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DESIGN AND MANUFACTURING OF COMPOSITE SPHERICAL MIRRORS FOR THE GRAAL CERENKOV PARTICLE DETECTOR

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Abstract

This paper reports the manufacturing cycle set-up and the production results of the spherical mirrors to be installed in the GRAAL Cerenkov detector. Up to 121 mirrors have been assembled and checked. Production tips and statistics are reported here as a record for future similar application

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1 MIRROR SPECIFICATIONS

The Cerenkov detector for the GRAAL apparatus will be equipped with a rotation ellipsoid as reflective surface [1]. Given its dimensions, the reflective surface is not a continuous mirror, but is tiled with 106 spherical mirrors having square section, partly overlapped on their edges.

Optical simulations proved that the complete collection of photons is achieved when the radii of curvature of the single mirrors are between 1500 and 3500 mm. Then the specified radius of curvature have been set to 2700 mm with a tolerance of ± 100 mm, that are values that the common experience knows as relatively easily feasible. Furthermore, a sphericity better than 0.75 mm have been requested, to take into account of local faults that could happen on the surface.

As a general rule, mirrors should be as much particle-transparent as possible, in order not to shade too much the following detectors in the apparatus. A radiation length equivalent to a 3 mm-thick Plexiglas sheet has been considered as a satisfactory compromise for the mirrors.

Mirrors should give their best reflectivity in the UV range, between 300 and 700 nm of wavelength.

2 SURFACE COATINGS

The reflective surface is obtained by coating a Plexiglas sheet with a 100 nm-thick layer of Aluminum, known to have satisfactory reflectivity in the wavelength interval of interest; then a 100 nm-thick protective layer is laid over the aluminum one. The adopted coating process UNAXIS LV ALFLEX-UV guarantees a reflectivity better than 80% in the range 300÷700 nm of wavelength, in not less than 90% of the treated pieces.

As the process is carried out in a high vacuum facility, only components that are known not to de-gas or release vapors are allowed by the Supplier: that requirement had a heavy influence in the assembling process, as will be stated below.

3 STRUCTURE OF THE MIRRORS

Mirrors made of a simple 3 mm-thick Plexiglass sheet, spherically shaped by thermal formation and then coated, proved not to be a viable solution for the series production. As a matter of fact, probably because of residual stress inside the material, once shaped the Plexiglass sheets loose relatively quickly their curvature: none of more than 12 prototypes kept the curvature and met the requirements a week after the thermal formation. A male-female mould, different settings of the temperature cycle and experience with slightly different materials didn't lead to a result.

Then we customized an already assessed technology [2), 3)], where a Plexiglass sheet is first spherically shaped, then glued onto a spherically shaped sandwich composite panel, and finally aluminum coated under vacuum. Our optimization mainly pointed at a reduction of the costs, keeping the forming mould already available and accepting, where possible, worse characteristics of the mirrors.

In principle, the sandwich panel could feature skins with surface roughness low enough to be directly aluminum coated, provided that the mould roughness and the resin excess of the skins are controlled. Anyway the coating supplier strongly refused that options, as he feared it would have heavily polluted his high vacuum installation. Then we had to foresee a Plexiglass sheet, to be coated before gluing it onto the sandwich structure. We decided to use 0.5 mm-thick Plexiglass sheet, that is the minimum that practically can be safely handled: the surface shouldn't be bent too much, to avoid the coating to detach. The poor stiffness of those sheets allowed us not to pre-form them, being confident that the glue bond will give the Plexiglass the curvature of the sandwich and not vice-versa. Given the optical requirements of our detector, we accepted the relatively poor surface quality that those thin sheets of Plexiglass typically are known to have.

Several tests proved that, even with 0.5 mm-thick Plexiglass sheet, the aluminum mould available, machined to a surface roughness R_a = 0.8 μm, didn't transfer its faults to the mirror so that it couldn't be accepted; then, we didn't coat nor optically polish the mould.

An attempt to glue an aluminum-coated Mylar sheet 0.1 mm-thick directly onto the sandwich support failed as, because of its low thickness, the Mylar reported on the surface the weaving of the carbon fiber cloth underneath, then showing poor optical properties. This phenomenon, known as “telegraphing effect”, is still noticeable where a 0.5 mm thick Plexiglass sheet is adopted, but much less evident, with no practical influence on the optical performance of the whole detector. Anyway, it must be said that detector optical requirements are not particularly stringent.

We investigated several combinations of skins and core; we achieved the best results with a 5 mm-thick core of ROHACELL 51 foam combined with carbon fiber pre-preg fabric CC 200 PW skins, though also fiberglass fabric gave promising results. Such a structure has a radiation length comparable to the 3 mm-thick Plexiglass sheet originally foreseen, and a weight of 150 gr/mirror. ROHACELL 51 is a commercial closed-cell rigid foam plastic based on PMI (polymethacrylimide) which does not contain any CFCs. Its properties are listed in annex 1 attached below. Of course, other combinations of materials can be possible and even better; the choice we made was limited also by the relatively small amount of items to be produced and the consequent availability of material. Therefore, we made any possible effort to use widely diffused materials that could be available in any Manufacturer’s stock or easily procured.

4 MANUFACTURING CYCLE

The complete manufacturing cycle has been set-up, in collaboration with Plyform, collecting all the experiences we made in the pre-production phase.

As mentioned before, the 0.5 mm-thick Plexiglass sheets, cut in squares of 262 mm by 262 mm, are first coated in a vacuum deposition facility. Both their surfaces, after deposition, are protected with an adhesive Mylar sheet, blue-colored on the coated surface, transparent on the other one.

The coating supplier specified that the Mylar sheet shouldn't stay on the coated surface more than 8 weeks, because of risk of chemical reaction that could damage the coating. Then we set up a process that could reduce the total time of manufacturing close to the above requirement, with 3 identical forming moulds.

A mould is made of an aluminum, massive, convex male surface, where the sandwich structure is formed with the vacuum-bagging technique and cured at 127°C/2 bar g for 2 hours in autoclave. The same mould is then used to glue the coated Plexiglass sheet to the sandwich; during this operation, a female, carbon fiber-made, mould is used too, in order to help the whole panel to follow the mould curvature.

Some simple but useful special tools have been assembled to help the operator during ROHACELL 51 and carbon fiber fabric cutting and panel assembling.

As the first prototypes showed that some resin in excess flowed, at the mould outer edge, between the mould and the Plexiglass sheet, then damaging the coating, the assembly side length have been kept 10 mm larger than required. Then, after curing, the assembly is trimmed to the final dimensions, cutting away the damaged areas.

The series production has been carried out at Plyform clean room, after the following manufacturing cycle:

1. ROHACELL 51 is cut in square 200 mm by 200 mm, using the purpose-made special tool;
2. Carbon carbon pre-preg fabric is cut in 4 squares 300 mm by 300 mm;
3. The mould is accurately cleaned, using a soft moist cloth; then dried with clean compressed air;
4. 2 squares of pre-preg are laid on the mould, at 0° and 90° respectively;
5. the ROHACELL 51 square is laid on the pre-preg, and centered by means of the centering mask;
6. the other 2 squares of pre-preg are laid on the ROHACELL 51, at 90° and 0° respectively; care has to be taken to align the fabric, in order to prevent the panel to swirl after curing;
7. set up the vacuum bag and cure at 127°C/2 bar g for 2 hours in autoclave;
8. let the sandwich cool down at room temperature and then carefully take it out from the mould;

9. carefully sandpaper (paper n° 400) the concave sandwich surface where the Plexiglass has to be glued on; then degrease with acetone and carefully clean, to avoid any dirt or dust on the surface;
10. carefully clean, with a moist soft cloth, the Plexiglass sheet on the coated side, without taking off the protective blue foil; then dry with clean compressed air;
11. detach the adhesive label on the transparent foil on the Plexiglass sheet and put it on the convex side of the sandwich;
12. remove the transparent foil on the Plexiglass sheet, then lightly sandpaper the non-coated surface (paper n° 400). Finally, degrease with acetone and carefully clean, to avoid any dirt or dust on the surface;
13. lay off a 0.1 mm-thick layer of adhesive, using the appropriate tool, on the sandwich structure;
14. carefully clean the male mould and cover it with a tedlar foil without holes;
15. put the Plexiglass sheet on the mould, with its coated surface that mates the mould surface; use the appropriate tool to position it;
16. put the sandwich structure previously assembled on the Plexiglass sheet;
17. set up the vacuum bag and cure at room temperature for 6 to 8 hours;
18. remove the vacuum bag
19. trim to shape the assembly, as specified, using a diamond saw, keeping the part in the purpose-designed vice with the coated face top-oriented;
20. remove the protective blue foil and put on another protection, as soft paper;

check as foreseen in the Quality Control Plan.

A Quality Control Plan has been agreed with the Supplier. It is based on the following points:

- check of the raw material certificates of origin;
- preliminary check of the coated Plexiglass sheets: they should have the specified dimensions and the protective blue foil should perfectly adhere to the surface, with neither air bubbles trapped in nor wrinkles;
- check of the bonding between Plexiglass sheet and sandwich structure: a visual inspection should confirm the correct bonding along the edge of the assembly;
- check of the reflective surface, that should have no scratch, indentation, crack, resin excess, glue trace. Light should be uniformly reflected everywhere;
- overall dimension check;
- curvature check: 100 points uniformly located on the reflective surface should be measured, and spherical radius if curvature and sphericity calculated, using the computerized measuring machine available at our Institute;
- filling in the Quality Control data sheet.

As clients, we kept the right to finally accept also some of the mirrors that, after the Quality Control Plan, should have been rejected. As a matter of fact, some low quality mirrors could be installed at the outer edge of the ellipsoidal reflective surface, where a low rate of events is expected to impinge.

5 PRODUCTION STATISTICS

Up to 121 mirrors have been assembled, then with 15 items in excess compared to the required 106, to be used as spares. Production statistics can be found in Tab. 1 and Fig. 3-4.

Generally speaking, the production yield could be considered satisfactory. 38% of the manufactured mirrors didn't fully meet the geometrical requirements, but only very few of them was actually unacceptable and had to be handled as non-conform items. As a matter of fact, only those items that featured a damaged reflective surface have been rejected. Then, a further batch of mirrors will be probably necessary to complete detector surface tiling.

A large number of local faults on the surface was noticed, varying in shape, distribution and number from mirror to mirror. We couldn't relate those faults neither to tools finishing and cleanliness nor to any other production parameter. We guess that the reason could be the presence of dust between the coated Plexiglass and the protective blue Mylar sheet, or surface faults of the Mylar sheet itself. As the detector doesn't have strong optical requirements, surface finish has been considered acceptable for most of the mirrors. Given the small number of good coated sheets available, we decided not to carry any test gluing the Plexiglass without the Mylar on.

6 CONCLUSIONS

The manufacturing process we set up allowed to produce mirrors that, though often rather close to requirements, could fully meet the requirements only with a 62% yield. However, detector optics are not that optimized, then most of the mirrors out of spec will be able to be installed as well.

In view of future use of that technology, a selection of thicker Plexiglass sheets, up to 1 mm, is strongly advisable, as well as careful purchase specification and acceptance of that material. Given that most coating suppliers will never accept to pollute their high vacuum facilities for a small batch production, it seems rather unlikely to coat the mirrors after the Plexiglass has been bonded to the sandwich. Anyway, the protective film, though prevented the coating to be scratched, has probably been the reason of most of the geometrical local faults we noticed on the surfaces. A further development should investigate the possibility to bond the reflective sheet without the protective film on.

REFERENCES

(1) M. Castoldi et al, The design of a gas Cerenkov particle detector for the GRAAL high energy polarised photon facility, INFN/TC-99/17

(2) G. Adams et al, The CLAS Cerenkov detector, submitted to Elsevier preprint

(3) E. Cisbani et al, Lightweight spherical mirrors for Cerenkov detectors, submitted to Elsevier preprint

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TABLE 1: PRODUCTION STATISTICS

	TOTAL	**%**
Mirrors produced	121	100
Out of curvature	9	7.4
Out of sphericity	24	19.8
Out of both curvature and sphericity	1	0.8
Damaged coating	19	15.7
Large local geometrical faults	10	8.3
Definitely unacceptable	19	15.7

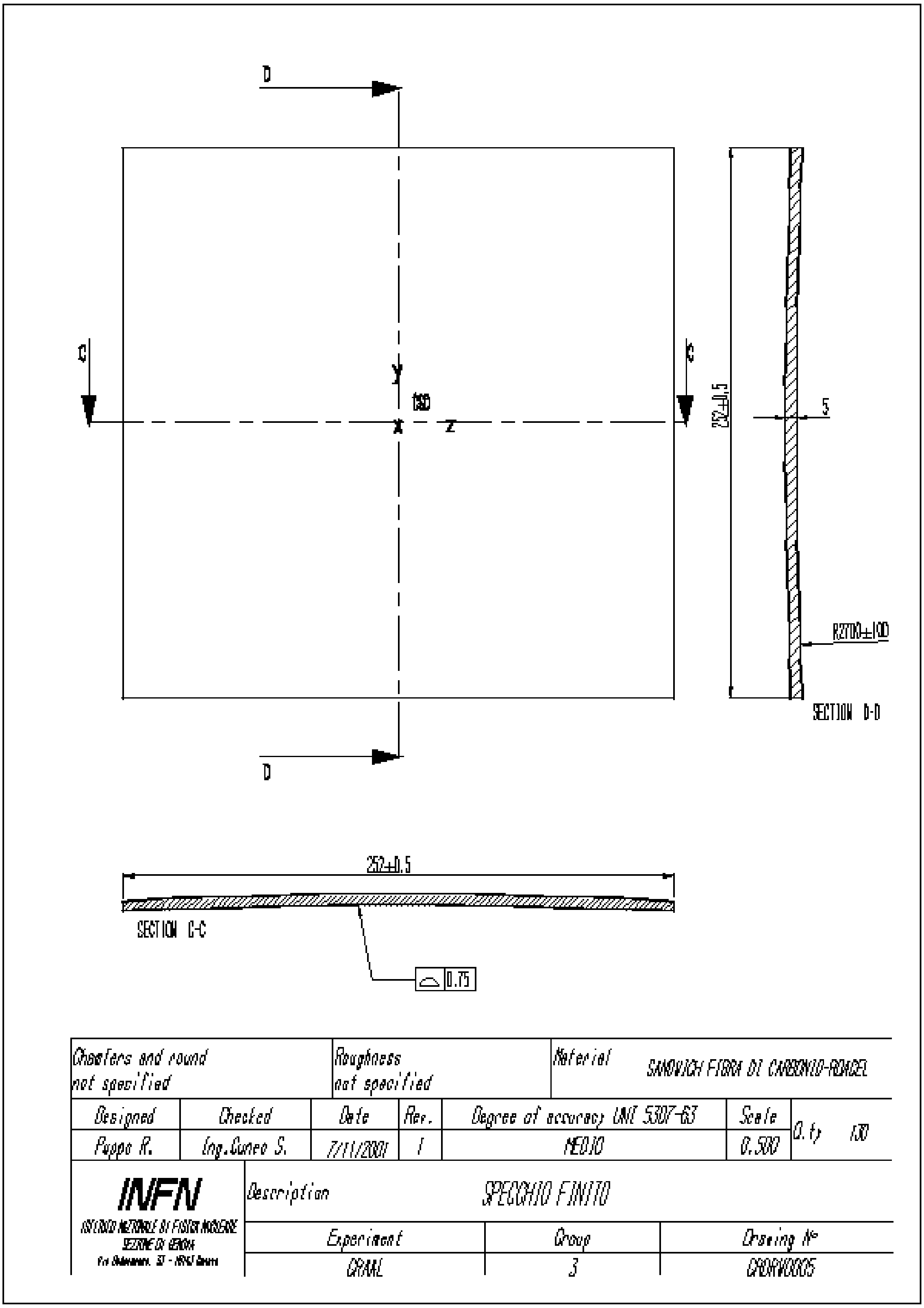

FIG. 1: Mirror assembly executive drawing

FIG. 2: A finished mirror

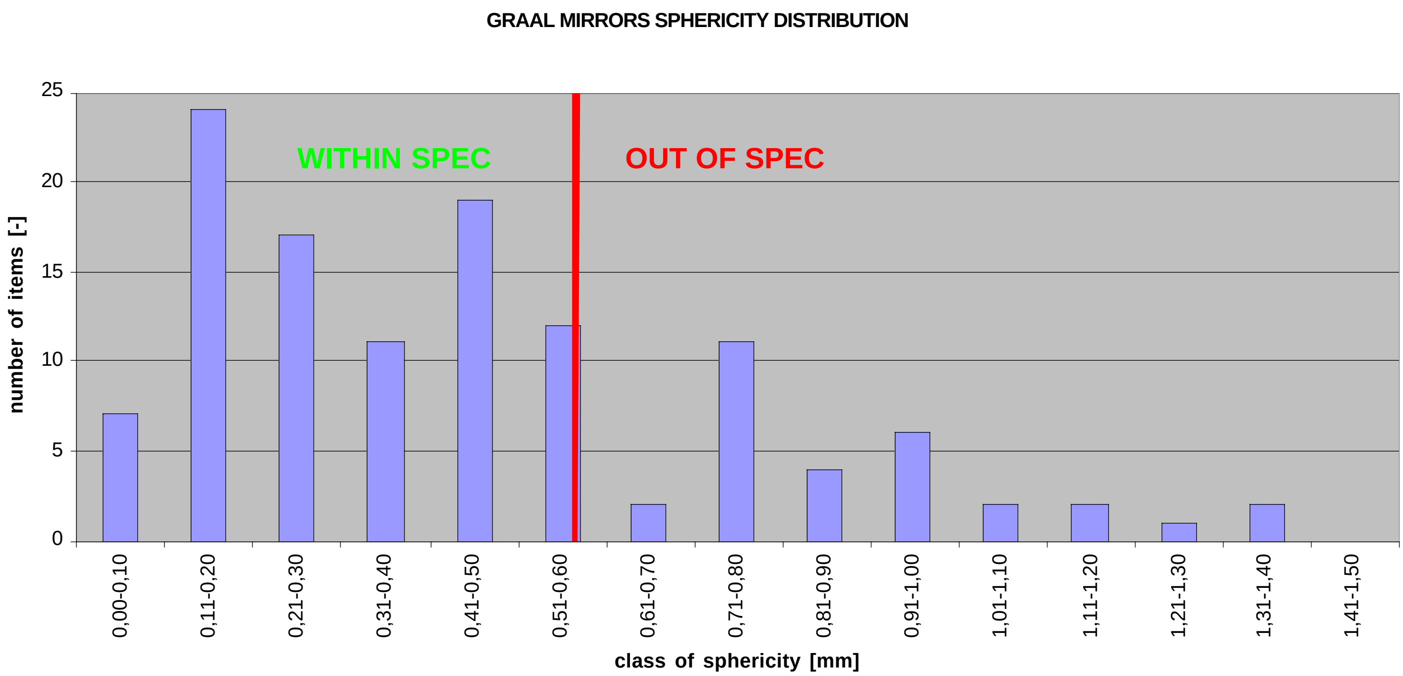

FIG. 3: Mirrors sphericity distribution

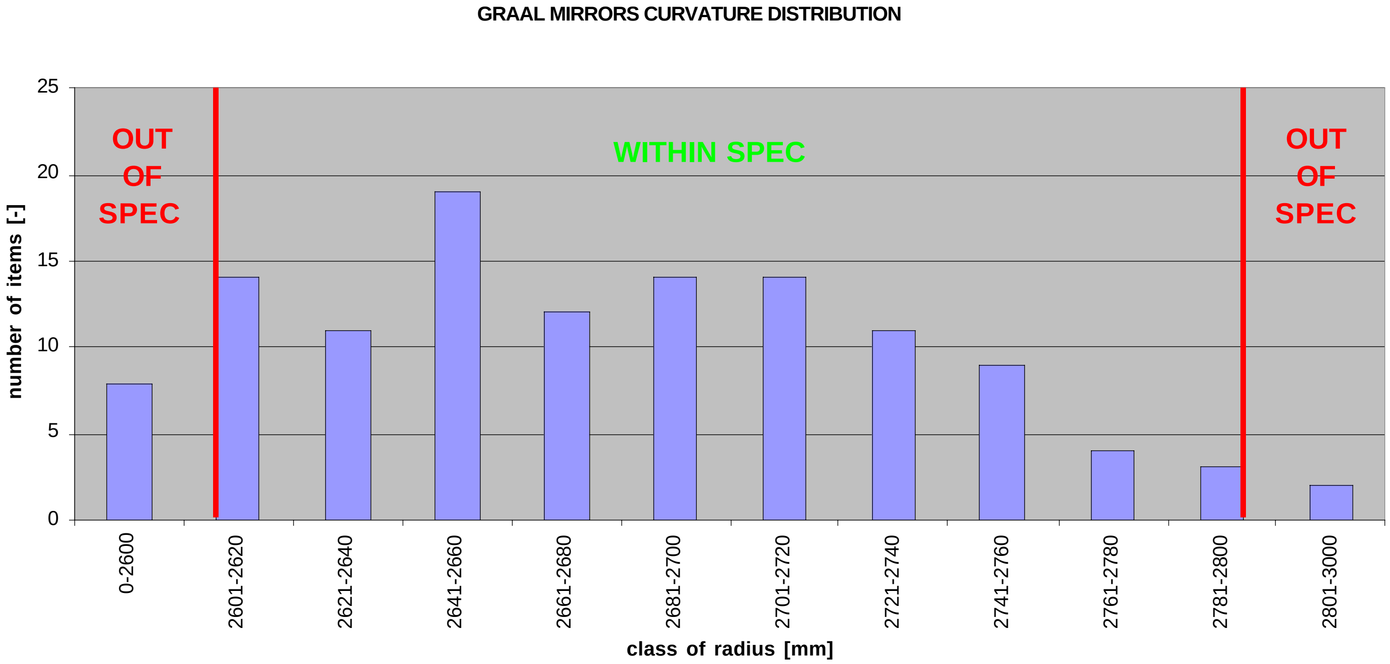

FIG. 4: Mirrors curvature distribution

ANNEX 1: ROHACELL 51Æ 51 Polymethacrylimide (PMI) Rigid Foam Data-Sheet

Subcategory: Composite Core Material; Polymer; Polymethacrylimide; Thermoset

Material Notes:

ROHACELL 51 51 is a low density grade and a very high strength:weight ratio.

General ROHACELL 51 Information: ROHACELL 51 is a closed-cell rigid expanded plastic material for lightweight sandwich construction. It has excellent mechanical properties, high dimensional stability under heat, solvent resistance and, particularly at low temperature, a low thermal conductivity. The strength and moduli values are the highest are the highest for any foamed plastic in its density range. ROHACELL 51 is manufactured by hot forming of methacrylic acid/methacrylonitrile copolymer sheets. During foaming this copolymer is converted to polymethacrylimide.

Physical Properties	**Metric**	**English**	**Comments**
Density	0.0513 g/cc	0.00185 lb/in3	ASTM D 1622-63
Water Absorption	17.4 %	17.4 %	Equilibrium at 98% RH
Moisture Absorption at Equilibrium	1.3 %	1.3 %	15% RH
Moisture Absorption at Equilibrium	2.6 %	2.6 %	30% RH
Moisture Absorption at Equilibrium	4.2 %	4.2 %	50% RH
Moisture Absorption at Equilibrium	5 %	5 %	65% RH
Water Absorption at Saturation	15 %	15 %	Vol %; 50 days immersion at 20ƒC.
Moisture Expansion	Max 2 %	Max 2 %	50 days immersion at 20ƒC.

Mechanical Properties	**Metric**	**English**	**Comments**
Tensile Strength, Ultimate	1.86 MPa	270 psi	ASTM D 638-68
Elongation @ break	4 %	4 %	ASTM D 638-68
Modulus of Elasticity	0.0686 Gpa	9.95 ksi	ASTM D 638-68
Flexural Yield Strength	1.57 MPa	228 psi	ASTM D 790-66
Compressive Yield Strength	0.883 MPa	128 psi	ASTM D 1621-64

Shear Modulus	0.0186 Gpa	2.7 ksi	ASTM C 273-61
Shear Modulus	0.0206 Gpa	2.99 ksi	ASTM D 2236-69
Shear Strength	0.786 MPa	114 psi	ASTM C 273-61

Thermal Properties	**Metric**	**English**	**Comments**
CTE, linear -100ƒC	24 µm/m-ƒC	13.3 µin/in-ƒF	
CTE, linear 20ƒC	33 µm/m-ƒC	18.3 µin/in-ƒF	ASTM D 696-70
Thermal Conductivity	0.029 W/m-K	0.201 BTU-in/hr-ft_-ƒF	ASTM C 177-63
Maximum Service Temperature, Air	180 ƒC	356 ƒF	Dimensional stability per DIN 53424