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Construction of PVC Extrusions for the NO ν A Near and Far Detectors

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Abstract

NO ν A, or NuMI Off-Axis ν_e Appearance experiment, is a long-baseline neutrino experiment using an off-axis beam produced by the main injector (NuMI) neutrino beamline at Fermilab. The experiment is designed to study ν_μ to ν_e oscillations. It consists of two PVC and liquid scintillator detectors and a beamline upgrade. The far detector weighs 14 kton and will be located in Ash River, Minnesota, 810 km from NuMI. The smaller, 220 ton near detector will be located underground at Fermi National Accelerator Laboratory. Each detector consists of planes of PVC extrusions containing liquid scintillator and wavelength shifting fiber. The PVC extrusions are made using a formula specially designed for high reflectivity, ease of extrusion and tensile qualities. Custom extrusion dies and extruding procedures have been created to ensure a uniform product that holds to strict dimensional and material tolerances. The construction of the NO ν A near detector on the surface (NDOS) extrusions will be presented, addressing the challenges of creating physics quality PVC extrusions and the QA techniques used to ensure that quality. Finally, preparations for construction of the far detector will be discussed.

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1. The NO ν A Experiment

The NO ν A or NuMI Off-Axis ν_e Appearance experiment is a next generation physics experiment designed to probe many of the remaining fundamental questions about neutrinos and their properties. The experiment consists of three main components: a beamline upgrade to the NuMI beamline, a large, 14 kton far detector and a smaller 220 ton near detector. The goals of the NO ν A experiment include a measurement of θ_{13} , a determination of the mass hierarchy via the MSW effect, a measurement of the CP-violating phase δ_{CP} and a precise measurement of $\sin^2(2\theta_{23})$.

The location of both the near and far detector is designed to maximize sensitivity of the experiment to neutrino oscillations. The far detector is located on the surface in Ash River, Minnesota, a distance of 810

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km from the origin of the beam at Fermi National Accelerator Laboratory. It is 14 mrad off-axis compared to the NuMI beamline direction. The near detector will be located underground at the Fermi National Accelerator Laboratory site, and is also 14 mrad off-axis. Since the detectors are off axis, the expected neutrino beam energy spectrum is narrowly-peaked at 2 GeV. This reduces backgrounds in ν_e appearance searches corresponding to the first oscillation maximum [1].

2. The NO ν A Detectors and NuMI Beamline Upgrades

The near and far detectors are built to be as similar as possible to allow for cancellation of systematic uncertainties due to neutrino flux and cross section modeling. Both detectors are made of planes consisting of PVC extrusions. The PVC is made using a special formula designed for reflectivity, good mechanical properties, and ease of extrusion, containing 15% titanium dioxide by weight. The detector planes consist of a number of long PVC cells extruded in 16 cell extrusions, alternating between horizontal and vertical orientation to allow for 3-D event reconstruction. Each cell is filled with liquid scintillator, and light is collected by a loop of 0.7 mm diameter wavelength shifting fiber contained in each cell. Figure 1 shows diagrams of a PVC extrusions and cells. The completed far detector will contain approximately 360,000 PVC cells. The liquid scintillator is composed of mineral oil with 5% pseudocumene. The entire detector is read out by 32-pixel avalanche photo-diodes (APDs) coupled with low noise amplifiers. The APDs have 85% quantum efficiency and operate at a gain of 100. They are cooled to -15 C to reduce noise.

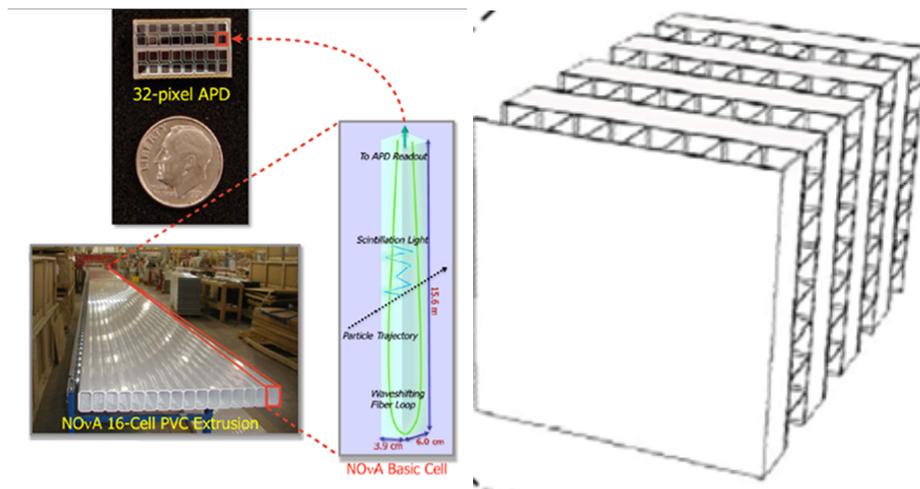


Fig. 1. NO ν A PVC Extrusions and Cells

PVC extrusions and cells. The right panel illustrates a single PVC cell filled with wavelength-shifting fiber and liquid scintillator and a 16 cell PVC extrusion. The right panel illustrates how PVC extrusions are glued together with alternating horizontal and vertical orientations in the NDOS detector.

The existing NuMI beamline will be upgraded for the NO ν A experiment from its existing power of 320 kW to 700 kW of beam power. The 10 μ s-pulse cycle time of the Main Injector will be decreased from 2.2 s to 1.3 s via slip stacking in the recycle ring. The intensity per cycle will be increased by increasing the number of Booster batches from 11 to 12 by installing new Radio Frequency (RF) stations and a new injection kicker magnet. Finally, the target and horns will be upgraded to accommodate the increased proton intensity. These upgrades will occur during the 2012 shutdown of the Fermi National Accelerator Laboratory accelerator facilities. They will result in an increased intensity of 4.9×10^{13} protons per pulse, or 6.0×10^{20} protons on target accumulated per year of running [1].

2.1. The Near Detector on the Surface

A prototype near detector, called the NDOS or Near Detector on the Surface, was completed in March 2011. This prototype is a full test of all the construction techniques needed to make a working near detector: fabricating PVC extrusions, assembling detector modules with fibers, using the modules to build the detector segments, known as “blocks” [2], and installing optical readout, electronics, and the data acquisition system [3]. The NDOS is currently housed on a surface building at Fermi National Accelerator Laboratory.

At the current location, the detector can measure neutrinos from the booster beam (on axis) and NuMI beam (6.1 degrees off axis) as well as measuring cosmic ray particles. The first neutrino candidate was detected in the NDOS on December 15, 2010. In the first three months of running, the NDOS collected data from 5×10^{19} POT NuMI exposure. The data taken from the NDOS can be used for a number of goals including exercising the calibration scheme, benchmarking the Monte Carlo simulation, demonstrating electron neutrino selection and cosmic background suppression as well as a variety of physics results [4].

A prototype extruding die and extrusion line was used to create the NDOS extrusions. The PVC resin and power formulations, extrusion methods, and quality control techniques were prototyped using the NDOS.

2.2. Construction of the NOvA Near and Far Detectors

The NOvA far detector is scheduled to begin construction in early 2012 and will be finished by the fall of 2013. The detector will be commissioned as it is built and data will be taken with the partially finished detector. The Near Detector underground should also be functional by 2013 and ready for data taking. A planned run consisting of 3 years of neutrino running and 3 years of anti-neutrino running will begin in 2013. An illustration of the construction of the far detector is given in Figure 2.

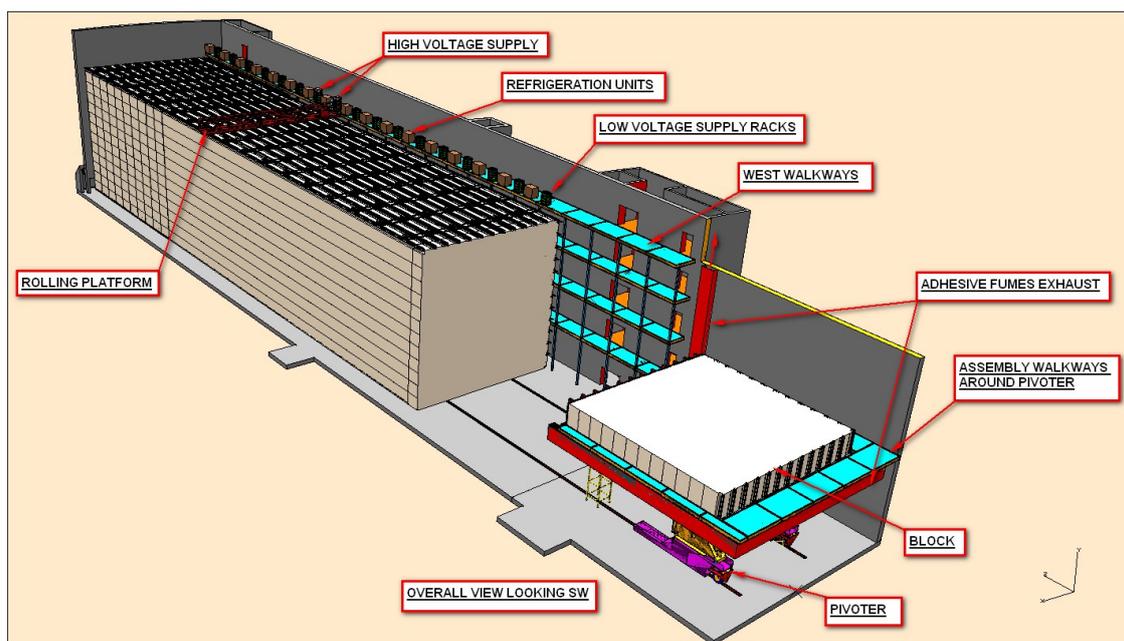


Fig. 2. Far Detector Construction

The NOvA far detector. The 14 kiloton far detector will be located in Minnesota, just south of the U.S. Canadian border.

3. Construction of PVC Extrusions

Creating physics quality extrusions for the NOvA detectors has presented a number of challenges. A custom PVC resin had to be formulated in order to create PVC with high reflectivity. An extruding procedure

was developed using custom extrusion dies and a dedicated extrusion line. Finally, a number of quality control tests were created. These test were designed to mostly be completed during the extruding procedure at the factory.

3.1. PVC Resin and Powder for NOvA Extrusions

A custom resin and powder mixture was created for the NOvA extrusions. The resin was specially designed with physics needs in mind. The material needed to have a high reflectivity while maintaining good tensile properties, in particular the 20-year creep properties. The high reflectivity is insured by including 15% titanium dioxide in the PVC recipe. Initially, several formulations using rutile titanium dioxide were considered. However, it was discovered that extrusions with anatase titanium dioxide resulted in modules with about 15% higher scintillation light yield than those using rutile titanium dioxide. This is primarily because the reflectivity spectrum is higher in material with anatase titanium dioxide rather than with rutile titanium dioxide, as shown in Figure 3. The relative light yields of material formulated with rutile and anatase titanium dioxide are shown in Figure 4. The final PVC formulation, called NOvA-27, also contains a number of additives meant to stabilize it at high temperature, to lubricate the material during processing and to provide the material with acceptable tensile qualities. This formulation is given in Table 1. During the creation of NDOS extrusions, the mechanical properties of the anatase PVC compounds were found to be strongly dependent on the mixing procedures used at the PVC blender. In particular, improperly mixed batches produced brittle extrusions when subject to impact.

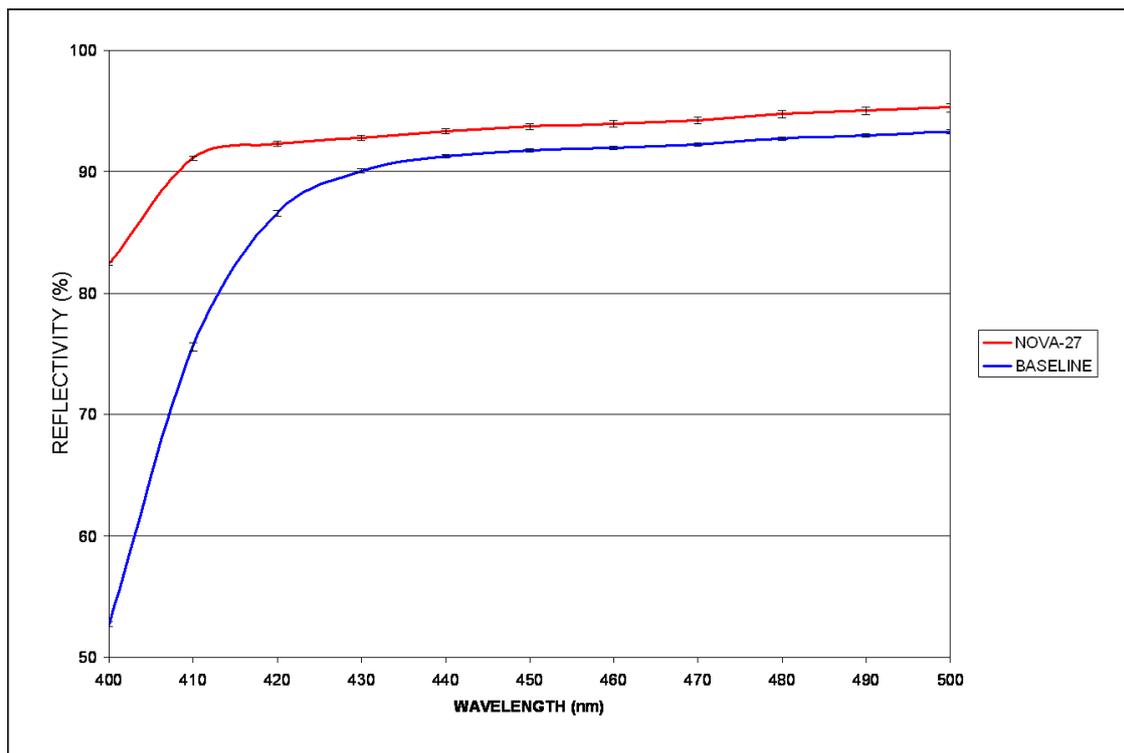


Fig. 3. PVC Reflectivity

PVC Reflectivity as a function of wavelength. NOvA-27 PVC formulation is compared to a similar formulation using rutile TiO_2 , rather than anatase TiO_2 in the PVC, labeled 'baseline'. This demonstrates that the formulation using anatase PVC has higher reflectivity over many wavelengths.

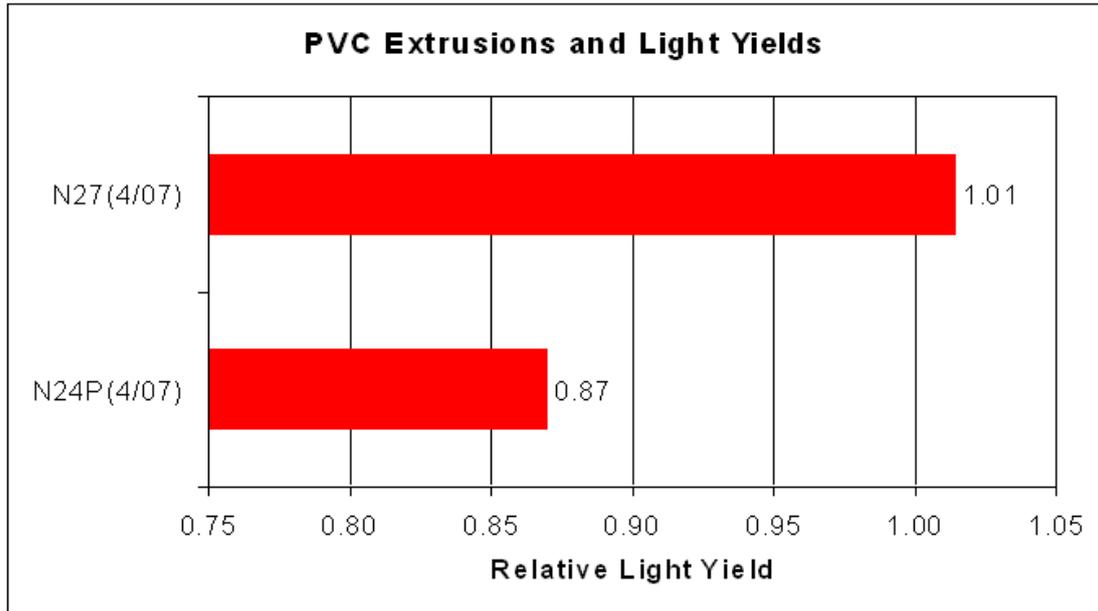


Fig. 4. Scintillation Light Yield Comparison

Scintillation light yield comparing modules made using different titanium dioxide in the PVC formula. The NOvA-27 PVC formulation is compared to a similar formulation using rutile, rather than anatase, labeled N24P.

3.2. Extruding Procedure for NOvA Extrusions

A dedicated extruder line was used to create the NOvA extrusions. The NDOS extrusions were made using a Kraus-Maffei (KMD-60) Twin Screw extruder. Each screw in this machine has a 60 mm diameter, and the extruder has a PVC output rate of 550 lbs/ hour. Custom extruding dies were designed for the NOvA experiment. For the far detector, a new KMD-90/32 extruder will be used that has twice the throughput rate. New dies, calibrators and cooling tanks have also been purchased.

4. QA and QC and The Extruding Factory

A number of quality control tests were performed to ensure physics quality extrusions. The measured properties include mechanical properties, reflectivity, and dimensional measurements. The mechanical properties of the PVC were measured with a drop dart test, tensile test, pressure test, vacuum test, and a creep test. The dimensional measurements for the NDOS were measured by hand with calipers, but the measurements for the far detector will be made with an Optical Gaging Probe (OGP) metrology camera. Finally, reflectivity was measured using an table-top spectrophotometer.

In the factory, a small sample for testing was created following every full length extrusion. An isolated cell vacuum test was done on every full length extrusion. The dimensional measurements of each extrusion were tested by checking the dimensional measurements of the sample using the OGP camera. The pressure tests, reflectivity measurements, and drop dart tests were done on every other sample. Tensile tests were performed from samples taken once per day. Finally, creep samples were created bi-weekly, and creep tests are ongoing.

4.1. Mechanical Tests

The pressure tester is a specially designed machine which works by pressurizing alternate cells, in order to test the internal webs and outside walls. This tests PVC integrity to a 150 psi burst pressure. It also tests

Category	NOvA-27 (parts per hundred)
PVC	100
Tin stabilizer	2.5
Titanium dioxide anatase	19
Calcium stearate	0.8
Paraffin wax	1.1
Oxidized polyethylene	0.2
Glycerol monostearate	0.3
Acrylic impact modifier	4
Processing aid	1
Total (phr)	129
Weight % titanium dioxide	15

Table 1. NOvA-27 formulation used in NOvA PVC Extrusions.

the overall strength of the material as well as the strength of the knit lines.

The vacuum tester checks for web knitting and buckling in the entire extrusion by pumping vacuum from every other cell of each full length extrusion. The final testing apparatus allows for automated control of vacuum pumping and monitoring.

The drop dart test used is similar to the standard dart test. A small metal dart was dropped on to the extrusions from varying heights, and the height at which the PVC breaks was recorded. Information about the way in which the PVC breaks was also recorded. The minimum drop dart value was 35 inches with a 8 lb weight. A brittle failure or fracture was an indication of poor material, while deep and shallow dimples prior to failure generally indicate material with good ductility. Separation along the knit lines can indicate poor fusion of the PVC along the knit lines. Such poor fusion was found in early NDOS prototype modules, and corrections were made to the final extrusion die ensure good knitting in the final NOvA extrusions. A final production version of the drop dart test is in the prototyping phase. It consists of fully automated testing, including auto clamping and an internal anvil. This is designed to enhance the consistency of test results.

The modules, yield and stress test come from a tensile test that was done daily off-site. Tensile test results can indicate knitting problems and other failure modes. Additionally, creep samples are started every two weeks.

Pictures of the apparatus for each of the mechanical tests are shown in Figure 5.

4.2. Dimensional Measurements: OGP Camera

The dimensional measurements of the far detector extrusions will be measured using an OGP unit. This unit measures the flatness, web thickness, location and perpendicularity, wall thickness, radii, overall and individual cell height and width of each extrusion. A table of required dimensions for each extrusion is given in Table 2.

4.3. Reflectivity and Light Yield

The reflectivity of each extrusion is measured with a Hunter Laboratories tabletop spectrophotometer. The measurement is taken in non-specular mode. The setup is shown in Figure 6. Reflectivity is measured in the wavelengths from 360 nm to 500 nm. Measurements were taken from both the interior and exterior of the extrusions. The reflectivity measurements were then used to create a relative light yield using a Monte Carlo simulation. Relative light yield is measured as a percentage of the light yield of a perfect reflector. During the creation of the NDOS prototype extrusions, the reflectivity and light yield proved to be an excellent tool for catching a number problems such as rutile contamination in the titanium dioxide or overheating and burning of the PVC during the extrusion process, to name a few.



Fig. 5. Photographs of quality assurance tests of mechanical properties
Pictures of the PVC QA tests, shown at the extrusion factory. In the top panel, the pressure test is on the left, the drop dart on the right. The vacuum test is shown on the bottom.

Dimension	Acceptance criteria (mm)
Flatness	≤ 0.5
Web minimum thickness	≥ 3.0
Web location	± 2.0
Web perpendicular	≤ 1.0
Top wall minimum	≥ 4.5
Bottom wall minimum	≥ 4.5
Outer wall minimum thickness	≥ 4.5
Individual cell height	66.1 ± 0.5
Trough	$56.6 - 59.5$
Internal radii of the outside corners	8.0 ± 0.5
Width	634.5 ± 1.0

Table 2. Dimensional Tolerances for PVC Extrusions.

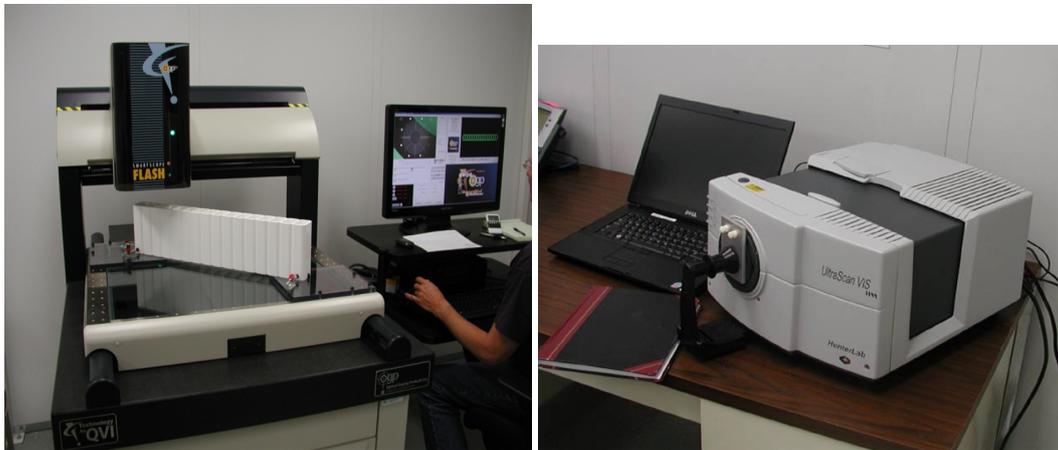


Fig. 6. Photographs of Dimensional and Reflectivity testing Apparatus

Pictures of the PVC QA tests, shown at the extrusion factory. The OGP camera is on the far left and the spectrophotometer is on the right.

5. Conclusion

The NO ν A detector has been created with a novel technology of PVC extrusions filled with liquid scintillator and read out by APDs. In order to create physics quality PVC extrusions, several new procedures and techniques had to be developed. This included new resin, new appropriate extruding machines and dies and tooling and a new quality control procedure. The extrusion and quality control techniques were prototyped using the near detector on the surface, and are now in use for full production mode for the NO ν A near and far detectors.

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