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PRELIMINARY DESIGN OF THE JUNCTION BOX PRESSURE VESSELS FOR THE NEMO EXPERIMENT - R&D PHASE

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Abstract

According with the R&D philosophy of the first phase of NEMO experiment, an extensive investigation have been carried out in order to find practical alternatives to the standard design of pressure vessels for junction boxes that should operate on the sea bed for a long lifetime.

Both technical and economical points of view have been considered, as well as reliability. Possible suppliers have been contacted to check the feasibility of the different solutions and estimate their cost. A final trade-off has been proposed, to help the collaboration to choose the solution for the detector prototype phase.

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1 INTRODUCTION

The NEMO detector is large scale-underwater neutrino telescope, where solutions already used in other experiments (ANTARES, AMANDA, etc) are applied to a significantly larger scale. A simple sizing-up of the components already used could lead to unpractical solution, from both technical and economical points of view. The junction box containers are the most critical mechanical items of the detector as, housing "nodes" of the electrical network, their failure would imply the black-out of large parts or even the whole detector. Furthermore, their maintenance would require an expensive recovery operation in open sea. Then they should withstand the pressure load in a marine environment, at an acceptable corrosion rate and keeping the water tightness for the whole operating life.

Since now, in those applications the above-mentioned reasons lead to a precautionary design, where high performance and expensive alloys, as titanium, were largely used. Usually, all the electronic equipment were housed in dry atmosphere, at atmospheric pressure. Furthermore, the number of feed-through, that are a potential source of leak, have always been minimised; the vessel wall thickness have been designed to give a considerable corrosion allowance, with stress peaks always noticeably below the alloy yield limit and a buckling load several times higher than expected in operation.

With the same philosophy, the quality control, from raw material to final acceptance, is a crucial matter that needs to be assessed since the design phase. Non conformities cannot be allowed at all, as they would increase the risk of failures, even if the design is appropriate. An extensive Quality Control Plan should be mandatory, and must be strictly followed. It should be conceived from the very beginning of the project.

All those considerations make the junction box construction quite expensive and, given that in NEMO up to 9 of such items should be installed, an investigation focused on reliability and costs could introduce significant improvements in the detector budget.

2 LAYOUT OPTIONS

The present configuration of NEMO detector[2] foresees a sea bed network for power distribution, slow control and signal collection, arranged as follows (see fig. 1):

A main junction box is joined to the shore station via an electro-optical cable. The power is transmitted in AC at medium voltage, to minimise the losses along the line. At the junction box an electric step-down, 30 KW rated transformer reduces a first time the voltage, before power distribution to the secondary junction boxes. A standard "on the shelf" electronic module provides signal handling from the detectors.

Up to 8 secondary junction boxes collect the power from the main junction box and the signal from the detector "towers". Every secondary junction box should be linked to up to 8 towers; every junction box is linked to the previous and the following one. So, they form a "ring" that could be used as emergency line, in case of failure of the main connection between the main and a secondary junction box. All those connections are made via standard, well-experienced, deep-water sea cables with underwater mateable connectors. Every secondary junction box houses the same electronic module as the main one and a small step-down transformer for the last voltage reduction to the value required for towers feeding.

In this scenario, several junction box layouts have been evaluated. Given that both primary and secondary junction boxes should house the same electronic equipment and a transformer, and have about the same number of electro-optical links, we assumed that all they have the same design and dimensions. That should make easier the project management and, perhaps, allow a little saving of money.

We considered the following alternatives:

a) Standard construction, where the vessel is made of titanium grade 5 ASTM alloy, and the transformer housed inside (see fig. 2). That is the solution of the ANTARES detector[1].

b) Standard construction, where the vessel is made of titanium grade 5 ASTM alloy, and the transformer set outside. The feasibility of such layout depends on the availability of power transformers housed in fibreglass, pressure-compensated containers that could withstand the water attack for the required lifetime, with the required reliability. It combines the advantage of a reduction of junction box vessel dimension to a better cooling of both transformer and electronics, that so are thermally independent, with a positive effect on reliability. As 2 more penetrators are required on vessel walls to connect the transformer to the junction box electronics, it would introduce new potential sources of leaks and then reduce the expected reliability. Roughly speaking, you could tell the global reliability of the system is unchanged.

c) Vessel made of steel, housed in a fibreglass-made, pressure-compensated container filled with mineral oil, to avoid direct contact between steel and sea water, and the transformer housed inside. This is expected to be definitely cheaper than a),

d) Vessel made of steel, housed in a fibreglass-made, pressure-compensated container filled with oil, to avoid direct contact between steel and sea water, and the transformer set outside (see fig. 3). This solution is expected to be the cheapest at all, combining b) and c) alternatives .

Both alternatives c) and d) have the advantage that, in case of joint failure, dielectric oil and not water would enter the container, then reducing the risk of damage of the electronic equipment.

3 PRELIMINARY CONSIDERATIONS

As general specification, the underwater equipment of the detector should meet the following requirements:

- environment: sea water;
- operating depth: 3500 m b.s.l.;

- operating temperature: 12°C;
- operating pressure: 350 bar gauge;
- test pressure: 420 bar gauge;
- lifetime: 10 years of continuous operation, with no maintenance.

The above mentioned solutions required first to check their feasibility, trying also to find out any drawback that could significantly reduce the reliability of the system.

While titanium alloys are known to perfectly withstand sea water corrosion and fulfil the severe structural requirements of the application, an investigation have been done about the chemical compatibility of other materials mentioned in alternatives b), c) and d).

Carbon steel cannot withstand the corrosion attack, and even less if moderately alloyed; then the oil barrier is mandatory. Hardened and tempered steel can achieve strength comparable with titanium grade 5 or even higher, provided that the thermal treatment had been done properly, and can be easily forged as well. An appropriate selection of the alloy should allow the same vessel design for both steel and titanium.

Fibreglass is deemed to well withstand both sea water and mineral oil attacks, and the low operating temperature should further help. Several long-life experiences (oil tanks, automotive engine carters) confirm that. Anyway, care should be taken in resin and filler selection: a best choice, after the experience of several suppliers, should be a vinyl-ester resin (as Dow Derakane 411, for instance), while even a less expensive polyester resin could work.

Both alternatives c) and d) would imply the contact of the outer sheath of the interconnecting cables, made of polyurethane, with mineral oil. Generally speaking, polyurethane should be chemically compatible with mineral oil, but cables supplier didn't give its advice on the matter.

Power transformers operating in oil-filled, pressure-balanced containers are often used in tethered underwater vehicles[3]. In principle, their container could be made of whatever material, then also of titanium or fibreglass, in order to withstand the corrosion attack for the required lifetime. Anyway, they are not "on the shelf" components, but custom-designed and manufactured. As far as we could know, there's no experience of continuous operation of these items at nominal pressure and temperature long enough to be compared to our requirements. But, generally speaking, transformer suppliers feel comfortable about long term operation of their equipment in the above mentioned conditions.

The same cables, penetrators and connectors used in ANTARES[1] have been considered, as presently there are no practical alternatives.

4 VESSEL DESIGN AND STRUCTURAL SIMULATIONS

We assumed, as structural safety, that in operating conditions, the allowable stress had to be below the typical yield stress of the material divided by 1.5, and below the same value divided by 1.1 while in test conditions. After the ANTARES experience, we set the test pressure at 1.2 times the operating pressure. As there are no straight safety criteria to consider the buckling critical pressure when calculated after Eulero, we decide for the moment to accept only critical pressure at least 5 times larger than the test pressure. Even if a dimensioning where locally the material is stressed beyond the yield limit is in principle possible, we decided to stay always below the allowable stress, to be sure that no permanent deformation will ever occur. As the peaks of tension are expected around the penetrator holes, that should fit in with a tight clearance, this way the design should allow always correct dismantling and reassembling of the penetrators.

Comparative structural simulation proved that, given the operating conditions, the best compromise between weight and inside volume of the vessel is achieved when a spherical geometry is adopted. Such geometry allows also to have a vessel made of two halves, then minimising the number of joint surfaces and the risk of leakage. We arranged the 11 penetrators on the lower emi-sphere, with threaded blind holes on the mating surface, while the other emi-sphere features the through holes for the screws to keep together the two halves (see fig. 3). In the penetrator area, the inner surface becomes cylindrical (see fig 6), so that the consequent larger thickness allows to keep the peaks of stress around the holes below the stated limit.

We dimensioned the vessel as titanium grade 5 made, and we checked both Von Mises' stress and Eulero's critical pressure (see fig. 4 and 5). That means that the steel-made alternative requires a conveniently alloyed and tempered material, whose yield limit after thermal treatment could withstand the load as safely as titanium. Given steel Young's modulus, more than 2 times larger than titanium, there's no concern at all about buckling.

5 GENERAL LAYOUT

To optimise the fibreglass container dimensions, the transformer has been set on top of the junction box vessel, instead of aside (see fig. 3). Such a configuration has also the advantage that, being the transformer a source of heat, it shouldn't warm-up the junction box vessel.

Fibreglass container height has been oversized so that the cables could be easily routed from the vessel to the fibreglass walls see fig. 7), keeping their bending radii above the minimum allowed.

Fibreglass container diameter have also been sized taking into account of a reasonable distance between neighboring penetrators, that should help ROV operations.

Underwater mateable connectors should be secured onto fibreglass flanges internally fitted on the container walls. As presently those components don't feature any joint, a precise requirement should be given the supplier so that any leakage of oil from the fibreglass container through the connector hole could be prevented.

Both vessel and transformer should rest on brackets, fitted on the global framework or on the internal walls of the fibreglass container, depending on what junction box option will be taken. In case of fibreglass container, it should rest on its feet on the global framework; in principle, it could be designed as self-standing the loads, but probably its base should be too large to match the sea bed load capacity, then becoming unacceptable in terms of weight and volume of oil to be filled with.

As it shouldn't withstand the pressure, fibreglass container cover could be elliptical or flat. Being the tightness requirements not dramatically stringent, a simple flat joint could prevent the oil leakages through the cover flange. Provisions have to be made to equilibrate the pressure, allowing the communication between oil and outside sea water. Filling and emptying gates should be foreseen as well.

Being presently unknown the handling requirements during deployement and the sea bed carrying capacity, the framework that should house the junction box assembly couldn't be designed yet. Anyway, its design shouldn't be heavy influenced by the option for the junction box that will be taken.

6 MARKET SURVEY

We asked several suppliers, of both metal and fibreglass crafts, to send their best budget tenders for the items as outlined in the executive, preliminary drawings here attached (see fig. 6 and 7). The pressure vessel had to be offered in both titanium grade 5 and steel alloy with a minimum yield strength, when tempered, of 765 MPa. The tender had to be based on a batch of 3 items, as it should be in the R&D phase of NEMO. No structural simulation of the fibreglass container have been done; nevertheless, the expected loads have been specified as well as a roughly estimated thickness of the walls, so that the suppliers could work out homogeneous tenders. Hereafter the averaged costs from the tenders, VAT excluded:

Titanium junction box (option "b")	70000 €;
Steel junction box complete with fibreglass container (option "d")	27500 €.

Although, given the preliminary character of the design and then of the tenders, fluctuations in the above listed values are likely, anyway the difference between the two solutions is much larger than expected. All the suppliers explained that they are not equipped to forge spherical shells of the required dimensions; special tools would be necessary, but their high cost is not compatible with a small batch production. Then they should shape the spherical shells cutting away material from a full cylinder: that would mean that a final piece of titanium weighing 100 Kg would imply 825 Kg of wasted titanium. The steel option would have a final weight of 170 Kg and imply 1400 Kg of wasted steel. Given that raw titanium grade 5 presently costs approximately 25 €/Kg, while an appropriate raw steel alloy could cost 2 €/Kg, and that manufacturing cost is roughly the same, the difference is explained. We esteem that, with the appropriate tools, a manufacturer should be able to offer the titanium solution at a price only 35% higher than the steel one. Anyway, it must be noted that titanium price heavily depends on market and availability at the moment of the purchase, and then is subject to significant fluctuations.

An alternative manufacturing cycle could allow a significant reduction of the cost difference between the two solutions: every half sphere should be made of two parts (see fig. 8). A spherical cap, shaped from a titanium circular plate 35 mm thick, should be full penetration, TIG welded to a forged annulus with welding electrodes of the same alloy. Then the welded joint should be fully X-rayed; finally, a complete machining on the lathe of the surfaces should give the piece the final shape. This solution have been applied to the SARA AUV (Autonomous Underwater Vehicle) designed and assembled by TECNOMARE, rated to operate at 1000 m depth in the Antarctic Sea. An average budget price for a complete titanium junction box manufactured as last described is 45000 €, that means a saving of about 25% and a total cost 64% higher that the steel junction box.

7 CONCLUSIONS

The alternatives we studied for the NEMO junction boxes generally proved to be feasible; the pending points about the underwater cable polyurethane sheath compatibility with oil and pressure-balanced transformer reliability anyway need further investigation. The market survey gave an order of magnitude to the costs, and confirmed the steel solution as the cheapest one. The price difference between the two solution ranges from 30 to 60%, depending on the present price of the raw material and the tools the supplier is equipped with, that can allow him to set up a more cost-effective manufacturing cycle. We expect that, if the volume requirements given by the electronic equipment should be considerably reduced, then the cost difference between the two solutions could become much less significant.

8 REFERENCES

(1) Antares Technical Design Report
(2) Nemo R&D technical proposal
(3) N. C. Forrester, "Power transformer design for tethered underwater vehicles", Woods Hole Oceanographic Institution, Woods Hole MA 02543

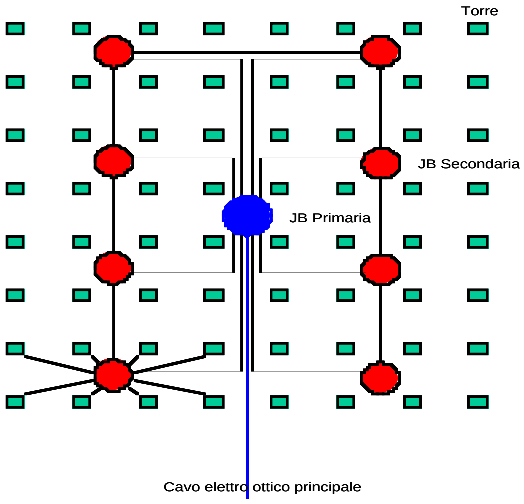

Fig.1: NEMO sea bed network layout

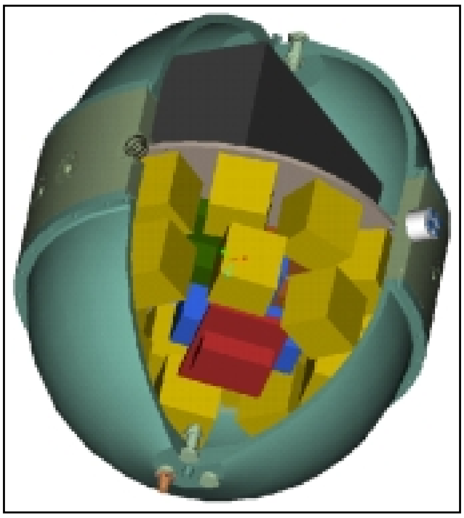

Fig. 2: ANTARES JB layout

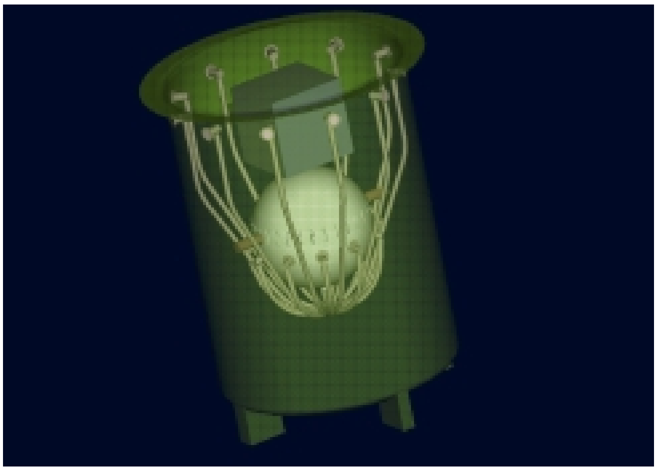

Fig. 3: NEMO d) solution JB layout

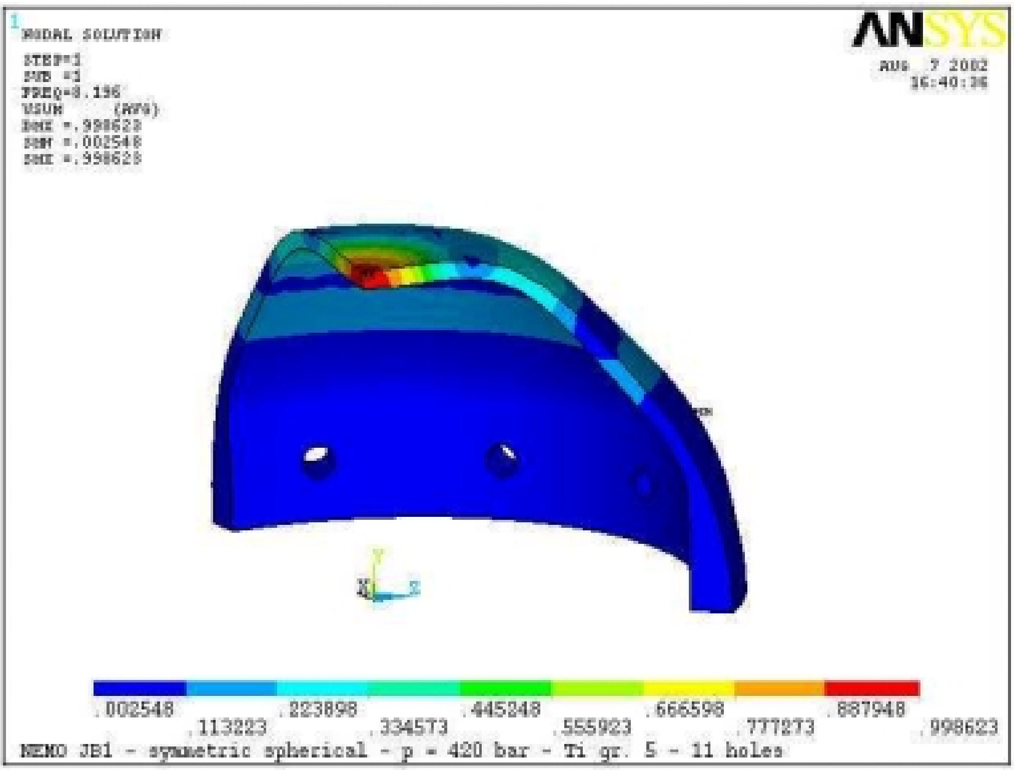

Fig. 4: FEA analysis of the JB with penetrator holes - Eulero's buckling load

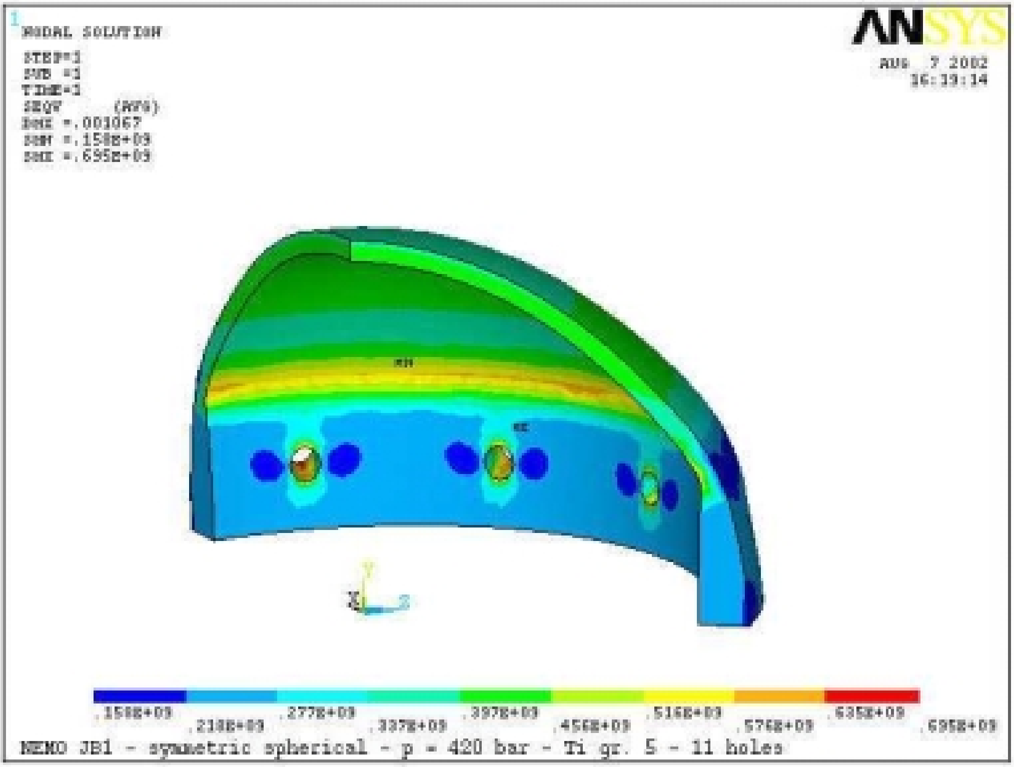

Fig. 5: FEA analysis of the JB with penetrator holes - Von Mises' stress

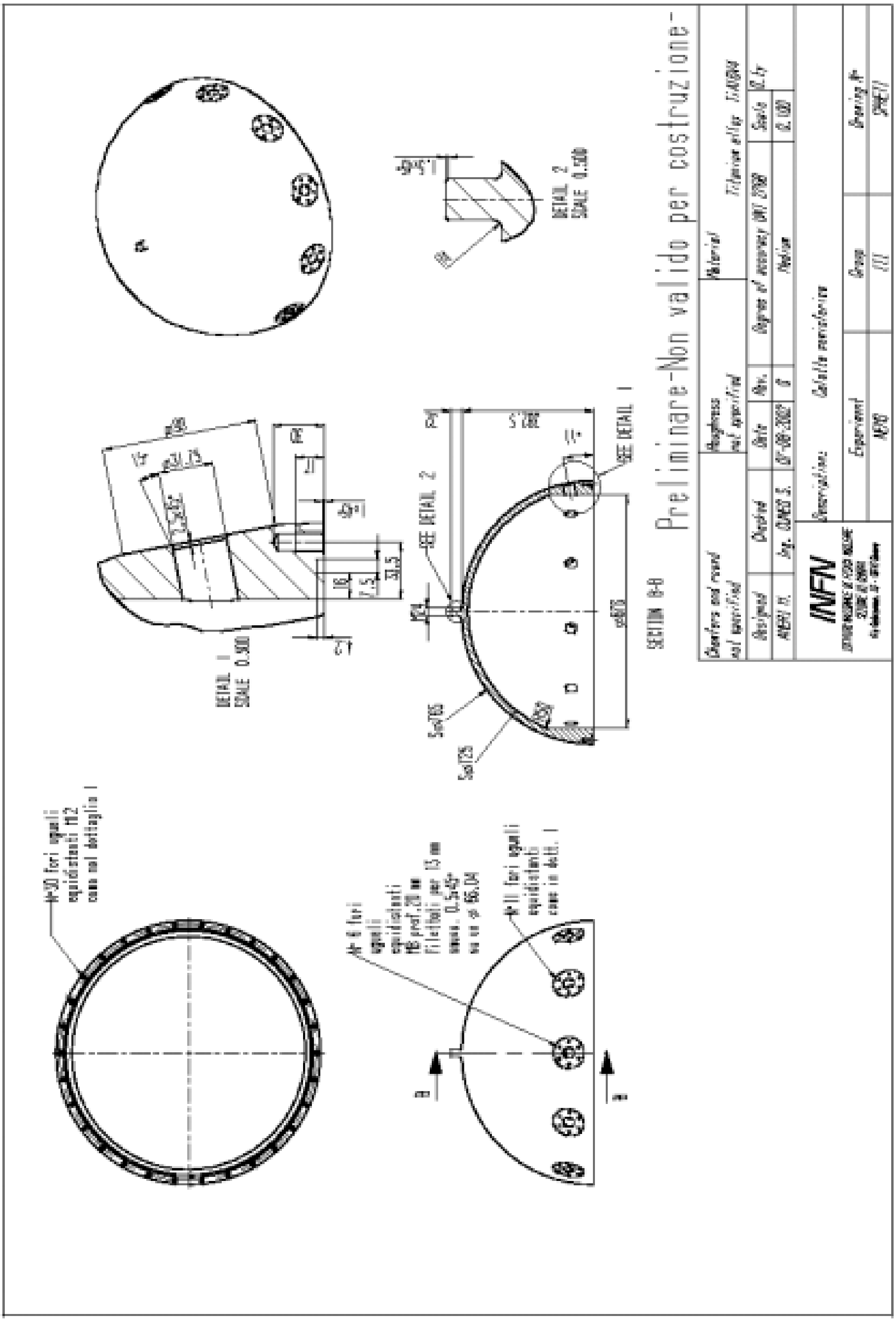

Fig. 6: preliminary executive drawing of the pressure vessel

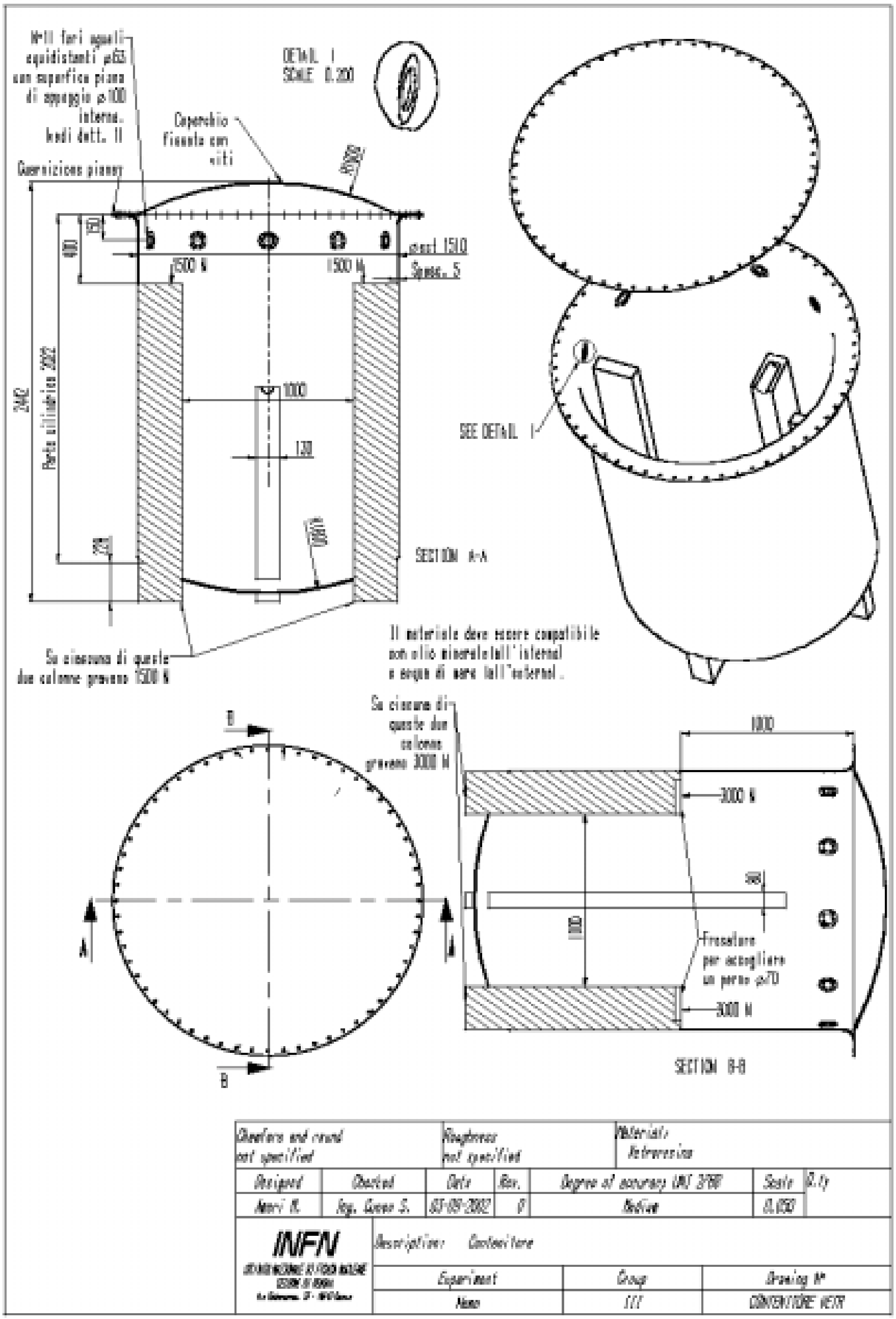

Fig. 7: preliminary executive drawing of the fibreglass container

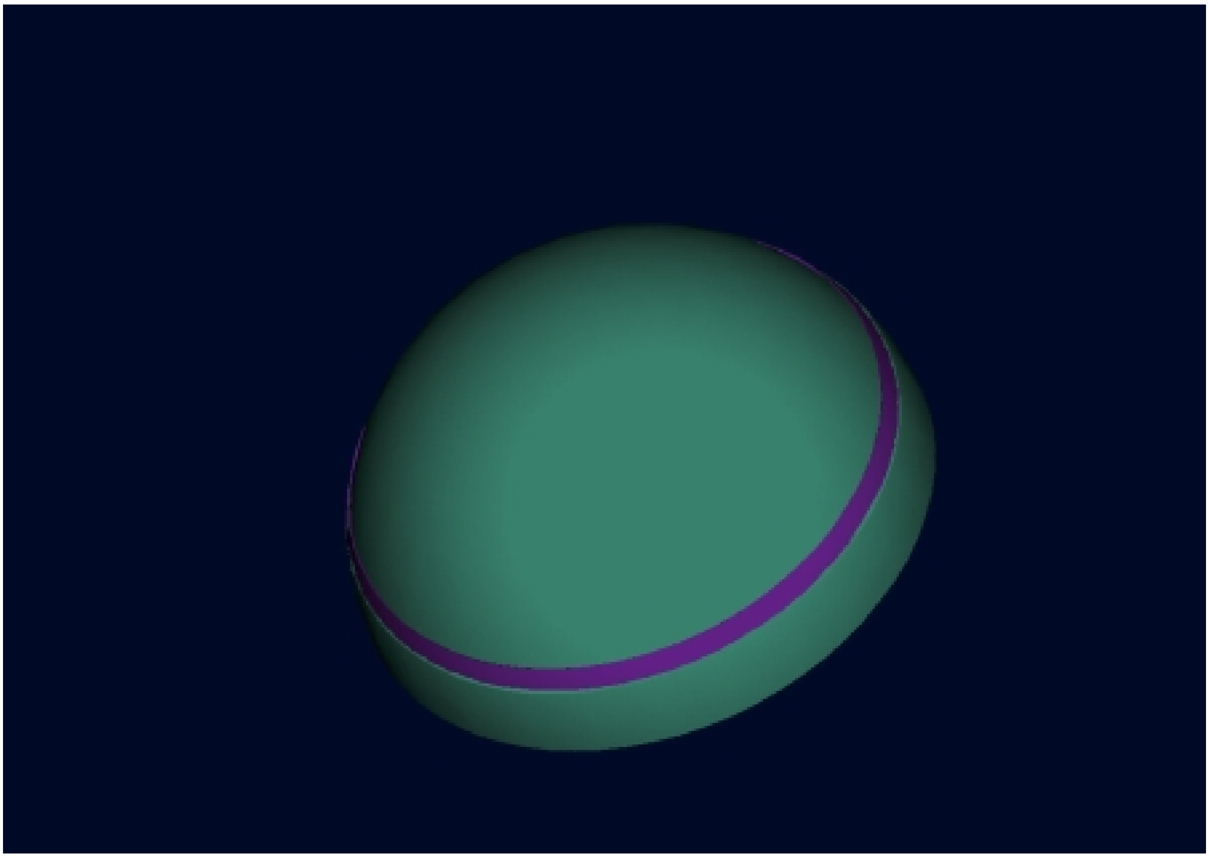

Fig. 8: alternative manufacturing solution