LONG TERM DEEP SEA EXPOSURE EFFECT ON THE MECHANICAL PROPERTIES OF FILAMENT WOUND COMPOSITES

Astrinos Z. Papadakis[1], George K. Konstantinidis[2] and Nicholas G. Tsouvalis[3]

[1] Shipbuilding Technology Laboratory, School of Naval Architecture and Marine Engineering, National Technical University of Athens, Iroon Polytechniou 9, GR-15780, Zografos, Athens, Greece
Email: astpapad@mail.ntua.gr
[2] Shipbuilding Technology Laboratory, School of Naval Architecture and Marine Engineering, National Technical University of Athens, Iroon Polytechniou 9, GR-15780, Zografos, Athens, Greece
Email: konidis_92@hotmail.com
[3] Shipbuilding Technology Laboratory, School of Naval Architecture and Marine Engineering, National Technical University of Athens, Iroon Polytechniou 9, GR-15780, Zografos, Athens, Greece
Email: tsouv@mail.ntua.gr

Keywords: composite materials, filament winding, housing, underwater, testing

Abstract
Filament wound composite materials are increasingly used in deep sea applications such as pressure housings, underwater pipelines, AUV's, etc. Their long term exposure in deep sea conditions would possibly lead to material properties degradation. For this purpose, several batches of composite filament wound specimens together with two small filament wound CFRP cylindrical housings were exposed to deep sea conditions for several periods of time. After completing the predetermined period of exposure, each batch was lifted and the mechanical properties of the specimens were measured via proper mechanical tests. Additionally, comparison between the results of a dry reference batch and the immersed specimens was made in order to investigate possible material degradation. Regarding housings, strains were continuously measured during their immersion in deep sea, in order to investigate any possible development of creep effects due to the extensive exposure to large hydrostatic pressure. The results for both the specimens and the cylinders showed that in general, the filament wound composite materials are not significantly affected by the deep sea environment conditions.

1. Introduction

Filament winding is a fabrication method for manufacturing common cylindrical structures using fibrous composite materials. Filament wound composite materials are increasingly used in deep sea applications such as pressure housings, AUV's, etc. Specifically, the need for lightweight structures for the exploration of the deepest parts of the oceans, in addition to a need for a long autonomous lifetime, has led to thorough research based on the use of composites for the construction of pressure housings [1-3]. However, their long term exposure in deep sea conditions could possibly lead to material properties degradation and/or creep. Thus, it is important to study the potential effect of the simultaneous action of water and large hydrostatic pressure on their structural response, in order to be able to carry out an adequate structural design.
For this purpose, during the present work, several batches of composite filament wound ring, arc and straight specimens [4] were manufactured, exposed to deep sea conditions for various periods of time and then retrieved and mechanically tested. A reference batch of dry specimens was also initially tested. The examined materials were 12K and 60K carbon fibers and E-glass fibers, all combined with

the same epoxy resin system. In addition to the specimens, two filament wound small CFRP housings were manufactured and deployed together with the above specimens.
The specimens and the housings were deployed in the sea north of Crete Island, Greece, in a depth of about 900 m. All specimens and housings were properly mounted on a metallic frame manufactured by the Hellenic Center for Marine Research (HCMR) (figure 1).

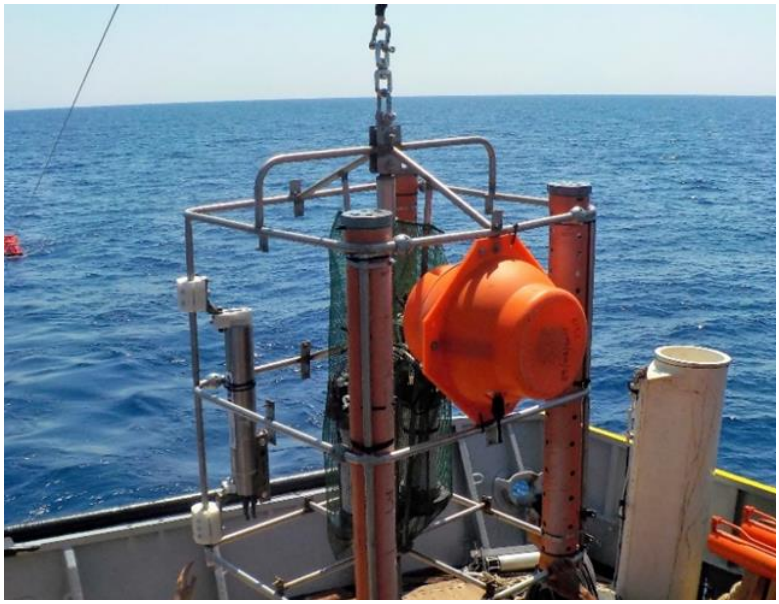

Figure 1. The frame holding the specimens and the cylinders, before its first deployment in the sea.

The magnitudes measured for all specimens were water absorption, Young's modulus and strength in the fiber direction and perpendicular to it and finally shear properties. Regarding the cylindrical housings, their structural response was continuously monitored through strain gages. The frame was lifted approximately every 10 months and one batch was removed for testing, whereas housings' strain data were extracted from the data logger.

2. Specimens and Materials

Three composite materials were selected for the manufacturing of the filament wound specimens. More specifically, two different carbon fiber types were used (12K Torayca T700 and 60K PYROFIL TRH50 60M) and additionally one glass fiber (E-glass 1062 multigene roving). Regardless of the selected reinforcement, in all cases the composite matrix consisted of a common epoxy resin system (Voraforce TW 100 Epoxy Resin, Voraforce TW 150 hardener and Voraforce TC 3000 catalyst).
Regarding the types of the material characterization specimens, four types of specimens were manufactured from each of the three materials investigated; straight specimens for the determination of mechanical properties perpendicular to the fiber direction, straight specimens for the determination of shear properties and arc and ring shaped specimens for the determination of the material properties along the fiber direction. All specimens were manufactured and tested according to previous work of the authors [4]. The specimens were extracted from filament wound cylinders with inner diameter equal to 100 mm and thickness equal to 5 mm. The specimens that were intended to be used for the determination of the material properties parallel and perpendicular to the fibers were cut from a hoop wounded cylinder whereas the ones used for the shear properties determination were cut from a $\pm 55^{o}$ wound cylinder.

In total, three complete batches of specimens were tested during the present work. The first one was kept dry and used as a reference batch, while the two others were deployed in the deep sea where they remained for several periods of time. All batches consisted of 6 specimens of each type. Regarding the deployed batches, 4 out of the 6 specimens were covered with proper gel coat in order to increase their protection against water absorption.
Apart from the specimens, two pressure housings were manufactured and also deployed in the deep sea. Both housings were made of carbon fibers. For the first one, the 12K fibers were used, whereas in the second, the 60K fibers were applied, respectively. The nominal dimensions of the cylinders were identical. Specifically, their length was 350 mm, their inner diameter was 110 mm and their wall thickness was 6 mm. In addition, metallic caps were properly mounted on both ends of the housings in order to ensure sealing. Similarly to the specimens, the housings were protected from sea water exposure through the use of gel coat. Finally, at mid length of the housings' outer surface, several strain gages were applied in order to measure the circumferential strains developed during their immersion in deep sea. Typical views of both the specimens and the housings are presented in the following figures 2 and 3, respectively.

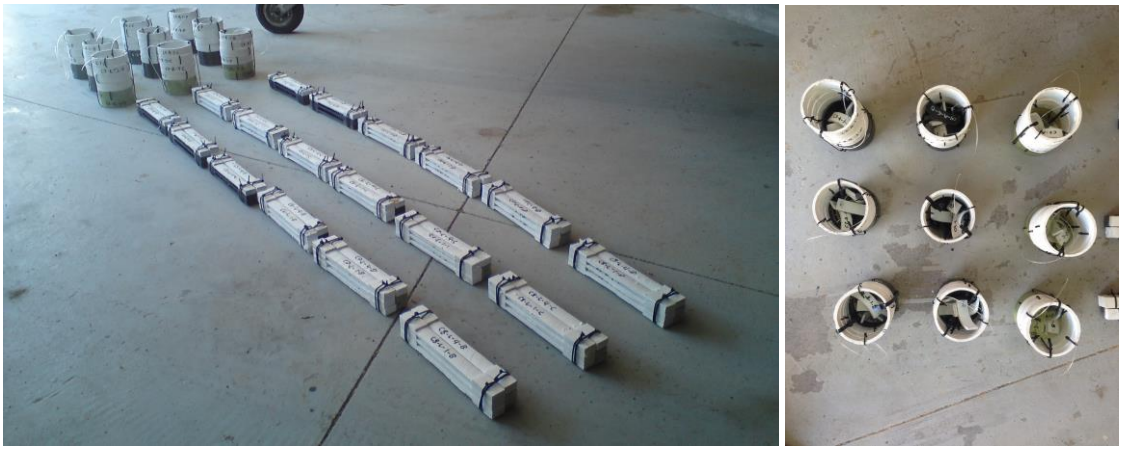

Figure 2. General views of the specimens before their first deployment

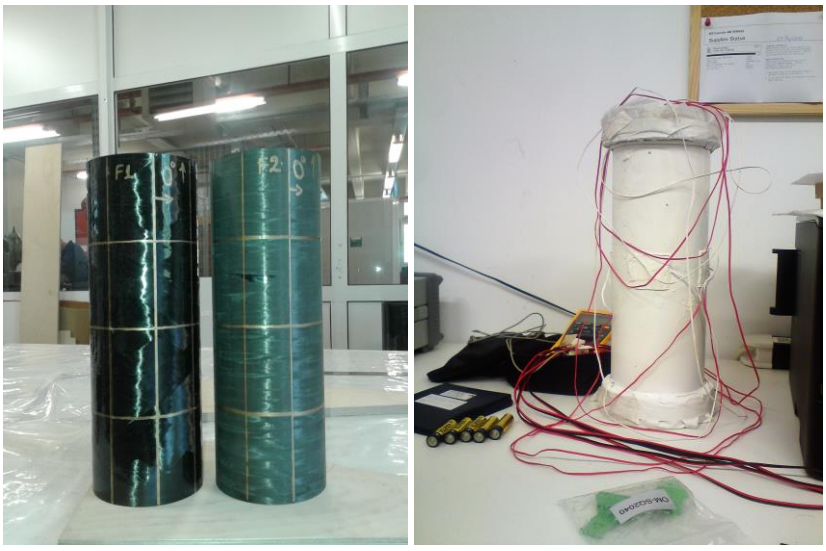

Figure 3. General views of the housings before (left) and after (right) the application of the gel coat

3. Experimental Procedure

The specimens and the housings were mounted on a metallic frame that was specifically built for the purposes of the present work by the Hellenic Center of Marine Research (HCMR). The metallic frame, consecutively, was attached on a stable anchorage which was installed at a research station of the Aegean sea, in the north of Crete island, Greece. The depth at which the metallic frame was deployed was approximately 900 m. Regarding specimens, they were stored in plastic perforated tubes in order to protect them from getting detached from the frame (figure 4).
Concerning housings, in total four strain gages were used on each of them for the measurement of the circumferential strains on their outer surface. All gages were installed in the mid length of the housings. Specifically, one gage was installed on the 12K housing and three gages were installed on the 60K housing, with 90^o circumferential distance between each other. The strains were measured with the use of a data logger that was also deployed together with the housings and was sealed with the use of proper equipment (figure 5). The data were recorded every 6 hours and during each lift they were extracted and processed.
Approximately every 10 months, the frame was lifted and a batch of specimens was collected in order to be tested. Right after their collection, the specimens were externally dried and weighed. The same procedure had also taken place before their initial deployment so as to provide comparable results in order to investigate the possible water absorption during their exposure to the deep sea conditions.
Regarding material characterization tests, they were carried out at the facilities of the Shipbuilding Technology Laboratory of the School of Naval Architecture and Marine Engineering of the National Technical University of Athens, with the use of a hydraulic testing machine. The followed procedure was proposed and described in previous work published by the authors [4, 5].
As far as the measured magnitudes are concerned, strength and Young's modulus in the fiber direction were obtained by both a 3 point bending test of the arc shaped specimens, and by a split-disk tensile test of the ring specimens [6]. Regarding properties in the direction perpendicular to the fibers, the corresponding strength and Young's modulus were determined via tensile tests applied to the respective straight specimens. Finally, shear properties were also extracted with the application of tensile tests to the ±55^o wound specimens.

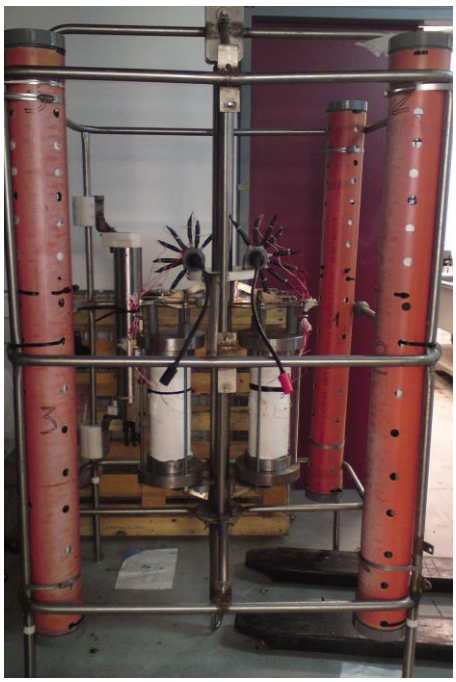

Figure 4. The metaling frame with the plastic tubes used for the storage of the specimens

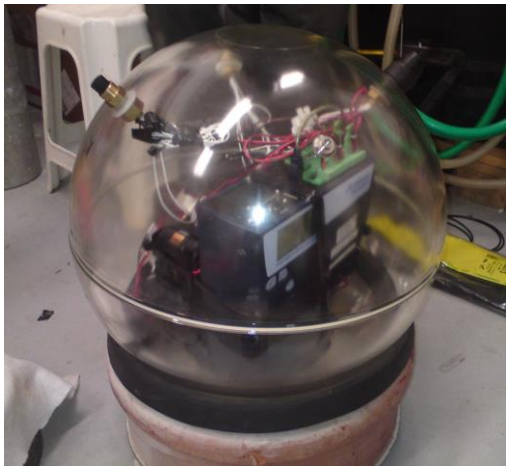

Figure 5. Data acquisition system protected inside a sealing sphere

4. Results

The weighing of the specimens after both the first and the second lift and the comparison of the results with the ones obtained before the initial immersion in the sea indicated that there was no clear indication of water absorption in any type of specimens. More specifically, not only the gel coat protected specimens but also the "unprotected" ones had almost exactly the same weight before and after their long time exposure to the wet environment. Indicatively, the maximum weight increase that was observed was 1.5 % in one GFRP specimen, however this behaviour showed no repeatability and as a result, was considered to be random.
Regarding material characterization tests, the results are presented in the following tables 1-4 for batch A (dry reference batch), batch B (10 months exposure) and batch C (20 months exposure). Average values are presented in these tables, whereas repeatability was in most cases within acceptable limits.

Table 1. Ring specimens results (properties in fiber direction)

Specimens Batch	E_1 (GPa)		
	12K	*60K*	*Glass*
A	179.04	150.34	55.07
B	180.94	155.98	53.50
C	174.83	146.57	50.63

Table 2. Arc shaped specimens results (properties in fiber direction)

Specimens Batch	E_1 (GPa)			σ_{max} (MPa)		
	12K	*60K*	*Glass*	*12K*	*60K*	*Glass*
A	131.17	112.23	49.55	1060.93	872.68	1066.05
B	162.22	138.58	62.69	1266.04	1108.64	1283.94
C	143.30	120.70	43.71	1170.97	971.57	1011.44

Table 3. Straight specimens results (properties perpendicular to the fiber direction)

Specimens Batch	E_2 (GPa)			σ_{max} (MPa)		
	12K	*60K*	*Glass*	*12K*	*60K*	*Glass*
A	10.86	7.87	17.68	26.08	21.08	44.17
B	11.11	7.86	16.76	22.82	18.67	54.93
C	11.39	-	16.73	24.08	-	46.85

Table 4. Straight specimens results (shear properties)

Specimens Batch	G_{12} (GPa)			τ_{max} (MPa)		
	12K	*60K*	*Glass*	*12K*	*60K*	*Glass*
A	4.61	5.02	4.61	9.23	7.87	9.88
B	4.38	4.18	4.15	8.46	7.72	9.30
C	4.14	3.99	3.82	7.49	7.68	8.98

Finally, in figures 6 and 7, the readings obtained by the strain measurements during the housings' stay in the deep sea are presented. Specifically, figure 6 presents strain measurements during the first period of exposure, whereas figure 7 presents the respective results of the second period.

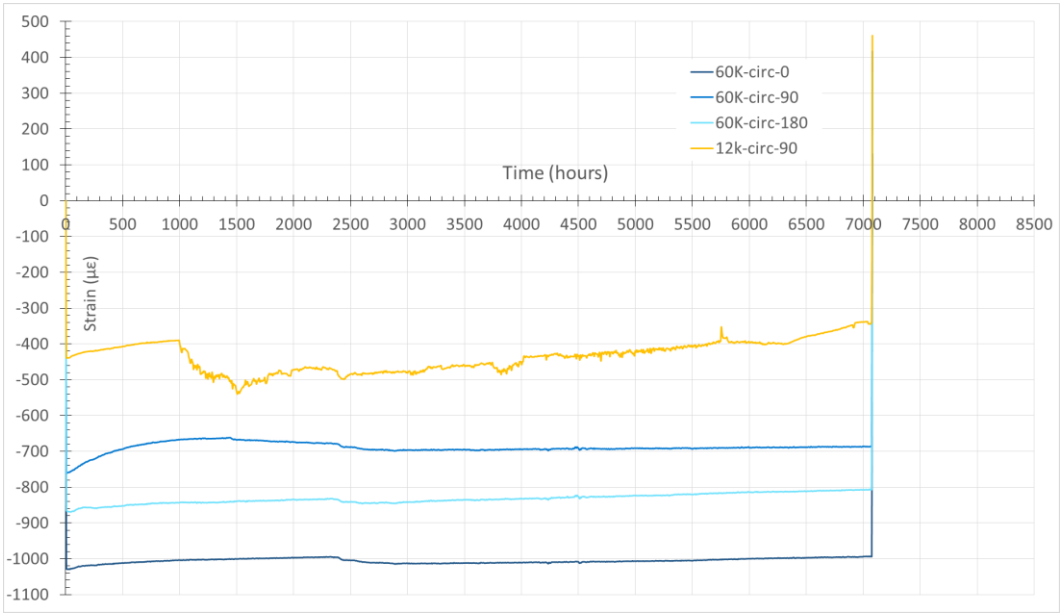

Figure 6. Circumferential strains during the first period of deep sea exposure

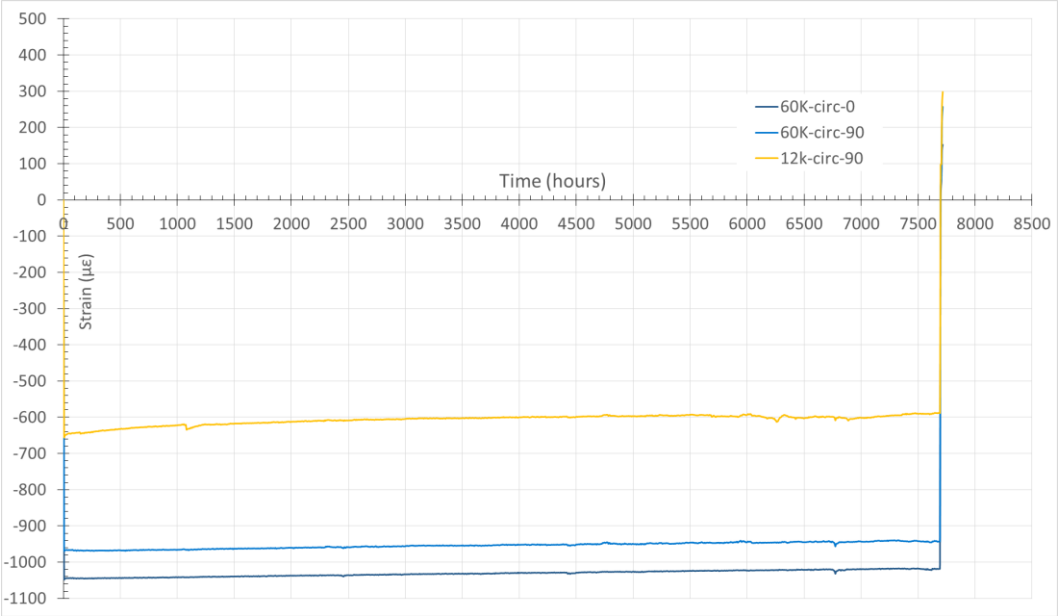

Figure 7. Circumferential strains during the second period of deep sea exposure

5. Conclusions

The weight measurements of the specimens before and after their immersion in the sea and their exposure to deep sea environment conditions provided strong proof that carbon fiber and glass fiber filament wound composite materials do not suffer from water absorption, regardless of the simultaneous effect of water and large hydrostatic pressure. The use of sealing gel coat was also proved to have no significant effect.

Regarding material properties, the results that have been extracted do not in general provide information that indicate any degradation of the materials due to their exposure in deep sea. Specifically, as far as the ring specimens results are concerned (Table 1), a consistent behaviour is exhibited among the three batches, for all materials. The fact that the 60K carbon fibers exhibit slightly lower values compared to the 12K ones, is in perfect compliance with previous work of the authors [4]. However, it should be pointed out that the coefficient of variation regarding batches B and C of the 60K carbon and the glass fibers was 10%-15%, a fact that emphasizes the significant dispersion of the results in this kind of tests. Concerning the results of Table 2, a significant increase (almost 20%) is presented between batches A and B, followed by a decrease of approximately 10-15%. This behaviour is consistent in all materials and for both the Young's modulus and the strength. However, it is not an indication of degradation of properties and needs to be studied more thoroughly in order to arrive to reliable conclusions. Furthermore, Table 3 which provides information regarding matrix dominated properties, presents a constant behaviour among the batches. In this case, the difference between the results among the various materials is due to manufacturing reasons and is not at all associated with any affection of the sea environment on the materials. The results about strength exhibit values of coefficient of variation higher than 10%, indicating the usual dispersion when measuring strength. Finally, the shear properties presented in Table 4 exhibit a continuous decrease between the consecutive batches for both shear modulus and shear strength. The percentage of change varies from 2% to 15%, however, the fact that this behaviour is consistent could be used as the only indication that shear properties are possibly slightly affected by the exposure in the deep sea environment.

Concerning the pressure housings response, figures 6 and 7 show that, in general, the strain level measured from all sensors remained almost stable during the whole period of exposure in the sea and in both immersion periods. More specifically, figure 6 indicates that the three sensors installed on the 60K carbon fiber housing measured strains from 700-1000 με, depending on the position on the

housing. On the other side, the sensor used for the 12K housing measured strains between 400 and 500 με. The noise observed in this last sensor doesn't exhibit a specific trend and cannot be explained by the other results, however, it is not attributed to a housing's failure. In addition, it is observed that the general strain level of the 60K cylinder is higher than the respective level of the 12K. This fact can be explained by the real thickness of the housings. Specifically, in the case of the 60K one, thickness was measured equal to 5 mm in contrast to the 6 mm respective dimension of the 12K housing. As far as the second period of exposure is concerned (figure 7), the constant strain level recorded by all sensors is again presented. In this case, the strains in the 60K housing were measured by two sensors since a failure occurred in the third one. The aforementioned general observations exclude the possibility of the development of creep effects, depicting that the studied filament wound composite structures are extremely resistant to deep sea environment conditions and thus, highly recommended for several underwater applications.

Acknowledgments

The authors sincerely thank HCMR for providing equipment and carrying out the deployment and lifting operations and B&T Composites for providing all specimens tested.

References

[1] Graham, D. Composite pressure hulls for deep ocean submersibles. *Composite Structures* 32(1-4): 331-343, 2015.

[2] Tsouvalis, N., Chauchot, P., Livingstone, F., Papazoglou, V., van Tooren-Antonelli, V. and Williams, J. Structural design of deep water composite pressure housings – material selection and modeling guidelines, *Proceedings of the 8th International Marine Design Conference, Athens, IMDC'03*, 2003

[3] Ross, C. A conceptual design of an underwater vehicle. *Ocean Engineering* 33(16): 2087–2104, 2006

[4] Papadakis, A.Z. & Tsouvalis, N.G. Use of Different Geometries Specimens for the Material Characterization of CFRP Filament Wound Cylinders. *17th International Conference of Experimental Mechanics, Rhodes, Greece*, July 2016.

[5] Papadakis, A., Themelakis, J., Tsouvalis, N. The effect of geometric and manufacturing parameters on filament wound composites split disk test results, *Proceedings of the 17th International Congress of the International Maritime Association of the Mediterranean (IMAM 2017), Lisbon, Portugal*, October 2017

[6] Kinna, M.A. NOL Ring Test Methods. Naval Ordnance Lab., White Oak, Md, 1964