CDF/DOC/PLUG UPGR/CDFR/2582
UR-1370 ER-40685-820
September 30, 1994

Techniques for Optical Isolation and Construction of Multi-Tile Assemblies in Scintillator Tile-Fiber Calorimeters Using White Epoxy

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Abstract

In this technical note some of the details of the construction of large multi-tile assemblies (megatiles) for the CDF tile-fiber plug-upgrade calorimeter are described. These very technical details are of interest for LHC detectors which are considering the use of tile-fiber calorimeters. In order for the tile/fiber technique to become viable, procedures were developed to optically isolate and at the same time form a cohesive mechanical bond between the individual cells contained within each multiple tile grouping.

Introduction

The CDF Hadron End Plug Calorimeter is described in detail in the University of Rochester report UR-1360 [1]. The detector consists of 432 towers per endcap with 22 layers of sampling in each tower for a total of 17184 individual channels, which are read out with wave shifting optical fibers. The end plug region is divided into twelve 30^o ϕ sectors comprising groups of 36 (for layers 0 to 2) and 32 (for 3 to 21) towers. For each layer tiles inclusive to 30^o ϕ sectors are bound together in an aluminum encasement called a "pizza-pan." Use of the megatile concept reduces the number of detector elements to 536 integral components.

A early version prototype calorimeter [2] was previously constructed using individually cut, light sealed, installed with wave shifting optical fibers, individually wrapped in protective layers of light reflecting material, and tightly fitted into their respective pizza-pan encasements. This method was labor intensive and due to the delicacy of the fibers, highly susceptible to damage, and not easily accessible for repair. The megatile concept was introduced as an effort to reduce the amount of labor required for production and increase the mechanical integrity of the upgraded plug calorimeter.

In the note, we concentrate on the production methods that were developed (and successfully implemented and tested) for the megatile cutting and bonding. The task was to produce optically separated tiles rigidly connected by cohesive mechanical bonds. Details about quality control measures taken during production are described in U. of Rochester Note UR-1371 [3].

The megatile construction method employs the use of separation grooves cut into a single sheet of Kuraray SCSN38 scintillator to create the internal tile configuration (the last 0.010" of scintillator is left uncut such that the multi-tile assembly is physically connected together during all stages of production). The separation grooves are injected with a TiO_2-loaded epoxy which creates an opaque, light-reflective barrier between adjacent tiles. When the epoxy cures, the cells internal to the megatile are optically isolated from adjacent cells and are bound together into a rigid single component megatile. As described in detail in UR-1360, a black line is drawn on the bottom covering the last 0.010" of uncut scintillator in order to minimize the optical cross talk between the neighboring tiles.

In this note, we discuss the development and application of methods employed for the gluing of the megatile assemblies during the CDF Hadron Calorimeter Plug Upgrade production. Problems throughout the research and development and production phases necessitated alterations in both production methods and also some minor alterations in the design of the calorimeter itself. This note first addresses problems involved in the development and fabrication of the epoxy resin used to bind and optically isolate adjacent tiles in the "megatile" sheet. Production is discussed in two sections describing the preparations for and injection of epoxy into the tile-separation-groove in one section and the post-injection and touch-up procedures in the other section.

Injection of epoxy into separation grooves occasioned problems associated with inadequate sealing of the tops of the grooves during injection as well as problems caused by the curing properties of the designated epoxy. Although these problems were never entirely eliminated, their ability to disrupt production were effectively brought under control through subtle alterations in the separation groove layout and comprehensive production methods that rendered the effects of these problems both predictable and easily treated.

1 Preparation of Separation Groove Epoxy Resin

1.1 Components Used in Separation Groove Epoxy

When our research began on reflective (white) epoxies for use in the CDF Plug Hadron Calorimeter Upgrade, an epoxy resin was procured from Bicron Corporation (BC-699 reflective epoxy resin). The need to develop our own epoxy arose because the Bicron resin could not be economically produced in sufficiently large quantities required for the CDF Plug Upgrade production. In choosing epoxy resins and curing agents, our primary concern was in finding low-color, radiation hard and easily handled compounds. Since most radiation hard epoxy resins tend to be dark in color, they require larger quantities of white pigment be added to achieve the desired reflectivity in our separation grooves. Excessive amounts of filler tends to render pure resin more susceptible to crystalization, thus limiting its shelf life and possibly reducing its mechanical cohesiveness. A facsimile resin of the Bicron epoxy was synthesized by Dr. Jay Hoffman [4] using commercially available pure resins and white pigments. The components chosen were Dow Corporation DER-332 epoxy as the base resin and Dupont Corporation "Ti-Pure R700" titanium dioxide powder as the white pigment. During the research and development period and subsequently during the first four layers of megatile production (layers 18 to 21), when demand for the TiO_2-loaded resin was slow, Dow Corporation DER-736 epoxy resin was mixed in with DER-332 to slow resin crystalization and increase the shelf life of the TiO_2-loaded resin. In subsequent production, when resin storage was no longer an issue due to the volume of megatiles being produced, the DER-736 variant was eliminated. Details of the fabrication of the DER-736 variant are included in this note. Throughout development and production, Texaco Corporation Jaffamine D-230 was used as our curing agent. Once cured, this resin proved satisfactory for our needs despite the possibility of slight surface discoloration which can be caused caused by extended periods of exposure to UV light from unfiltered florescent lights and windows. In this section, we discuss handling instructions for components of the TiO_2-loaded epoxy, instructions for its fabrication, mixing, and storage procedures.

1.2 Handling Instructions

Proper handling of the TiO_2-loaded resin and any of its constituents is important to guard against contaminants that might create unpredictable properties in the resin as well as to avoid any unnecessary exposure to these industrial chemicals. Although none of these chemicals are considered a serious health hazard, inhalation of TiO_2 dust can cause lung damage just as extended exposure to epoxy resins and curing agents can lead to skin sensitivities. Therefore it is best to limit exposure and avoid any unnecessary exposure by taking precautions such as wearing particle masks and gloves. It is recommended that while handling TiO_2, particularly when dispensing it from a storage container, a particle mask be worn to guard against inhalation of TiO_2 dust. Similarly, latex gloves should be worn while handling DER-332, DER-736 and Jaffamine D-230 to prevent skin exposure to these chemicals. Furthermore, to limit inhalation of vapors from these chemicals, it is recommended that all handling of these chemicals be conducted inside a hood. In the event of skin exposure to any of these chemicals, ethyl alcohol is effective in removing residual traces. Consult the

MSDS records for more detailed instructions. Finally, since the work area is prone to spillage, a large pane of glass should be used to cover the work area. The glass is easy to clean and thus expedient to avoiding contamination of the epoxy components.

1.3 Equipment

Equipment used in the formulation of our TiO_2-loaded epoxy resin included an Ainsworth DE-series digital scale, a VWR Scientific brand ball mill, a four quart capacity Roalox ball mill jar with nine alumina-glazed mixing balls, a VWR Scientific model 1350FD convection oven and miscellaneous disposable cups and utensils used for mixing and storage. When anticipating the quantity of TiO_2-loaded resin required for production, it was calculated from epoxy usage based on a prototype megatile that our maximum anticipated daily needs would be satisfied by approximately 600 grams of mixed epoxy. Based on this conservative estimate a four quart capacity ball mill jar was chosen [5]. After determining that the neoprene gasket used to seal the ball mill jar was slightly reactive with the TiO_2-loaded epoxy components, it was replaced with a custom made teflon gasket.

1.4 Fabrication of TiO_2-loaded Epoxy

Since the melting point of pure DER-332 is 42^o C, crystalization frequently occurs at room temperatures. Proper precautions had to be taken to avoid the presence of epoxy crystals during preparation of TiO_2-loaded resin and especially when the Jaffamine D-230 curing agent was added since crystallized epoxy resin might cure at a rate different than uncrystallized epoxy resin, and thus might have weakened the epoxy bond. To eliminate the possibility of crystalization, the DER-332 was placed in an oven at 62^o C for at least three hours prior to use. As mentioned earlier, during the the development stage and also during the initial stage of Plug Upgrade production, DER-736 epoxy resin was mixed in with the DER-332 resin to lengthen the TiO_2-loaded resin's shelf life. While the addition of DER-736 did not prevent crystalization, it did extend the typical shelf life from approximately three days to over two weeks thus enabling us to mix many small batches over a period of weeks without having to contend with epoxy resin crystals clogging our epoxy injection apparatus. Numerous tests were made comparing the optical response of tiles with separation grooves filled with the straight DER-332-TiO_2 resin and the DER-736-DER-332-TiO_2 derivative and it was concluded that there were no discernable difference in the light output of the tiles. The only observed difference between the two resins was that the cure time of the DER-736 derivative was approximately 40% longer then the straight DER-332-TiO_2 epoxy.

When the DER-332 resin was decrystallized, a quantity of 300 grams of it was measured in a container and immediately poured into the ball mill jar [6]. In a

formulation	DER-332	DER-736	TiO_2	Jaffamine D-230
1	100	0	50	32
2	90	10	50	32

Table 1: The ratios of components and curing agent, by weight, for two formulations of TiO_2-loaded epoxy resin.

separate container, 150 grams of TiO_2 powder was measured and dispensed into the ball mill jar. To assist in the mixing, a number of mixing balls, specified by the manufacturer, was placed in the ball mill jar (in the case of our four quart ball mill jar, the number was nine). Below we summarize the component ratios for the two formulations of TiO_2-loaded resin. Formulation one is the straight DER-332-TiO_2 resin discussed above and formulation two is the longer shelf life variant using DER-736-DER-332-TiO_2.

The ball mill jar was then sealed according to the manufacturers instructions and set rolling on the ball mill at a rate of 15 to 20 revolutions per minute. The ball mill was then monitored for 10 to 15 minutes to watch for any signs of leakage caused by improper sealing of the ball mill jar. Within four hours on the ball mill, the epoxy resin mixture generally becomes completely crystallized at which point, no further mixing occurs. At this point, the ball mill jar was removed from the ball mill, its seal loosened and the jar placed into the convection oven at 62^o C for two or more hours in order to decrystallize the epoxy mixture. Once the TiO_2-loaded epoxy resin in the jar has become decrystallized, the ball mill jar is re-sealed and placed on the ball mill again for at least four hours [7]. When the jar has been on the mill for at least four hours it is again removed, its seal loosened, and is placed in the convection oven for another two hours. The TiO_2-loaded resin is then ready to be dispensed into storage containers for storage or immediate mixing with the Jaffamine D-230 curing agent. Simple storage of TiO_2-loaded resin consisted of dispensing the resin into sealable containers. For convenience during future mixing, enough space was left in the container to allow the prescribed quantity of Jaffamine D-230 curing agent be added such that mixing can occur in this container.

1.5 Storage

When the Jaffamine D-230 curing agent was added to the TiO_2-loaded resin, the epoxy was either immediately used for epoxy injection into the megatile separation grooves, or it was fast frozen in liquid nitrogen and subsequently placed in cold storage at -10^o C [8]. The proper mixing ratio of curing agent to resin is listed in table 1. In either case, the mixed epoxy was transferred into EFD Corporation compatible syringe barrels for ease of injection into the megatiles. The syringes were loaded by pouring the mixed epoxy into barrels fitted with stoppers over their tips to prevent epoxy leaking from the barrel [9]. Since EFD syringe barrels must accommodate a piston and the EFD fluid dispenser barrel coupler, the syringe could only be 2/3's filled. To fit syringe pistons onto the barrels, the piston was lightly pressed into the barrel until the barrel was adequately sealed such that it could be turned upright without epoxy leaking out through the bottom. Once upright, the stopper was removed from the syringe tip and the piston was inserted until all air had been expelled from the barrel. Once this had been accomplished, the stopper was refitted to the barrel. At this point the epoxy was ready for use in megatile production or cold storage for future use. For long term storage, the syringes were flash frozen by placing them in a dewar flask filled with liquid nitrogen. When the syringes had reached equilibrium with the liquid nitrogen they are removed from the Dewar and placed in a freezer at -10^{o} C.

1.6 Miscellaneous Problems: UV Light Sensitivity

Like many phenol-based epoxies, DER-332 is sensitive to UV. After extended periods of exposure to regular unfiltered florescent lighting, the surface of the cured epoxy gradually yellows. Several tests were performed to determine how much this might effect the epoxy once it is injected into the megatile separation grooves. One test consisted of taking four samples of cured epoxy and leaving one sample directly under a florescent lamp, another sample partially covered with SCSN38 scintillator, the third sample was entirely covered by SCSN38 scintillator and a forth sample was kept in a darkened cabinet. The uncovered sample gradually yellowed over a course of a month, the partially covered sample gradually formed a shadow with the area shaded by the scintillator remaining white, the third sample remained white as did the sample in the cabinet. From this test it was concluded that were the megatile to be exposed to UV light for long durations, the scintillator would absorb most of the UV preventing the TiO_2-loaded epoxy from yellowing. To confirm this, various old tile samples with injected epoxy which were produced during the preceding year, were broken apart to determine if the epoxy adjacent to cells had yellowed. The epoxy flush with the surface of the tile was noticeably yellowed but no such yellowing was observed in the interior of the tile despite the fact that the tiles have been casually exposed to direct sunlight for many months (it is unlikely that megatiles, once completed and packaged into their pizza-pans will be exposed to significant levels of UV-unfiltered light).

2 Preparation of Megatile Separation Grooves For Epoxy Injection

The preparation of the megatile for epoxy injection consisted of examining the separation grooves for flaws that could complicate epoxy injection, sealing the grooves with Kapton tape, placement of air release holes in the tape and final preparation of the TiO_2-loaded epoxy for injection. Materials used in this procedure included the EFD Corporation Fluid dispenser system and accessories, CHR Industries 1.0" wide, 0.0015" (0.038 mm) thick K104 Kapton tape, and 1.0" wide, 0.003" (0.064 mm) thick K250 Kapton tape.

Between the time the scintillator sheet received its separation grooves and when the injected epoxy had cured, the megatiles contained within the sheet were extremely delicate, susceptible to irreparable damage if handled too vigorously. During this period, in order to minimize any such stresses that might have damaged the tiles, the megatiles were placed on a rigid stretcher used to transport the megatile between the Thermwood table the glueing stations and the various storage and curing racks.

2.1 Megatile Separation Groove Layout

Each megatile is in the form of a 30^o sector. In terms of the coordinates of these sectors, a lattice of three radial and nine (for layers 3-21) or ten (for layers 0-2) tangential separation grooves are cut into a sheet of scintillator, defining the cells internal to the megatile (refer to figure 1). In order to facilitate epoxy injection, several modifications in the megatile separation groove layout were made. Early on in the development of methods to inject epoxy into megatiles, it was determined that the injection process was considerably complicated by the lack of constraints in the path of injected epoxy into the separation grooves. Then as now, Kapton tape was used to seal the separation grooves in order that epoxy could be injected into the tiles. Due to the asymmetry of the internal tile shapes defined by the separation grooves, epoxy injected at one point did not flow uniformly around each tile but instead spread out at a uniform rate in all directions, trapping air in the separation groove when the shorter edges of tiles were filled before longer ones. Air release holes were placed where needed to expel trapped air but as more of the megatile was filled, the number of segments with trapped air increased until the injection process itself became unworkably complicated. Despite efforts to prevent air gaps in the separation grooves utilizing above methods, the early versions of completed megatiles required extensive touch-up work to fill voids left by air trapped in the separation grooves.

2.2 Separation Groove Modifications and Miscellaneous Problems

After the extensive problems associated with injected epoxy into the unmodified separation groove design, several modifications were introduced. Each megatile was divided into three separate injection regions wherein the separation grooves from different injection regions were prevented from intersecting one another. The three radial separation grooves defined the axis of each injection region. "Dams" of material were placed along the peripheries of each injection region so as to prevent epoxy from one region moving into an adjacent region. The original dams consisted of shims of white plastic that were permanently embedded into the megatiles. Because these dams were prone to leakage, we decided to replace them by leaving 4mm segments of scintillator in the separation grooves uncut at the dam sites, later cut out when the epoxy had cured (refer to figure 2). Placement of these dams simplified the megatile separation groove pattern into the three radial grooves with a single flange of tangential groove on either side (refer to figure 3). This modification eliminated the problem of air gaps caused by the uneven flow of epoxy around individual tiles. In addition, injection problems that occurred at one part of the megatile would only effect the one region being injected rather than the entire megatile as was the case with the unmodified design. An added advantage was that voids that did occur were almost always located at the edges of the injection regions and thus simple to find. Another modification to the design of the separation grooves was to extend the grooves beyond the the periphery of the megatile. This modification was necessitated by a property of the epoxy to contract in volume as it cured. The extension of grooves beyond the periphery of the tile by at least 1 cm prevented the need to touch up these points when the epoxy had cured since these points were cut away when the completed megatile was cut from its scintillator sheet. The middle injection region, unlike the two adjacent injection regions had a long un-bisected groove which, due to the larger volume of epoxy enclosed, would form a much larger (8 to 10cm) air gap once the epoxy had contracted than the void formed in the shorter grooves. Since there was not enough space on the SCSN38 scintillator plate to extend the groove straight 2 or 3cm beyond the periphery of the megatile, we extended the groove by bending it off to the side instead.

Early on in the megatile development we encountered problems associated with the separation grooves cut too deeply resulting in epoxy seepage through the bottom of the tile during injection. Because no satisfactory method could be found to halt the seepage once it had begun, any such incidents might result in the loss or degradation of the megatile due to difficulty of cleaning epoxy from the underside of the scintillator. Thus an important part of the preparatory work was the examination of the separation grooves for cut-through portions. Another observed problem was that chips of scintillator occasionally became imbedded in the separation grooves, forming a partial dam, requiring that addition care be taken during injection lest these section remain unfilled.

2.3 The Taping Procedure

In the taping procedure, the overlapping of tape at groove intersections was unavoidable due to the lattice structure of the separation groove layout. At points where the tape overlapped, an unavoidable seam was formed between the scintillator surface and the overlapping tape, creating a potential path for injected epoxy under pressure to leak out of the groove. In order to minimize this seam, we used the thinnest available silicone based adhesive tape, 1.0" wide K104 (0.0015" thick), at all such crossing points. Since this tape was too flimsy to withstand the pressure from the epoxy during injection, it was overlaid with the thicker 1.0" wide K250 (0.003" thick) tape. Due to the extensive handling required during the application of Kapton tape, silk gloves were worn to reduce potential damage to the scintillator surface. Silicone based adhesive tape was chosen based upon tests performed over a period of six months that indicated that there was no measurable degradation in tile efficiency caused by contact with the silicone adhesive. The tape application was done in three phases.

In the first phase of taping, K104 Kapton tape was measured into strips from 1.5" to 2" long and cut from its roll using a fresh razor to assure a smooth edge to the strip. These strips were placed lengthwise along the tangential grooves at the intersection of radial and tangential separation groves such that they were bisected lengthwise by the radial groove and widthwise by the tangential groove. It was particularly important that the strips extend away from the radial groove by more then 1/2" since otherwise they might have been entirely overlapped by the K250 tape applied in the third phase of taping. Were this to occur, it would defeat the point of applying the K104 tape since the seam between the scintillator surface and the tape would be defined by the thicker K250 tape instead of the intended K104 tape. Due to its thinness, this tape was difficult to lay smoothly. We found the best results were achieved by first lightly touching it at the intersection point and then, with a silk-gloved finger, smoothing it out towards its edges until the entire strip was flush against the surface of the scintillator absent any wrinkles (refer to figures 4 and 5).

In the second phase of taping, K250 Kapton tape was precisely measured and applied lengthwise along the tangential grooves. The length of these strips were measured such that they overlapped the strip of K104 tape laid down in the first stage of taping but leaving a 1/4" margin between the end of the K250 strip and the radial groove. Furthermore, the ends of the strips were beveled such that they became parallel to the radial groove so as to maintain this 1/4" margin with the radial groove. Legs of the separation groove on the periphery of the megatile need only have been beveled on the one end abutting the intersection but on legs on the interior of the megatile, these strips needed to be cut to length and beveled and carefully positioned such that they fit between the two intersecting radial grooves (refer to figures 4 and 6).

In the third phase of taping, K250 Kapton tape was applied lengthwise along the three radial grooves. These long strips needed to be carefully positioned such that they overlapped both the strips of K104 applied during the first phase of taping and the strips of K250 applied during the second phase of taping (refer to figures 4 and 7).

2.4 Final Preparation Before Epoxy Injection

Prior to the injection of TiO_2-loaded epoxy into the megatile separation grooves, there were several final preparations. The three injection points corresponding to the three injection regions were prepared, the tape sealing the separation grooves was carefully smoothed down, holes were punched at specific locations to permit the release of air from the separation grooves during epoxy injection, 1" strips of K250 tape to re-seal these holes once epoxy has filled their leg of the groove, was dispensed and placed near the air release hole for convenient use. Pressure settings on the EFD were determined by the gauge of the syringe needle, the extent in which the epoxy has been pre-cured before injection as well as the operators optimal rate of injecting epoxy, sealing air-release holes, etc... During regular injection, we used a syringe tip with an inside diameter of 0.51 mm (EFD "purple" tip 5121-B) with pressure settings typically between 45 psi at the start of injection and 30 to 35 psi towards the end of injection. For touch up work, since the epoxy was pre-cured in an oven to hasten the cure time once injected in the tile, we used a larger syringe tip with an inside diameter of 0.58 mm (EFD "pink" tip 5120-B) and pressure settings as high as 50 psi to compensate for the epoxy being thicker and more difficult to inject.

As noted earlier in section 2.2, each megatile was divided into three injection regions, each with one point from which to inject epoxy. These injection stations were located along each of the radial grooves at a point ideally situated such that equal volumes of separation groove to be filled exist above (towards the tip of the megatile) and below (towards the base of the megatile) and that when epoxy was injected, it would reach either extreme of the injection region at near the same time (refer to figure 3 for the locations of the three injection stations). The reason for positioning the injection points here was to minimize the pressure of epoxy on the tape seams. As the air-release holes were sealed during injection, the tape masking the separation grooves functioned like a balloon, building up pressure throughout the tile and would occasionally lead to the tape seams bursting requiring extensive epoxy removal from the surface of the tiles as well as touch up work in the separation grooves themselves. The air-release points also effectively served to release pressure in their immediate vicinity so that towards the end of injection when only a few air-release holes remained open, the areas furthest from the holes were at the highest relative pressure and thus most prone to bursting. Further, if one side filled long before its opposite side (e.g. if more then one foot of separation groove remained to be filled on the other end), we sealed the original injection point and created a new injection point at a point near the region left to be injected but inside the area already injected.

The injection stations were prepared by laying three additional thicknesses of K250 Kapton tape over the groove at its center and puncturing the tape with a stylus of diameter narrower then the outside diameter of the syringe tip. When the syringe was fitted to the injection point, it had to be well enough sealed to prevent epoxy from welling up through this hole during injection. Because some epoxy inevitably did leak from the injection hole, strips of K250 tape were placed along the radial strip of tape to prevent epoxy from running onto the scintillator surface. When the injection point leaked extensively (e.g. forming a puddle larger then 3 cm across), injection was halted, the injection site cleaned [10] and the three pieces of tape at the injection site were replaced with new pieces and a new injection hole poked through the tape. Once the injection points were ready, six syringes [11] were retrieved from the freezer (corresponding to the six injection regions per scintillator sheet) and placed in the convection oven at 62^o C for fifteen minutes. The purpose of heating the epoxy had less to do with thawing it (it would reach room temperature by itself in only 10 minutes after removal from the freezer) than to heat the epoxy above room temperature since the epoxy flowed easier with less pressure the warmer it was. Tests were performed to determine what effect various periods of time in the open had upon the work-life of the epoxy. A time period of 15 minutes was chosen after it was determined that the work-life after heating was longer then one hour (more then twice the time required for two workers to inject a megatile sheet).

2.5 Epoxy Injection

The three injection regions for each megatile were injected one at a time using a foot peddle switch to control the EFD during injection. To guard against running out of epoxy during injection it was important to use one syringe per injection region and dispose of all but one the syringes after completing each injection region rather then using it for subsequent regions. The reason for avoiding the use of these partially used syringes was that during injection, an air bubble usually formed inside the syringe barrel and because it was difficult to gauge how much epoxy remained in the barrel, the air bubble itself could be injected into the separation groove occasioning extensive touch-up work. The one syringe saved was returned to the freezer to be used in the event touch-up work was later required. Air-release holes were sealed just as the front of epoxy approached the hole, swiftly placing the 1" strip of K250 over the hole and smoothing it down. In the event the hole was not sealed quick enough and even a small amount of epoxy was trapped under the strip of K250, injection had to be immediately halted, the tape removed from the hole, the area around the hole cleared of all epoxy and a fresh piece of tape placed over the hole. The tape seal on top of the air-release hole had to be perfectly flush with the tape surrounding the hole because even a small amount of epoxy trapped between would inevitably continue to grow until it reached the edge of the strip and then burst onto the scintillator surface. This repair had to be made quickly since prolonged stoppage resulted in leading edges of the injected epoxy settling out in the groove such that when injection resumed, air-bubbles frequently occurred requiring subsequent touch- up work once the epoxy had cured. Due to the symmetry of the injection regions, epoxy would reach the end of two flanges at the same time requiring the use of two hands at all times and hence the need for the foot operated EFD switch. At the start of injection, the epoxy flowed quickest gradually slowing as the quantity of epoxy in the grooves increased, creating resistance through surface tension with the walls of the separation grooves. In addition, as the epoxy branched out into additional flanges the pressure was consequently released by many air-release holes at once slowing further the pace of epoxy progressing toward the air-release holes. However, in the final stage of injection when the number of air-release holes dropped below six, the advance of epoxy hastened requiring that the injection pressure be reduced so as to maintain a reasonable pace for the operator to seal the remaining air- release holes and be alert for any breaches of the tape seal. Once each injection region was completed, the epoxy dispenser was removed, the epoxy injection hole was sealed and the epoxy dispenser was repositioned over one of the remaining injection stations until the entire megatile sheet had been injected.

3 Separation Groove Epoxy Curing procedure and Touch-up Procedures

One problem that occurred during production that had not previously been a concern during our research and development period was the length of time it took for the TiO_2-loaded epoxy to cure. During the summer months, the epoxy cured in approximately 24 hours but as the colder months arrived, this cure time doubled and sometimes tripled. There were different curing agents available that could speed up cure times but we were reluctant to modify the TiO_2-loaded resin since it would require a considerable time be spent repeating tests for radiation hardness, mechanical integrity, etc... We opted instead to attempt to manipulate the curing environment to better maintain a regular and consistent production schedule. Methods were employed to heat the megatiles during curing but because the resin became less viscous when heated and consequently more susceptible to leakage through the tape seams, care had to be taken that the megatiles not be heated too much or too soon after epoxy injection. In this section, we discuss procedures employed to facilitate fast and high quality curing of the separation groove epoxy, touch-up procedures used to repair flaws in the separation groove epoxy injection and final preparations made to the megatiles once they had received their final Thermwood machining and were ready for insertion into their pizza-pans.

3.1 The Curing Procedure

As mentioned earlier in section 2.2, the legs of the separation grooves at the periphery of the megatiles were extended beyond the actual edge of the megatile by several centimeters. This was done because it was observed that the epoxy slightly contracted as it cured, drawing air through the dozens of tape seams (48 on layers 0 to 3 and 42 on layer 3 to 21) and creating several dozen small touch-up areas around these seams. By reopening the air release holes along the periphery of the megatiles after the completion of epoxy injection, as the epoxy contracted during curing, air was drawn into the megatiles into these regions that would later be cut away and thus not require any subsequent touch-up work. After reopening these holes, the stretcher carrying the megatile sheet was moved from the injection table onto a rack where it was allowed to room temperature cure for at least twelve hours. In that time the epoxy would cure sufficiently that it was completely immobile but possibly still a little tacky to the touch [13]. The next step was to move the megatiles into a room heated to 32^o C where it was left for at least 5 or 6 hours to fully cure. On the rare occasion that a seam did break (this was generally caused by forgetting to reopen the peripheral air release holes before the megatiles were placed in the oven. As the epoxy heated, it expanded until eventually one or more seams per injection region would burst to relieve the pressure). We found it better to re-seal the broken seam but wait until the epoxy had fully cured before carefully chipping away any epoxy in contact with the scintillator surface. Due to the smoothness of the scintillator surface, it was possible to remove all trace of epoxy without damaging the scintillator.

3.2 Tape removal and Touch Up of Separation Grooves

Before tape removal could commence, the epoxy had to be tested to determine if it had cured. The epoxy was considered sufficiently cured if while slowly pulling up a piece of the tape masking, the epoxy under the tape retained the contour of the tape and did not deform in any way. If the epoxy still remained soft and pliable, it was left in the oven for at least an hour and then tested again. Once the epoxy was sufficiently cured, the stretcher carrying the megatile sheet was removed from the heated room and placed on a table where the kapton masking tape was carefully removed in reverse order to how it was placed over the separation grooves (refer to section 2.3). When removing the tape, especially the long radial strips, the tape should be peeled off the megatile in such a way as to limit vertical stresses on the tile. During production there were two instances where the megatile was heard to crack when the tape was pulled straight up off of the separation groove. The tape should be removed by pulling the tape horizontally in the direction of the groove. As before silk or nylon gloves were worn to limit the amount of direct hand contact to the scintillator. After all the tape was removed, the entire length of separation grooves were inspected for signs of air gaps. In addition, the surface of the scintillator plate was inspected for areas where epoxy had spilled onto the surface.

Almost always, a tiny amount of epoxy would be drawn into the tape seams through capillary action and occasionally, larger quantities would pool up at either end of the seam. Other instances of epoxy spills on the scintillator surface came from poorly re-sealed air escape holes and accidental dispension of epoxy while the syringe was being located to its injection point. Of these spills, the epoxy seams were the most difficult to remove but due to their size and thickness [14], they were little more then cosmetic blemishes at the edges of the tiles and thus not necessary to remove. The larger pools and droplets of epoxy, by comparison, were much easier to remove. Because the epoxy did not adhere well to the finely polished surface of the scintillator, it was usually possible to remove epoxy with only minimal damage to the scintillator. The removal technique consisted of lightly placing a fresh razor blade on the edge of an epoxy spill, perpendicular to the scintillator surface such that it was partially imbedded in the cured epoxy. The razor was then quickly rotated upward into the plane of the megatile, "flicking" the epoxy off the surface of the tile. The spill would generally come away from the surface leaving only a small divot if insufficient care had been taken when applying razor blade to the epoxy. It was possible to remove the spill without any damage to the surface.

Epoxy gaps in the separation grooves usually occurred in the proximity of the air release holes or the injection sites. Gaps could also appear at poorly sealed seams where air could be drawn in through the seam during curing when the epoxy contracted. A third type of gap occurred when a syringe with insufficient epoxy was used and would inject air into the groove when it ran out of epoxy. Of these gaps, we divided them into two categories of sizes: gaps up to one inch long and gaps larger then one inch. The smaller gaps were not considered a danger to the structural integrity of the megatile and could therefore be touched up with Bicron BC-620 white reflective paint to make sure the tiles were optically isolated from one another. The larger gaps required additional reworking and epoxy injection.

When large gaps were located, a metal scribe the width of the separation groove was used to determine the actual size of the air gap[15]. When the air gap was suitably excavated from the groove, the resultant chips of cured epoxy were removed and strips of CHR K-250 kapton tape were placed over the gap. A razor blade was then used to cut out the narrow slit of tape above the gap such that the gap was masked in all directions by the strip of kapton tape. When gaps appeared at groove intersections, two strips of tape were laid across one another and cut as above without concern for the resultant tape seams[16]. The lengths of either end of these strips extended at least one inch beyond the region being touched up (refer to figure 8). When all touch up points were identified and prepared, epoxy was injected directly into the separation grooves using a hand-held EFD syringe at low pressure. Once filled, excess epoxy was removed using a Kim-wipe tissue drawn along the direction of the groove, careful not to wipe any epoxy off of the kapton masking tape onto the scintillator surface. Afterwards the megatile sheet was returned to the heated room and allowed to cure for 5 or 6 hours or until the epoxy was no longer tacky to the touch.

3.3 Final Touches Preceding Insertion into Pizza-pans

When touch up work was completed the megatile sheet was then returned to the Thermwood room to have all remaining machining performed (including fiber groove cutting, epoxy dam removal, bolt holes for the pizza-pan and the cut- out of the megatiles from their sheets). After returning from the final machining, exposed regions of the separation grooves and edges existed along the edge of the megatile as well as the places where epoxy damns had been removed. For ease of painting the edges, the megatiles were placed on pedestals in the shape of the megatile but a slightly smaller so that the entire megatile edge was exposed. This arrangement permitted all painting be performed without having to move the megatile, further limiting its handling. On the megatile edges we applied two coats of Bicron BC-620 paint applied with a sponge brush. The former epoxy dam sites were painted with BC-620 using a fine brush with a diameter small enough to fit into the separation grooves. Towards the end of megatile production, the paint brush was replaced by a toothpick as it was simpler to use and was more precise in the application of the paint.

The final step was the removal of the paper-backing from the un-machined underside of the megatiles and application of black lines above the separation grooves. The paper-backing was left on the underside of the scintillator sheet to protect the scintillator surface. Since silk was shown not to damage the scintillator surface, when it came time to remove the backing, the megatiles were transferred to a silk-covered table. The backing was removed using the same method employed removing the kapton masking from the separation grooves (refer to the previous section), careful not to pull the packing "up" off of the megatile but instead peeling it away horizontally from the scintillator so as to minimize any stresses that might have damaged the epoxy seams. When the backing was removed black lines were drawn above the separation grooves using a Pentech Corporation brand "Double-Shot" black marker pen and a straight-edge, wrapped with silk, was used to guide the pen. The purpose of these lines was to limit the amount of cross-talk between adjacent tiles as a result of light coming through the 0.010" of scintillator left when the separation grooves were originally cut. Once the ink had dried, the megatiles were ready for packaging into their pizza-pans.

References

[1] The detailed description of the CDF End Plug Hadron Calorimeter can be found in: P. de Barbaro et al., "CDF Plug Upgrade Hadron Calorimeter Design", U. of Rochester preprint UR-1360, CDF Note 2545 (May 1994).

[2] Reference: M.A.Lindgren, "The CDF Plug Calorimeter Upgrade", in Proceedings of the Third International Conference on Calorimetry in High Energy Physics, Corpus Christi, TX, 29 September - 2 October 1992, eds. P. Hale and J. Siegrist (World Scientific, Singapore, 1993), p. 61;

[3] P. de Barbaro et al.; " Quality Control Studies of Scintillating Tile/Fiber Megatile Production for the CDF End Plug Upgrade Hadron Calorimeter", U. of Rochester preprint UR-1371, CDF Note 2778 (July 1994).

[4] Private communication, Dr. Jay Hoffman, Fermilab.

[5] To ensure proper mixing, the ball mill is only filled to approximately 15% of capacity which amounted to about one half a quart of resin; sufficient to fulfill our needs.

[6] Since DER-332 has a fairly high viscosity at room temperature, we found it easier to dispense when it is still fresh from the oven. Further, we found that if we poured the heated cup of DER-332 resin straight into the ball mill jar without attempting to scrape the sides of the container, about 10 to 15 grams would remain in the cup, held by surface tension. By re-using the same cup to measure and transfer the 300 grams of DER-332 each time, the amount transferred was 300 $\pm$ 5 grams. The exact amount transferred was precisely measured by weighing the measuring cup before the 300 grams of DER-332 was added, after it was added and after it was transferred to the ball mill jar. Measurement errors of this magnitude did not result in any problems in the ability of the epoxy to cure or its mechanical cohesion.

[7] Because the ball mill jar has been heated to 62^o C, it is uncomfortable to handle with bare hands so insulated gloves should be worn.

[8] When this storage method was first proposed, tests were carried out to determine the shelf life of the flash frozen epoxy. When the epoxy was shown to be effective after two weeks in the freezer, we were confident enough to employ this technique as part of our production procedure. In practise, the actual length of time spent in storage rarely was longer then one week.

[9] When epoxy use was small (less than 10cc's) we used a device manufactured by EFD Corporation for loading many barrels in succession. Its primary handicap was that this system proved inconvenient due to constraints on the size of the reservoir used to load the syringes and thus only a few (six or seven) of

the 30cc barrels used for megatile injection could be filled at once making the procedure of negligible convenience once production expanded beyond one megatile sheet per day.

[10] When cleaning epoxy around an injection point or a poorly re-sealed air-release point, if any epoxy leaked onto the surface of the megatile, it was important not to disturb it. Any effort to remove epoxy from the scintillator surface generally would only spread the epoxy but in addition, it would also scratch the scintillator. Further, once the epoxy cured, it could usually be removed from the scintillator surface without any damage to the scintillator.

[11] Two workers were assigned to work on a megatile sheet, each injecting three regions. If only one person was available, the operation was broken into two shifts, injecting one megatile (three injection regions) at a time and consequently only three syringes rather then six were prepared for each shift.

[12] Our default barrel was a 30cc capacity barrel which was sufficient to fill the largest of the injection regions (layer 21 middle injection region).

[13] It was critical that the epoxy be sufficiently cured before being moved to the heated room since when heated, the epoxy sometimes re-liquified and could be drawn by capillary action out of the groove and into the tape seams and onto the scintillator surface resulting in the need for touch-up in the grooves and the careful removal of cured epoxy from the scintillator surface.

[14] The thickness of these spills were limited by the dimension of the tape seam itself which was approximately 0.0015". Considering the fact that variations in the thickness of the scintillator varied on the order of 0.004", such protrusions were probably insignificant

[15] The edges of the air gaps were dictated by the surface tension of the epoxy as it cured; the epoxy clung to the bottom and sides of the separation groove as well as the kapton masking tape, creating an elongated "shell" of epoxy. The removal of the tape would reveal part of the insides of this shell, but in order to fill the entire gap, the remaining overhanging cured epoxy had to be removed using the scribe to break off and pull up the pieces.

[16] Because the epoxy applied during touch up was not injected under pressure but instead applied directly into the groove where needed, the tape seams drew only negligible quantities into them requiring no further touch up.

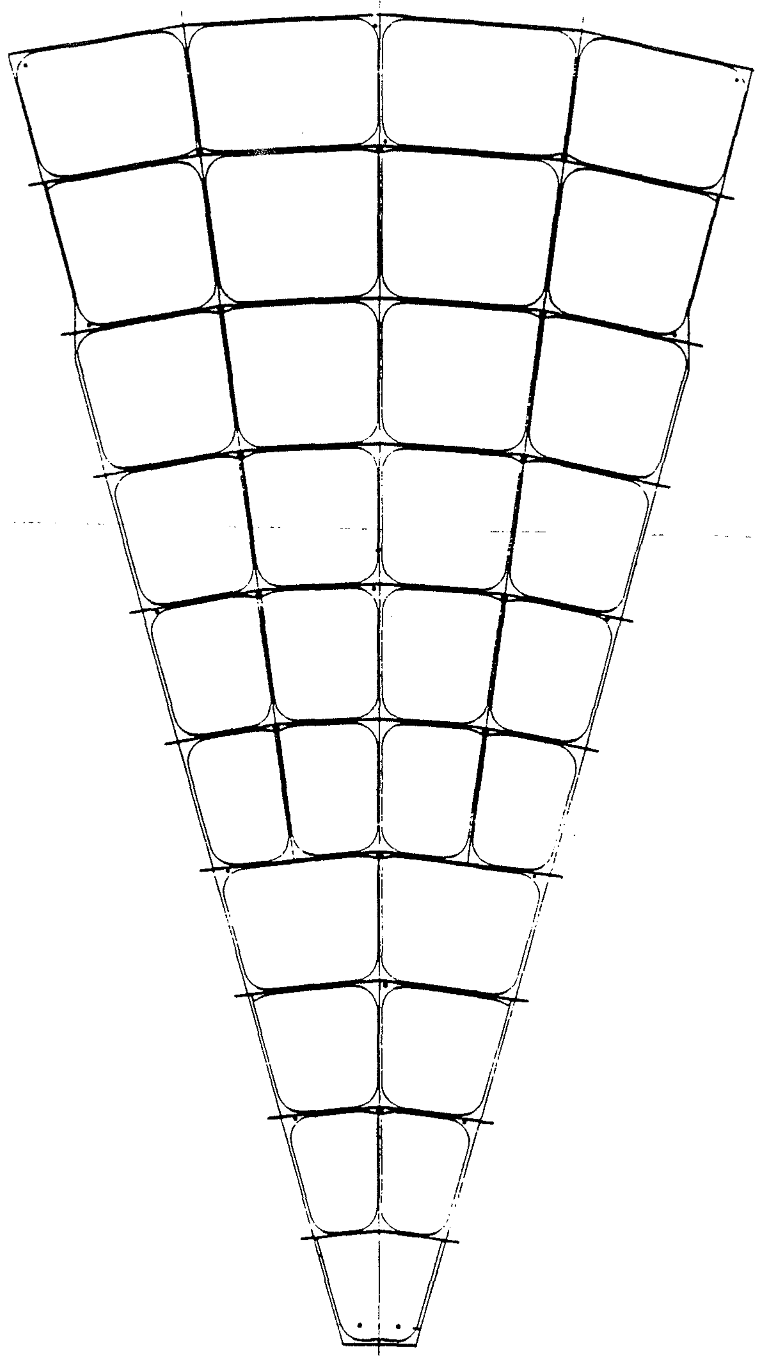

Figure 1: The Megatile separation and fiber groove layout.

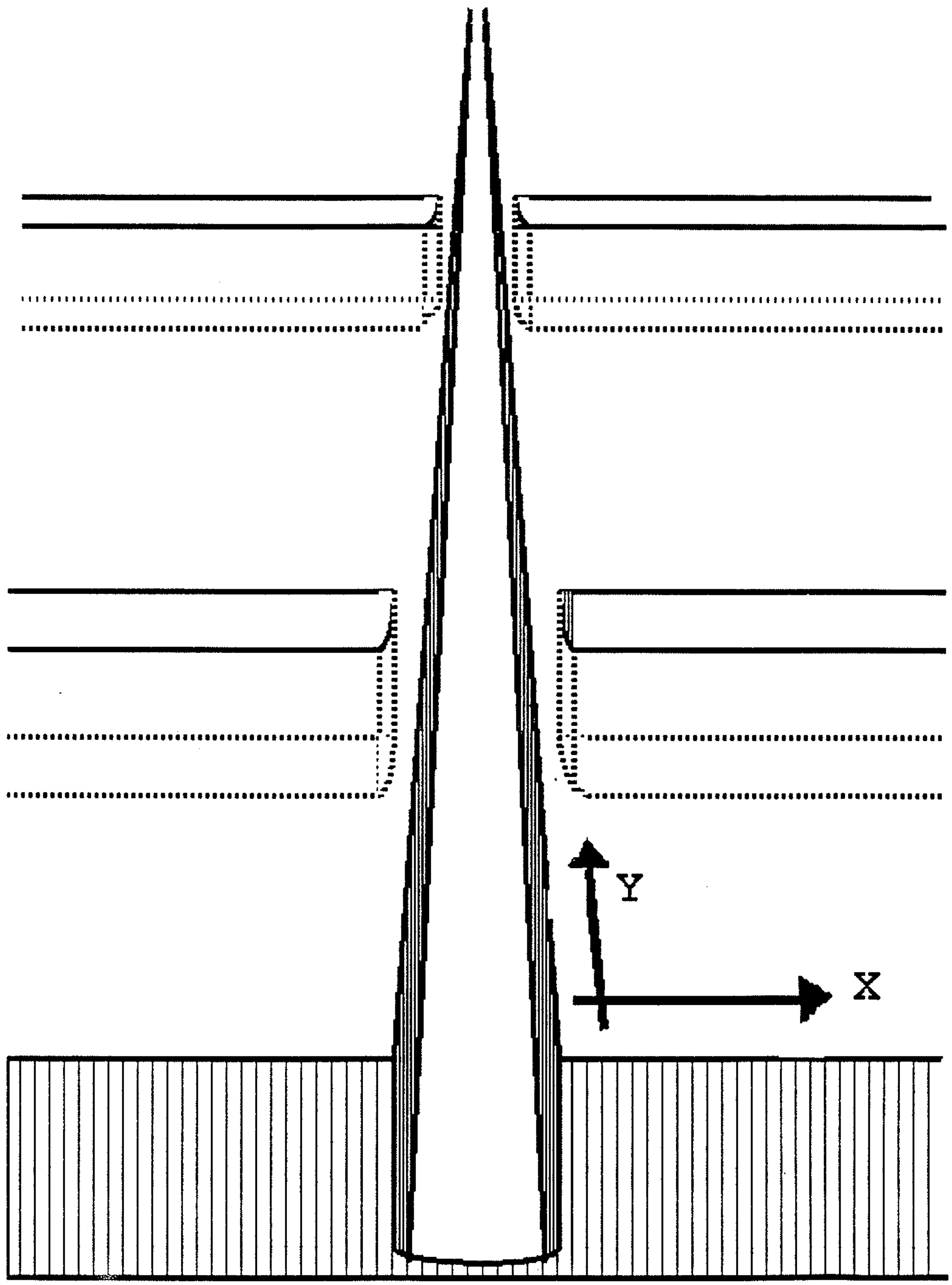

Figure 2: Separation groove perspective drawing. Injection regions are kept separate by leaving portions of the scintillator uncut until after the epoxy has cured, at which time these uncut portions are removed. In the figure, dams of uncut scintillator prevent the horizontal grooves from intersecting the vertical groove.

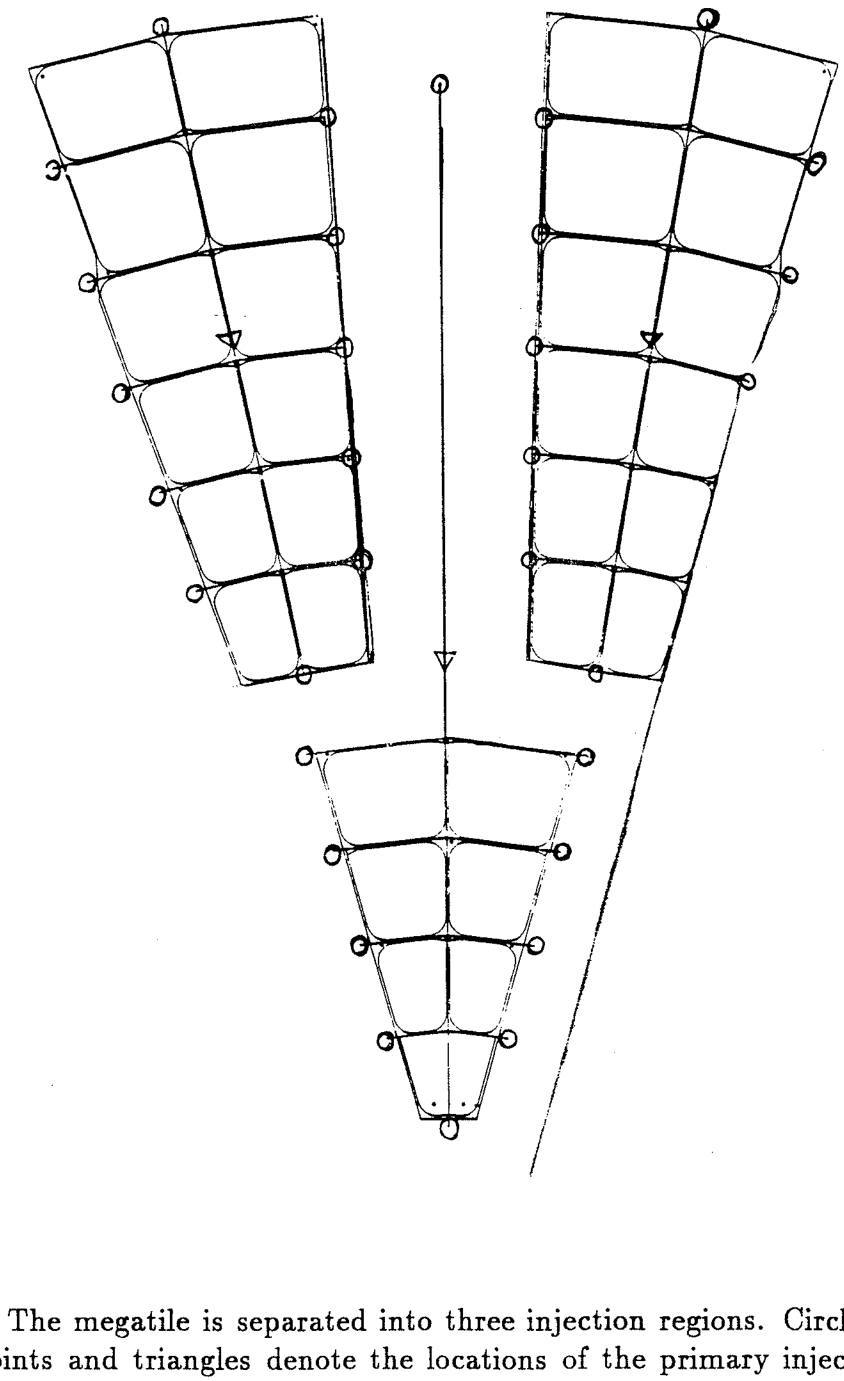

Figure 3: The megatile is separated into three injection regions. Circles denote air-release points and triangles denote the locations of the primary injection point for each injection region.

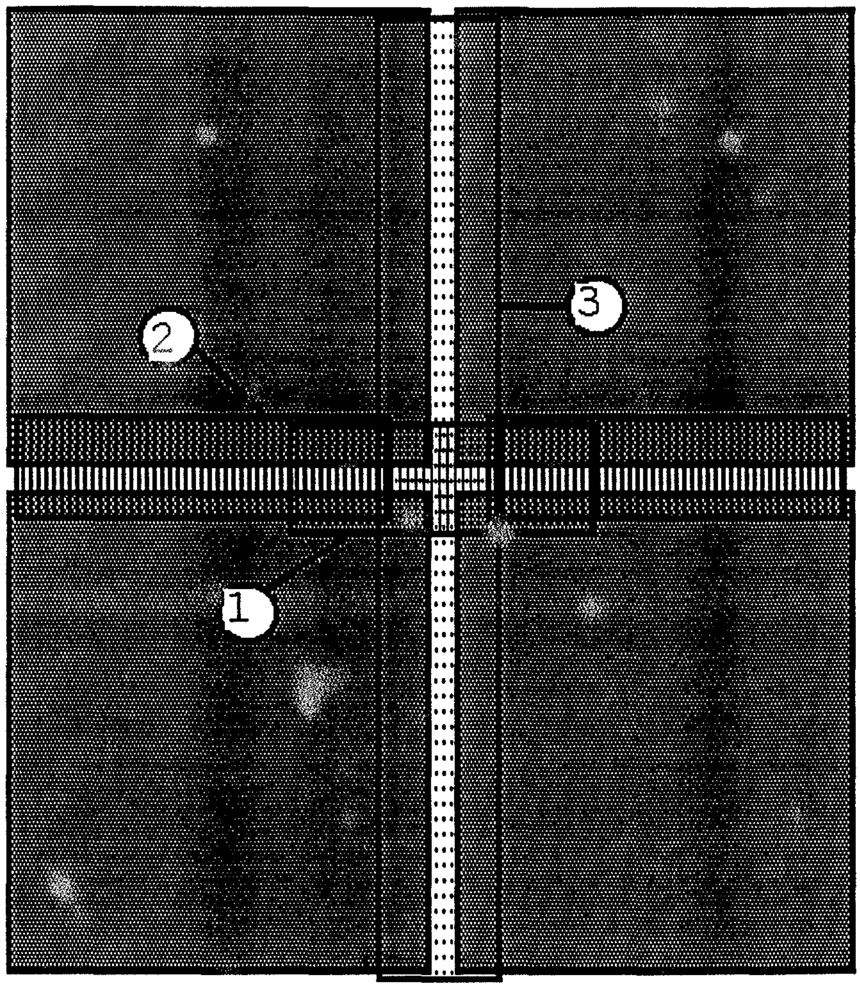

Figure 4: Tape seams created by over-lapping layers of Kapton tape. The dotted lines denote the locations of seams. The numbers indicate the three taping phases, in their respective order. 1) 0.0015" thick Kapton tape. 2) 0.003 " thick Kapton tape. 3) 0.003 " thick Kapton tape.

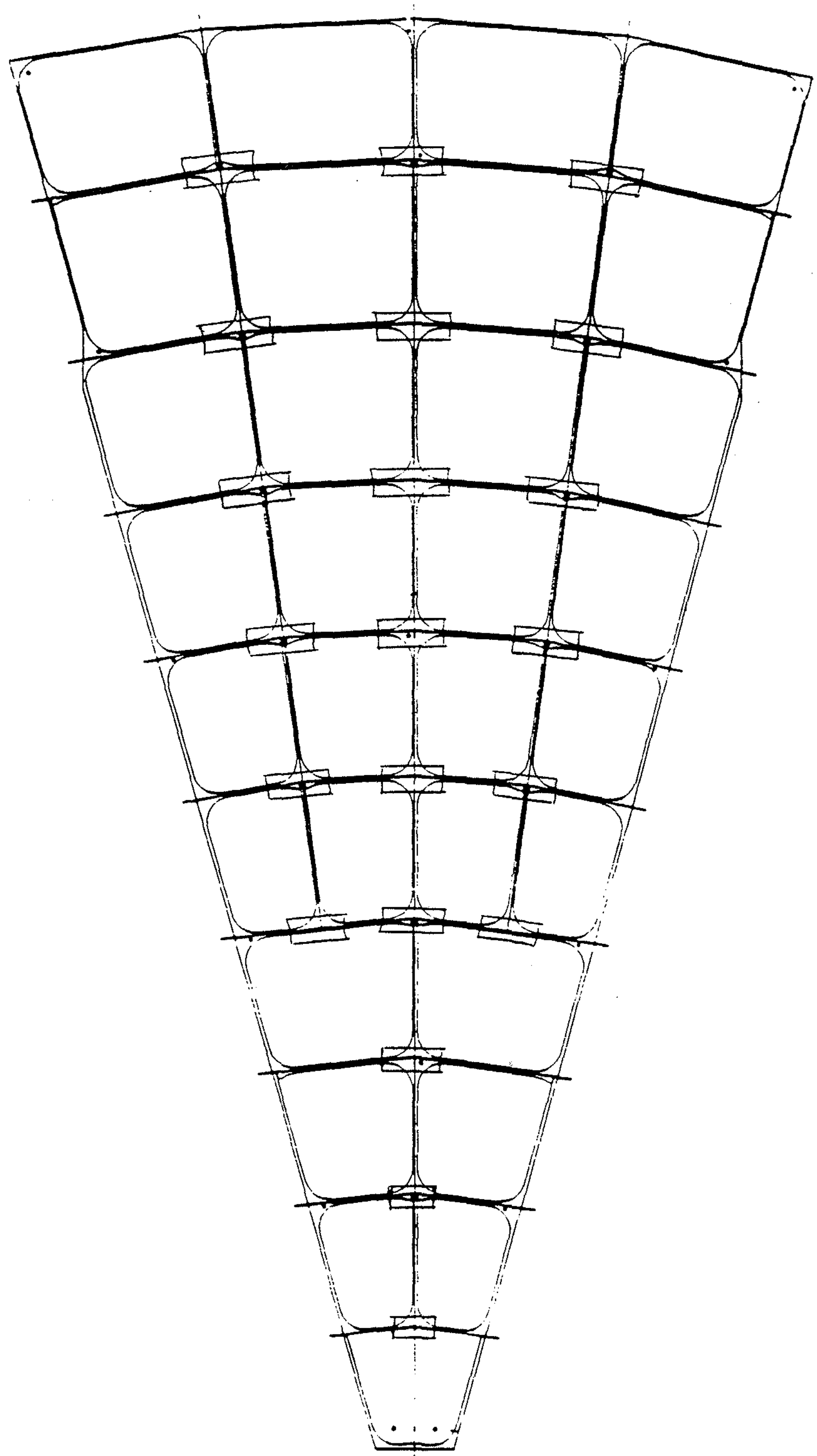

Figure 5: Application points for the first phase of Kapton tape application (0.0015" thick Kapton tape).

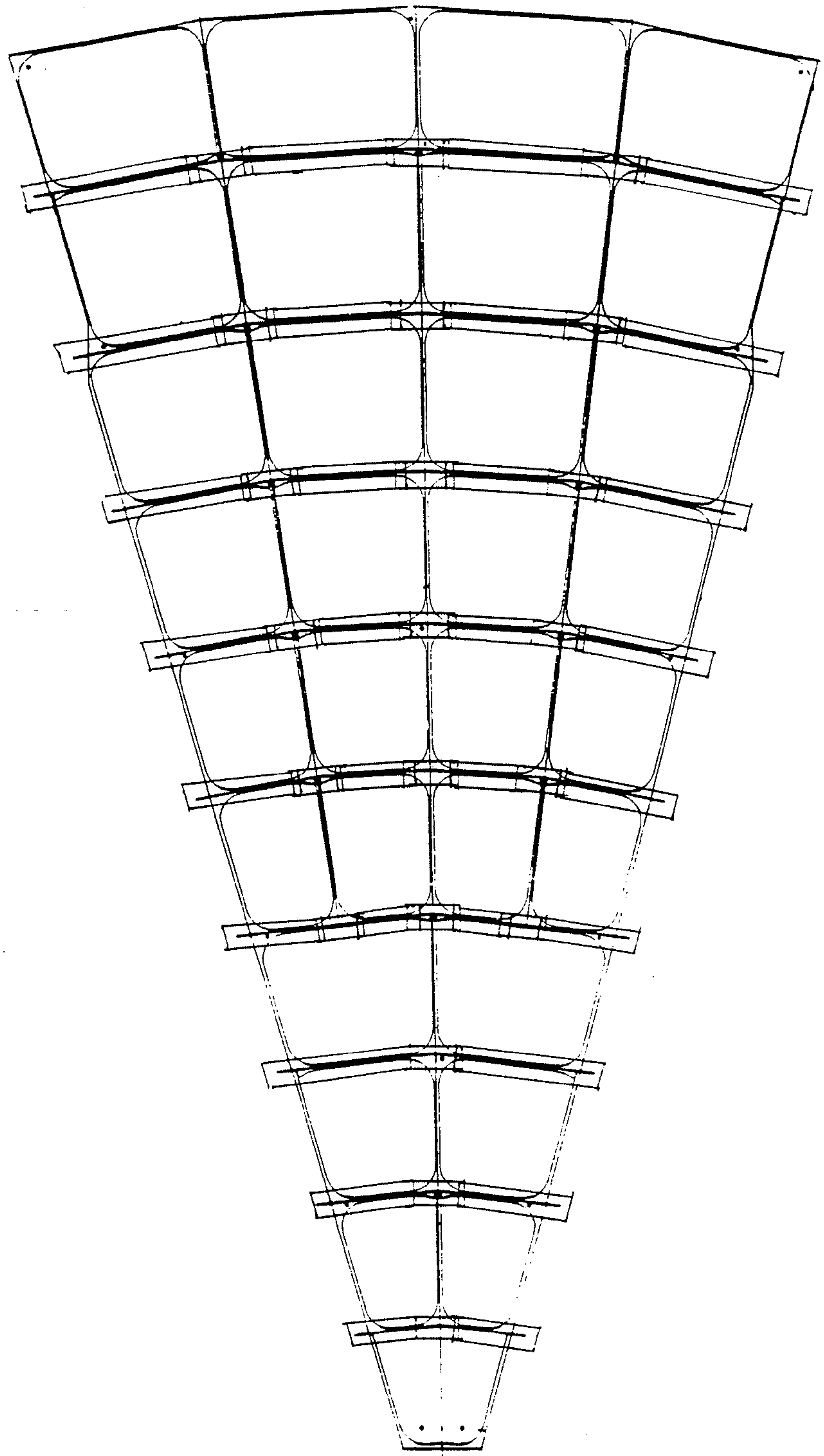

Figure 6: Application points for the second phase of Kapton tape application.

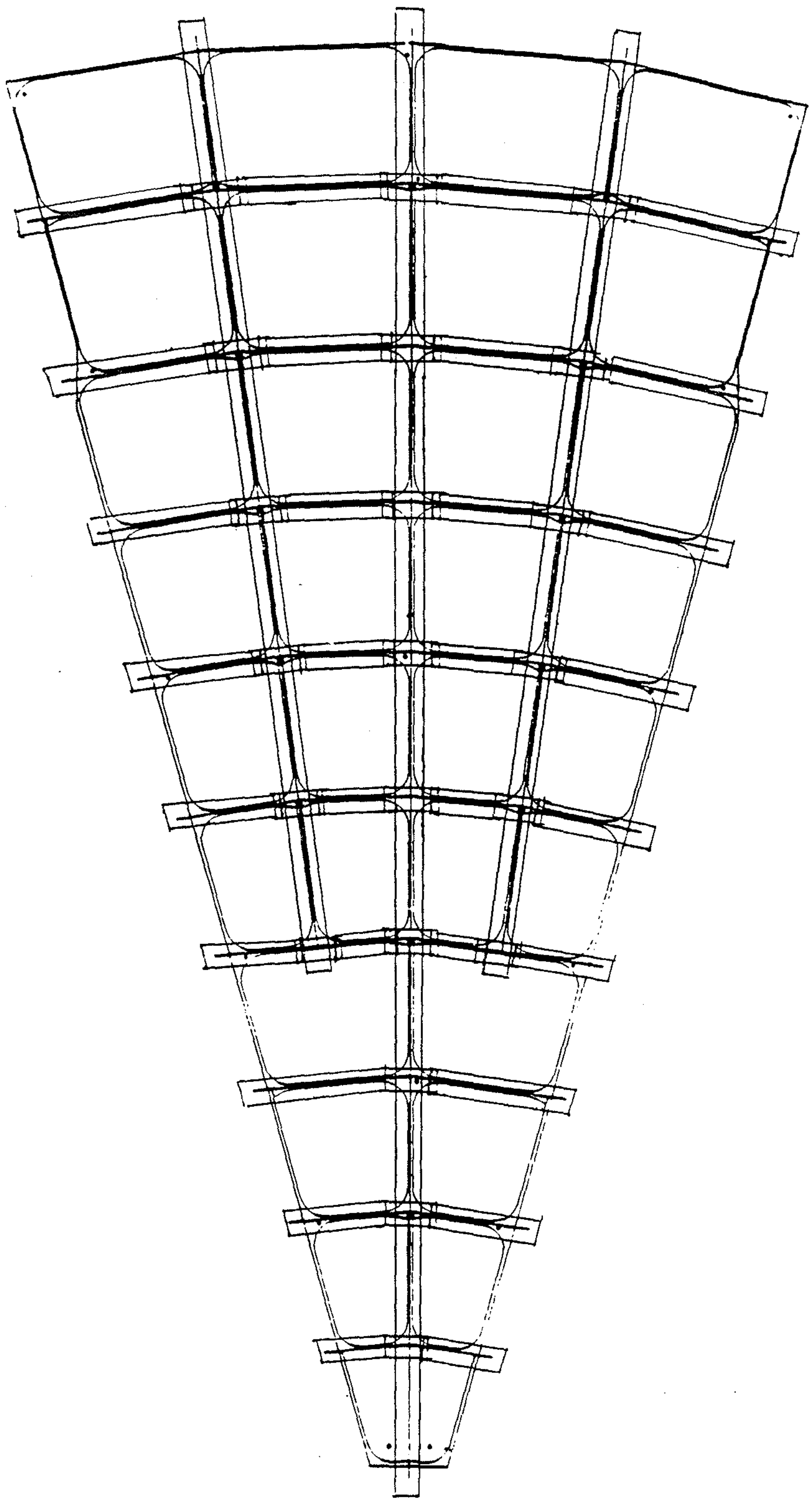

Figure 7: Application points for the third phase of Kapton tape application (0.003" thick Kapton tape).

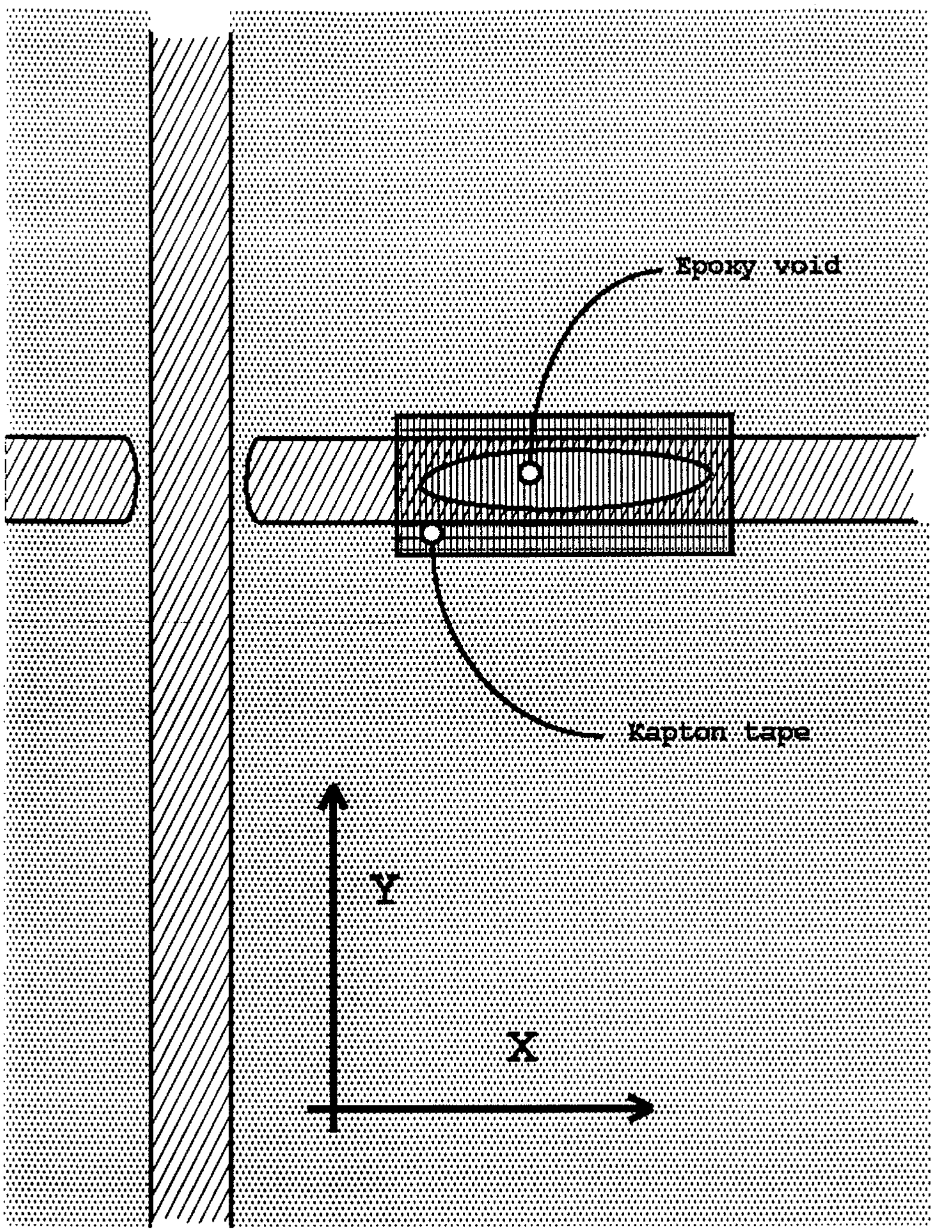

Figure 8: Masking touchup points using Kapton tape.