The first P0Dule test has been completed. Based on the preliminary results we can conclude that the P0Dule design has enough mechanical strength to meet our design requirements.

1 Introduction

The goals for the first P0Dule prototype at SBU were the verify the construction techniques, and measure the mechanical strength as a validation of the FEA models used during the design process. The construction techniques were demonstrated last fall, and we have just completed the first round of prototype testing. The goals of this first round of testing were to:

1. Demonstrate that the peel forces near the edge of the P0Dule were not sufficient to separate the skin from the frame. For this test to succeed, the skin must not separate from the frame after several cycles of the water load.

2. Demonstrate that an unbraced P0Dule could support the full volume of water without failing. This is a test of an extreme failure mode that cannot be realized in the actual detector, but which if a P0Dule can pass guarantees a large safety factor. For this test to succeed, the P0Dule must support 150 liters of water.

3. Demonstrate that the unbraced P0Dule has a significant mechanical safety. Ideally, this test should determine the failure strength of the design and verify that the FEA model is correctly predicting the failure mode.

4. Determine the P0Dule deflection under load to verify the details of the FEA model. Since we don’t have a measuring table large enough to determine the central P0Dule thickness, this will happen in two stages. The deflections will be measured under load, then test holes will be drilled in the center of the P0D and the thickness measured.

These are particularly stringent tests when done on the first P0Dule prototype since it is based on a R0 design. This revision is designed around triangular bars with a 13 mm height, and a 26 mm base.

2 Prototype Design

The prototype is based on the P0D R0 Design. This design was completed in Spring/Summer 2006, and is based on the assumption of a 13 mm by 26 mm triangular scintillator bar. In this design, the P0Dule is 32 mm thick. The basic design of a P0Dule can be found in the P0D preliminary

*Wrote the text and conclusions
design report [?]. Since this is the initial P0Dule prototype, it main purpose has been to test our assembly and construction ideas, and to verify the mechanical strength of the design. As such, it was constructed from readily available PVC sheets. The main variances from the P0Dule R0 design are:

- The “planks” constructed of extruded styrene bars were replace with planks constructed of half inch PVC sheets. Two planks were constructed of PVC bars cut from 1/2 inch PVC sheets and epoxied as specified in the P0Dule design. The remaining planks were constructed of solid PVC.

- Since 1/2 inch PVC (nominally 12.25 mm, but typically slightly less) was used to approximate 13 mm thick planks, the prototype is approximately 2 mm thinner than the R0 P0Dule. Because of this, the P0Dule prototype is substantially weaker than the R1 baseline and represents a stringent test of the design strengths. In addition, since 1/2 inch PVC is produced with a rather low tolerance, the overall thickness of the P0Dule must be measure after construction.

- No fibers were installed in the design.

- The frame was constructed to mock up the overall stiffness of the final design, but in order to save machining costs only the sensor mounting holes where drilled. The P0Dule mounting holes were added after construction to allow the it to be mounted on a lifting jig.

- When a mounted in a super-P0Dule, a P0Dule will be clamped between two neighbors. For this reason, in the R1 design, the body holes are used for P0Dule mounting. Since we have only constructed a single P0Dule for testing, threaded holes are used in place of the body holes. The effect of the adjacent P0Dule is mimicked using steel clamps attached.

Since the goal of this prototype is to test the mechanical strengths of the P0Dule, a very crude mock-up of the water target and the rest of the super-P0Dule were used. The main variances from the R1 and R2 designs are as follows:

- The P0Dule prototype was constructed to match early design drawings. For this reason, the dimensions varied with respect to the size of the R1 and R2 designs. The prototype outer dimensions are 2310 mm by 2400 mm. The outer dimensions for the R1 and R2 P0Dules are 2200 mm by 2330 mm.

- The water target frame was constructed of wood that was planed to the appropriate dimensions. Gaskets were not used because this prototype is not intended to test the leak containment properties of the water target design. The prototype water volume dimension is 2200 mm by 2330 mm by 30 mm, while the water volume in the R1 design is 2100 mm by 2230 mm by 30 mm. The water volume in the R2 design is

- The rest of the super-P0Dule was mock-up using the strong-back that lifted the P0Dule off of the vacuum chucking jig.

In the time since the prototype construction was begun, we have moved to design revision two. In the P0Dule R2 design, the 13 mm by 26 mm bars are replaced by 17 mm by 33 mm bars. This has the effect of increasing the P0Dule thickness to a nominal 38.54 mm. In addition, the lead sheet that was in the center of the R1 P0Dule has been removed. The Water Target R2 design has also changed. While the water target has remained at 30 mm thick, to improve our knowledge
Figure 1: The surface deflection predicted by finite element analysis for two P0Dule design revisions. The upper figure shows the estimated deflection for the P0Dule prototype described in this note. The lower figure shows the predicted deflection for the P0Dule R2 design.

of the water in the fiducial volume, the frame has now been increased from approximately 50 mm to 250 mm wide. This has the effect of reducing the span over which the P0Dule must support water by about 400 mm. All of the changes made between the R1 and R2 designs are expected to increase the strength of the P0Dule.

3 Expectations Before Testing

A finite element analysis has been completed for the prototype P0Dule design by Dave Warner. This analysis is based off of measurements taken from the prototype as installed at SBU, and is simplified to approximate the P0Dule as a solid sheet of PVC. The simulated water level is taken to be 1750 mm (69 inches as measured during testing). In the analysis, the edges are fixed assuming a rigid water target frame without stress relief. An FEA was also done for the P0Dule R2 design which has a reduced water target size. The R2 design is simulated with the water target full.
Figure 1 shows the calculated deflections for the P0Dule prototype and the R2 design. The maximum deflection for the prototype design is approximately 55±15 mm with a 1750 mm water level. The maximum deflection for the R2 design is 12±4 mm.

Figure 2 shows the calculated stress estimated in the two FEA calculations. The maximum stress for the prototype is estimated to be approximately 11 MPa. The maximum stress for the R2 design is estimated to be 4 MPa.

4 Testing Procedure

Testing began by first measuring the offset of the P0Dule surface from a fiducial plane. These measurements were taken with an accuracy of approximately 0.2 mm, and were demonstrated to be repeatable. Measurements were on a grid with six inch spacing in the vertical (Y direction), and 12 inch spacing in the horizontal (X direction). In addition, measurements were taken on the centerline.

The P0Dule was tested by filling three water bags placed in the space between the lifting strong-back, and the prototype. The bags were filled at roughly 4 ℓ per minute, maintaining approximately the same volume in each bag. Filling continued until we found the first indication of failure in the outer skin. There is no indication that of failure in the epoxy joints. A total of 225.2 ℓ of water were added to the target volume, or approximately 50% more than the maximum required during normal detector operation.

After filling was terminated, the deflections were determined by once again measuring the offset of the P0Dule surface from a fiducial plane using the same measurement grid. The measured deflections can be found in Table 4. We also determined the water level corresponding to 225 ℓ to be approximately 1750 mm.

5 Analysis

This round of testing at SBU has determined the mechanical strength of the first P0Dule prototype which is constructed out of PVC cut from sheets, and follows the first design revision with a lead sheet in the middle of the P0Dule. Since it's constructed from “bars” cut from PVC sheet, the thickness of the P0Dule is about 29 mm (compared with 38.5 mm in the R2 design). In addition, the XY dimension of the water target in our first prototype is substantially larger than in the R2 design (the prototype water target is 2000 mm by 2330 mm. The current baseline design has a water target concentrated in the fiducial volume so the dimensions are about 1700 mm by 1830 mm.

The P0Dule successfully met each of the testing goals:

1. Preliminary inspection shows no evidence of the skin peeling away from the frame.
2. The unbraced P0Dule demonstrated the ability to supported 150 ℓ of water.

---

1A 30% uncertainty has been taken for the FEA. This corresponds to the uncertainty in the material moduli, and the simplifications in the model.

2In the SBU tests water bags are needed to provide the proper forces against the P0Dule, but are not themselves being tested. The original plan was to use a tyvek “potato-chip” bag manufactured for the UW water target tests. These bags are performing quite well in the UW cycle tests. Unfortunately, the bag installation technique was misunderstood leading to a puncture. Four surplus HDP bags manufactured as shipping packages were found as possible replacements for the tyvek bag. One of the four HDP bags was found to leak in preliminary testing. The remaining bags worked quite well for the purposes of this test.
Figure 2: The surface stress predicted by finite element analysis for two P0Dule design revisions. The upper figure shows the estimated stresses for the P0Dule prototype described in this note. The lower figure shows the predicted stresses for the P0Dule R2 design. The stress concentrations at the edges of the target region will be alleviated in the design using standard relief techniques.
Table 1: The maximum deflections observed in the P0Dule prototype test.

<table>
<thead>
<tr>
<th>Thickness 0.506&quot;</th>
<th>Water Height</th>
<th>Bag 1</th>
<th>Bag 2</th>
<th>Bag 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement error ~0.1%</td>
<td>Volume (liter)</td>
<td>1727 mm</td>
<td>1756 mm</td>
<td>1765 mm</td>
</tr>
<tr>
<td>Inches</td>
<td>12</td>
<td>24</td>
<td>36</td>
<td>Center = 43.25</td>
</tr>
<tr>
<td>84</td>
<td>-0.8 mm</td>
<td>0.0 mm</td>
<td>-0.5 mm</td>
<td>-0.4 mm</td>
</tr>
<tr>
<td>78</td>
<td>3.6 mm</td>
<td>6.6 mm</td>
<td>8.2 mm</td>
<td>8.2 mm</td>
</tr>
<tr>
<td>72</td>
<td>6.7 mm</td>
<td>12.8 mm</td>
<td>15.5 mm</td>
<td>16.4 mm</td>
</tr>
<tr>
<td>66</td>
<td>7.5 mm</td>
<td>16.7 mm</td>
<td>22.1 mm</td>
<td>22.7 mm</td>
</tr>
<tr>
<td>60</td>
<td>13.4 mm</td>
<td>23.4 mm</td>
<td>28.8 mm</td>
<td>29.9 mm</td>
</tr>
<tr>
<td>54</td>
<td>16.0 mm</td>
<td>28.0 mm</td>
<td>34.5 mm</td>
<td>35.5 mm</td>
</tr>
<tr>
<td>48</td>
<td>17.6 mm</td>
<td>31.2 mm</td>
<td>38.8 mm</td>
<td>40.2 mm</td>
</tr>
<tr>
<td>42</td>
<td>18.7 mm</td>
<td>33.9 mm</td>
<td>42.2 mm</td>
<td>43.5 mm</td>
</tr>
<tr>
<td>36</td>
<td>19.8 mm</td>
<td>35.1 mm</td>
<td>43.6 mm</td>
<td>45.0 mm</td>
</tr>
<tr>
<td>30</td>
<td>19.3 mm</td>
<td>34.4 mm</td>
<td>42.3 mm</td>
<td>43.9 mm</td>
</tr>
<tr>
<td>24</td>
<td>17.9 mm</td>
<td>31.6 mm</td>
<td>38.7 mm</td>
<td>40.0 mm</td>
</tr>
<tr>
<td>18</td>
<td>15.0 mm</td>
<td>26.0 mm</td>
<td>31.7 mm</td>
<td>32.6 mm</td>
</tr>
<tr>
<td>12</td>
<td>10.0 mm</td>
<td>17.7 mm</td>
<td>21.2 mm</td>
<td>21.9 mm</td>
</tr>
<tr>
<td>6</td>
<td>3.4 mm</td>
<td>6.1 mm</td>
<td>7.7 mm</td>
<td>8.1 mm</td>
</tr>
</tbody>
</table>

3. The unbraced P0D supported 225 ℓ of water before the test was terminated. This is far beyond the amount of water that will be placed in the target during normal running. The ultimate failure mode was found to match the FEA expectations with the skin yielding before an epoxy joint. This demonstrates that the epoxy bond strengths are sufficiently well modeled and that the model predictions can be used to evaluate the designs.

4. The deflections were measured. The measured values are agree with the expected deflections at about the 25%.

The based on a preliminary FEA model and scaling between designs, measured and observed deflections agree at the 25% level.\(^3\) Given the agreement, we can safely use the measurements made during this test to estimate the safety factor of the P0Dule R2 design. As mentioned above, the baseline design is expected to be substantially stronger than the first prototype so this test is extremely stringent. To be successful, a P0Dule needs to support approximately 150 liters of water, and withstand a maximum deflection of 30 mm\(^4\). We have tested the P0Dule to far past it’s requirements and demonstrated that the P0Dule prototype can support 225 liters of water with a maximum deflection of 45mm, demonstrating that it can support the required water volume. Since the measured prototype deflection, and the FEA estimates are in agreement, we can translate this into a safety factor of at least 2.7±0.8. This is based on the very conservative\(^5\) assumptions that the skin was the weakest component of the P0D, and that the stresses were uniformly distributed across the face of the skin.

\(^3\)The deflections were measured after the polystyrene skin had begun to weaken, therefore this represents an upper limit on the disagreement between model and observation.

\(^4\)A 30 mm deflection can only happen at the ends of the water target or if two adjacent water targets have simultaneous leaks. Within the interior of the water target super-P0Dule, the maximum deflection due to a single target leak is 15mm.

\(^5\)and incorrect
The test was terminated when the outer polystyrene skin developed a crack. While a bit alarming, this is extremely positive since a crucial question for this test was if the epoxy used would withstand the stresses of a large deflection. In addition, the final deflections were measured after the skin had developed it’s first crack demonstrating that the structure continued to act as a solid block of polystyrene. From this we can infer that the large plans of epoxy which provide the structural integrity remained intact.

6 Conclusions

The P0Dule design has been demonstrated to meet our design requirements under very stringent conditions. Based on the tests done with the first P0Dule prototype, we can conclude that no design changes are required in the P0Dule mechanical design. The design changes that are implemented in revision 2 for budgetary and physics reasons further increase the safety margins.

Further prototype testing is planned to determine the behavior under multiple fill/empty cycles. This will test for progressive failure as the epoxy joints are flexed.

With the success of the test, I’d like to congratulate Dave on a great design. I also want to thank Jack for all of the hard work putting this test together and working out all of the bugs.