A Primer on TDR Probe Construction[1]

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Introduction

There are many ways to make probes for time domain reflectometry (TDR) measurement of the water content of porous materials. At Bushland we experimented with several bifilar (two rod) and trifilar (three rod) probe designs before settling on the trifilar probes whose construction is detailed in this document. Our probes are generally inserted horizontally into the side of a soil pit so as to provide measurements of water content of several fairly thin layers of soil near the surface. Typical depths are 2, 4, 6, 10, 15, 20, and 30 cm in an array of seven probes, each one directly above or below the other. The pit is backfilled to approximate field bulk density, and the cables are buried at about 10 cm depth up to the point where they emerge from the ground to enter a multiplexer case. Probes are usually installed well ahead of the measurement season so that the soil in the pit may come into equilibrium with the undisturbed soil around it. Because we push the probes into the undisturbed soil, our probe rods are pointed and the diameter of the rods was kept to 1/8 inch to make insertion as easy as possible. With this rod diameter, it is good to keep rod-to-rod spacing to not more than 3 cm (Knight, 1992). We also make a 15-cm hand-held probe that is used by pressing it vertically into the soil to make measurements of water content to 15 cm. The rods in this probe must be heavier to withstand repeated insertions during transect measurements, so the rod diameter is 3/16 inch. Some of the photographs shown here are of the construction of a hand-held probe. Over nearly ten years of constant field use, the type 316L stainless steel rod has withstood corrosion very well.

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[1] Mention of trade names or other proprietary information is made for the convenience of the reader and does not imply endorsement by the USDA, Agricultural Research Service.

We decided to use a trifilar design because Zegelin et al. (1989) showed that it eliminated the need for an impedance matching balun. Also, Alsanabani (1991) showed that a trifilar probe could measure to within 2 cm of the soil surface without needing a separate calibration or correction. The soil at Bushland contains a swelling clay that, although not at all saline, still conducts the high frequency components of the TDR signal when wet. To ensure that we obtained wave forms that were interpretable at high water contents we limited the length of our buried probes to 20 cm. For other soils, we have made probes up to 1.5 m in length using the same basic design, and successfully used them. The 1.5 m probes are in use at Ismailia, Egypt in a deep aeolian sand. We have also built mini-probes as short as 5 cm with 1/16 inch diameter rod and 0.64 cm spacing. These are used in soil columns and for measurements in crusts. Details of construction are appended to this document.

Because we do long term monitoring, we needed probes that would be resistant to corrosion. So, the probes described here are made from acrylic and epoxy resin, and all electrical connections are potted in the epoxy. Experience with several hundred probes over nearly ten years has never resulted in a problem with the connections in the probe handle. Early on, we used crimp-type BNC connectors for the cable ends. Experience showed these to be prone to failure, and we have since used a clamp and solder type connector that has never failed when used within a rain tight case.

For automatic data collection it is useful for all probes to have the same dimensions both outside of and within the probe handle, so that automatic wave form analysis programs can routinely reduce the wave forms to water contents without errors induced by errors in rod lengths, either in the soil or in the handle. (But, note that the TACQ program for running a TDR system can accommodate a different rod length in the soil for each probe if these lengths are known and entered into the program setup). Also, if the rod spacing in the handle is consistent, then a single spacer can be used to space the rod ends of each probe as it is inserted into the soil, and the rods will not create air gaps as they are pushed into the soil. The construction methods detailed here allow for consistent and accurate rod spacing and length, both within and outside of the handle. With the single exception of the polyurethane molds the needed equipment is readily found in, or can be built in, most workshops.

Materials List:

Acrylic plastic, 1/4 inch thick.

Stainless steel rod, 1/8 inch diameter, type 316L. Available at welding supply houses. Avoid rod with stamped ends.

Coaxial cable, type RG58/U, tinned braided outer conductor with at least 95% coverage, tinned stranded inner conductor. Allied product no. 708-9855, Alpha 9058AC RG58A/U coaxial cable; or Belden #8219 RG58A/U.

Epoxy potting resin. Two part compound including base and hardener. $58.00 per quart from Virden Perma-Bilt, Amarillo, TX. A long cure (≥24 h) resin will be much more water resistant than short cure resins.

Mold release. Frekote LIFT mold release and Frekote 700-NC releasing interface.

Carbon black. Used or new photocopier toner works well. Only needed if opaque probe handles are desired.

Bare, tinned 22 gage copper wire.

Male, clamp type BNC connectors. Altex part no. 9021, BNC male solder & clamp connector.

Rosin core solder, small diameter.

Silver solder and flux (Welco #5).

vinyl tape (electrician's black tape).

Equipment List:

Polyurethane potting molds.

Cable cutting jig for cutting cable to reproducible length.

Table saw and thin carbide blade for cutting plastic pieces.

Drill press, jig, 1/8 inch diameter bit, and 3 cm aluminum spacers for drilling plastic pieces.

Bench sander for removing potting compound flash from potted probes.

Rod shear and stop for shearing pointed stainless steel rods to length.

Vise and wood block for soldering rods to 22 gage wire and to cable.

Assembly jig for assembling rods to plastic pieces and soldering outer conductor.

Length jig for glueing rods in plastic pieces at precise length.

Potting jig for holding molds and probe assemblies during potting. May be same as length jig.

Holding arms for holding partly finished pieces.

45 Watt soldering iron.

Wood spacer blocks with three 1/8" diameter holes drilled at 3 cm center-to-center.

Small binder clips for clamping plastic pieces (two per piece).

Plastic Piece Preparation:

Using a thin carbide blade in a table saw, cut the 1/4 inch thick acrylic plastic sheet into long strips 1.4 cm wide. Note that a relatively rough edge, as obtained by sawing, is preferable for good adhesion of the potting compound. The glassy edge obtained by scoring and snapping does not make for good adhesion. Cut the plastic strips into lengths 7.5 cm long (one per probe) and sand one side to improve adhesion of the epoxy potting compound.

Set up the drill press with the L-angle jig and 1/8 inch diameter bullet nosed bit. (The bullet nosed bit does not wander as badly as regular bits). Use the L-angle jig and the 3-cm aluminum spacers to drill three holes spaced 3 cm apart and centered from end-to-end and side-to-side in the plastic. Hold the plastic down during drilling. The bit will pull up on the plastic, and if the plastic moves up an oblong hole will result and the fit of the stainless steel rod in the hole will be poor. Discard pieces with oblong or oversize holes.

Figure 1. View of the L-angle jig for drilling holes in acrylic pieces with exact separation and in line. Note clamps holding jig to drill press.

Figure 2. Closer view of 3-cm wide aluminum spacers, and acrylic piece in position for drilling first hole. Note that drill bit is for 3/16 inch rod.

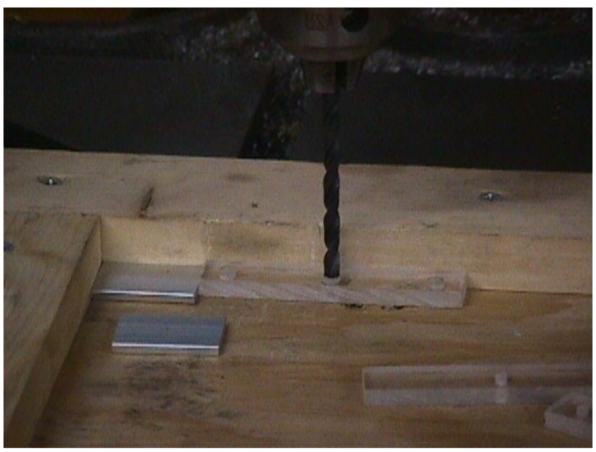

Figure 3. One spacer has been removed and acrylic piece has been moved against remaining spacer before drilling second hole.

Figure 4. The second spacer has been removed and the acrylic piece has been moved to the corner before drilling the third hole.

Rod Preparation:

Set up the rod shear and length stop for correct length using a pre-measured length standard. Return the standard to its box. Generally the rod length should be the nominal probe length (eg. 20 cm) plus 1.35 cm. The 1.35 cm is the length of the rod that will be encased in the plastic handle.

Bevel a 1/8 inch diameter type 316L stainless steel rod on both ends using a bench grinder with a medium to fine grit carborundum wheel. Flat the pointed ends slightly with the grinder.

Run the rod through the shear until it hits the length stop and cut it. Remove the cut end and put in a box.

Reverse the rod and cut the other pointed end and place in box.

Continue beveling, flatting and cutting the rod until it is too short.

Place the waste rod in a waste box for recycling.

Repeat until enough rods are prepared for the production run.

Figure 5. Beveling the end of the rod. The rod in this photo is 3/16 inch diameter, not the 1/8 inch diameter rod that we commonly use.

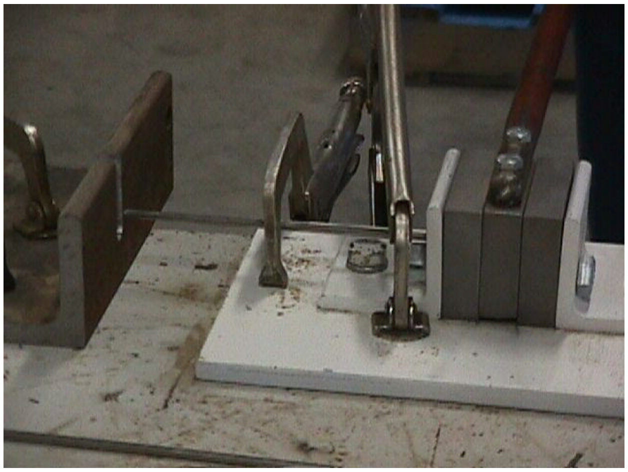

Figure 6. The rod shear is clamped to the table top (right), and the rod stop is clamped in position (left) using a standard length rod (21.35 cm) inserted into the shear so that it butts against the cutting edge. Note the vertical slot in the rod stop. It is used for removal of a rod after cutting.

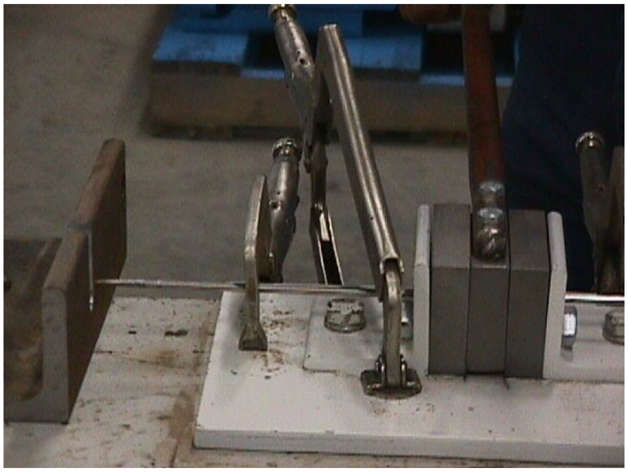

Figure 7. A pointed rod is inserted through the shear (from the right side of this photo) and butted against the rod stop (on left in photo). Pressing the shear handle cuts the rod to exact and reproducible length. The rod is extracted by bending it slightly so that it passes through the slot in the rod stop.

Cable preparation:

Cut the RG58/U coaxial cable to length (normally 3 or 4 m) using pre-measured length gauge (e.g., a length of plastic pipe with a tongue cut in one end for cable clamping and marks for various cable lengths). Cut as many pieces as needed for a production run.

For all lengths of cable:

Strip 1.5 cm of outer insulation from one end.

Separate the braid (outer conductor) and form a pigtail on one side, exposing the inner insulation.

Strip about 1.3 cm of inner insulation from the end, exposing the center conductor, and twist the conductor strands together.

Figure 8. Using a coaxial cable stripper to cut through the outer (black) insulation prior to removing it.

Figure 9. Separating the outer braid so that a pigtail can be twisted.

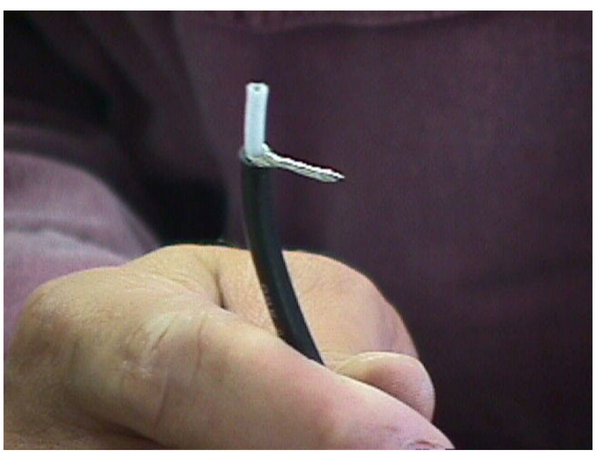

Figure 10. After 1.5 cm of outer insulation was removed and the outer braid twisted into a pigtail.

Figure 11. Stripping insulation from the inner conductor of the coaxial cable.

Put a stainless steel rod in one hole in the wood block (block should be clamped in vise).

Wrap the center conductor around the end of the rod, apply flux (Welco #5) and solder with silver solder.

Remove the rod from the block and hang the cable with rod attached on a holding arm.

Repeat until all cables are prepared.

Figure 12. A wood block a in vise used for holding rods while soldering. A metal block may also be used as in Fig. 13.

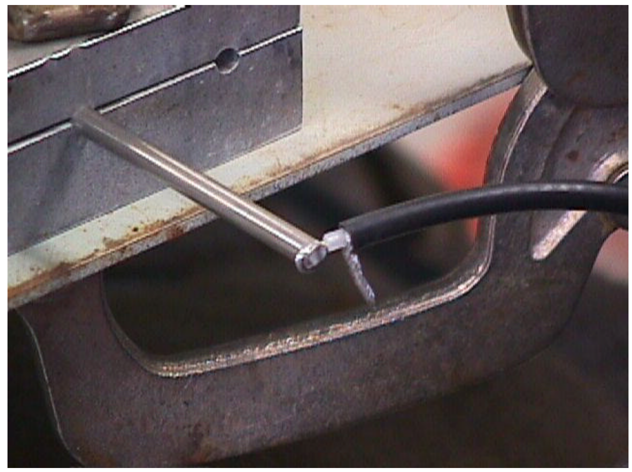

Figure 13. The middle rod with the cable inner conductor soldered to it with silver solder. Note that the outer conductor is twisted into a pigtail.

Outer rod unit soldering:

Cut 22 gage tinned, solid, bare wire to 9.5 cm length (one per probe).

Place two stainless steel rods in the outer holes (spaced 6 cm apart) in the wood block (block previously clamped in vise) or in aluminum clamping blocks.

Wrap the 22 gage wire once around the end of one rod, apply flux (Welco #5) and solder with silver solder (45 Watt iron).

Wrap the other end of the 22 gage wire around the end of the other rod and solder. When finished the wire should be loose between the rods (Fig. 15).

Figure 14. An alternative to a wood block for holding the rods during soldering is a machined aluminum clamping device. The wire between the outer rods has been soldered.

Remove rods from the wood block and set aside.

Repeat until all outer rods are prepared.

Probe assembly:

Place a pre-drilled plastic piece against a wood block clamped to the table, with the sanded side away from the block. The wood block is pre-drilled with three oversized holes spaced at 3-cm center-to-center.

Place the ends of the outer rods in the outer holes in the plastic and press rods through holes until about 2 cm of rods are left above plastic.

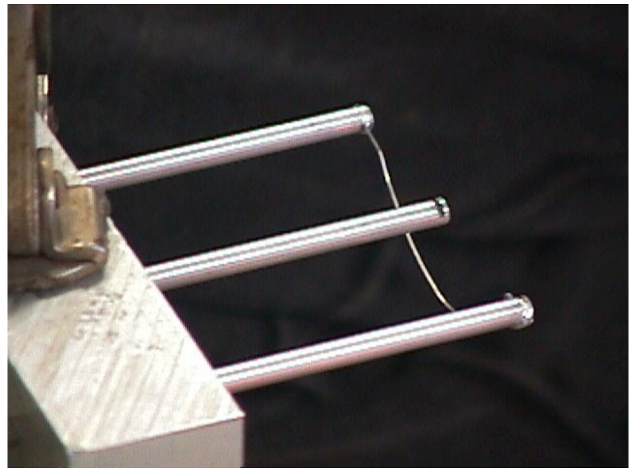

Figure 15. Closer view of wire soldered to the outer two rods. The center wire of the coaxial cable will be soldered to the center rod.

Place the center rod in the center hole in the plastic and press through until even with outer rods.

Rotate the center rod if necessary so the cable pigtail is centered over the long axis of the plastic piece.

Figure 16. Pressing outer rods through holes in acrylic piece. The wood block clamped to the table has holes for all three rods.

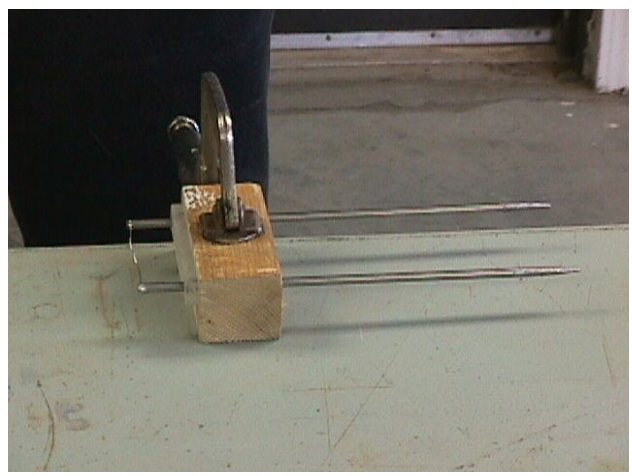

Figure 17. The outer rods after being pressed through the holes in the acrylic piece. They will be pressed through slightly more when the rod length is set.

Twist the pigtail (outer conductor) around the 22 gage wire and solder with rosin core solder leaving some slack in the 22 gage wire on either side of the center conductor.

Remove the probe assembly from the jig and hang on a holding arm.

Repeat until all assemblies are finished or enough assemblies are finished to use all molds.

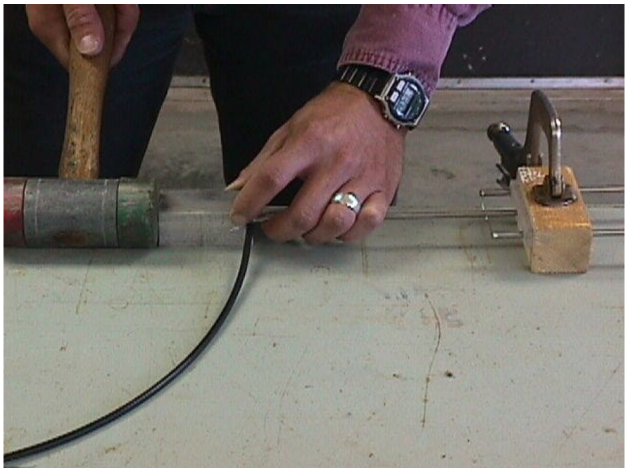

Figure 18. Pressing the center rod (with cable already soldered to it) through the center hole of the acrylic piece.

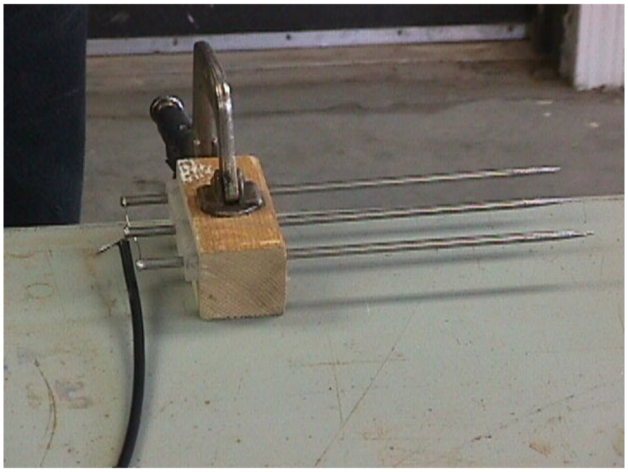

Figure 19. The center and outer rods have been pressed through the holes in the acrylic piece. The pigtail is not yet soldered to the wire connecting the outer rods.

Setting probe length:

Place the probe assemblies on the length jig (previously adjusted to correct length) by running the rods through the holes in the metal plate at the top of the jig and taping the cable to the overhead pipe. Leave a little slack in the cables.

Place wood spacers on the ends of the rods.

Clamp the plastic pieces to the top metal plate using binder clips.

Press the rods through the plastic until they bottom out on the bottom metal plate, making sure that the rods are square with the metal plate and all rods touch the bottom plate. This requires some adjustment of the wood spacer block so that the rods will slide through it and it is square with the jig (horizontal) when all is done.

Repeat until all assemblies are in the jig.

Glue the rods to the top of the plastic pieces using epoxy glue. Use long cure, two part epoxy, such as Devcon 2-ton® epoxy. Avoid quick curing epoxies such as Devcon 5-Minute epoxy. Most quick curing epoxies are water soluble.

When the glue has set (several hours or overnight) remove the clamps and wood spacers and place the assemblies on a holding arm.

Figure 20. The length jig. The lower aluminum rail is fixed to a sheet of plywood that is independent of the jig stand and may be moved up or down using the threaded rods located at the left and right sides. Using a rod, or rods, cut to precise length, the jig may be adjusted to have the desired distance between the top aluminum rail (center of photo) and the lower rail.

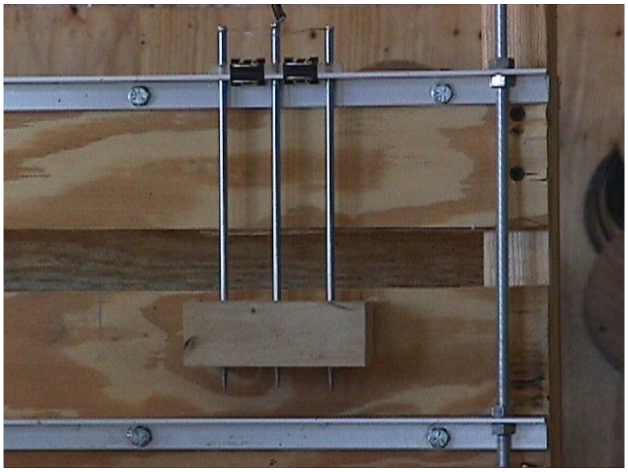

Figure 21. The probe assembly has been placed on the top rail with the rods running through oversized holes in the rail. The acrylic piece is clamped to the top rail with two binder clips. A wood block is placed over the ends of the rods to maintain correct spacing. Rods are not yet pressed into final position.

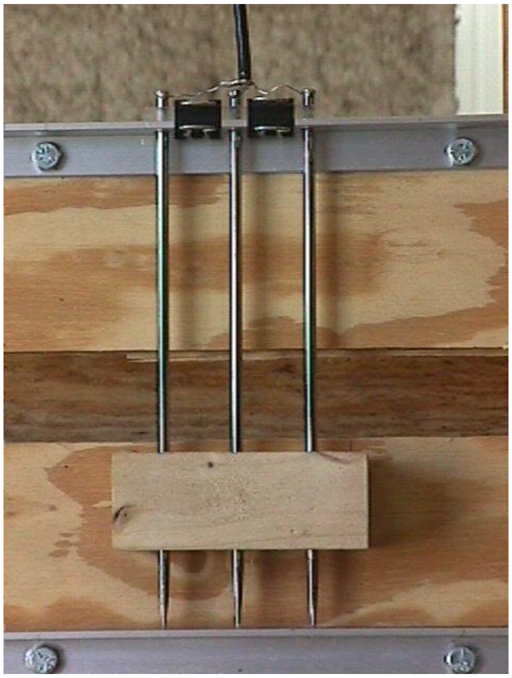

Figure 22. The rods have been pressed down through the acrylic piece until they touch the bottom rail.

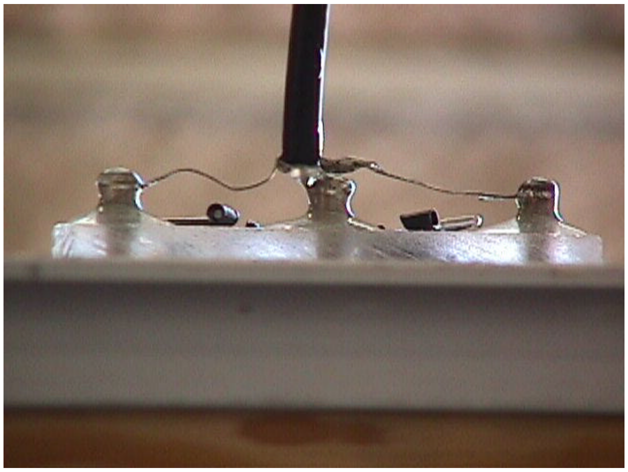

Figure 23. View from the back of the jig showing the rods glued with epoxy to the top of the acrylic piece. The pigtail was previously soldered to the wire connecting the two outer rods.

Potting of assemblies:

Place the molds on the top metal rail of the potting jig and spray with the first release compound, Frekote lift.

Wait one half hour and spray with the second release compound, Frekote 700-NC.

Figure 24. Top view of a polyurethane mold and spray cans of release compound.

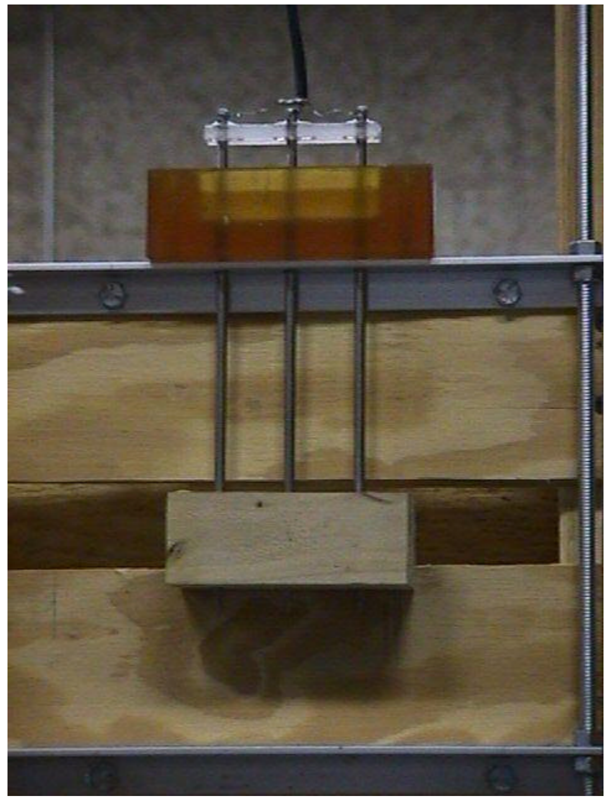

Figure 25. The probe assembly is partially inserted into the mold. The wooden block maintains rod spacing during casting and curing.

Place the probe assemblies in the molds by pressing the rods through holes in the molds. Tape the cable to the overhead pipe. Make sure that the plastic pieces bottom out on the bottoms of the molds. Use wood blocks to press on the tops of the rods to achieve contact between the plastic piece and the bottom of the mold, but avoid excessive force as this may break the bond between the rods and epoxy glue.

Repeat until all molds are filled with assemblies.

Mix the epoxy potting resin. (Add carbon black or used copy machine toner if opaque handles are desired. The color is not necessary). For 16 probes, use 6.5 fluid ounces each of the base and hardener resins and one tablespoon of carbon black. Use a disposable aluminum bread pan and mix well using a wooden spatula or bamboo rods. The pan can be used several times before disposal. Note that the 1:1 mixing ratio for the epoxy from Virden PermaBilt is actually 1:1 by mass. But the mixing ratio for this epoxy is non-critical and a 1:1 mix by volume works just fine. One may also add 20% by volume of hollow glass microspheres sold by 3M. The microspheres will improve (lower) the permittivity of the handle and result in a white or cream-colored handle.

If smaller quantities of resin are mixed it is wise to weight the components rather than using volume measurements. Weighing fairly large measured volumes of each component will give the density of each, which then can be used to calculate the weights (masses) needed for correct mixing, including the 20% by volume of glass spheres.

Figure 26. Plastic cups used to measure out volumes of spherical glass beads (left) and parts A and B epoxy resin (center and right).

Figure 27. An aluminum dish with potting compound components added, prior to mixing with a wooden spatula.

Pour potting compound into the molds using a rod to pour along and control drip. Or, pour the epoxy down the side of the cable. Fill molds to the top, plus a little.

When all molds are full wait a few minutes and pop any bubbles that appear at the surface. Bubbles may be popped using a pointed rod or a heat gun or blow dryer.

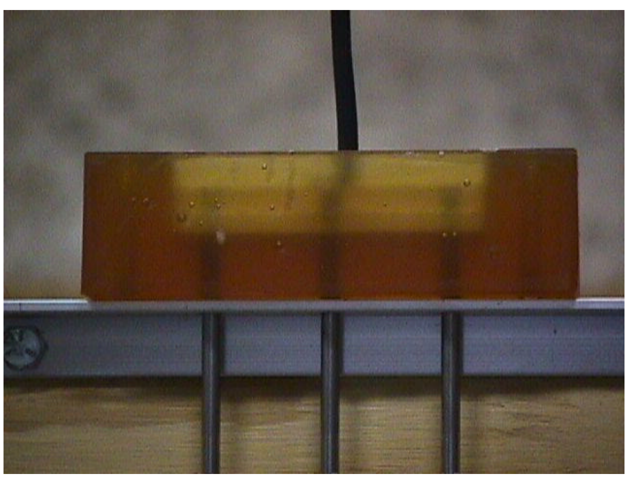

Figure 28. The acrylic piece has been pushed to the bottom of the mold prior to adding potting compound.

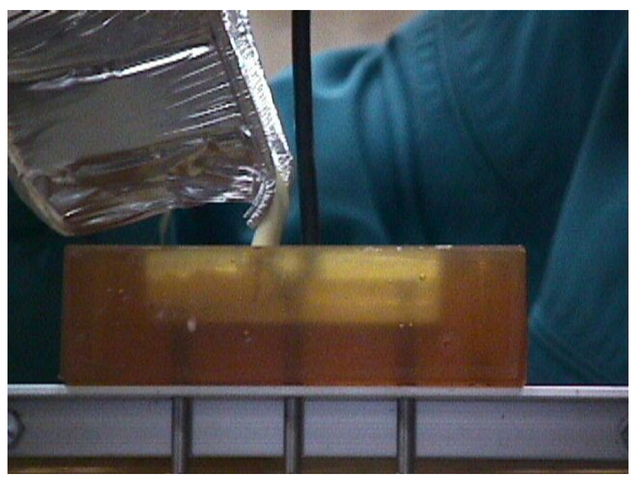

Figure 29. Pouring the thoroughly mixed epoxy potting compound into the mold. In this case the color is white due to the addition of hollow glass spheres to improve dielectric properties.

Add epoxy to any molds that are not quite full.

Return after one hour and pop any bubbles that appear.

Allow 24 hours to cure at room temperature, more if below room temperature.

Remove the potted assemblies from the molds by running a dull knife between the mold and newly formed probe handle on both long sides of the mold, followed by lifting the mold and tapping the bottoms of the rods against the top metal rail on the jig. The probes should slide out easily if the molds were properly sprayed with release compound.

Hang the cables over a holding arm.

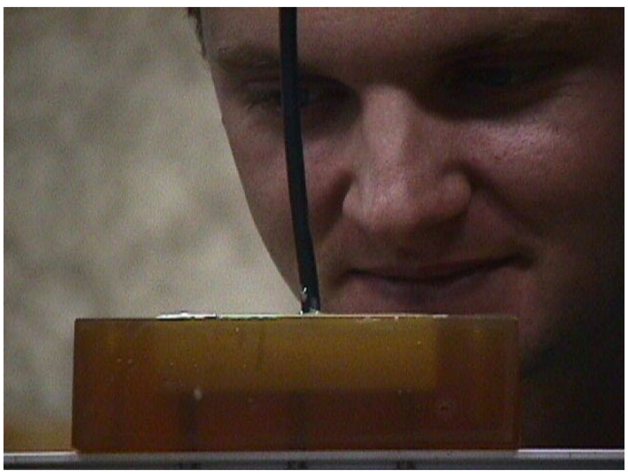

Figure 30. Brice Ruthardt inspects the mold filled with potting compound.

Figure 31. The finished probe after removal from the mold.

Attaching BNC connectors (clamp/solder type):

Place the nut, metal washer and rubber washer on the cable.

Strip the end of the cable using a coaxial cable stripper that has been set to cut through the outer insulation on one side and the inner insulation on the other (side closest to the end). The deep cut should be about 3 mm from the cable end, while the shallow cut should be about 9 mm from the end.

Place the metal cone over the outer braid and slide until it seats against the end of the outer insulation. Then fold the outer braid over the cone, holding it in place at the end of the outer insulation.

Twist the center conductor strands together and tin them with solder.

Place the center pin in a vise and tin it with solder.

Figure 32. A coaxial cable stripper sold by Radio Shack. The blade on the left side (visible on top of stripper in this view) is set to cut through only the outer cable insulation. The blade on the right side (not visible here) is set to cut through the outer insulation, cable braid, and inner insulation, but not through the center wire of the cable.

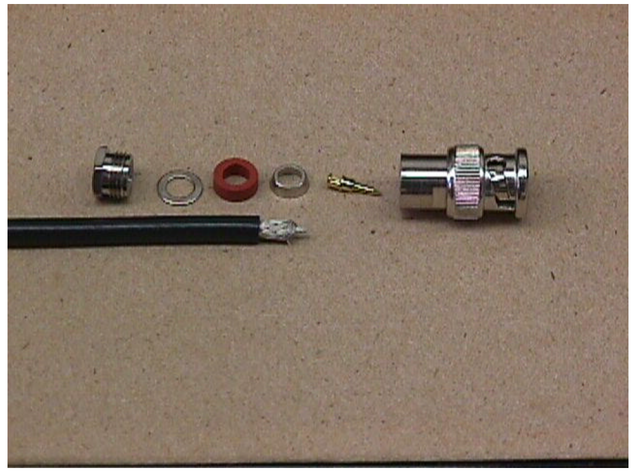

Figure 33. A stripped cable end and components of the BNC connector, from left to right: nut, washer, rubber compression ring, cone, center pin, and connector body. A 3-mm long section of the cable is stripped to the inner conductor, and an additional 6-mm length has the outer insulation stripped from the outer braid.

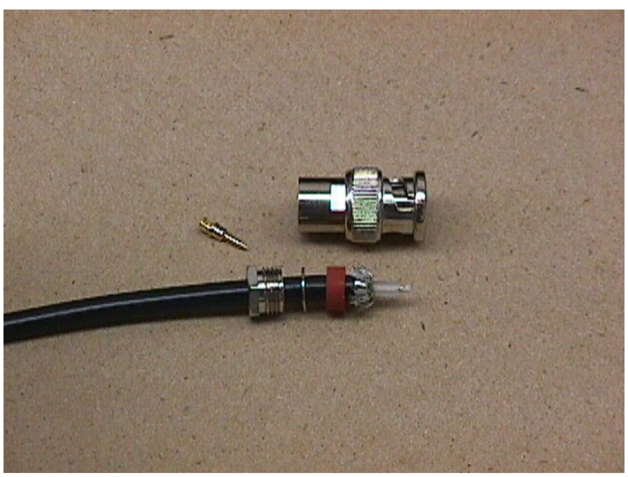

Figure 34. The nut, washer, and red rubber ring have been placed on the cable. Then, the cone was placed over the braid until it seated against the cut edge of the outer (black) insulation, and the braid was folded back, covering the cone.

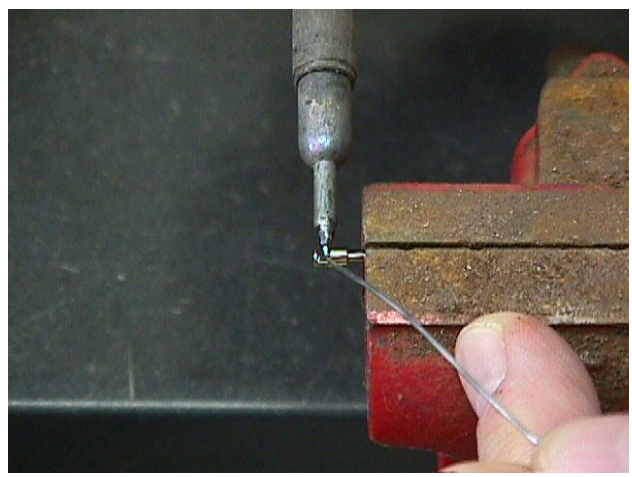

Figure 35. The center pin has been secured in the vise and is being tinned.

Solder the center conductor into the center pin.

Release the vise and place the body of the connector over the pin.

Screw the nut into the body of the connector using pliers to get a tight connection.

Repeat until all connectors are on.

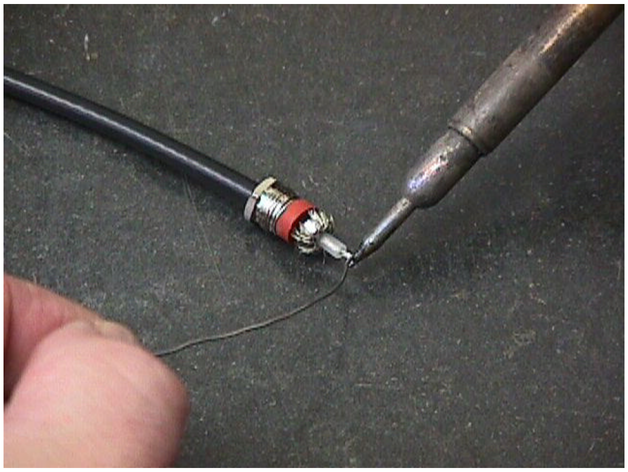

Figure 36. Tinning the center conductor.

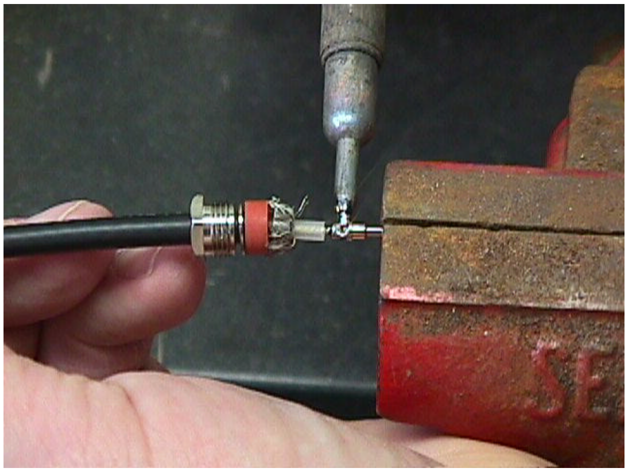

Figure 37. Soldering the center conductor inside the center pin. The solder in the center pin is melted first, then the cable end is pushed into the hole in the end of the pin.

Figure 38. The cable with components in place for final assembly during which the nut at left is screwed into the body at right.

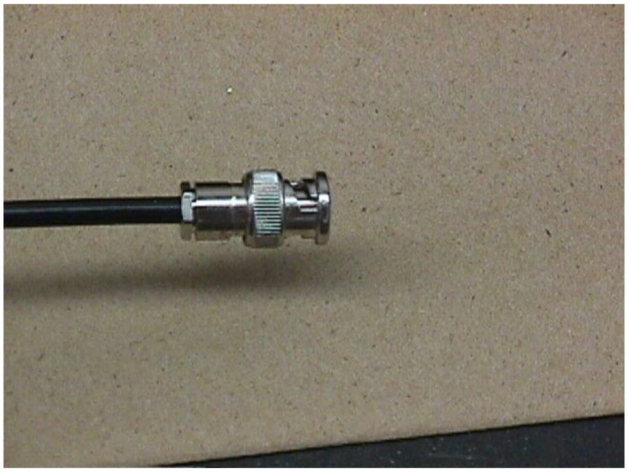

Figure 39. The finished connector.

Finish and Testing:

Use a bench sander to remove excess epoxy (flash) from the top sides of probes. If the acrylic piece was pressed tightly against the bottom of the mold there should be little or no flash on the side of the probe handle where the rods are. Remove any flash on the handle around the rods.

Remove any epoxy adhering to the rods. The rods should be clean over their entire length.

Straighten any rods that are out of alignment. All rods should be parallel and square with the probe handle.

Test each probe by immersing the probe in a container of water and plugging it into a cable tester. The trace on the cable tester screen should closely match the bottom trace in the figure below. Absence of a first peak or obvious short (trace drops off the screen) are causes for rejecting the probe. Wiggle the connector and watch the trace to make sure that the connector is not loose or poorly soldered. The trace should not move or disappear when the connector is wiggled.

The first peak in the trace should appear at the same position on the cable tester screen for all probes with the same cable length.

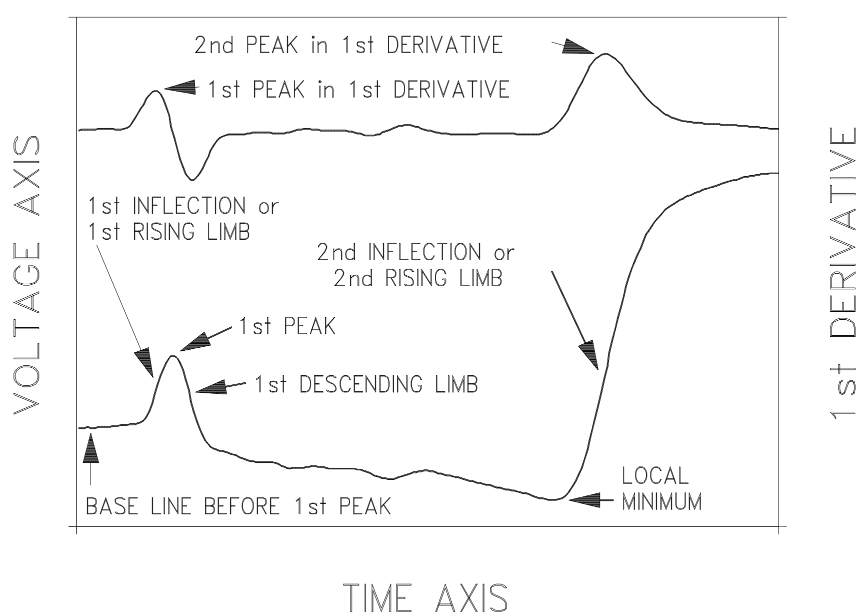

Figure 40. A typical wave form (bottom trace) for a TDR probe in wet sand.

TDR Microprobe Manufacture (5 cm probes with 1/4 inch rod spacing)

Special Considerations:

Exact rod length, both outside the probe handle (5 cm length) and within the handle (1.35 cm length) is critical for these short probes. Length inaccuracies that would constitute a minor percentage of water content for longer probes will cause larger errors for small probes. Holding the rods parallel and separated by 1/4 inch during soldering is crucial because passing the rods through the acrylic plastic piece becomes virtually impossible if the spacing isn't correct. Due to the short length of the rods it isn't feasible to solder the cable to the rods after the rods have been pushed into the plastic piece - the plastic melts. Grinding the excess epoxy from the probe handle after potting is time consuming and prone to error. Having molds made would make the potting step easier, eliminate the grinding, and result in a nicer looking and more reproducible product.

Materials List:

Acrylic plastic, 1/4 inch thick.

Stainless steel rod, 1/16 inch diameter, type 316L. Available at welding supply houses. Avoid rod with stamped ends.

Coaxial cable, type RG58/U, tinned braided outer conductor with at least 95% coverage, tinned stranded inner conductor. Allied product no. 708-9855, Alpha 9058AC RG58A/U coaxial cable; or Belden #8219 RG58A/U.

Epoxy potting resin. Two part compound including base and hardener. $58.00 per quart from Virden Perm-Bilt, Amarillo, TX.

Mold release. Frekote LIFT mold release and Frekote 700-NC releasing interface. (Not needed for microprobe construction without molds.)

Carbon black. Used or new photocopier toner works well. Only needed for opaque probes.

Male, clamp type BNC connectors. Altex part no. 9021, BNC male solder & clamp connector. RF Industries #RFB-1100-2.

Rosin core solder, small diameter.

Silver solder and flux (Welco #5).

vinyl tape (electrician's black tape).

Blue masking tape, 1 ½ inch wide, or 1 inch wide if that is all that can be found.

Equipment List:

Cable cutting jig for cutting cable to reproducible length.

Table saw and thin carbide blade for cutting plastic pieces.

Drill press, jig, 1/16 inch diameter bit, and 1/4 inch spacers for drilling plastic pieces.

Bench sander for removing excess potting compound from potted probes.

Diagonal cutters, fine file, and bench grinder with fine grit wheel for cutting and trimming rods to length.

Vise and jig blocks for soldering rods to cable with correct spacing.

Potting jig for holding probe assemblies during potting.

Holding arms for holding partly finished pieces.

45 Watt soldering iron, 15 Watt soldering iron.

Plastic Piece Preparation:

Using a thin carbide blade in a table saw, cut 1/4 inch thick acrylic into long strips 1.4 cm wide. A relatively smooth edge is preferable for good contact with the masking tape that is used to form a potting boat.

Cut strips into lengths 7 cm long (Note: the final length is 2.5 cm and you may cut to this length but a longer length is advised. See note below).

Set up drill press with L-angle jig and 1/16 inch diameter bit.

Use jig and spacers to drill three holes spaced 1/4 inch apart and centered from end to end (over the 2.5 cm final length) and side to side in the plastic. Hold plastic down during drilling. The bit will pull up on the plastic. If the plastic moves up an oblong hole will result and the fit of the stainless steel rod in the hole will be poor. Discard pieces with oblong or oversize holes, or with the 3 holes not in a straight line.

Cut pieces to final length of 2.5 cm. (Note: the longer initial length helps keep the piece straight in the jig - 2.5 cm pieces may be used but tend to wobble in the jig because of their shortness and minor imperfections in the saw cuts. The wobbling can cause the holes to not be lined up in a straight line.)

Repeat until enough pieces are ready.

Rod Preparation:

Generally the rod length should be the nominal probe length (eg. 20 cm) plus 1.35 cm. The 1.35 cm is the length of the rod that will be encased in the plastic handle. Prepare a length gauge by cutting a length of 1/16 inch diameter rod to slightly longer than 6.35 cm and trimming both ends with a file to exact length. Trim so that the ends are flat, and square with the long axis of the rod.

1) Flatten a 1/16 inch diameter type 316L stainless steel rod on one end using a bench grinder with a medium to fine grit carborundum wheel.

2) Place the length gauge (e.g. 6.35 cm long rod for 5 cm microprobes) parallel to the rod and use the diagonal cutters to cut the rod by moving the cutters to the end of the length gauge and cutting. This produces a piece that is slightly too long.

3) Repeat steps 1 and 2 until as many pieces as needed are made.

4) Use a fine file or the bench grinder to trim the pieces to exact length, comparing to the length gauge frequently. Trim the end that was cut with the diagonal cutters (the other end has already been ground flat). If the grinder is used, be careful to take off only a little metal at one time and compare to the length gauge frequently - otherwise it is easy to take off too much and end up with a short piece. Do not try to trim the pieces while the length gauge is held against them. This will inevitably cause the length gauge to be shortened.

Place waste in waste box for recycling.

Cable preparation:

Cut RG58/U coaxial cable to length (normally 3 m) using pre-measured length gauge (Example: a plastic pipe with tongue cut in one end for cable clamping and marks for various cable lengths). Cut as many pieces as needed at one time.

For all lengths of cable:

> Strip 1 cm of outer insulation from end.
>
> Separate braid (outer conductor) and form two pigtails at opposite sides, exposing inner insulation.
>
> Strip about 1.3 cm of inner insulation from end exposing center conductor and twist conductor strands together.
>
> Twist the pigtails to a 45 degree angle from the center conductor and on opposite sides of the center conductor. Tin the center conductor and pigtails with rosin core solder.

Repeat until all cables are prepared.

Rod soldering:

Prepare a jig that will hold three rods parallel to each other and spaced 1/4 inch apart.

Put 3 stainless steel rods in the jig and clamp so that all three ends are in a plane perpendicular to the long axis of the rods.

Using silver solder and flux, tin the ends of the rods.

Solder the cable center conductor to the center rod with about a 1/8 inch overlap. Solder the pigtails to the ends of the outer rods, overlapping the pigtails and rods. Cut away excess length of the pigtails using diagonal cutters. Throughout this step the aim should be to avoid creating any sharp projections in the wave guide. Do not cut excess length of the rods. If the rod end sticks out beyond the pigtail, resolder so that the pigtail overlaps the rod with no excess rod showing.

Remove rods from jig and hang cable with rods attached on holding arm.

Probe assembly and rod length setting:

Prepare a 5 cm length standard for use in this step.

Place ends of rods in holes in plastic and slide rods through holes until about 2 cm of rods are left above plastic.

Using 5 cm standard length rod for comparison, slide rods through plastic until exactly 5 cm of each rod is exposed on the side of the plastic opposite the solder connections to the cable. Using super-glue, glue each rod to the plastic on the side where the solder connections are. The setting of exact length and gluing may be done for each rod separately, but all rods will have to be close to the exact length to prevent binding of the rods in the holes. An easy way to do this is to run one rod a little more than 5 cm through the plastic (keeping the other rods at or just a little less than 5 cm), then place the length standard against the rod and hold the probe assembly vertically with the ends of the rods against the table top. Press down on the plastic causing the rod to slide through the plastic until the plastic bottoms out against the length standard. Then glue the rod that has been set to length. Repeat for the other two rods.

Remove assembly from jig and hang on holding arm.

Repeat until all assemblies are finished.

Potting of assemblies:

Coil the cables and tape then to the potting jig with the probe assemblies hanging straight down.

Wrap one inch wide masking tape around the plastic pieces with one edge of the tape even with the bottom of the plastic (side where the rods come out) and the other edge coming up away from the plastic and forming a boat around the soldered cable ends. Use a small amount of silicone sealant around the bottom of the plastic to seal the joint between the tape and plastic. Use the blue, easy release masking tape.

Mix epoxy potting resin adding carbon black (copy machine toner works well) for color if desired. For 16 full size probes use 6.5 fluid ounces of each of the base and hardener resins and one tablespoon of carbon black. Use a disposable aluminum deep bread pan and mix well using a wooden spatula or bamboo rods. The pan can be used several times before disposal. Note that the 1:1 mixing ratio for the epoxy from Virden PermaBilt is actually 1:1 by mass. But the mixing ratio for this epoxy is non-critical and a 1:1 mix by volume works just fine. Also note that for the microprobes much less epoxy is needed. We mixed 80 g of part A and 80 g of part B and poured 7 microprobes and had epoxy left over.

Pour potting compound into masking tape boats using thin bamboo rod to pour along and control drip. Fill boats to top. If a thin bamboo rod is not available you can just pour the epoxy down the side of the cable. In fact this is easier.

After all molds are full, wait a few minutes and pop any bubbles that appear at surface.

Add epoxy to any molds that are not quite full.

Return after one hour and pop any bubbles that appear.

When the epoxy has stiffened enough (overnight or later afternoon if the first pour was made in the early morning), extend the boat higher by wrapping another length of masking tape around the first with enough overlap to seal. If 1 ½ inch wide masking tape can be found then this second pour may not be necessary.

Pour potting compound into the extended boats and repeat the bubble popping.

Allow 24 hours to cure at room temperature, more if below room temperature (about 68 °F).

Use a bench sander to remove excess epoxy from the sides of the potted assembly. Normally this entails sanding away the epoxy until a rectangular form is obtained with the dimensions of the plastic piece dictating the dimensions of the potted form.

Hang cables over holding arm.

Attaching BNC connectors:

Place nut, metal washer and rubber washer on cable.

Strip end of cable with coaxial cable stripper set to cut outer insulation on one side and inner insulation on the other. The stripper sold by Radio Shack works well.

Place metal cone over outer braid and fold outer braid over cone holding it in place at end of outer insulation.

Twist inner conductor strands together.

Place center pin in vise and tin it with solder.

Tin center conductor.

Solder center conductor into center pin.

Remove from vise and place body of connector over pin.

Screw nut into body of connector using pliers to get tight connection.

Repeat until all connectors are on.

Finish and Testing:

Use the methods described previously for larger TDR probes.