Hyper-Kamiokande interior component design: structural simulation and materials proposal for Cherenkov radiation sensor support[a)]

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This article addresses the engineering challenges of the Hyper-Kamiokande project in collaboration of the Mexican team, focusing on the design of the **sensor mount** capable of withstanding operational conditions, using a 3D printable material, and capable of lasting 20 years. The study emphasizes in achieving a design with the least amount of deformation to maintain the efficiency of the photo-multiplier tubes (PMTs). This article reports the procedure to reach the proposed solution, the limitations the team faced, and next steps.

Keywords: Hyper-Kamiokande, Sensor Mount, Pressure resistance, photo-multiplier tubes (PMTs)

I. INTRODUCTION

Since it's proposal in 1982 at the University of Tokyo, the Kamiokande project has given a lot to talk about in the scientific community.
The Kamiokande is named after the Kamioka laboratory and the Nucleon Decay Experiment (NDE) - KamiokaNDE. Its principal objective began to study proton decay and space neutrinos, in order to study supernovas and their relation to black holes. The second iteration of this project, called Super-Kamiokande (S-K), started in 1991 and its construction was complete in 1996. The current iteration, now under construction, the Hyper-Kamiokande, has been of great help to the scientific development. Scientists that have worked on the project have received now 2 Physics Nobel Prizes (2002 and 2015), and it is expected to receive one after its completion in 2027.

A. Neutrino Detection: How does it work?

The H-K, uses arrays of multiple photo-multiplier tubes (mPMTs) to detect light emitted when a neutrino interacts with matter, creating a electrical signal that is sent for processing. Every mPMT has 19 PMTs and is contained in a compact 50 cm wide structure with an acrylic dome at the top, and plastic walls in the shape of a cylinder.

B. Mechanical

Inside every mPMT there is a structural support for the PMTs that provides not only fitting them, but also provides integrity against deformation of the interior components.
In operational conditions, these supports must withstand the weight from all the water

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surrounding the detector, but is not directly in contact with the water, that is the purpose of the acrylic dome.

II. THEORETICAL BACKGROUND

A. Neutrino Detection

Neutrinos are subatomic particles that belong to the group of leptons. In 1931, Wolfgang Pauli was the first physicist to theorize them in order to explain energy conservation during beta decay, a type of nuclear decay. These particles have neutral charge and a very small mass, although not negligible.

Neutrinos, due to their intrinsic properties, rarely interact with matter, which enables them to travel long distances without being bothered. In addition, since they are neutral particles, they are able to pass through electromagnetic fields without being deflected. Moreover, neutrinos have spin 1/2, meaning that they are fermions and follow the Pauli exclusion principle, which rejects the possibility of occupying the same quantum state.

In particle physics, neutrinos are interesting cases because they can escape extremely dense objects, such as star nuclei, thus possessing information about astrophysical phenomena and providing insights into fusion of the sun, supernovae and black holes. Detecting them has been a big challenge for physicists due to their low interaction with matter, although new technology has enable scientists to detect and study them in recent years.

B. Proton Decay

Proton decay is a theorized form of decay into subatomic particles. Physicists have predicted this phenomena through the *grand unified theories* (GUT). Despite developing several experiments to detect it, proton decay has never been observed. The most recent estimates suggest that proton lifetime is about 10^{34} years[1].

C. How does the H-K work?

H-K has the main objective of studying fundamental particles through photon emission, which will be detected by the PMTs. This devices are highly sensitive as they are able to detect a single photon, thus darkness inside the tank is essential for good performance.

H-K will be located several hundred meters below the surface to avoid undesired radiation and interactions with other particles. The S-K found neutrino oscillations, which demonstrate that neutrinos have mass[2].

The main container has a height of 71m and it will be filled with highly purified water, thus avoiding possible interactions detected by anything but neutrino. Structures containing the sensor mount and PMTs will be located on the walls, top, and bottom of the tank, where electromagnetic radiation will be detected[2].

D. Sensor mount materials

Simulations and mount analysis are subject to the requirements established, including using 3D printable, lightweight, low-cost, and sustainable materials. In addition, their mechanical properties must suit the environment in which they will be located[3].

According our preliminary research, the set of potential materials complying the requirements was reduced to the following list:

- PLA and/or some PLA+ variation.

- PETG.
- Nylon.
- Polycarbonate.
- Polyethylene resin.
- Melamine resin

PETG was taken into consideration due to its heat resistance for 3D printing (up to 70 °C), ease and practicality such as PLA, and good thermo-mechanical resistance. Compared to PLA, it is more flexible and durable. Although it is more resistant than PLA, it is not recommended to manufacture for support structures since it cannot withstand heavy weights and pressure. Moreover, PETG is a highly water absorbent material, for which it is recommended to locate it in fresh and dry environments. Since the sensor mount will be exposed to a semi-liquid optical medium, PETG will not be a good candidate for the study[4].

PLA and PLA+ variations are one of the best materials for 3D printing and currently they are the most used due to their low density. However, PLA tends to bend and break because it is highly sensitive to heavyweight and high pressure conditions, as well as to temperatures above 60 °C[4].

On the other hand, nylon is an outstanding material in terms of hardness, flexibility, and resistance, thus a good recommendation for 3D printing prototypes. Despite these advantages, it is as water absorbent as PETG, which might cause material deterioration, deformation and, therefore, loss of detection efficiency[4].

In the North American market up to September 2023, the average cost of nylon was of 4.56 USD/kg, according to *CHEMANALYST* (a real-time software of chemicals and petrochemicals price analysis). Simulations indicate that for 3D printing the sensor mount at 30% scale 13 g of nylon resin are required. Therefore, the estimated total cost for printing with this material at the original size is of 0.20 USD[5].

Similar to nylon, up to June 2023, the average cost of resins was of 100-500 USD/kg for professional and/or industrial, according to *ALL3DP* (specialized site in information and quotation of 3D printable materials). For practical and simplification purposes, the price of resins is of 50 USD/kg. In this study, printing resins is not feasible due to its high price and limited access to 3D printers[6].

Another interesting material is polycarbonate, which excels in terms of hardness and durability among the candidates[4]. The latter property mentioned being of great value to the project, since it complies with the requirement of life expectancy. Polycarbonate is characterized by highly flexibility, though less than nylon resin, which enhances its manipulation, and resistance to humidity[7].

E. Optical medium

Inside the acrylic dome, between the sensor mount, space will be occupied by an optical medium. This medium, SilGel, is synthesized by Isomex, and its properties are listed in the data sheet.
The main component of SilGel is low-hardness and translucent silicone, which enables it to be compressible. This characterized must be taken into consideration while simulating stresses on the sensor mount due to the pressure it will exert on it.

For the real experiment, a compound of two derivatives of SilGel will be used to occupy free space and enable solidification of the substance. Those derivatives are labeled as SilGel 612 A and SilGel 612 B, and the amounts used will be 20 kg and 20 kg respectively.

Risk factors of using this material must be analyzed in order to develop strategies to prevent loss of detection efficiency and/or issues with equipment. The main risk of occupying free space with it is that in case of leakage and in combination with water, it can be a hydrogen emitter, which is highly flammable. In addition, SilGel is a substance that is harmful for humans in case of contact. Thus, complete and detailed protocols must be planned to prevent human and equipment damages[8].

F. Evaluation of sources

The primary source for our project were the meetings with Dr. Cuen, being the link between the university and the H-K project in Japan, Canada, and Italy. The purpose of these meetings was to clarify doubts, verify the course of the project, and receive feedback of our progress and our plans later on for the project.

The secondary sources for the project were scientific articles, master's thesis, material's technical pages and data sheets, and pages related to the Hyper-Kamiokande project. To have certain facts for the project, the information recovered was compared to other sites/material to verify the veracity of these facts.

III. TARGET PROBLEM DEFINITION

Using computational simulations, we will put to test the geometry of the using different materials and methods.
The `STP` file of the mPMT mount alone provided by Dr. Cuen will be used. For this we first need to separate such piece from the entire assembly inside the program, in this case, `Solidworks`.
The project stages are planned to analyze the durability and correct assembly of the pieces taking into consideration the material and its possible deformation to optimize photon detection and structural stability. It is also considered that this design will be mass produced and should ensure quality. We will set simulated durability tests to study the effect of hydrostatic pressure over the dome and the mPMT mount, which will be submerged 71 meters underwater.
Finally, a sustainability analysis using the CML method (from `Solidworks`), where we analyze the carbon footprint, total consumed energy, air acidification, and water eutrophication of the purposed material.

IV. METHODOLOGY, IMPLEMENTATION AND EVALUATION OF ALTERNATE SOLUTIONS

A. Methodology

1. Functionality

The requirements for of the solution is that it has to be 3D printable in a durable material, enough to withstand the conditions for 20 years underwater, as well as the next points:

- High pressure. Given that the detector is consists of a cylindrical tank filled with high pure water with dimensions of 68 m of diameter and 71 m of height, the highest pressure 706 110 Pa on the bottom of the container. The selected materials should be ready to withstand such conditions.

- Price. As it is intended to mass produce, select materials with low price market must be used without reducing the quality. It is intended to try different 3D printable materials testing its durability.

2. Additive manufacturing

We performed a research on commercial 3D printable materials looking for availability and affordability, to then make a comparison on the stress and durability tests.
The tested materials are polyethylene terephthalate (PET); polyamide 6 (PA); acrylonitrile butadiene styren (ABS); nylon; poliester resin; melamine resin, each one with distinct properties (table Our principal interest here is in the Young coefficient, Poisson coefficient, cutting modulus, density, compression modulus and elastic limit.

3. Use of project management techniques from PMI

The proposal of the PMTs mounting is though to be standardized internationally, which is why this design is to be optimized to be implemented and approved in the Hyper-Kamiokande. For this project we count with the sensor drawing file, the constitutive act, requisite documentation and theoretical background. For this project, we planned five stages:

- Project planning. For this stage we aim to evaluate the resource effectiveness and minimize project risk.
- Design proposal. For this we aim to evaluate the geometry for later material selection (it is already selected by the project)
- Material selection. We will assess finite volume force and pressure simulations, as well as rupture (Young modulus), to ensure the resistance under water for 20 years.
- Computer simulation. Obtain results using finite body simulations, as well as posterior evaluations such as the sustainability and studies for printing.
- Result documentation. Interpret and communicate effectively the results using graphs, images and data.

Some of the identified risks for getting into the results of this project are the lack of software resources, supervisor availability, time overestimation for computer simulations, and changes in internal and external expectations. Some of the actions to mitigate such risks involve sessions with the project supervisor, as well as sessions with software experts.

B. Implementation

1. Preliminary simulations

a. ***Pressure Analysis.*** Inside the cylinder, the mPMTs will be subject to the hydrostatic pressure of water; however, this pressure exerted will not be of the same magnitude throughout the piece but depends on its geometry. With the help of `MATLAB` software, a numerical solution was given to the height-dependent equation (z axis) in the range of 0 to 500 mm (x & y axes) corresponding to the dimension of the piece, and the results were graphed.

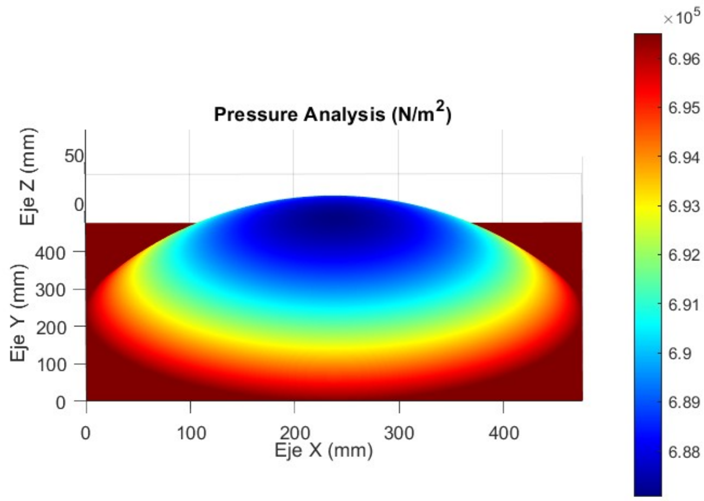

FIG. 1. Hydrostatic pressure exerted as a function of the depth given by the geometry of the piece.

The maximum pressure will be present at the bottom of the arrangement, equivalent to 700 kPa exerted directly on the steel structure of the cylinder and the lowest points of the piece. On the other hand, the part where the least pressure is exerted is at the highest points of the crest 10 cm from the steel, with a maximum difference of 10 kPa, which is less than 1.5%.

b. ***Deformation analysis for the acrylic dome.*** With the help of `Solidworks` software, a stress simulation was developed orthogonal to the hemispherical surface of the 8 mm thick dome, applying a uniform force in the negative z axis on the area of the contact surface.

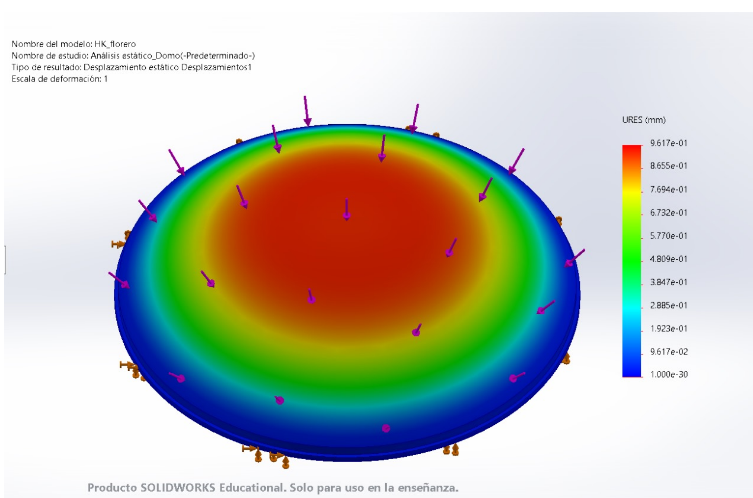

FIG. 2. Simulation of deformation of acrylic dome subjected to hydrostatic pressure.

The maximum deformation corresponds at the red zone with a displacement of one millimeter. The highest tolerance acceptance is 2 mm in this case.

c. ***Deformation analysis for the mPMT support.*** The same process as the previous analysis was carried out, however, in this case 6 simulations were run, one for each material investigated in the additive manufacturing section (IV A 2).

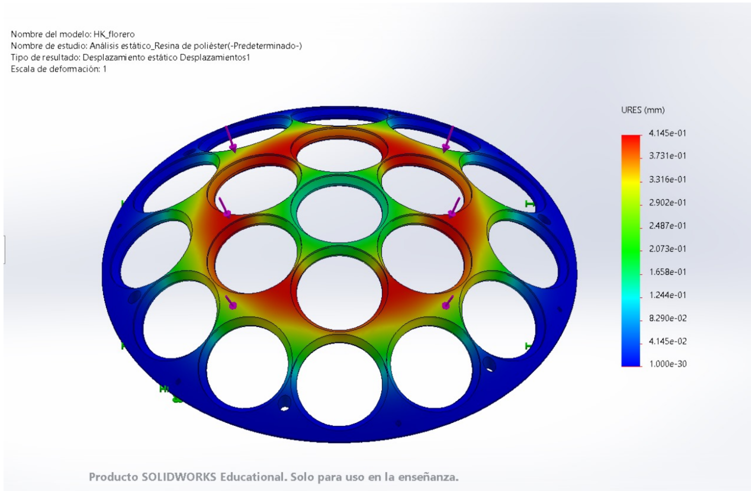

FIG. 3. mPMT support stress simulation (using poliester resin).

V. JUSTIFICATION AND IMPACT ON ENGINEERING: RESULTS, FUTURE RECOMMENDATIONS AND CONCLUSIONS

Using design thinking methodologies, we pretend to expand the knowledge around the material use possibilities for this piece of the experiment, by providing better mechanical properties, longer duration, and with this ensure a better sensibility to the Cherenkov radiation by the sensors.

The impact on engineering of this study for this experiment is to better the understanding of Cherenkov radiation, which is hypothesised to be beneficial for future communications technology, as well as providing more information on neutrino properties. But in the present this will be beneficial to the team of scientist building the H-K.

The H-K experiment will be beneficial to the scientific community by encouraging better understanding of the standard particle model as well as of the universe.

A. Results

1. Deformation analysis from pressure simulations

The previous simulations from figure 3 were conducted on the six proposed materials. From this the obtained results are seen in Table V A 1.

Material	Maximum deformation (mm)
Polyethylene Terephthalate (PET)	2.50356
Polyamide (PA)	2.84274
Acrylonitrile Butadiene Stirene (ABS)	3.06468
Nylon resin	0.906371
Polyester resin	0.414522
Melamine resin	10.3767

TABLE I. Maximum displacement in full mPMT mount geometry simulated with 6 different materials.

From such results we obtain that nylon and polyester resin offer the best results, for cost purposes PA, ABS and PET are in second category and Melamine resin is not usable for this purpose given the high deformation.

2. Young Modulus analysis

After analyzing the maximum displacement, we now study the Young Modulus to determine the rupture point of the surface, which are seen in figures 4 and 5.

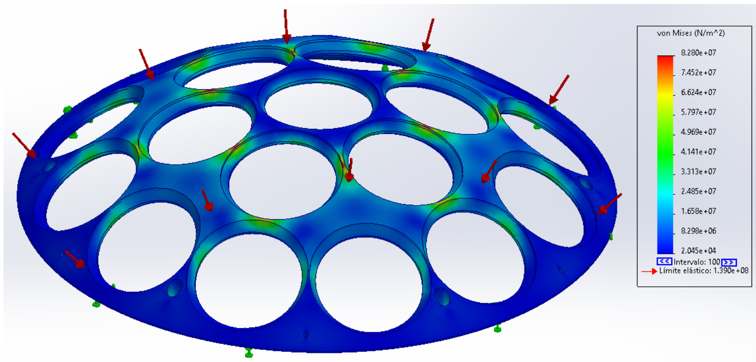

FIG. 4. Young modulus analysis of nylon mPMT mount.

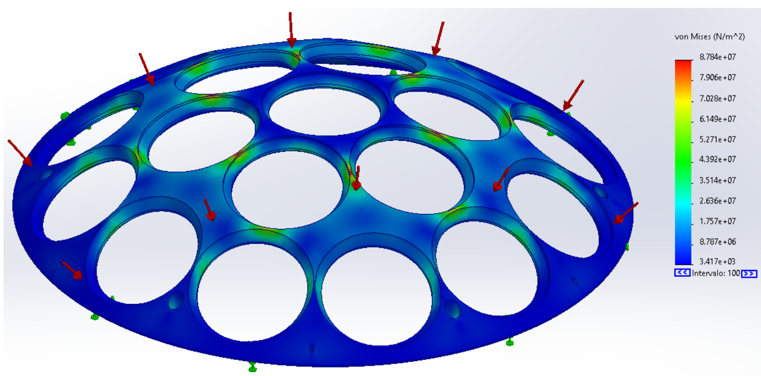

FIG. 5. Young modulus analysis of polyester resin mPMT mount.

As observed in figures 4 and 5, we know that both materials will resist the required pressure and rupture conditions.

B. Future recommendations

As we move forward with the Hyper-Kamiokande project, we are examining opportunities areas for future work and research to enhance results in refining the sensor mounts material to minimize deformations and optimizing the PMTs efficiency. Explore different laboratories capable of 3D printing the sensor mount in real life size with tests of the material proposed. Collaborating with expert researchers and professors to ensure environmental conscious results for the project with low carbon emissions. This efforts seeks to justify the final proposition and to pursuit the best optimal solution for the Hyper-Kamiokande Project.

1. Continuous project 1: Ray tracing

For future analysis it was built an optic simulation with the help of the Light Simulation tool in `ANSYS`. This simulation consists in 10 000 rays emerging from an outside source

pointing directly on the sensor mount. This simulation is made to compare and study the intensity flow of the light arrays through the sensor amount holes where the PMTs should be placed. During this simulation it should compare the base sensor mount, without any deformation, and the two materials chosen, nylon resin and polyester resin.
The point of this simulation is to find if the deformation affects the effectiveness of the sensors and analyze the interaction between the rays and the sensor mount. The purpose of this simulation is to find the most effective material with least possible deformation and has the capability to withstand the pressure and weight applied without breaking.
One of the setbacks of this simulation is the university license for ANSYS, since one of the many requirements that this simulation has is to have a heavy meshing capability to run it. The university license has a very limited amount of meshing capability.

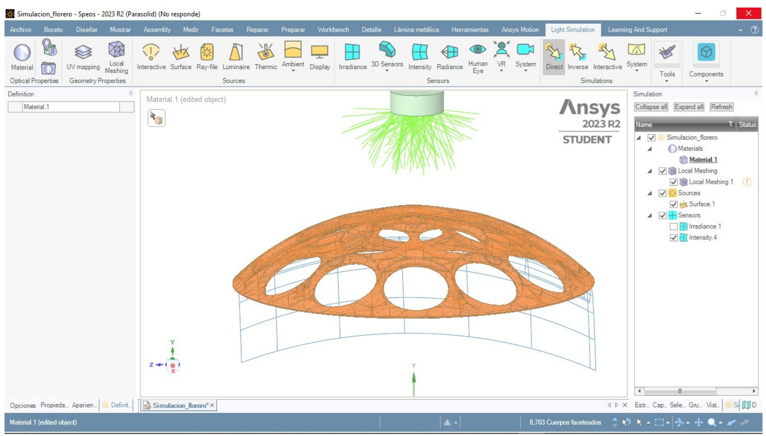

FIG. 6. First attempt to run a simulation on Ansys Speos

2. Continuous project 2: Sustainability analysis

Using CML methodology in the sustainability package in Solidworks we evaluated the sustainability report for the manufacturing and transport of an individual piece of nylon resin and polyester resin.
The parameters used for the study include: 900 km of maximum transport with terrestrial vehicles, 20 years duration, 20 years of use and this being a fully recyclable piece.

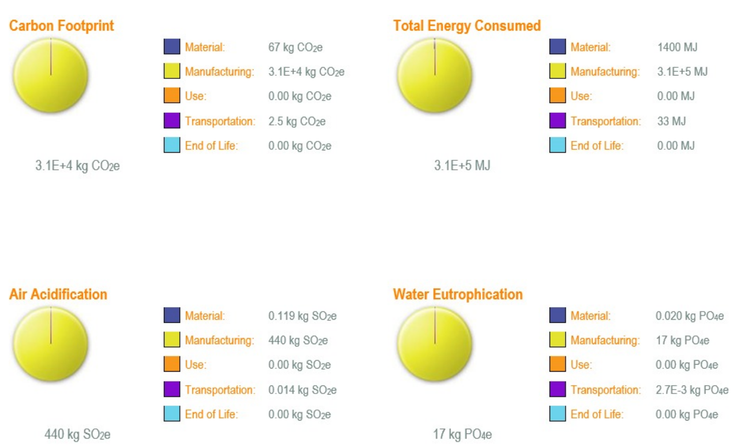

FIG. 7. Sustainability analysis of mPMT mount of polyester resin.

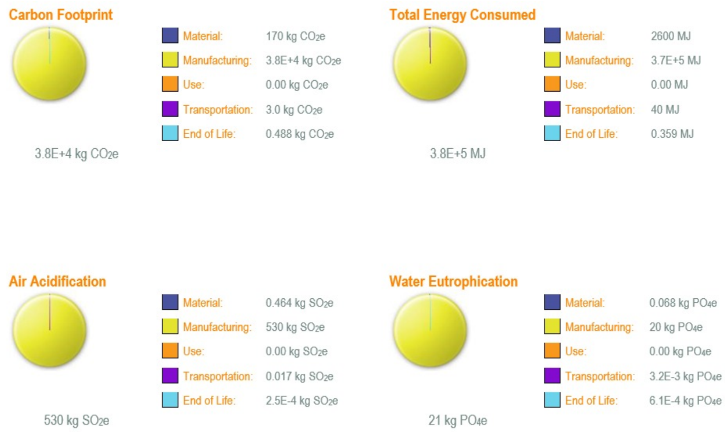

FIG. 8. Sustainability analysis of mPMT mount of nylon.

From figure 7 and 8 we observe that the carbon footprint of the polyester resin made PMTs mount is 18% smaller than the one made out of nylon resin, and the same for energy consumption. In both cases for both materials the majority of the percentage is because of manufacturing, and in second place the transportation.

3. Continuous project 3: 3D printing of full piece

For demonstrative purposes, we 3D printed in ABS in a 0.25 scale, 12.5 cm diameter, the mPMT mount (check figure 9). Most of the used material went into the production of the required supports to then 3D print the usable piece. A possible continuous research project arises as programming a 3D printer to print over an already made support for then printing the usable piece.

The price of our 3D printed piece is not valid for anything other than demonstrative purposes.

FIG. 9. 3D printed in ABS mPMT support.

C. Conclusions

After careful research, project planning and several computer simulations to achieve the completion of the ETM, we obtained results of the two best materials to use for the Hyper-Kamiokande project: poliester resin & nylon.

This after working with the prototypes in stress, pressure and rupture computer simulations. With this we were able to find the maximum movement of the original geometry, to find on both materials in the PMT mount to be less than 1 mm which is part of the project requirements. This materials also work with the 3D printable and accessible materials requirements.

Some of the substages such as the ray tracing simulations were not completed because of the software licence availability, because of the number of triangles required by the simulations being 8 times greater than the permitted by the student licence. The other one is the 3D printing of the full mPMT mount, because of the resource availability of the size and materials in the university (so we printed a 0.25 scale and in ABS instead of polyester resin or nylon resin), the available scale print took 12 hours to complete, so further time evaluation of the full size mounts is required.

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[1] A. Takenaka, K. Abe, C. Bronner, Y. Hayato, M. Ikeda, S. Imaizumi, H. Ito, J. Kameda, Y. Kataoka, Y. Kato, Y. Kishimoto, L. Marti, M. Miura, S. Moriyama, T. Mochizuki, Y. Nagao, M. Nakahata,

Y. Nakajima, S. Nakayama, T. Okada, K. Okamoto, A. Orii, G. Pronost, H. Sekiya, M. Shiozawa, Y. Sonoda, Y. Suzuki, A. Takeda, Y. Takemoto, H. Tanaka, T. Yano, R. Akutsu, S. Han, T. Kajita, K. Okumura, T. Tashiro, and ..., "Search for proton decay via $p \rightarrow e + \pi 0$ and $p \rightarrow \mu + \pi 0$ with an enlarged fiducial volume in super-kamiokande i-iv," Physical Review D **102**, 112011 (2020).

[2]K. e. a. Abe, "Hyper-kamiokande design report. url = https://arxiv.org/pdf/1805.04163.pdf," arxiv (2018).

[3]E. A. L.-C. . D. P.-Z. . M. P.-T. . J. C. Rocha-Hoyos, "Caracterización mecánica a flexión de materiales compuestos con matriz fotopolimérica reforzados con fibras de abacá y cabuya mediante impresión 3d," scielo (2019).

[4]R. Linan, "Los mejores materiales de impresión 3d resistentes al calor," (2020).

[5]CHEMANALYST, "Polyamide price trend and forecast," .

[6]L. Carolo, "3d printer material cost in 2023," .

[7]A&C_PlasticsInc., "Polycarbonate roofing pros and cons," (nd).

[8]Wacker, "Wacker silgel® 612 a/b," (nd).

[9]Kamioka-Observatory, "Overview — hyper-kamiokande," ().

[10]D. S. García, "Modeling of a multi-pmt optical sensor for icecube-gen2 in geant4 and monte carlo studies to optimize its sensitivity," (2020).

[11]Dassault-Systems, "Stress and strain," (nd).

[12]Kamioka-Observatory, "Overview — super-kamiokande official webiste," ().

[13]K. Nakamura, "Neutrino properties." review del Particle Data Group (2010).