP, as described in rapport 47110-MT-00004, 18/10/2010.
DeMaCo has checked this FEA analysis. The results are:

- Although the PED classification was based on liquid instead of gas, this led to the same PED classification. The vessel is cat. II;
- Design pressure was 1,5 bar @ -196℃, Also the limits 1,5 bar @ 150℃ (Bake out) and -1 bar @ 20℃ (Leak test) were evaluated. Pressure test at 20℃ also must be evaluated.
- Looking at the model there were signs of peak loads. These were probably caused by the rendering of the FEA model.
- During examination of the model using Codap only the tensile stress was considered, not the yield stress. Also stresses in hardened and low temperature condition were used, that will not be realistic in the welding area (both circumferential and longitudinal) at higher temperatures (which is > 50℃ when using Aluminium).

The following modifications were proposed and incorporated based on the design check:

- Design stresses based on PED/AD2000
- Flange thickness was increased.
- The material changed from AL1050 to AL5754. AL5754 is considered appropriate for pressure vessels by AD2000 (ref appendix A). For allowable design stresses the annealed state should be considered.
- The max. bake out temperature should be limited to 140℃. The material AL5754 may not be heated to temperature 150℃ or above as it may result in grain boundary precipitation of Al3Mg2 and disintegration in weld areas, acc. to EN13445-08:2010 par 7.7b.

The stress report is updated with the latest figures, and test condition (pressure test at ambient temperature) is added, Ref appendix G.

4.2 Cryogenic Design

We performed several cryogenic calculations, ref appendix H. The basis for these calculations was an emissivity level for the aluminium vessel and shields of 0,2. During normal operation (at start) the emissivity level is 0,1.
The cryogenic design check resulted in following proposed modifications:

- Safety valves, ref 8.2
  We advise to use a relief pressure valve with at least ∅92 mm flow area.
- P&ID (filling line, exhaust line, safety valves and instruments) ref appendix B
  In the P&ID our advise has been incorporated regarding separation of exhaust lines.
- Modification of the position of the filling valve (closer to the cryostat and less heat in leak);
- Modification (incl. test) of level sensor from pressure sensing to a capacitive measurement. The result is less gas bubbles, and better suited for the purpose. The level sensing will consist of two sensors, one for the overall range and one for the top level.
- Modification of drain system;
  A change was proposed for the method of draining of the inner vessel, using the formation of gas due to normal heat in leak on the installation as draining power. This leads to quick draining. When the degas valve HV1 is used for regulating the pressure to 80mbar (rather than closing completely), the draining will take approx. 5 hours.

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- Detail design and position of longitudinal welds in the inner vessel;
  Sharp edges inside the LN2 may be the core for gas bubbles. Therefore the welding seams can be moved to above LN2 levels. It is possible to acquire material sized such that only one longitudinal weld is needed. However by using two welds (above LN2 level) a lid is created for installation of instruments, while preventing crossed welding seams (that are a potential weak spot).
  The butt welds from vessel to flange cannot be prevented.
- Sizing of the exhaust;
  The exhaust flow must be laminar to prevent vibrations. This leads to an exhaust line of ∅100mm or bigger, depending on the emissivity level. Note on the calculations: The calculations were verifying calculations of the Nikhef calculations. We assumed the emissivity level of the aluminium vessel to be the same as the shields. As the vessel is much colder then the shield, our calculations are a bit negative and show critical flow at emissivity level 0,16. We decided to follow the Nikhef calculations on this point.

4.3 Produce ability

The material (AL5754) is readily available and shows good weld ability. To install tubes and instruments a welded in cover may be introduced as described in the paragraph above. This allows for easy installation.
All material must be specially cleaned and treated for UHV.

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5. Stainless Steel outer vessel

5.1 Pressure design acc to PED/CE

The stainless steel outer vessel was designed using a FEA analysis (Ideas) and calculated acc. to Codap allowable stresses, as laid down in report 47110-MT-00003, 31/08/2010.
DeMaCo has reviewed the model and the calculations. The outcome was:

- Calculations were based on allowable tensile strength only; no account was given to yield stress.

We advise the following modifications:

- Design stresses (tensile and yield) based on PED/AD2000

The vessel was PED Cat. III. By using a burst disc of lower pressure (0,5 bar(g)), the vessel is no pressure vessel acc. to the PED. The vessel is considered a pressure vessel by DeMaCo however, due to the resulting damage to the experiment when anything would go wrong. We therefore advice to specifically apply the rules of AD2000 (Manufacturing, NDE and pressure test) to be sure of design and manufacturing quality.
We recommend to make an update of the aforementioned report regarding allowable stresses, geometry and load cases for the final construction file, even though the loads were low to start with and have only been diminished.

5.2 Cryogenic design

The cryogenic design check of the outer vessel has resulted in:

- Safety valves (settings), ref 8.2
  We recommend to use the same free flow as determined for the inner vessel (∅92mm). This can be accomplished by using 4 DN50 burst discs, that are readily available.
- P&ID (filling line, exhaust line, safety valves and instruments) ref appendix B
  In the P&ID our advise has been incorporated regarding separation of exhaust lines.
- One feed through has been removed (the emptying line of the inner vessel) and can now be mounted within the exhaust line.

5.3 Produce ability

The material of the outer vessel Stainless steel 1.4301, 1.4306 or 1.4307 (304-compatible types) is a good choice regarding obtain ability and weld ability.
The material must be cleaned and treated to UHV standards.

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6. Phase separator and filling system

6.1 Pressure design acc to PED/CE

The proposed phase separator is a standard DeMaCo product, that complies to PED (Cat II) and AD2000, suitable to 12 bar(g) max. operating pressure. The safety valve is chosen at 0,5 bar(g) to prevent overpressure in the cryostat.

6.2 Cryogenic

The phase separator has been evaluated with the VIRGO system in mind. This brought us to the following design, Ref appendix E.
The phase separator is positioned as close to the application as possible, to prevent heat in leak and resulting GN2 bubbles.
The process line is positioned under a slight downward angle, to allow for available air bubbles to rise and be removed.
The nitrogen in the Phase Separator is at ambient pressure, but can at any later stage optionally be pressurized (to max. 0,5 bar) using a pressure regulated degas valve. This enables quick filling and cooling down.
The filling line to the experiment is made flexible, to prevent transfer of vibrations to the experiment.

6.3 Produce ability

DeMaCo standard.

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7. Safety system and exhaust

7.1 Safety of inner and outer vessel

For proper sizing of the safety valves, a risk assessment is required. A high level project risk assessment is not available at this time. Therefore we have determined the safety valve capacity according to our cryogenic standards. We considered the event of completely breaking the vacuum, leading to water condensation on the process wall. The resulting heat load leads to evaporation of LN2 that must be removed, without raising the pressure more then 10% above allowable working pressure. This 10% takes the complete exhaust system pressure drop into account. We have considered this load for both inner and outer vessel.
A proper high level risk assessment should be set up to evaluate whether this is the correct worst-case scenario.

7.2 Safety inner vessel

The heat load, that results from a total loss of vacuum, is determined at 3.8 W/m^2. This results in a flow of 7095 kg/h GN2 (gas) of -196°C. Using this mass flow we calculated a safety valve (acc to AD2000) with a flow area ∅ 90,5 mm and an opening pressure of 0.5 bar(g).
A second calculation was made by a supplier of safety valves; calculated acc. to DIN EN ISO 4126 for GAS and resulted in a flow area of ∅76,33 mm. This is no standard dimension; the next bigger size is ∅ 92mm. This was selected for the safety valve of the inner vessel.

7.3 Safety outer vessel

Nikhef decided to use a burst disc for this application, which we think is a good decision.
According to cryogenic regulations (CGA S-1.3-2005 Section 5.4) a vacuum wall needs a minimum safety disc area of 0.34 mm^2/liter contents of the process vessel.
At the same time the area and the opening pressure must be such that the process line or inner vessel cannot start buckling (caused by a rise in pressure due to the blowing-off).
A third requirement is that the pressure is not allowed to rise above 0,5 bar(g) in order to remain SEP acc. to the PED directive.
The aforementioned 0.34 mm^2/l of the process vessel results in a minimum exhaust area of 14.2 mm^2. This size will not meet the third requirement. Therefore DeMaCo suggests to use the same capacity as the inner vessel safety valve.
We are not sure whether we can locate a supplier that can produce a single break disk that meets these requirements, therefore the current design is based on 4 DN50 break discs in parallel (which are available at 0,5 bar(g) and capable of withstanding vacuum at the process side).

7.4 Exhaust lines

DeMaCo has indicated that exhaust and degas lines should not interfere. This prevents operating degas lines to influence the opening pressure of a safety line.
The sizes of the exhaust lines must be compatible with the safety device free flow area. The safety line resistance should be as low as possible. This is best performed by having the lines routed to a safe place, free flowing to ambient, as short as possible without any bends. This cannot be determined at this time, and is beyond the scope of this report. In the P&ID the lines have been separated.

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8. Operational modes

8.1 Introduction

In this chapter the operational modes are described, including our proposal to control these modes. The following modes are identified:

- Normal operation;
- Safety mode inner and outer vessel;
- Bake Out Inner vessel;
- Filling mode;
- Emptying mode;
- Emergency power failure.

8.2 Normal operation

This is the common mode of the installation in operation.
LN2 is supplied by the Phase separator. In the Phase Separator the LN2 pressure is regulated, and all GN2, formed by heat in leak as well as pressure drop is removed.
The Phase Separator LN2 level is controlled by CV1, regulated by LS1 Level transmitter.

CV2 (regulated by LS2) controls LN2 level in the Cryostat. HV1 must be open, EH1 is powered, controlled by T1 (T2 is a max. temp safety device). HV2 and HV3 are closed.

8.3 Safety mode inner vessel, outer vessel and phase separator.

This is the mode that occurs when, for whatever reason, the pressure rises to almost unacceptable levels.

- Inner vessel: Regardless of settings of valves, SV1 will open when pressure rises.
- Outer vessel: Regardless of settings of valves, BD(1-4) will open. NRV1 prevents the inlet of gas in any occasion.
- Phase Separator: Regardless of setting of valves, SV2 will open when pressure rises.

8.4 Bake out inner vessel

This is the mode that occurs when the cryostat, after reaching an unacceptable level of emissivity, needs to be baked out.
This situation may only occur after emptying of the inner vessel.
CV2 is closed. HV3 is closed.
GN2 from an external source flows through HV2 (open) into the vessel. EH2 is powered, controlled by T5 to 150℃ (T4 is a max. temp safety device).
HV1 is open, and exhaust gas is removed through the exhaust line. EH1 is switched off.
T6, T7 and T8 are used to monitor the actual temperature of the inner vessel at several locations. This gives a clear view of the actual bake-out temperature of the vessel.

8.5 Filling mode

This is the same mode as normal operation, except that CV2 is now regulated by LS3. At start during filling a lot of gas is formed at initial cool down. The cool down speed may be limited by the exhaust gas temperature when heater EH1 is not able to deal with the amount of gas. This means that CV2 is actually regulated by T1 rather then LS 3. When liquid starts filling the cryostat CV2 is regulated by LS3.

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8.6 Emptying mode

This mode is used to remove all LN2 out of the cryostat.
Draining power is created by normal heat inleak that results in evaporation of LN2. Therefore no additional power or pressure source is required.
CV 2 is closed. HV2 is closed.
HV3 is open. HV1 is used to create enough backpressure to have liquid drain through EH2 and HV3. The EH2 heater power must be sufficient to evaporate LN2 and heat the GN2, as the heater faces liquid in this mode. EH2 is controlled by T3.

8.7 Emergency power failure

All filling valves close to safe position: CV1 and CV 2 are closed, manual valves remain as is. The cryostat will empty by heat in leak over time.

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9. Full Scale Development

9.1 Introduction

- The responsibility of the supplier is not limited by this Design Document or by any specifications and regulations referred to by this document.
- The responsibility for the hardware, and for meeting the (functional) specifications of the design lies solely by the supplier. The supplier must guarantee to meet all specifications of this document. The supplier needs to make calculations (such as -but not limited to-strength, pressure drop, heat loss and safety valve capacity) to proof meeting the design requirements and guarantee proper and safe functioning of the delivered items.
- Design and manufacturing must meet all commonly acknowledged rules and regulations regarding the use and preservation of materials, environment and safety.
- The supplier must have a proven record for design and manufacturing of vacuum insulated cryogenic devices for liquid Nitrogen (80K) under applicable standards and regulations. Design, manufacturing, materials and (welding) processes must be suitable for pressure equipment and the use at the specified temperatures and in UHV applications.

9.2 General requirements

For design and manufacturing of the cryostat the following directives must be applied:
- 97/23/EC PED, Pressure Equipment Directive.
- Pressure equipment design code AD2000.
- Testing according to PED and AD2000;
- The supplier must be PED H/H1 certified.

The supplier must be certified for:
- Quality ISO 9001
- Welding quality according to ISO 3834-2
- Safety VCA** or equivalent (VCA** is Dutch SCC** certification).

9.3 Engineering

For references of the Basic Design: Ref. Chapter 3.
Materials acc. to ADW2 and ADW10, suitable for low temperature (80K) and elevated temperature (373 to 423K) usage
Additional requirements for the design:

Ultra High Vacuum:
- The design and processes must be suitable for the Ultra High Vacuum application.

Calculations:
- Calculations of heat load and pressure drop to show meeting the specifications;
- Pipe, pipe stress and pressure vessels calculations acc. to PED/AD2000
- Bellows calculated according to EJMA 1.000 thermal cycles.

Quality:
- A project specific Welding Plan must be part of the delivery;
- A project specific Quality, Test and Inspection plan must be part of the delivery.

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9.4 Purchase of Materials and Supplies

Materials acc. to design code (ADW2, ADW10) and PED,
Process pipe up to DN40 seamless pipe is adviced,
Certificates of all pressure bearing parts acc. to EN10204 type 3.1 (2.2)

9.5 Production

Welding:
The following regulations are applicable:

- Welding description (WPS) acc. to EN15607, ADHP2/1
- Welding method (PQR) acc. to EN15614, ADHP2/1
- Welders Qualification acc. to EN287-1, ADHP3
- Orbital welding acc. to EN1418, ADHP3
- Visual weld inspections (100%) ISO 5817 level B or better.
- After welding the welds must be pickled or brushed with a stainless steel brush.

Cleanliness:
Parts and assemblies must be cleaned to Oxygen Clean acc. to EN12300.
Parts, tools and assemblies must be cleaned suitable for UHV application acc. to NIKHEF procedure “Cleaning procedure vacuum parts/Stainless and Aluminum”
Production must be performed with processes (especially during handling and where cooling and cutting oils are involved) suitable for UHV application.
Production (after cleaning), assembly and storage must be performed in a clean and dust free area.
After each important step in production a check is required using an UV light in a darkened surrounding, to check for dust and grease.
Final cleanliness is checked by using a mass-spectrum meter to check for residue materials.

Tolerances:
Tolerances acc. to ISO2768 Part 1.

9.6 Quality and testing

9.6.1 Testing during production and installation:

- Visual weld inspection and dimensional check;
- Cleanliness;
- Vacuum test;
- Helium Leak test;
  - Test with Helium mass spectrometer (max. 1×10^{-10} mbar.l/s per weld and 1×10^{-9} mbar.l/s per assembly).
- Pressure test acc. to PED and AD2000, also in case of cat. SEP (Sound Engineering Practice PED art 3.3).
- NDE:
  - X-ray (min 10% of all butt welds, random during production, 100% of longitudinal welds for AL inner vessel) acc. to ADHP0 (vessels) and ADHP100R (piping);
  - Dye Penetrant test (min 10% of all socket welds, random during production) for welds that are not inside the UHV application. Welds at the envelope of the UHV are not DP tested.

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9.6.2 FAT

Factory Acceptance test, consisting of:

- Cold Helium leaktest using mass spectrometer(<1x10^{-10}mbar);
- Cold function test with LN2. This test consists of:
  - Cool down of process lines for at least two hours, and then check on:
    - Check for Cold Spots;
    - Valve Function test;
    - Level sensor test;
    - Test of all instruments and sensors;
    - Test of all heaters;
  - Check P&ID during connection test.
- Check on safety valve and break disc values (using the certificate);
- Vacuum level test (<1x10^{-9}mbar);
- A test using a Spectrum analyzer to determine the residue inside the chamber.

9.7 Documentation

- Result of the calculations;
- As built drawings (Lay-out and interface details);
- Safety guidelines and manuals;
- Installation, Operation en Maintenance Manuals;
- Spare parts list
- Declaration of conformity and/or CE certificate;
- Quality and Inspection plan;
- Welding documents;
- NDE results;
- Test certificates;
- Material certificates.

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10. Appendices

10.1 Appendix A. Properties of Aluminium 5754 acc. to AD2000 en EN458

10.2 Appendix B. P&ID

10.3 Appendix C. QA Plan

10.4 Appendix D. Planning

10.5 Appendix E. LN2 filling system 49736C

10.6 Appendix F. Quotation

10.7 Appendix G. FEA of Aluminum Inner Vessel

10.8 Appendix H. Calculations