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The development of PVC extrusions for a 14,000 Ton self-supporting structure for the detection of neutrinos

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The NOvA Neutrino Experiment is building a one of a kind self-supporting plastic structure, potentially the largest ever built. The PVC structure serves as a neutrino detector and is composed of 28 individual blocks that measure 51 feet high by 51 feet wide by 7 feet deep. The PVC needed for each block weighs approximately 400,000 pounds. The primary parts in the detector construction are 51-foot, 16-cell PVC extrusions. These extrusions form the basis of the detector modules which are laminated together in a crossed pattern to form the individual blocks and then filled with mineral oil. The hydrostatic loading on the extrusions results in complex loading of the laminated structure. In addition, the mass of the contained mineral oil is 1.7 times the PVC mass, thereby adding to the mechanical stress. The self-supporting nature of the detector places important structural requirements on both the PVC formulation and the extrusions. Similarly, the need for leak-tight seals along with block assembly requirements imposes narrow geometric tolerances on extrusions whose large size is pushing the manufacturing limit. Furthermore, due to the method of detecting neutrinos, another fundamental requirement of the extrusions is that it possesses exceptionally high reflectivity over a particular wavelength range. This requirement places additional restrictions on the components of the PVC formulation. Taken altogether, the PVC extrusions have to maintain important reflectivity characteristics, provide structural support to the detector, and meet relatively tight geometric requirements for assembly. In order to meet these constraints, a custom PVC formulation had to be created. One of the main features of the PVC compound was exceptionally high loading of anatase TiO_2 (to meet the reflectivity requirements). This fact combined with a large and complex extrusion profile presented difficulties in developing a PVC formulation. The final formulation and extrusion process were developed after an extensive R&D program which included industrial partners. We present a brief description of the purpose and requirements of the physics detector leading to the complex PVC and extrusion requirements, summarize the R&D process and discuss the lessons learned.

1 Introduce extrusion / PVC / Structure (size, scale)

A large and complex PVC cellular extrusion profile (Figure 1) has been developed for use as the basic structural element of a “one-of-a-kind” self-supporting 51-foot high structure, called a “Block”, whose cells are filled with liquid scintillator containing approximately 95% mineral oil and 5% pseudocumene. A Block contains about 400,000 pounds of extruded PVC and is filled with 700,000 pounds of liquid

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scintillator. It was designed for the specific use as a neutrino detector for a physics experiment called NOvA. In total NOvA is comprised of 28 such Blocks with a total mass of 14,000 tons.

This extrusion must meet several diverse but significant requirements. First it must provide a highly reflective surface as part of the physics performance requirements. Second, the laminated PVC structure is self-supporting, even after it is filled with liquid. Third, the extrusion profile is large (66 mm high x 635 mm wide) and yet must meet specific tight geometric tolerances to facilitate the assembly. The high-reflectivity requirement drove the need to develop a custom formulation containing a large loading (15% by weight) of titanium dioxide (TiO_2) while minimizing or eliminating common additives that may absorb light. Anatase TiO_2 was selected for its superior reflectivity characteristics at short wavelengths in comparison to that of rutile TiO_2, which is normally used in PVC formulations.

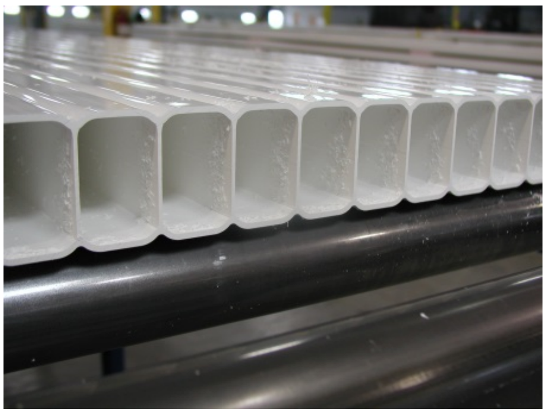


Figure 1 (a) Closeup of 16-cell PVC extrusion, freshly cut. (b) Two full-size 16-cell extrusions 51 feet long placed side-by-side.

The NOvA experiment is located in Ash River, Minnesota, approximately 810 km away from the Fermi National Accelerator Laboratory (near Chicago), where a beam of neutrinos is created and aimed toward the Ash River site. The location was chosen specifically to study certain properties of neutrinos as they propagate 810 km underground. By analogy, as in a flashlight beam, the neutrino “spot size” gets broader with distance so that only a small fraction of the original neutrino beam produced at Fermilab is intercepted by the Ash River detector. Neutrino experiments require large detectors, and this experiment requires one of the biggest detectors in the world (and likely the largest self-supporting plastic structure in the world), yet at an affordable cost.

Neutrinos seldom interact with matter, but when they do ionizing radiation is often a byproduct. The NOvA experiment contains a scintillating mineral oil compound that generates light in the presence of ionizing radiation. Use of scintillating materials is common in nuclear and particle physics as well as other fields of research, including the medicine, chemistry and biology. Owing to the very large volume of the NOvA detector, light produced deep within the detector cannot be detected directly. NOvA uses fiber optics running the length of each cell within the 51-foot long module to capture the light and to transport it to avalanche-photodiode (APD) photo-detectors attached to the manifold covers (Figure 3). Since the fibers are very thin (0.7 mm in diameter), light may not strike a fiber immediately due to the small cross-sectional area of a fiber. The light is trapped within a PVC cell and bounces off the cell walls a number of times (averaging 8 to 10 bounces) before being captured by the fiber (Figure 2, Figure 4). This “bouncing” is predominantly based on a diffuse reflection component, therefore a “shiny” or “glossy” PVC with a large specular-based component is not of help here. It is critical that the PVC surface does not absorb light, especially in the blue to near UV wavelengths, which is the color of the scintillation light. This drives the requirement of a highly reflective (non-absorptive) PVC extrusion.

It would have been preferred to make extrusions with 32 cells (1270 mm wide and 66 mm high). However, because of the challenge of making such a large profile with tight dimensional tolerances, it was decided to produce extrusions with 16-cells (635 mm wide by 66 mm high) and to subsequently join two extrusions side-by-side to form one "Detector Module", 51 feet long and 1270 mm wide. To contain the liquid, modules are sealed on one end with a flat PVC plate and on the other end with a PVC manifold, which allows insertion and routing of fiber optics to transport the scintillation light to the photo-detectors.

Before filling the PVC detector modules with liquid scintillator, the modules are assembled into a "Block Structure" by placing twelve modules side-by-side on a large mechanical platform, then placing a second layer of twelve modules on top of it, oriented perpendicular to the first layer. An adhesive is applied to the outer surfaces between the two layers to form a laminate. This procedure is repeated 32 times with alternating layers placed in orthogonal directions, resulting in a Block with 32 layers of detector modules. This overall process is shown in Figure 3. The fully-assembled Block is rotated via the mechanical platform and moved into position at the laboratory in Ash River.

A block is a structure approximately 51 feet high by 51feet by 7 feet thick. A total of 28 blocks are built in this way to make up the final detector size of approximately 51 feet high by 51 feet wide by 194 feet long.

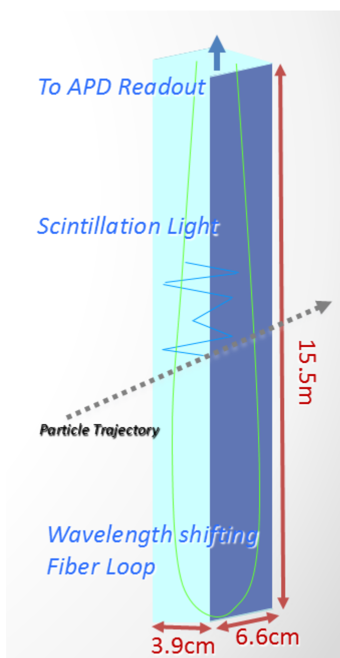

Figure 2 Radiation particles passing through the scintillating liquid within a cell produces light which reflects off the PVC walls multiple times until being captured by a "wavelength-shifting" fiber optic loop. Light within the fiber optic light travels the length of the extrusion and is detected by an "APD" photo-detector.

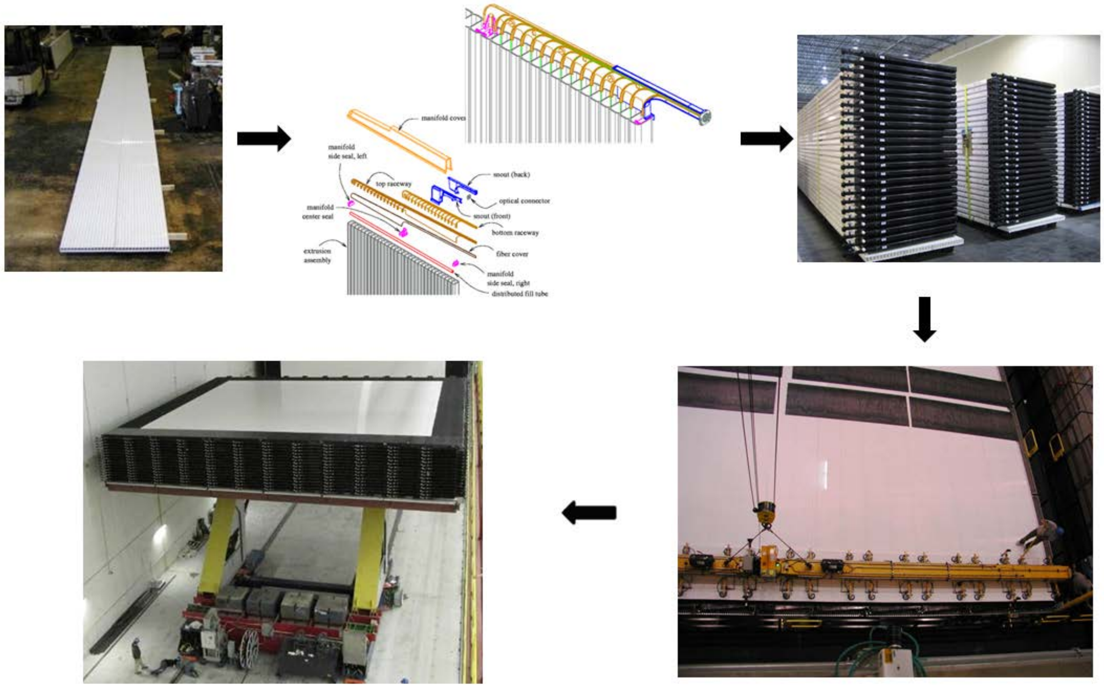

Figure 3 Extrusions are glued edgewise to form modules which are then arranged side by side to form a 51 foot square plane.

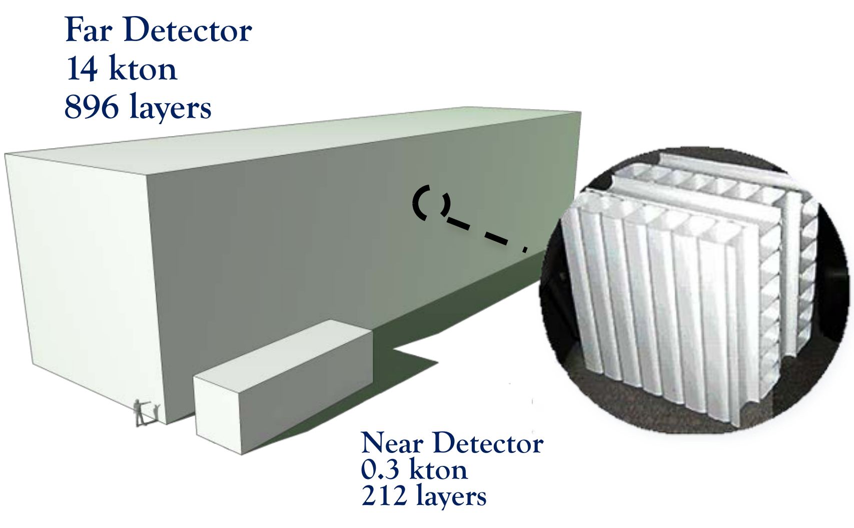

Figure 4 Schematic illustrating the size of the two NOvA detectors and the alternating orientation of the PVC extrusions. Note the person depicted in the figure to provide a reference scale.

2 Requirements for extrusion as part of a physics detector

The PVC extrusions provide a critical function with regard to both the physics and structural performance of the detector. We discuss these primary requirements below.

2.1 *Reflectance properties*

Large gains in the physics performance of the detector and reduction in electronics cost are realized with even small improvements in the PVC reflectivity in the wavelength range from 360 nm to 500 nm. This need for high reflectivity in a specific wavelength range is the primary technical criterion for the PVC. The available rigid PVC compounds such as those used in standard pipe formulations do not yield sufficiently high reflectivity due to less than optimal amounts of TiO_2 and additives that absorb light. In rigid PVC these additives are meant to stabilize it at high temperatures, to lubricate it during processing, to increase the impact characteristics, to provide a particular color, to lower the price of the final product, etc. These additives play a role during extrusion and in the final product. Figure 5 shows the large difference in reflectance of a commercially available white PVC and an early NOvA PVC formulation loaded with 15% rutile TiO_2. Although the reflectance of the NOvA formulation is clearly superior, it was difficult to extrude and changes to the formulation were necessary. Understanding the effect of each component was the key to formulating a PVC resin with the highest reflectivity possible while maintaining extrudability and mechanical properties.

In searching for the highest reflectivity, TiO_2 was studied in detail. Our requirements resulted in the need for an untreated TiO_2 powder and for testing both rutile and anatase crystallizations form. Although anatase TiO_2 was not very commonly used in PVC, the reflectivity spectrum in the region between 360 nm and 420 nm of anatase TiO_2 is higher than in rutile TiO_2. NOVA-24 was the most promising PVC formulation using rutile TiO_2. Anatase TiO_2 had been tested in other mixtures with great results regarding reflectivity. Since NOVA-24 worked nicely in an industrial extruder with a multi-cell die, the same composition was approached for anatase TiO_2. A graph of the scintillation light spectrum superimposed with the reflectance of NOVA -24 and NOVA-27 extruded PVC as a function of wavelength is shown in Figure 6(a). The anatase NOVA-27 PVC resin formulation (Table 3) tested extensively from R&D trials to early production runs resulted in 14% more light collected (Light Yield) than the equivalent rutile formulation (NOVA-24), as shown in Figure 6(b).

1.1 *Mechanical properties*

The second technical criterion concerns the material strength of PVC. In addition to containing the liquid scintillator and providing a surface with high reflectivity, the PVC extrusions form a self-supporting structure. The detector was designed using mechanical properties of typical PVC pipe formulations so the main issue was that these properties would not be degraded in the custom formulation. Analyzing and designing a suitable structure requires an understanding of specific mechanical properties. Strength requirements are normally defined by the material yield and ultimate stress. The PVC material must meet the minimum mechanical properties listed in Table 1. The structural analysis is carried out based on these values. Therefore the structure depends on these minimum values.

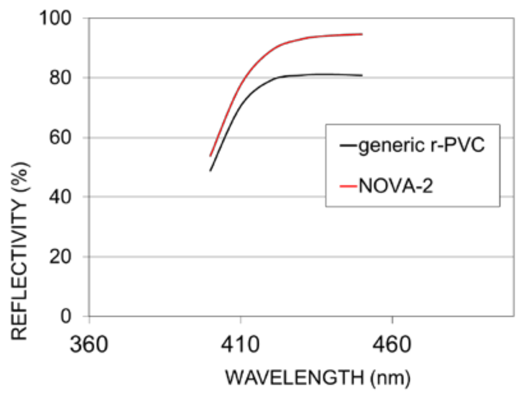

Figure 5 Reflectance of commercially available white PVC (black curve) is compared to the reflectance of an early NOvA formulation loaded with 15% rutile TiO2 (red curve).

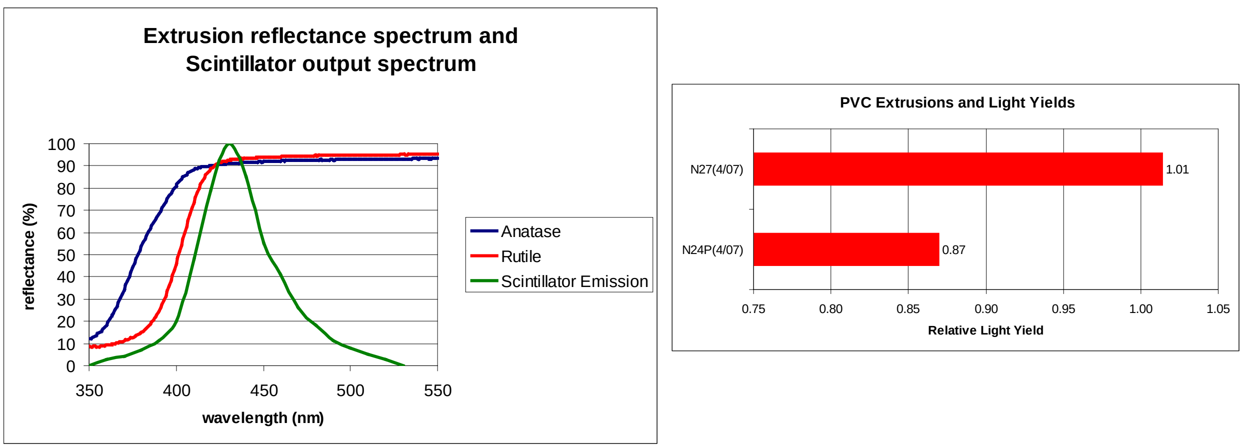

Figure 6 (a) Scintillator light spectrum (green curve) is superimposed on a reflectance graph of extruded PVC made with NOVA-24 (15% rutile) shown in red and NOVA-27 (15% anatase) shown in blue. (b) The total light collected from a scintillator-filled extrusion made with NOVA-24 (lower bar) and from a scintillator-filled extrusion made with NOVA-27 (anatase).

The values in Table 1 refer to the short term (or instantaneous) properties of PVC. For this structure, the long term structural performance of the PVC is of primary importance. The situation is complicated by the fact that PVC is viscoelastic at room temperature. This implies that the material will deform over time (creep) under a state of constant load. This can be seen as a lowering of the effective stiffness of the material over time. The most serious implication for the NOVA structure pertains to the structural stability which is a function of stiffness. The reduction in stiffness over time creates the potential that a structure that is initially stable could become unstable at some future time leading to catastrophic failure. To design against this situation with a quantifiable factor of safety, the time dependent creep modulus is needed at a time equal to the expected lifetime of the structure. The design lifetime of the NOvA structure is 20 years. Since it is not practical to wait 20 years to measure the creep modulus, this value is determined by predictive methods. The structural analysis required that the creep modulus (after 20 years) be greater than 75,000 psi. In order to minimize creep related deflections, the stresses in the blocks are kept below 700 psi which is well below the yield and ultimate stresses requirements. In addition to the strength and stiffness properties, the PVC must have sufficient impact strength (as a measure of ductility) and exposure to the liquid scintillator should not lower any of these values significantly.

The strength properties of rigid PVC turned out to not be strongly influenced by optimization of the PVC formulation to attain high reflectivity although anatase TiO_2 did prove to be problematic with regards to impact and ductility.

Table 1 Minimum mechanical properties of the NOvA PVC compound

Material Property	Value	Test Method
Modulus of Elasticity (Instantaneous, t=0)	450,000 psi	ASTM D638
0.2 % Offset Yield	4000 psi	ASTM D638
Ultimate tensile Stress	5500 psi	ASTM D638
Creep Modulus	See Table (2)	ASTM D2990

Table 2 Minimum values of time dependent (Creep) Modulus

Time [Years]	Modulus [psi]
0.5	262,631
4	145,544
10	100,713
20	72,046

2.2 Extrusion details, features

The third technical design criterion requires that the certain profile dimensions be within specified tolerances to facilitate assembly of modules and blocks. These include thickness, flatness and straightness of the outside edges (bond two 16-cell extrusions to make one 32-cell module), the overall profile (manifold and bottom plate must mate to two extrusions properly), and the overall flatness (upper and lower extrusion surfaces must attach in the process of block assembly). The size and complexity of the extrusion along with the high TiO_2 loading made meeting the tolerances very difficult. To meet these strict dimensional tolerances in a production setting required considerable iteration between extrusion process, die design (geometry), PVC formulation, and PVC compounding which were in principle the responsibility of distinct entities.

The NOvA far detector is constructed by bonding the PVC vertical and horizontal extrusions using adhesive. It is essential that the quality of bonding is preserved. The flatness requirement of the PVC extrusions is a key factor to ensure quality adhesive bonding. Only a maximum intra- surface gap of 0.75 mm. (30 mils) across the 240 square meter bonding surface is allowed. The adhesive is a two-part custom formulation, Plastic Welder 60, devised by Devcon.

3 Need for custom PVC

NOvA PVC is designed to be highly reflective by adding substantially more titanium dioxide (TiO_2) to the PVC resin than is normally used in commercial applications. This can yield reflectivity values as high as 92% at 430 nm, near the peak of the scintillator emission spectrum. However, in order for any PVC compound to be extruded, a number of processing ingredients must be added to the mix. Great care must be taken to ensure that these ingredients have a negligible effect on the reflectivity of the extruded material

TiO_2 is available commercially in two crystalline types: rutile and anatase. Rutile is generally used throughout the PVC industry but anatase is not. PVC with anatase is said to be more difficult to extrude and the extrusions do not perform well outdoors, exposed to sunshine and rain. However, anatase offers an advantage to NOνA because it extends the high reflectivity of PVC by approximately 30 nm to wavelengths below 400 nm. This extended range is enough to overlap most of the short-wavelength tail of the scintillator emission spectrum

Since the NOνA experiment is conducted indoors, we have decided to use the anatase form of TiO_2. Mechanical strength tests and light yield tests show no adverse effects due to the use of anatase when exposed to liquid scintillator.

3.1 PVC Resin Composition

Selection of the quantity and type of TiO_2, the processing aids and the PVC polymer was made after almost two years of R&D, which included consultation with James Summers, an expert on PVC production, and close interaction with two commercial compounding companies, an independent plastics laboratory, and two commercial extruding companies and their production staffs. The ultimate goal of the R&D was to produce a formulation that, when extruded, produced PVC extrusions with excellent reflectivity, mechanical strength and geometrical shape.

PVC will not extrude without the addition of processing aids to the polymer, which typically includes between 5 and 10 ingredients. In the extruding process, the PVC resin is subjected to pressures of up to 4,000 psi and temperatures of nearly 400 °F for a significant period of time. The processing aids (stabilizers and lubricants) are added to the PVC polymer and the TiO_2 to keep molten resin flowing through the die without sticking, burning and decomposing. Care must be taken to ensure that processing aids do not have adverse effects on the reflectivity or strength of the extruded product.

The reflectivity requirement of NOνA posed a challenge in the selection of specific processing aids, the type of PVC polymer and the type and brand of TiO_2. Extensive laboratory R&D was performed on over two dozen formulations with particular attention paid to reflectivity; those with satisfactory results were extruded and their extrudability, mechanical properties and reflectivity evaluated.

Commercially available PVC resins are proprietary and their reflectivity properties are not optimized for NOνA. In order to control all of the ingredients and, in some cases, the brand names of ingredients, we have developed a resin formulation that meets NOνA requirements for reflectivity, strength and extrudability. This resin is called NOνA-27 (N-27) and its composition is listed in Table 3. The net result is a rigid PVC compound with 15% anatase TiO_2 by weight.

N-27 resin produces an extrusion with density equal to 1.49 gm/cc. Given this density and the nominal profile dimensions, the extrusions weigh 14.1 kg/m.

Table 3 Composition of N-27 rigid PVC compound.

INGREDIENT	COMMERCIAL BRAND NAME	PARTS PER HUNDRED	PER CENT
PVC	Shintech SE950EG (high reflectivity)	100	77.5%
Tin stabilizer	Rohm & Haas Advastab TM-181 20% monomethyl tin	2.5	1.9%
Titanium dioxide anatase	Kronos 1000 anatase titanium dioxide	19	14.7%
Calcium stearate	Ferro 15F calcium stearate	0.8	0.6%
Paraffin wax	Ferro 165 paraffin wax	1.1	0.9%
Oxidized polyethylene	Ferro Petrac 215 oxidized polyethylene	0.2	0.2%
Glycerol monostearate	Rohm & Haas F1005 glycerol monostearate	0.3	0.2%
Acrylic impact modifier	Arkema Durastrength 200 Acrylic impact modifier	4	3.1%
Processing aid	Rohm & Haas Paraloid K120N processing aid	1	0.8%
	Total	129	100%

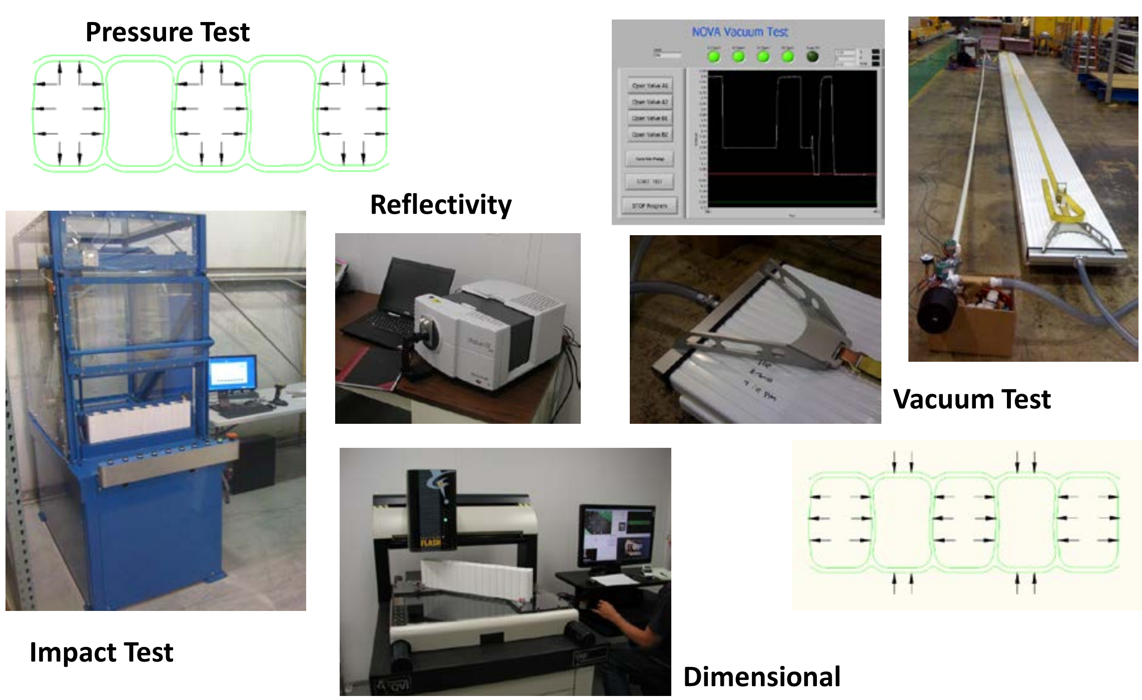

Figure 7 Some of the unique QC tests and equipment designed for these extrusions.

4 Extensive and unique QC

Due to the importance of meeting the many and varied requirements placed on these extrusions, an elaborate QC program was established. This program involved either unique tests or common tests specialized for our purpose. For QC purposes, a 6-inch cutoff was taken after every 50 foot extrusion and tested destructively. The cutoffs were subjected to dimensional, impact, pressure, and reflectivity tests. The pressure test (to failure) subjected alternating cells to pressure thereby checking the integrity of the outerwall and web knits. This test was done with a custom pressure tester. The impact test was similar to a drop dart test. Due to the time involved, a custom automated pendulum type impact machine was developed. The reflectivity was tested by measuring the light yield using a HunterLab, UltraScan VIS, reflectometer and a special algorithm. The dimensional tolerances (over 150 dimensions) were checked using an OGP optical measuring device which also was automated. In addition, each extrusion was subjected to a vacuum test to confirm the web integrity. This custom device was also automated to save time. An additional cutoff was taken daily and sent to ANL where samples were made for tensile testing of the bulk material and the outer wall and web knits. All of the data was uploaded daily to a project database.

5 Discussion / Lessons learned

5.1 Extrusion

The first attempts in PVC formulation tried to make PVC compounds with only a few components and large amounts of rutile TiO_2. These products tended to be dry and did not extrude well in industrial conditions even when using a small die with just 4 cells. It was necessary to have most of the components found in a typical rigid PVC formula. Therefore the approach had to be to minimize absorption in the components. Shintech SE950EG was chosen for its superior clarity. As stabilizers both Advastab TM-181 (20% monomethyl tin) and TM-182 (80% monomethyl tin) were tested. Although TM-182 yielded an extrusion with slightly higher reflectivity than TM-181, it did not protect over time as well from degradation during the extrusion process. Several rutile and anatase TiO_2 products were tested. Kronos 1000 anatase TiO_2 was selected because it yielded the highest reflectivity. The manufacturer and product for the calcium stearate, the paraffin wax, the oxidized polyethylene, the glycerol monostearate, the acrylic impact modifier and the processing aid underwent a few changes from the early R&D process to the final extrusion production mostly due to changes in availability. Nonetheless once the components were fully tested, the formulation was unchanged.

It was important to test the PVC formulation under extrusion conditions similar to those of the final production. The problem was not the reliability of the reflectivity results. It was quickly evident that a short extrusion run using a small extruder with a small die did not expose the PVC compound to the extrusion conditions encountered in an extrusion test utilizing a large die, in particular a very wide die like the one needed for the NOVA extrusions. Because results varied under different extrusion conditions, it was necessary to have the NOvA die and the final extruding line setup to learn about the actual stability properties of the PVC compound formulated and the mechanical properties of the extrusions prepared. NOVA-27 PVC while meeting all of the performance requirements set out above was a difficult compound to prepare and to extrude. Determining the best operating settings, compounding techniques, and die features required many iterations between the parties involved.

5.2 Mechanical properties

The preparation of the NOVA-27 PVC required close attention. The untreated anatase TiO_2 yielded more variations to the final PVC compound which affected the extrusion process and the final mechanical properties of the extrusion. Initial developments with rutile TiO_2 provided excellent ductility in standard tensile tests and high impact strength. The switch to anatase TiO_2 initially brought with it serious reductions in ductility and impact strength. After considerable efforts, ductility comparable to that originally obtained with rutile was achieved by improving the dispersion of the anatase. Over the course of production, variations in ductility were observed between the bottoms and tops of the extrusion as well as the web knits discussed further below. These problems could be improved by raising temperatures in the extrusion process but this was limited by difficulties with NOVA-27 sticking in the die.

From a QC point of view, drop dart impact tests served as a good quick on-site leading indicator of ductility issues although tensile testing was used as the final decision of ductility.

Time-temperature superposition tests were used as a method of estimating the long term creep of the NOvA formulations. The creep properties were found to be relatively independent of formulation. Predictions base on accelerated creep tests showed good conservatism when compared to long term studies. The effects of "physical aging" (which has been shown for PVC that increasing t_e by a factor of 10 decreases the creep rate by a factor of 10 and shifts curve along the time scale to the right [2,3]) was observed. The creep tests revealed that for our material, stresses ranging from 300-700 psi showed no significant stress dependence and are consistent with the claim of linear viscoelastic behavior below the design stress of 730psi.

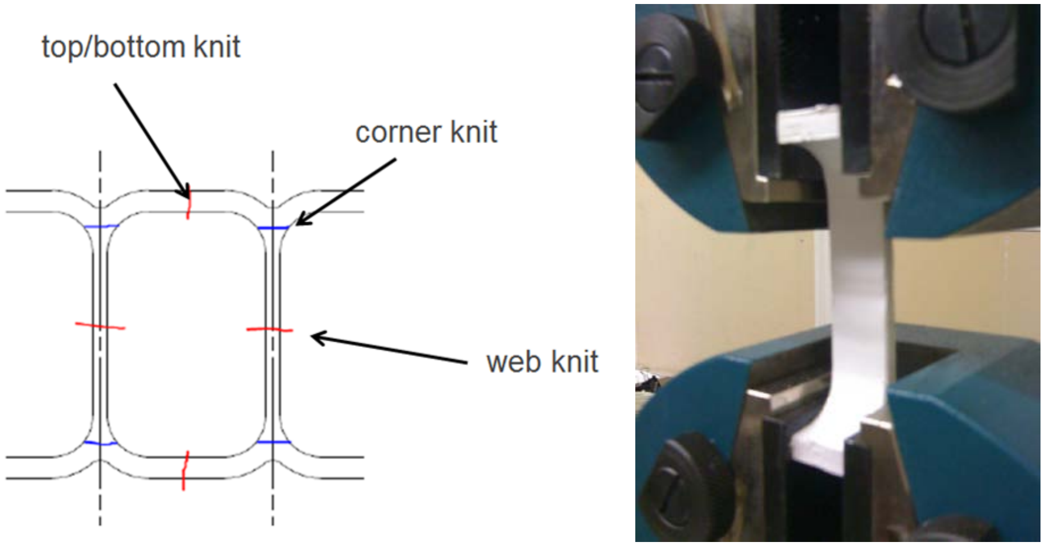

Figure 8 Locations of knit lines in a single cell and the wen knit tensile test specimen and set-up.

Due to the complex shape of the die and high number of internal cells, the extrusion profile has a very high number of knit-lines where material passes over a die support and rejoins shortly before exiting the die. There are 77 knit locations in the profile (Figure 8Figure 10). While most performed well, the central knits in the webs were of reduced strength and ductility compared to the bulk material. This reduction is generally more pronounced in the central webs (3-13) while the outermost webs (1,2,14, 15) reveal no serious reduction. The variation in ultimate tensile strength (UTS) is shown in Figure 9 (top). It can be seen that the more central web knits fail about 85% the ultimate strength (lower in some cases). More pronounced is the difference in ductility when failure occurs. The elongation at break expressed as crosshead travel is shown in the lower of Figure 9. A clear difference between the break at elongation is seen between the outer web (1) and the inner webs (4,8,10) . Inspections of the failure surfaces revealed that the web 1 samples failed in the bulk material. That is, the knit line was as strong as the bulk material. The exact opposite is true for the inner webs which all failed clearly at the knit line. While the strain is not directly measured normally, indications are that the failure strain is slightly over 2%. As a further comparison to the bulk PVC properties, Figure 10 is a histogram of the UTS and failure elongation for the standard tensile samples taken from the tops and bottoms of the extrusions (with no transverse knit lines). The UTS of web knits 1 is consistent with the bulk material UTS. Similarly, one can see that elongations well above 20% are generally expected. Figure 10 shows a comparison of the UTS and elongation at break during the web knit test for webs 1 and 8. This reveals that the web 1 knits behave similar to the bulk material whereas the web 8 knits have reduced strength and markedly reduced elongation.

The web knit test results reflect short time (load applied over minutes) tensile tests and one cannot conclude that the knits would survive to the same level of creep strain under long loading times (20 years). Since the predicted level of strain is comparable to the short time strain measured, a study of the creep rupture times for the web knits was undertaken.

Creep rupture tests involve applying a fixed load and recording the time of failure. It is expected that the failure stress plotted versus log time is linear (with a conservative departure from linearity at low stresses). Using this linearity, longer time creep rupture can be extrapolated.

Initial creep rupture testing was done at Argonne National Laboratory (ANL) using the Universal testing machine for various stresses such that failure was recorded in times on the order of seconds and days. For much longer time, a fixture was constructed at Fermilab National Accelerator Laboratory (FNAL) and two tests were run at lower stress and for much longer times. Both tests were performed at nominal room temperature using samples cut from web 7 which are considered to be among the worst. The results are shown in Figure 11 and labeled as ‘ANL-Tinius Olsen’ and ‘FNAL-fixed weight’ respectively. Linear extrapolation of these results suggests that the web knits will not fail during the twenty year life. Due the time required to run these tests, additional tests were performed at elevated temperature with the hopes of gaining predictive capability and further to confirm that the failure mechanism was similar. Creep rupture tests were performed at 60 °C to evaluate the process (performed at Illinois Institute of Technology). These results are also shown in Figure 11 and labeled as ‘at 60 °C’. As is seen in the figure, the data is consistent with the expected shift in log time due to the higher temperature. Then using these results as the prediction for creep rupture at 20 years, we get agreement with the extrapolated room temperature values. A typical failure surface from a web knit test is shown in Figure 12. The surface indicates different failure zones with the central region showing a more brittle fracture as compared with the more ductile appearance on the outer edges. Based on other results, it has been shown that this central region maintains about 85% of the bulk UTS. It is postulated that during strain controlled tensile testing, this central region fails first at a very low strain (<2%) with the load then transferring to the outer area with significantly less area to support the load thereby leading to premature rupture compared to the bulk material. That is, the central region of these center web knits provides strength but almost no ductility.

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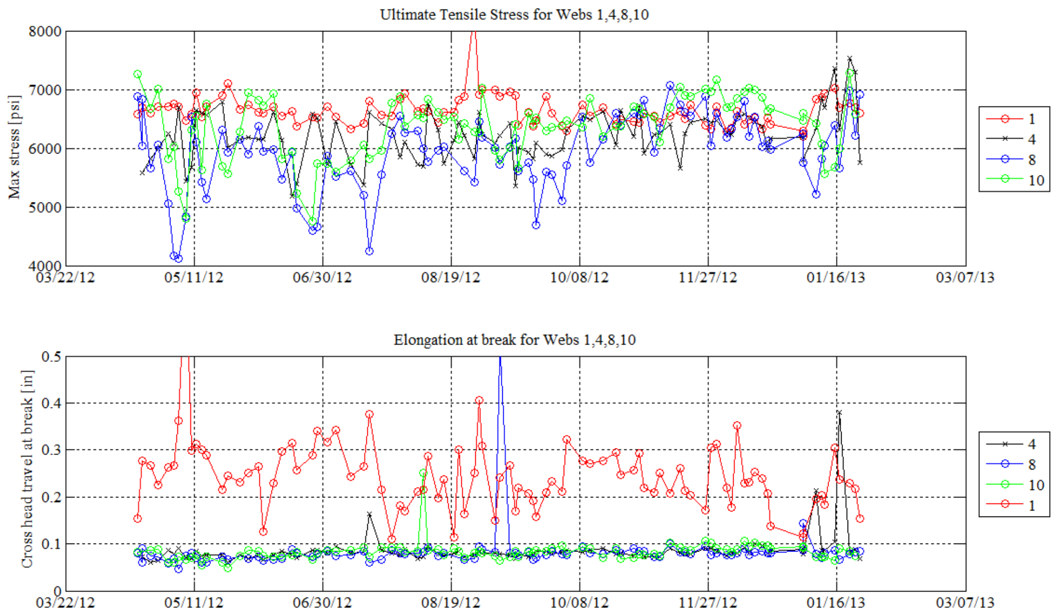

Figure 9 Ultimate tensile tress and elongation for webs taken from QC testing.

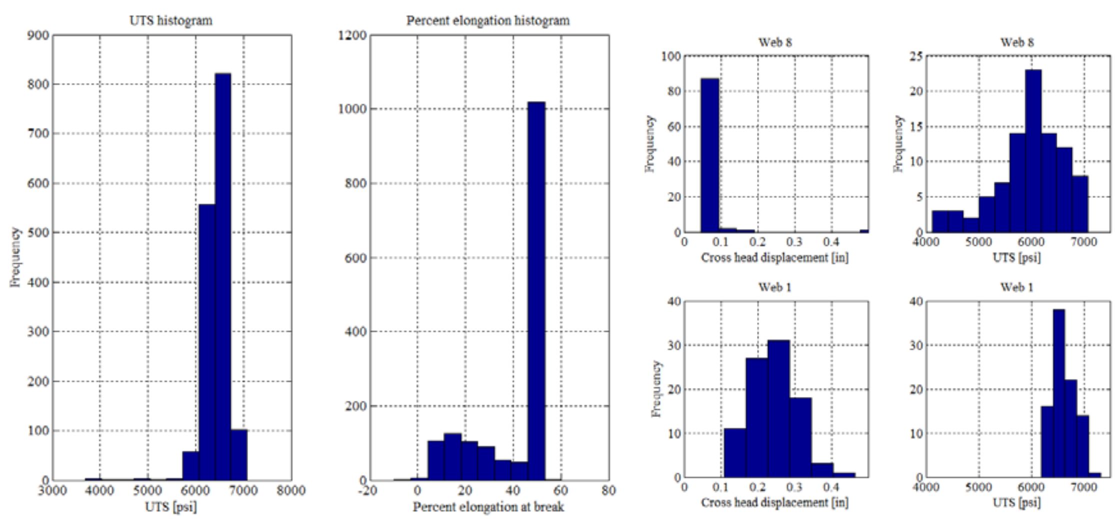

Figure 10 Left plot: Histogram for UTS and percent elongation for standard tensile samples made from start of production until Jan. 2012. Right plot: Histogram shwing difference in elongation and ultimate tensile strength of central (web8) and outer (web 1) webs.

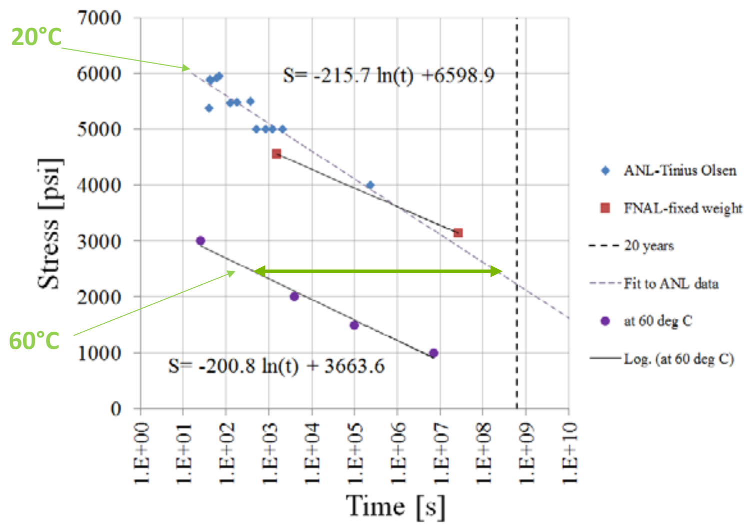

Figure 11 Web knit creep rupture test comparison.

Figure 12 Typical failure surface of central web knit showing distinct failure surfaces.

5.3 Geometry

The assembly of the modules and blocks required relatively tight tolerances. Achieving these was problematic particularly due to the difficulty of extruding our unique formulation. The biggest challenges were maintaining thick enough webs without creating an imbalance in the overall profile thickness. There was also trouble in maintaining the internal cell radii although it could be expected due to the lack of sizing for internal cells. While we had to accept dimensions different from those originally planned, we did find the final dimensions to be relatively repeatable which was our primary goal. In our early production experience, we found that we had to open up several tolerances such as the web location in order to not unnecessarily reject otherwise excellent extrusions. Our choice was to make a modification to the auxiliary matching parts if needed.

6 Summary/conclusion

A complex PVC extrusion was developed to form the main components of a large self-supporting structure. The high TiO_2 loading needed due to reflectivity requirements presented considerable difficulties in extruding. The extrusions were successfully made after an extensive R&D effort which required iteration between the formulation, extrusion process, die design, and PVC compounding process.

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8 References

1. Brostow, W. and Corneliussen, R.D., *Failure of Plastics*, Hanser, 1986.
2. Struik, L.C.E., "The Mechanical Enhancement of Physical Aging", Polymer, Vol. 21, August 1980, pp. 962-7.