DEVELOPMENT OF A LARGE SUPPORT SURFACE

FOR AN AIR-BEARING TYPE ZERO-GRAVITY SIMULATOR

By Kenneth E. Glover

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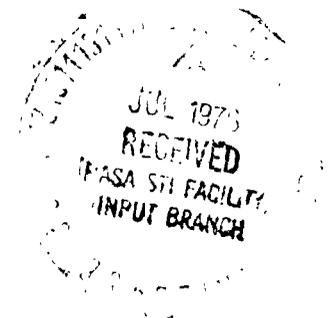| 1. Report No. NASA TM X-72780	2. Government Accession No.	3. Recipient's Catalog No.
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SUMMARY

This report describes the methods used in producing a large, flat surface to serve as the supporting surface for an air-bearing type zero-gravity simulator using low clearance, thrust-pad type air bearings. Major problems encountered in the use of self-leveled epoxy coatings in this surface are discussed and techniques are recommended which proved effective in overcoming these problems. Performance requirements of the zero-gravity simulator vehicle which were pertinent to the specification of the air-bearing support surface are also discussed.

INTRODUCTION

A relatively large, smooth and level surface was developed for use as the air-bearing supporting surface in a zero-gravity simulator. This simulator was developed as part of the Skylab experiment T020 which employed a foot-controlled maneuvering unit (FCMU) described in reference 1. The requirements for the physical characteristics of this surface evolved as a result of early exploratory studies of the FCMU. These requirements could not be met within reasonable cost limits using conventional fabrication techniques for flat surfaces. Consequently, an effort was undertaken to use a relatively new technique developed for a similar application, as reported in reference 2. This technique employed a slow-hardening epoxy material to form a level, smooth and hard surface. The surface was leveled by the action of gravity on the material while it was still in the liquid state. The first attempts to apply this technique, as discussed in reference 2, produced unsatisfactory results and several improvements in the technique were necessary in order to achieve the desired results.

It is the purpose of this paper to discuss the refinements that were applied to this technique and to document the physical characteristics of the surface that was produced. It is believed that this refined technique can be used at a reasonably low cost in producing large level surfaces suitable for other specialized applications which utilize precision air-bearing support systems.

Requirements for the Air-Bearing Support Surface

The T020 experiment was concerned with the maneuvering characteristics of the FCMU while operated in zero-gravity conditions. A relatively large floor area was used for operation of an air-bearing supported mock-up of the FCMU to simulate three-degree-of-freedom motion of the FCMU under the influence of zero-gravity conditions. The air-bearings were used to minimize the friction of the simulator vehicle as it moved across the level floor under the influence of the small cold-gas thrusters on the FCMU. Three factors relating to this floor were of primary interest in providing an adequate simulation of the zero-gravity performance of the maneuvering device; namely, surface area, roughness and slope.

The size and shape of the surface were dictated primarily by the types of maneuvers to be studied in the experiment, and by the availability of floor space for the simulator. To permit control of the environmental conditions, the simulator was located in a large hangar-type building and housed in an existing quonset-hut type of structure with maximum dimensions of about 12 by 18 meters. Requirements to house support equipment within this structure and to allow personnel to move around without walking on the air-bearing surface itself limited the maximum dimensions of the working surface to 9 x 15 meters with a total area of 112 square meters. The shape and dimensions of this surface, shown in figure 1, proved to be suitable for all of the maneuvers used in the experiment.

Roughness of the air-bearing supporting surface is important because of its influence on the friction of the air-bearings as they move over the surface. Any protrusions, due either to general surface roughness or to localized surface imperfections, will drag against the working face of the bearing unless the protrusions are substantially less than the thickness of the air film lubricating the bearing. These bearings were designed to operate at a nominal clearance of about .005 cm. However, because of misalinement due to slight asymmetric loading on the bearings, the surface had to be clear of any imperfections exceeding about .002 cm in height above the surface.

The requirements for the maximum slope of the surface were based on criteria relating the influences of this slope to the time necessary to perform particular maneuvers under the simulated zero-gravity conditions as discussed in Appendix A. Essentially, these criteria dictated that the local surface should not exceed a deviation of $.00198^{\circ}$ from the horizontal. This is equivalent to a maximum slope of .0035 cm/m or a deviation of about .053 cm in elevation over the total area. To visualize the impact of this requirement, the maximum allowable component of the gravity vector in the horizontal plane of the FCMU is equivalent to a force of .05 newtons acting on the system weighing 1512 newtons.

Characteristics of the Surface Material

The material used to fabricate the support surface was a commercially available two-component epoxy surfacer which was compounded specifically to provide relatively low viscosity and long setting time as discussed in

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reference 2. The material was supplied in .189 m^3 (50 gal) kits which included .114 m^3 (30 gal) of resin packed in a 55 gallon drum and .075 m^3 (20 gal) of hardner packed in 5 gallon buckets. The resin component was supplied with black pigment added to render the finished surface opaque. Both components exhibited a moderate tendency for heavier elements to settle from suspension during storage. No special storage requirements were specified for either component.

The two components appear to have about the same viscosity (1200 to 1600 centipoises specified by the manufacturer). When freshly mixed, the epoxy appears to have about the same viscosity as either of the components and it pours and flows about like 50 wt. motor oil. The two components mix readily but, because it is desirable to avoid air entrainment, the stirring should be done slowly. It is essential that the two components be thoroughly mixed, otherwise portions of the poured material will fail to cure properly.

The chemical reaction between the two components of the epoxy is exothermic and the rate of reaction increases rapidly with increased temperature of the mix. These characteristics severely limit the pot life of the mix because the surface area per unit volume in the mixing container is insufficient to dissipate the heat of reaction without a substantial temperature rise. If the material is held too long in the mixing container the viscosity of the mix increases rapidly with consequent deterioration of the flow and gas release characteristics. The material should be poured as quickly as possible and before the exothermic heat build-up advances more than two or three degrees. When the material is poured in thin layers, the surface area is adequate to dissipate the heat of reaction so that the reaction proceeds slowly at essentially ambient temperature. Higher ambient temperatures (and consequently higher component temperatures) tend to increase the rate of reaction, especially in the mixing container, whereas lower temperatures tend to retard it.

In setting, the epoxy exhibits a gradual increase in viscosity as it changes from the liquid to the plastic state. The time from mixing until the surface becomes tack-free is called the gel period and is specified as being between 16 and 24 hours at 21°C (70°F). The curing period is described as the time required, after the gel period, for the plastic to develop about 90 percent of its ultimate strength and is specified as being 14 days at 21°C. There is little apparent shrinkage of the material during the gel and curing periods.

The cured epoxy is sufficiently tough and resilient to withstand substantial transitory loads and the occasional impact loads encountered in normal simulator use. Nevertheless, the material is susceptible to cold flow or plastic creep and will deform at normal room temperature after a few days under sustained static loading of only a few kg/cm^2. Elevated temperatures tend to reduce the tolerance of the plastic to static loads and at about 70°C (150°F) it is noticeably pliable. At ambient temperatures, the glossy, smooth surface with which the epoxy normally cures is only moderately resistant to scratches. However, this lack of surface scratch resistance is of no serious consequence in this application.

Location of the Air-Bearing Simulator

The air-bearing simulator was located in a hangar-type building with a concrete floor which was in excess of 50 centimeters (20 ins.) thick. This concrete had a relatively smooth finish and the area used for the air-bearing support surface was free of structural joints. However, steel anchor plates about 12.7 centimeters (5 ins.) in diameter were cast into the concrete, flush with the surface and spaced approximately 1.5 m (5 ft) on centers in an orthogonal pattern.

The air-bearing support surface was housed in a 12 x 18 meter (40 x 60 ft) quonset-hut-like enclosure, made of fabric reinforced sheet plastic spread over a framework of steel pipes and cables. The hut ends were of wood frame construction with the plastic stapled to the outside of the frame. A small positive pressure was maintained inside the hut to reduce the infiltration of dirt from the rest of the hangar. During the winter, the temperature in the hangar was maintained at approximately 21°C (70°F). No air conditioning was available during the summer, therefore, the temperature in the hut varied up to about 32°C (90°F). The relative humidity was usually within a few percent of that in the outside atmosphere, generally within the range of 40 to 80 percent.

Preparation of the Subsurface

The concrete floor had a substantial accumulation of grease and wax from its previous use. Preliminary tests with the epoxy surfacer indicated that it would not bond to the surface with this contamination. A small test area was successfully cleaned by grinding with a 24 grit silicon carbide stone, however, no equipment was available locally to grind the large area efficiently. After several scrubbings with chemical cleaners failed, the cleaning was finally accomplished by dry sandblasting. This was an effective cleaning method, but a substantial effort was required to remove the sand and dust from the surfaces of the open frame structure and skin of the hut. Undoubtedly, this effort could have been reduced considerably by wet grinding the surface or by erecting the enclosure after the concrete was cleaned.

The effectiveness of the various cleaning methods was evaluated on the basis of the strength of the bond between a test sample of the epoxy and the cleaned surface. In these tests the samples were poured to a depth of about .32 cm (1/8 inch) over an area of about 900 cm^2 (1 ft^2) and allowed to cure for about 10 days. After this short curing period the dam, which was used to contain the sample, was removed and the plastic layer was peeled loose from the concrete by simply pulling on one of its edges. Although no force measurements were made in these tests, little effort was required to separate the samples from the concrete which was inadequately clean, and the plastic separated cleanly from the concrete in those cases. On the other hand, in cases where the concrete was adequately cleaned, there was a nearly continuous coating of concrete particles stuck to the underside of the plastic. To separate these samples appeared to require some three to four times the effort of those where the cleaning was less satisfactory.

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White pine strips were bonded to the cleaned concrete with a strong filler-type adhesive to make a permanent dam around the periphery of the air-bearing support surface. The dam might better have been made of metal because wood particles subsequently wore off the dam and interfered with operation of the air bearings. However, this problem was reasonably well solved by painting the exposed strips with three coats of the epoxy.

Before the first coating was poured, the clean, dust free concrete was primed with the epoxy surfacer. This coating was thoroughly brushed in to ensure complete wetting of the subsurface and to increase the probability of a good bond over the entire area. This was also thought to increase the flow rate of the subsequent layer of surfacer and thus increase the probability of obtaining a level finished surface. The primer coating was allowed to set tack-free before the remainder of the material was poured.

Each time a new coating was poured over an existing layer of epoxy, the older surface was sanded all over with 60 grit abrasive cloth to break the surface glaze. After each sanding operation all the interior surfaces of the hut were wiped thoroughly with damp cloths and the floor was scrubbed with clear water until no evidence of dust remained. Soap and other cleaning agents were avoided in cleaning the floor to prevent any possible residue which might interfer with the bond of the new surface. The bonds thus established with the concrete and the subsequent layers of surfacer showed no evidence of breaking down after several years of use.

Elevation Surveys

Surface coatings were poured over the air-bearing floor at four different times over a period of about four years because of successive failures to obtain an adequately level surface for good operation of the simulator. In preparation for the pouring of each new coating, an elevation survey was made of the existing surface which was to be the base for the new surface. For the first two coatings, the surveys were made by the standard method for differential leveling using an engineer's transit as described in reference 3. Elevations were read at about 20 points which were thought to represent the extreme elevations of the surface. These data were used only to verify that the material planned for the coating would cover the highest points with sufficient margin to ensure a continuous surface.

The survey made in preparation for the third coating was made with a precision tilting level using the standard procedure described in the instructions with the instrument. Elevation measurements were made at points 1.5 m (5 ft) on centers over the whole surface. These points corresponded to the locations of the anchor plates in the concrete subsurface, but care was taken to avoid locating the standard rod over the plates themselves. These data were used to calculate the volume of material required to bring each 1.5 x 1.5 m section into planar register with the highest point in the whole surface. In making these calculations each section was assumed to be a rectangular solid with a base area of 2.3 m^2 (25 ft^2) and with a height equal to the average of the differences between the elevations of the four corners and the

highest point in the whole surface, as indicated in the sketch of figure 2a. Additional material was then added to give the coating a nominal thickness of .63 cm (.25 in.).

In preparation for the fourth coating, the survey was made with the precision tilting level using the refined procedure described in appendix C. Relative elevations read at the corners and the center of each 1.5 m square section of the third surface are given in figure 3. These data were used to calculate the required material more accurately than for the previous surface. In this case, each square section was assumed to be made up of four truncated triangular prisms formed on the sides and diagonals of the square, as illustrated in the sketch of figure 2b. The height of each prism edge was taken as the difference between the elevation of the point being considered and the highest point in the whole surface. Sufficient material was also added to give this coating a nominal thickness of .63 cm. The resulting volume was converted to weight on the basis of 1.13 g/cm^3 (9.4 lb/gal) to determine the weight of material to be poured in the square section.

Methods Used in Mixing Epoxy

The epoxy was mixed in 50 gallon batches in the 55 gallon drums used as shipping containers for the resin component. A different method was used for mixing the two components for each of the four coatings poured for the air-bearing support surface. Although all of these methods appeared to mix the material reasonably, none of them was fully adequate. Some of the major problems encountered during the fabrication process were partially attributable to deficiencies in the mixing of the materials.

For the first coating, the material was mixed by hand with a wooden paddle. In this case, the coating gelled to the tack-free condition in about 8 hours and cured with a substantial number of bubbles trapped in the surface. The excessively rapid gel rate was thought to be caused in part by over-mixing and excessive holding time in the mixing container. The trapped bubbles were attributed to excessive air entrainment during the mixing operation and to degradation of the gas release characteristic due to the excessive holding time during the mixing operation.

In mixing the material for the next coating, the drums were resealead after the hardner was added and the two components were mixed by rolling the drums slowly across the floor for about 30 turns. This coating gelled in about 18 hours and cured with no trapped gas bubbles in the surface. However, there were several small areas where the material never hardened completely, indicating incomplete mixing. These soft spots were all in the areas where the mixing drums were drained and, had the drums not been drained, this may very well have been the best mixing method used.

The material for the other two coatings was stirred with hand held propeller-type mixers. In the first of these, a mixer was made using a small boat propeller attached to a shaft and driven with a large variable speed drill motor. This coating gelled in about 16 hours with many air bubbles trapped in

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the surface. Some of the bubbles resulted from air entrainment during the mixing operation but the pouring operation was also the source of a large part of this problem. The entrapment of these bubbles in the surface was attributed to excessive holding time during the mixing operation, which allowed the gel to progress too far before the material was poured.

In the final coating the same mixer was used but it was augmented with a standard paint mixer in order to reduce the mixing time. The paint mixer incorporated two smaller propellers on a common shaft driven by a relatively high speed synchronous motor. In order to minimize the progress of the chemical reaction during the mixing and pouring operations considerable care was taken to chill the material before mixing and to prevent any significant temperature rise during the mixing operation. Even though the gel period for this coating was quite long, it cured with a moderate amount of bubbles in the surface. In this case the trapped gas was attributed to excessive air entrainment during the mixing operation.

Methods Used in Pouring the Different Coatings

In the first two coatings, the surfacer was poured from 5 gallon buckets which were partially filled from the mixing drums. No particular effort was made to fill the buckets consistently from one time to the next. The buckets were dumped at the edge of the previously poured liquid until the 50 gallon batch was exhausted. With each new 50 gallon batch, the pouring was started at a different corner of the surface with the intent that the different bodies of liquid would flow together near the center of the surface.

In the first coating, however, the material failed to flow out to the center of the surface and left about 20 percent of the area uncoated. Flow lines were evident over most of the covered area when the epoxy hardened and there were large deviations in elevation over most of the surface. Also, there was a substantial number of gas bubbles trapped in the surface of the material. The failure of this coating to achieve a smooth, level surface was attributed primarily to the viscosity of the material in the liquid stage which appeared to be two to three times that of the samples used in the preliminary bonding tests.

The thickness of the first coating was intended to be only .47 cm (.187 in.) and a thicker coating possibly would have flowed out more uniformly. Consequently, in an effort to promote the leveling process, the thickness of the second coating was increased to .63 cm (.25 in.). The material for this coating appeared to have about the correct viscosity as judged on the basis of how rapidly it flowed from a wetted stirring paddle. Although the resulting surface cured with no trapped gas bubbles and was otherwise substantially improved over the first one, the material still failed to flow adequately to produce a sufficiently level surface for good simulator operation.

This second failure led to the consideration that the flow of the material required to cover the complete surface in a thin layer to a uniform level might be in excess of the capability of the material. Accordingly, the

procedure for pouring the third coating was to divide the surface into small areas and to distribute the material to these areas inversely proportional to their elevations, thus requiring less gravity flow in the thin coating. Each of the small areas (approximately 1.5 m square) was poured with the volume of material calculated to bring its surface into planar register with the rest of the finished surface. Temporary dams made of 2 cm square wood strips were used to confine the liquid to its intended area until the adjacent areas had been poured. Then the dams were removed to allow the liquid to flow together to form one continuous coating. Using this procedure, the material was required to flow over distances of only about 1 meter or less and most of the flow was achieved within a few minutes of the time the material was poured. Thus the major portion of the time during which the epoxy remained liquid was available for the gravity force to act on the small differences in elevation due to the "piling" of the liquid around the pouring point and to the inaccuracies in measuring the material for the individual sections.

The third surface was significantly improved but still did not completely meet the requirements for the simulator. The maximum deviation in the elevation of this surface was .091 cm (.036 in.) over the whole surface and the maximum deviation in 1.5 m (5 ft) was .025 cm (.010 in.) as determined from the data shown in figure 3.

The techniques used in pouring the third surface were further improved for the fourth coating. A small amount of solvent (4 percent by weight) was added to the mix to reduce the viscosity and increase the gel time. The quantity of material needed in the small sections was determined more accurately by improving the survey technique and increasing the accuracy of the calculations, as noted previously. Also, the epoxy was measured by weight rather than by liquid volume. The resulting surface proved satisfactory for the simulation requirements.

Final Procedure

In an attempt to prolong the gel period of the fourth coating and thus lengthen the time available for the leveling flow to mature, the temperature inside the hut was reduced as much as practical. This coating was poured in March to take advantage of the natural cooling of the weather. The hut was vented and the circulation fan was temporarily ducted to the atmosphere to pump cold outside air through the hut. The main building heat was turned off about a week before the coating was poured, and the heat remained off for about three days afterwards. The fan was run continuously during this period. Outside temperatures ranged from about 4°C at night to 18°C in the day (40° to 65°F) during this period. Just before the coating was poured the temperature of the surface was measured at 16°C (62°F).

Because the temporary wooden dams used to divide the surface into smaller sections for the previous coating were unwieldy and one of them had broken near the end of the operation, the dams used for the final coating were made of lightweight aluminum angle oriented with the edge of one leg against the floor. Dental dam rubber was looped loosely over the bottom edge of the dam

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and bonded along both sides to form a flexible seal between the dam and the floor, as shown in figure 4. To facilitate handling, the dams for three sections were ganged together to form a single unit with dimensions 1.5 x 4.5 meters (5 x 15 ft) as illustrated in figure 5.

Four of these units were required in pouring the surface and the starting locations for them were as indicated by the solid lines in figure 5. Units A and B were poured; then unit A was moved to position four. Units C, A and D were then poured in that order before units B and C were moved to positions 6 and 7. This general procedure was repeated until the whole surface was covered. The dams were moved by simply lifting them and passing them over the last filled section to the next position. The inside ends of the units were lifted with a long tube fitted with a hook at one end to allow the worker to reach across the filled section to an eyebolt centered in the end of the unit.

Just before each section was poured, the old surface was brush painted with some of the material measured for the section. After priming the surface, the remaining material was poured into the center of the section with care being taken to avoid splashing the liquid and creating unnecessary bubbles.

Although only about .802 m^3 (212 gal) of the epoxy were required for this coating, five 50 gallon kits were used in order to avoid pouring the material from the bottom of the drums. In both the second and third coatings there had been small isolated areas of the surface which had failed to harden completely. Because these spots were in areas where the drums had been drained, it was thought that some of the material at the bottom of the drums had been poorly mixed. To reduce the chances of a recurrence of this problem, about 10 to 15 kilograms (2-3 gal) of the mix were left in each drum when the fourth coating was poured.

The material required for each 1.5 m square section was drained into a bucket through a valve fitted into the drum head, weighed to the nearest .45 grams (.001 lb) of the calculated weight and poured into the section. The bucket was then reweighed to determine the residual due to incomplete draining. A quantity of material equal to this residual was weighed into a smaller container and then added to the section to make up the loss. The draining of these "make-up" containers was timed with a stop watch and held constant at 30 ± 1 seconds while the container was used for each section. This procedure was quicker and more accurate than allowing the larger container sufficient time to drain.

These mixing and pouring operations required several workers to perform the various tasks and, to minimize the holding time of the mix, it was essential that the operations be well coordinated. In pouring the previous surface, considerable confusion existed among the workers concerning the sequence and timing of the various activities so that a routine was not established until the job was nearly complete. The resulting delay of the operation was thought to have contributed to the poor results with the third surface. Consequently, the procedure for pouring the fourth surface was

rehearsed until the routine was well established before the actual pouring was started. Apparently, this practice was effort well spent because the actual pouring operation went efficiently from the start.

The mixing and pouring operations were started at about 9:00 a.m. and were completed at 11:30 a.m. About 53 hours later the surface was still somewhat tacky to the touch. During this period the plastic was tested several times by dipping a small stick into a corner of the surface and observing how the liquid flowed from the stick and how rapidly the surface recovered from the disturbance. The plastic appeared to remain sufficiently fluid to allow fairly free flow up to about 30 hours with the flow becoming gradually more sluggish so that very little flow could occur after about 50 hours. After about 69 hours the surface was tack-free but still pliable. The hangar heat was turned on at that time while the outside air was pumped through the hut for another 15 days. The coating was allowed to cure for about 21 days before any loading was applied.

Results of the Fourth Surface

The fourth coating cured with a moderate number of bubbles in the surface, along with a few small airborne inclusions. The bubbles ranged up to .3 cm (1/8 in.) in diameter with most of them being .15 cm or smaller. Typically, 5 to 15 percent of the bubble was exposed above the surface with the meniscus around the bubble covering an area with a diameter of two to six times that of the bubble. Figure 6 is a photograph of typical bubbles in one of the less dense concentrations. The bubbles were considerably more concentrated in the areas where the edges of the temporary dams had been than elsewhere in the surface. Apparently this was caused by air which was introduced by the drippings when the dams were removed from the liquid. Using the procedure described in appendix B, the surface was scraped all over to remove all the surface protrusions which would interfere with operation of the air bearings. Figure 7 is a photograph showing a typical section of the surface after the protrusions were scraped away.

Several small areas (30 to 130 cm^2) failed to harden completely. These were all in the sections poured from the first mix and were pliable with a "spider-web-wrinkled" surface characteristic of the incompletely mixed material. These areas were repaired by the procedure described in appendix B. After this repair, the surface over these areas was measured and found to deviate only .0012 cm (.0005 in.), in the worst case, from planar register with the adjacent primary surface. Figure 8 is a photograph of one of the soft areas being cut out in preparation for the repair and the photograph of figure 9 shows a typical finished repair.

The use of the solvent in the epoxy caused a very subtle mottling of the normally glossy smooth surface. This effect, discernible only at shallow reflection angles, is shown in the photograph of figure 10. The shallow, discontinuous pattern was not measurable with a dial indicator at .00025 cm (.0001 in.) sensitivity. However, when the surface was rubbed with an unlubricated smooth plate, the wear patterns indicated that these lines were

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definitely raised above the rest of the surface. Test samples made with higher concentrations (up to 12 percent by weight) of solvent showed that the number and, to a lesser extent, the elevation of these crests increase with increased solvent content. This surface roughness was barely detectable with the dial indicator in the samples containing 12 percent solvent.

An elevation survey was made over this surface about 6 weeks after it was poured, and data from this survey are given in figure 11. Figure 12 is a topographic sketch of these data. The procedure used in making the survey is discussed in appendix C. These data show a maximum total deviation of .038 cm (.015 in.) over the whole surface with the largest deviation in a single 1.5 m section being .013 cm (.005 in.). This represents a significant improvement over the previous surface where the maximum total deviation over the whole surface was .093 cm (.037 in.) with a maximum of .025 cm (.010 in.) deviation in a single 1.5 m section, as discussed previously. The data in figure 11 also show that about 85 percent of the surface had deviations of less than half the maximum values and that about 90 percent of the surface met or exceeded the requirements specified for the simulator in appendix A. Performance of the simulator vehicle on the surface was satisfactory over most of the area but was degraded to unsatisfactory in the area which exceeded the specified requirements. This area is represented by the upper left hand corner of the sketch in figure 12.

Long Term Anomalies

Even though the epoxy hardened adequately to support transitory and short term static loads in excess of 50 kg/cm^2 within 2 or 3 weeks after it was poured, the material apparently continued to cure over a much longer period. The primary effect of the long term curing was an apparent gradual shrinkage normal to the exposed surface. For several months after the last coating was poured, there was no indication of an anomaly associated with this shrinkage. However, with continued aging, the areas over the steel anchor plates in the concrete subfloor gradually became elevated above the primary surface. This anomaly, in the form of a mound about the same diameter as the plates, was evident with each of the earlier coatings, however its onset was progressively longer after each successive coating. Also, the elevation of the mounds was progressively less with each successive coating. Apparently the steel plates had a retarding effect on the shrinkage of the material in their immediate vicinity.

Measurements made with a dial indicator showed that the worst of the protrusions over the anchor plates were elevated .007 cm (.003 in.) before the surface was first scraped. About 5 months after this first scraping, several of the worst protrusions which had reappeared were measured at .003 to .005 cm (.001 to .002 in.) above the primary surface.

The long term curing had a similar effect on the trapped gas bubbles also. Even though nearly all the bubbles near the surface were broken in the initial scraping operation, the areas surrounding the small remaining cavities

gradually emerged above the primary surface. These and the mounds over the anchor plates had to be scraped three times in some 25 months after the final surface was first used.

In another air-bearing application at the Langley Research Center, using the same type of epoxy for a large surface, the material cured with similar mounds over discontinuities in the subsurface. In this case the subsurface was concrete with several large steel plates covering tunnel openings in the floor. The single coating varied in thickness from about .63 cm to 2.5 cm (.25 to 1 in.). In the thicker portions, the surface over the steel plates was raised as much as .32 cm (.125 in.) above the primary surface while the worst of those in the thinner sections were raised about .076 cm (.030 in.). In that case no effort was made to remove the protrusions nor was any effort made to determine whether they increased with age. However, the one set of measurements does indicate that the thickness of a single coating and the size of the subsurface discontinuity may influence the height of the surface protrusion that results.

CONCLUDING REMARKS

In producing large level surfaces for use with thrust-pad type air-bearings, self-leveled epoxy coatings have substantial advantages in cost and precision over more conventional methods of fabrication. Results obtained with this material can be generally improved by observing certain precautions in the fabrication process.

1. The subsurface material should be homogeneous and free of structural joints and other discontinuities. If this is impractical, several coatings may be required to obtain a smooth surface over the discontinuities.

2. Each coating should be about .63 cm (.25 in.) thick unless the required flow path is considerably shorter than 1 meter from the pouring point.

3. The subsurface must be clean and dry to provide a good bonding surface for the epoxy. Good bonding also requires thorough wetting of the substrate with the liquid epoxy.

4. Test samples should be poured to check the performance of the material under the anticipated pouring conditions. Also, each container of the material should be checked to ensure uniformity from batch to batch.

5. The material should be chilled sufficiently to provide a free flow time of about 30 hours for the mix. This will result in a gel time of approximately 60 hours.

6. Temporary dams should be used to allow accurate metering of the material over the surface and minimize the flow required of the material.

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7. The pouring operation should be well organized so that the material is applied to all the area in approximately the same condition, and the mixing and holding time is minimized.

8. Air entrainment should be avoided in the mixing and pouring operations. Also, some residual should be left in each mixing container to avoid any material which may be poorly mixed.

9. Small surface defects can be corrected fairly easily as described in the appendix. The whole surface can be renewed by simply pouring a new coating using the same procedures.

10. In the use of the surface, long term concentrated static loads should be avoided.

APPENDIX A

REQUIREMENTS FOR AIR-BEARING SUPPORT SURFACE

Requirements for the supporting surface for an air-bearing type zero-gravity simulator are dependent to a major extent on the performance requirements of the vehicle to be used with it as well as on the size and working clearance of the bearings being used. In studying low energy propulsion systems such as the FCMU, which was the subject of this simulation, it is desirable that accelerations due to friction and gravity be zero. However, in practice, economic and other considerations usually dictate that something greater than the desired zero accelerations be accepted.

Preliminary evaluations of the FCMU indicated the extraneous accelerations should not require the operator to increase the number of his control inputs by more than about 20 percent over those required for the vehicle in undisturbed operation. It was found that this requirement limited uncommanded velocity changes to about .6 cm/sec (.02 ft/sec) in 15 seconds, and that inadvertent changes in the direction of the velocity vector were limited to about 10° in 15 seconds based on an initial velocity of about 3.048 cm/sec (.1 ft/sec). Also, it was found that the maximum acceptable drift, from a standstill, was about 15 cm (.5 ft) in 30 seconds when no control forces were imposed on the vehicle. This was necessary to allow the pilot time to assess his situation and initiate a trajectory with acceptable errors. These values were engineering compromises rather than absolute limits. However, they were considered suitable in that they did not cause an unacceptable increase in the pilot's workload and they were not unduly difficult to achieve.

With respect to surface slope, these requirements are very similar to one another, the most stringent being that for a maximum drift, from a standstill, of 15 cm in 30 seconds. Assuming perfect lubrication between the bearings and the working surface and an absence of other external forces, the maximum allowable slope angle is calculated simply as follows: From the force diagram shown below, the horizontal forces F_x due to gravity acting on any bearing are

$$\sum F_x = mg \, \text{Sin} \, \theta \, \text{Cos} \, \theta = ma_x \tag{1}$$
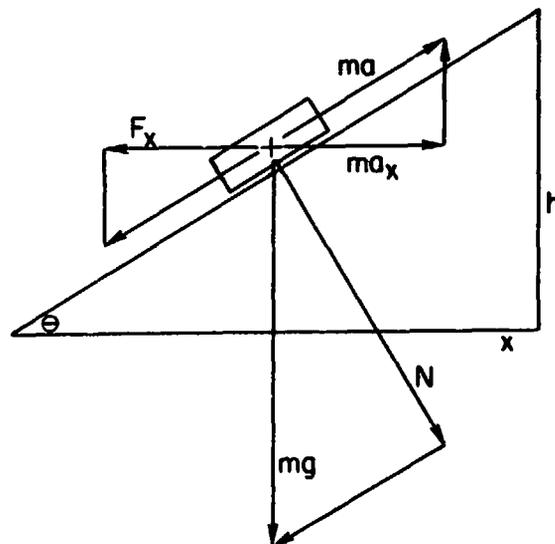
where

θ = Slope angle of the working surface

m = Mass of the bearing and supported load

g = Acceleration due to gravity (= 980.665 cm/sec^2)

a_x = Acceleration along the horizontal plane (cm/sec^2)

therefore: $a_x = g \, \text{Sin} \, \theta \, \text{Cos} \, \theta = g(\frac{1}{2} \, \text{Sin} \, \theta \, 2 \, \theta)$ \hfill (2)

When the bearing starts from a standstill it moves with uniform acceleration so that the displacement is:

$$x = \frac{1}{2} a_x t^2 \tag{3}$$

where; x = horizontal displacement (cm)

t = time (sec)

Substituting the value of a_x from (2):

$$x = \frac{1}{4} g \, \text{Sin} \, 2 \, \theta \, t^2 \tag{4}$$

$$\text{Sin} \, 2 \, \theta = \frac{4x}{gt^2}$$

Substituting the maximum values for x and t [15.24 cm (.5 ft) and 30 seconds respectively] gives the maximum acceptable slope angle.

$$\text{Sin } 2\theta = \frac{(4) \ (15.24)}{(980.665) \ (30)^2}$$

$$= .000069069$$

$$\theta = .0019787°$$

The elevation change in one section of the supporting surface (1.524 m or 5 ft) resulting from this slope is:

$$h = x \text{ Tan } \theta \doteq x \text{ Sin } \theta \tag{5}$$

so that: $h = x \text{ Sin } (.0019787°)$

$$= (152.4) \ (.0000345344)$$

$$h = .0053 \text{ cm}$$

Thus the change in elevation which will produce no more than 15.24 cm (.5 ft) displacement in 30 seconds is .00345 cm/m (or .000414 in/ft).

Considering the maximum allowable deviation, from a straight path, of 10° in 15 seconds at an initial velocity of 3.048 cm/sec (.1 ft/sec); the vehicle is assumed to have a constant forward velocity with a constant lateral acceleration normal to the initial velocity vector. After 15 seconds, the velocity vector is 10° displaced from the initial velocity as indicated in the sketch below.

Initial velocity vector

α=10°

Final velocity vector

θ
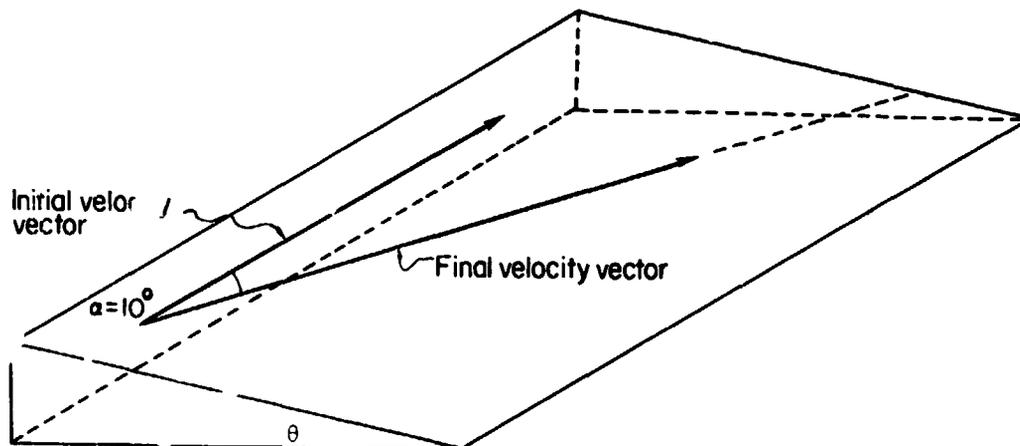
Since the lateral and horizontal displacements are proportional to the respective velocity vectors:

$$\text{Tan } \alpha = \frac{a_1 t}{V_o} = \text{Tan } 10^o = .176327 \qquad (6)$$

where; $\alpha = 10^o$ = angular displacement of velocity vector at $t = 15$ sec

a_1 = lateral acceleration (cm/sec^2)

V_o = initial velocity (cm/sec)

t = time (sec)

$$a_1 = \frac{V_o \text{ Tan } \alpha}{t} = \frac{1}{2} g \text{ Sin } 2 \theta \qquad \text{from (2)}$$

$$\text{Sin } 2 \theta = \frac{2 V_o \text{ Tan } \alpha}{gt}$$

Substituting the limiting values:

$$\text{Sin } 2 \theta = \frac{2(3.048) \ (.17327)}{(980.665) \ (15)}$$

$$\text{Sin } 2 \theta = .000073072$$

$$= .0020934^o$$

$$h = x \text{ Tan } \theta \doteq x \text{ Sin } \theta$$

Thus the corresponding elevation change in 1.524 m is:

$$\Delta h = (152.4) \ (.000036536) = .0056 \text{ cm.}$$

Therefore the maximum acceptable slope for the working surface to meet this requirement is .00365 cm/m.

The requirement for a maximum uncommanded velocity change of .6 cm/sec (.02 ft/sec) in 15 seconds is reduced to terms surface slope as follows. Considering the diagram on page 14:

$$\Delta V_x = a_x t = \left(\frac{1}{2} g \text{ Sin } 2 \theta\right)(t) \tag{7}$$

$$\text{Sin } 2 \theta = \frac{2\Delta V_x}{gt}$$

$$= \frac{2(.6096)}{(980.665)(15)}$$

$$\text{Sin } 2\theta = .00008288$$

$$\theta = .0023744$$

$$h = x \text{ Tan } \theta \doteq x \text{ Sin } \theta$$

For this case the elvation change in 1.524 m is:

$$\Delta h = (152.4)(.000041441) = .0063 \text{ cm}$$

That is, the maximum allowable elevation change for the surface to meet this requirement is .00414 cm/m.

Local irregularities or surface roughness are equally as important as the surface slope in the operation of air bearings. Any protuberance on the surface which exceeds the thickness of the air film will, of course, drag on the under surface of the bearing and interfere with the motion of the vehicle. In practice, the bearings are seldom loaded with exact symmetry, so that in operation they usually are tilted to some extent with respect to the working surface. Thus, the tolerable surface protuberances are always considerably less than the average clearance under the bearing. The bearing tilt due to asymmetrical loading can be reduced by increasing the bearing diameter. However, this corrective measure is limited by the inherent increase in inertia and other considerations.

In the FCMU simulation, the operating clearance for the bearings was between .0037 and .0063 cm (.0015 and .0025 in.). Experience with this simulator indicated that local irregularities protruding more than about .0012 cm (.0005 in.) above the surface interfered with the bearings to some extent. Reference 4 gives some of the structural details of the bearings used on this simulator along with test data for the bearings.

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APPENDIX B

TREATMENT OF SURFACE IMPERFECTIONS

Because of the substantial difficulty, due to gas bubbles and foreign particles and the influence of surface tension, in producing a large self-leveled surface with no imperfections, a technique was devised for removing small protrusions from the surface. Also, because of imperfect mixing and consequent incomplete curing in small sections of the plastic it was necessary to devise a method for replacing small sections of the surface. These methods proved effective in correcting minor problems which would otherwise have rendered portions of the surface unsatisfactory for use with the air bearings.

Removing Surface Protrusions

In removing surface protrusions it is essential that the excess material be removed without undercutting the adjacent surface. This was accomplished by using the surrounding flat surface as a guide for a scraping tool. An effective scraper was made by surface grinding the edge of a small flat plate which was then lapped on its broad face to provide a smooth working surface. These operations left a straight sharp cutting edge with zero rake and clearance angles which showed no tendency to dig into the plastic material during its use. (A similar tool ground with a small rake angle was also tried and was found to cut faster and to require less effort from the operator, however, it also showed a greater tendency to dig into the surface and was rejected for this reason.) The scraper was laid on the flat surface, lapped face down, and the cutting edge was pushed against the protrusion to remove a shaving, while a force was applied vertically to hold the plate flat against the plastic surface. This operation was repeated in a manner somewhat similar to the use of a hand plane until no further shavings could be removed from the protrusion.

Use of a tool of this type required substantial effort on the part of the operator and the longer the cutting edge the greater the effort required. However, to avoid undercutting the basic surface, the cutting edge had to be longer than the width of the section it was intended to scrape in order to allow the ends to serve as guides or depth controls running against the flat surface. In the cases where it was required to scrape the surface over the steel anchor plates, a cutting edge about 10 inches long was needed and its use taxed the operator to his limit. This effort was reduced substantially by using air as a lubricant under the cutter. To do this, a round aluminum air bearing was turned in a lathe to produce a cutting edge on the periphery of the working face of the bearing. This bearing had a diameter of about 40 cm (16 ins.) so that it provided some 127 cm (50 ins.) of cutting edge and was amply wide to dress the largest areas of concern in this surface. In use, this scraper was placed on a smooth area of the surface and pressurized just sufficiently to break the static friction - to about .0035 N/cm^2 (.5 to 1 psi). It was then operated in the same manner as the flat plate scraper and proved to be adequate for dressing the high spots in this surface.

Repairing Small Uncured Sections of Surface

Several instances were encountered where incomplete mixing of the liquid epoxy resulted in small areas of the surface which failed to narden properly. These areas were characterized by surface blemisheds or patterns of wrinkles having somewhat the appearance of spider webs. In these areas the body of the material remained pliable, somewhat like uncured rubber, and in one or two cases it actually remained slightly tacky. These areas interfered with the air-bearing operation because dirt particles could not be effectively removed from them and after a short time they formed a deposit which protruded above the parent surface. Also, occasional localized pressure on these areas caused deformation in which the displaced material created a surface protrusion which usually was more than sufficient to interfere with an air bearing.

To correct these problems, the soft material was removed along with a small amount of the adjacent hard material by cutting into the surface with a curved wood chisel and mallet. The resulting cavity had rough surfaces and was thus well suited to bonding with the liquid epoxy. This cavity was over-filled to a depth of roughly .076 cm (.030 in.) with the mixed liquid epoxy and allowed to cure 15 days or longer. After curing, the excess material was cut away with a scraper as described above to bring the surface into planar register with that adjacent to the repair.

Measurement of Local Surface Variations

Measurements of local surface deviations were made with a dial indicator sensitive to .00254 cm (.0001 in.) and a machinist's parallel bar. The parallel was placed on the flat plastic surface adjacent to the area to be measured with care being taken to ensure full contact between the surface and the mating face of the parallel. The dial indicator was mounted on the arm of a surface gage and the gage base was set on the parallel with the arm adjusted to bring the indicator over the area to be inspected. The indicator reference was established on the flat plastic surface and the dial was monitored as the gage base was passed along the parallel to bring the indicator stilus over the points to be measured. Care was used to maintain firm contact between the gage base and the parallel while the measurements were being made.

Using this technique for measuring, the scraping methods described above consistently produced surface corrections with a total indicator runout of .0015 cm (.0006 in.) or less. Although some of the scraped areas had maximum dimensions of about 18 cm (7 ins.), the overwhelming majority of them were less than 2.5 cm (1 in.) in diameter. Generally, the smaller the scraped area the smaller the indicated deviation of the repaired surface from the plane of the parent surface. In most of the repairs which were measured, no deviation was detectable in those with diameters less than about 2.5 cm.

During the scraping operation it was impractical to measure each of the scraped areas to determine whether it was satisfactory. However, it was observed that in addition to shaving off the high point on the surface, the

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scraper would also produce fine scratch marks or a wear pattern on the glossy plastic surface as it was moved back and forth against the protrusion. So long as the shaved area remained higher than the adjacent surface there was an area of unmarred glossy surface between the shaved area and the wear pattern. As the high area was shaved down the wear pattern gradually progressed inward toward the shaved area. When the two patterns came together the surfaces were essentially co-planar. This proved to be an effective means of determining when the scraping was adequate.

APPENDIX C

SURFACE ELEVATION MEASUREMENT TECHNIQUE

In order to make accurate estimates of the material distribution required for the fourth coating in the air-bearing surface several elevation surveys were made over the existing surface using a precision tilting level and the standard procedure described in the instruction manual furnished with the instrument. The instrument had a direct reading, micrometer elevation adjustment on the horizontal hairline with the scale graduated in increments of .001 inch around a 4.4 centimeter (1.75 in.) diameter adjustment knob. Thus it could be accurately adjusted and the differential elevations easily read from it. Two sets of typical data from these surveys are shown in figure 13. These data were read by the same observer on successive days from the same instrument setup. Initially the reference point was arbitrarily chosen but the same reference was used in every survey of the working surface. The point values represent elevations, in inches, relative to the reference with negative numbers representing points higher than the reference and positive values being points below the reference.

In these data, the difference between two readings of the same point, in many cases, is greater than the allowable deviation over a 1.5 m (5 ft) span as discussed in appendix A (1.5 m x .00345 cm/m = .0052 cm $\doteq$ .002 in. allowable, compared to .008 in. worst case difference in the survey data). Obviously this was an unacceptable error for measurements of the working surface. Even so, the general pattern for the data was confirmed by the free drift action of the simulator vehicle. Also, the pattern of the data roughly agreed from one survey to another.

To improve the accuracy of the elevation data, the standard elevation scale was replaced with a vernier height gage with a clean, sharp scribe. The height gage was mounted on a stand made of aluminum tubing with the ends plugged and machined perpendicular to the long axis of the tube. The lower base was relieved over its bottom face except for 3 feet [about 3 cm^2 (.5 in^2) each] equally spaced around the periphery. The height gage was clamped to the upper base of the stand to facilitate handling.

The scribe could be seen with sharp definition through the telescope over the full range of the survey [about .6 m to 15 m (2 feet to 50 feet)]. It was found that at the longest range the thickness of the telescope hairline is equal to .015 cm (.006 in.) on the instrument elevation micrometer. For this reason, the elevation micrometer was set at zero and the height gage was adjusted vertically to bring the scribe point into coincidence with the top edge of the horizontal hairline. The scribe was inverted so that, when viewed through the telescope, the point appeared between the bar above and the hairline below. For each reading, the height gage was lowered slightly and adjusted upward to the hairline so that the adjustment backlash was always on the same side of the adjusting mechanism. Elevations were then read directly from the height gage vernier.

This adjustment was made appreciably easier and more consistent by backing the scribe with matt white paper and illuminating it with a strong flashlight. With this improvement, the scribe was elevated until the first traces of white light appeared between the lower edge of the scribe and the upper edge of the horizontal hairline.

This technique was used in the survey made in preparation for pouring the final surface and in measurements of the final surface. Data from these two surveys are given in figures 3 and 11, respectively. In both cases the data were read with the level at two points, A and B as indicated in the figures. The top values in each figure were read from point A, the others from point B. Each set of data was spot checked at several arbitrarily chosen points, some of which were read several times. In every check case, the reading repeated within ± .001 inch. While this accuracy leaves something to be desired, it is considerably better than that achievable with the standard differential leveling technique.

Use of this technique requires some practice and considerable patience on the part of the telescope observer. When unpracticed observers were used, the spread in the data increased $\left[\text{to} \pm .013 \text{ cm } (\pm .005 \text{ in.}) \text{ in one case and} \right.$ $\left. \pm .008 \text{ cm } (\pm .003 \text{ in.}) \text{ in another} \right]$ for repeated readings of the same elevation value. These observers improved after a short period of practice but no attempt was made to measure the rate of improvement. Also, the height gage observer must exercise patience in adjusting and reading the gage. Here, the use of a strong magnifying lens and a strong flashlight proved essential in making rapid and accurate readings on the height gage vernier.

REFERENCES

1. Hewes, Donald E. and Glover, Kenneth E.: Development of Skylab Experiment T020 Employing a Foot Controlled Maneuvering Unit. NASA TN D-6674, 1972.

2. Catiller, John B. and Herman, John A.: A Technique for Applying the Finish Surface of Large Area Platforms Used for Gas-Bearing Zero-G Simulators. Air Force Aero Propulsion Laboratory. Technical Report AF APL-TR-67-119, 1967.

3. Davis, Raymond E.: Elementary Plane Surveying. McGraw Hill Book Co., Inc., 1955, pp. 51-84.

4. Stewart, Eric C.: Techniques for Evaluating the Components of Zero-G Bearing Simulators. A Thesis Presented to the School of Engineering Applied Science, University of Virginia, August 1972.
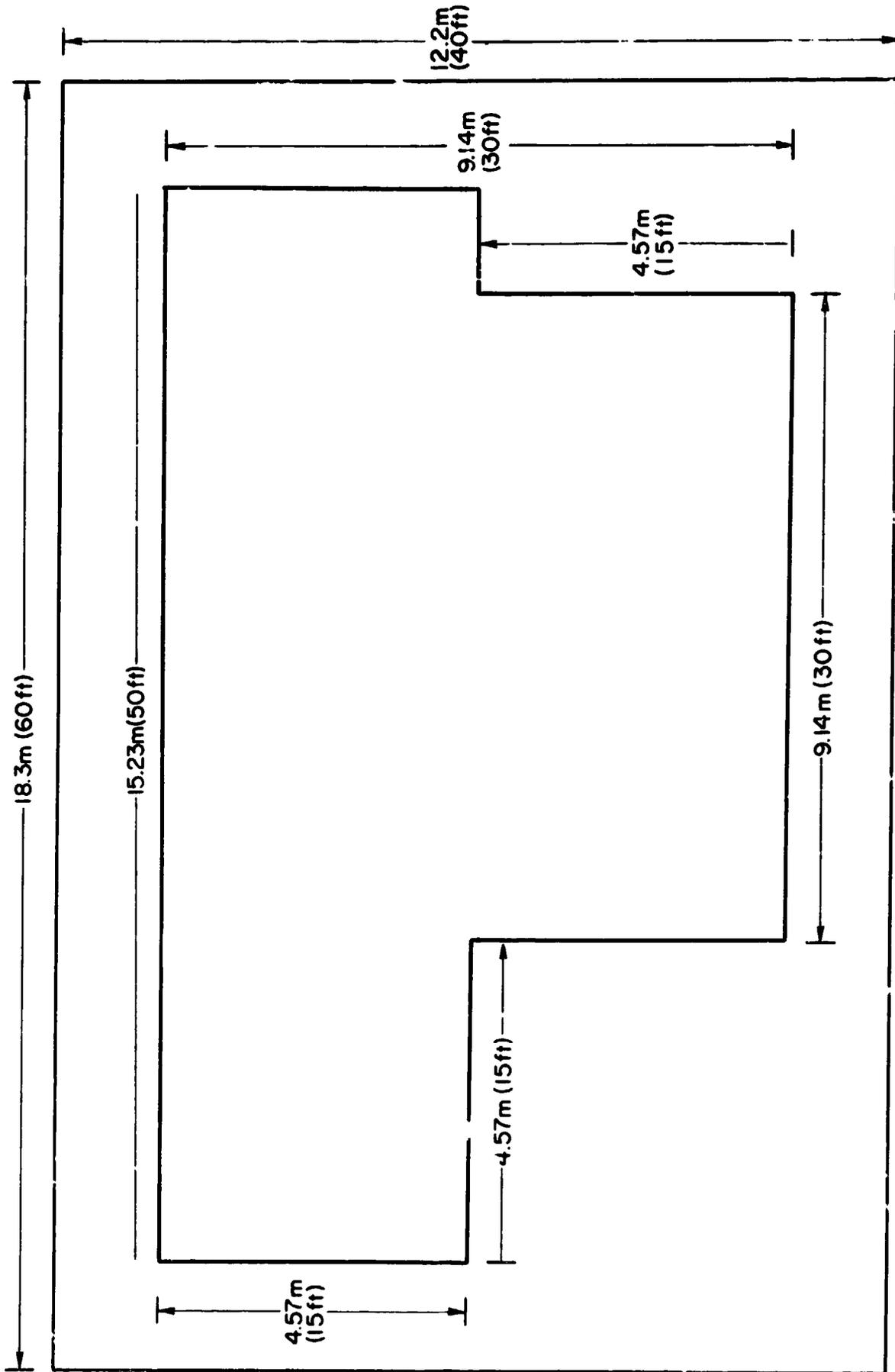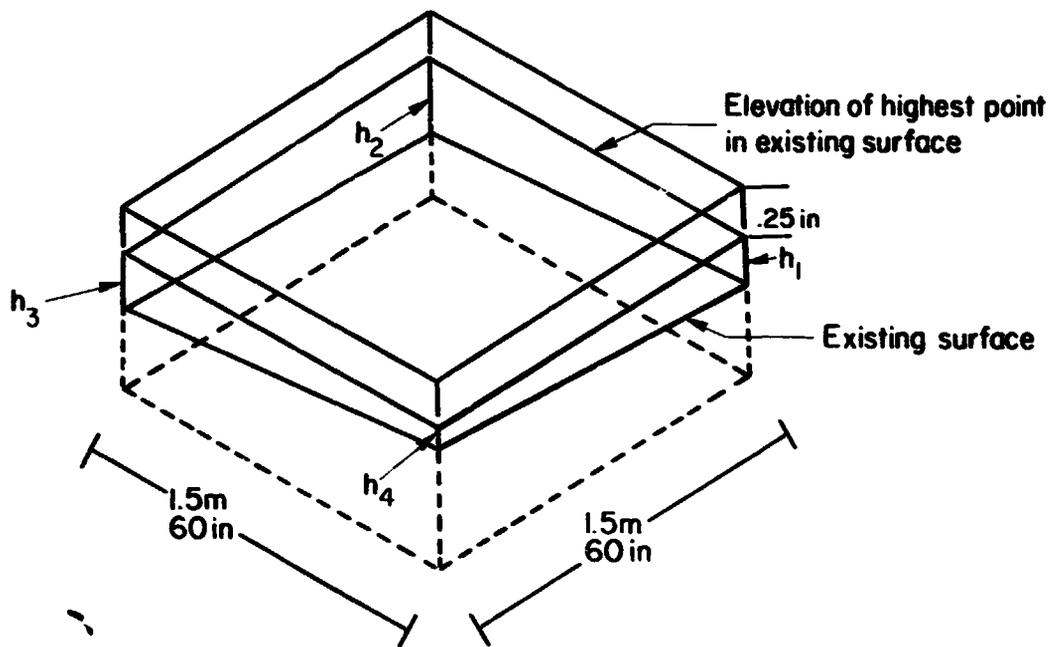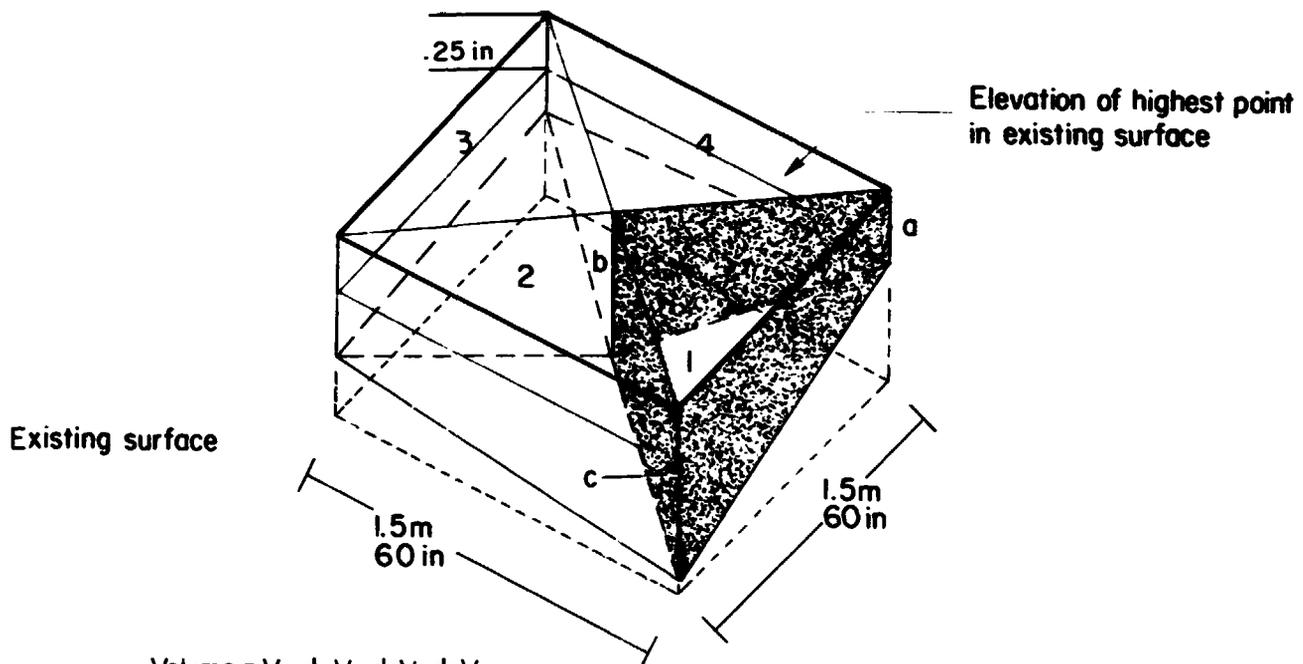
Figure 1.- Air-bearing support surface and enclosure dimensions.

12.2m (40ft)

18.3m (60ft)

9.14m (30ft)

4.57m (15ft)

15.23m (50ft)

9.14m (30ft)

4.57m (15ft)

4.57m (15ft)

$$\text{Volume} = \left(\frac{h_1 + h_2 + h_3 + h_4}{4}\right) + .25 \quad x\,60 \times 60 \text{ in}^3$$

Figure 2a.- Method of calculating volume required for pouring third surface.

$$\text{Volume} = V_1 + V_2 + V_3 + V_4$$

$$V_1 = 1/3\ A_r\ (a + b + c) + .25(60)(60)$$

A_r = urea of lateral faces of section I

Figure 2b.- Method used in calculating qu̲   ̲   ̲al to be poured
in each 1.5 m square section of ̲.̲.̲ ̲   ̲urface.

Figure 3.- Elevation data (as read in inches) from third surface, as determined from two transit locations, points A and B. Upper values read from point A, lower values read from point B. All values in inches, with negative values higher than reference point and positive values lower than reference.

4.5m (15ft)

1.5m(5ft)

1.5m(5ft)

.032m x .038m x .003m
aluminum

Both sides bonded
with rubber cement

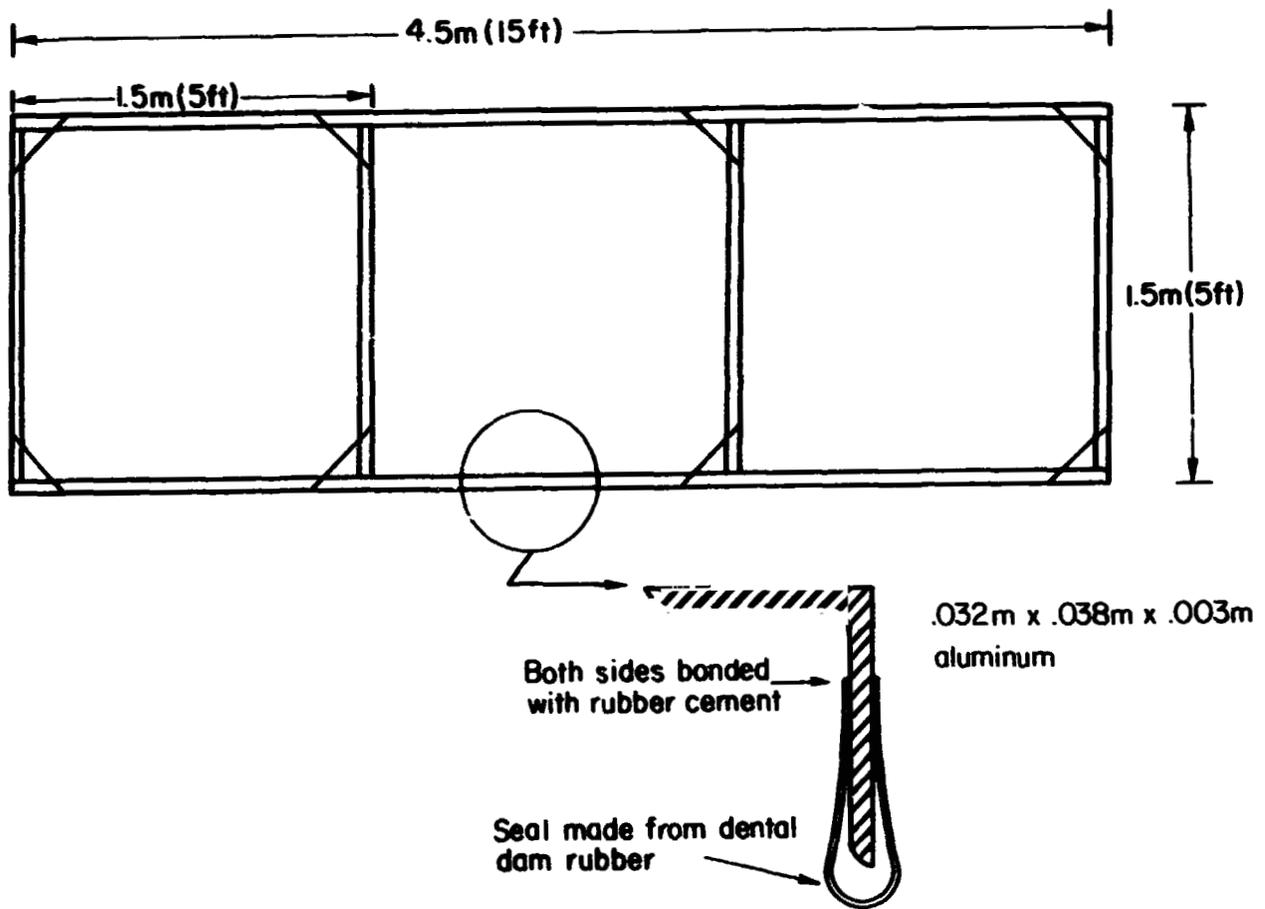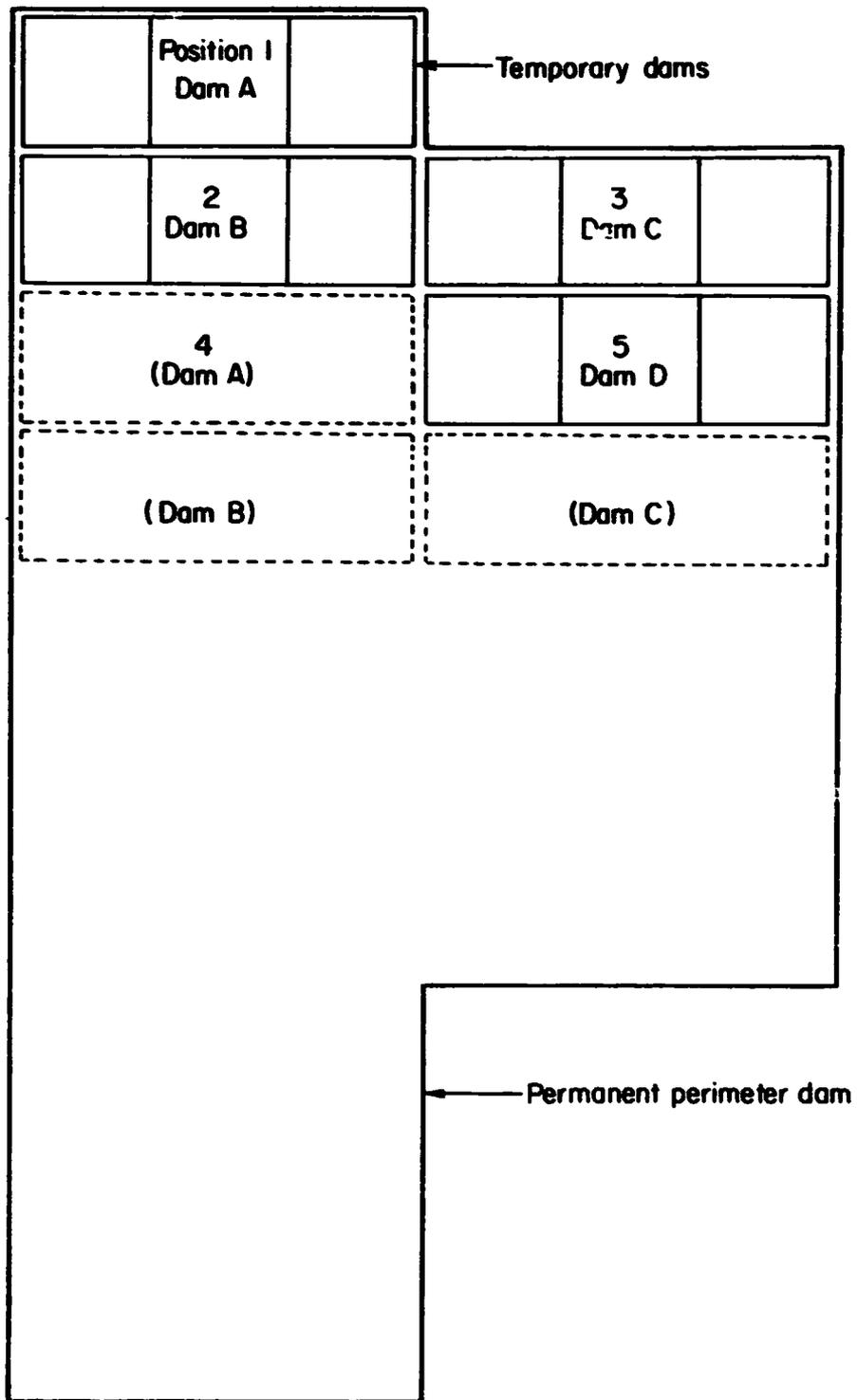Seal made from dental
dam rubber

Figure 4.- Temporary dam used in pouring fourth surface.

Figure 5.— Starting locations for temporary dams used in pouring final surface. Sections 1 and 2 were poured before dam A was moved from 1 to 4, sections 3, 4, and 5 were then poured before dams B and C were moved from 2 and 3 for use in positions 6 a d 7.
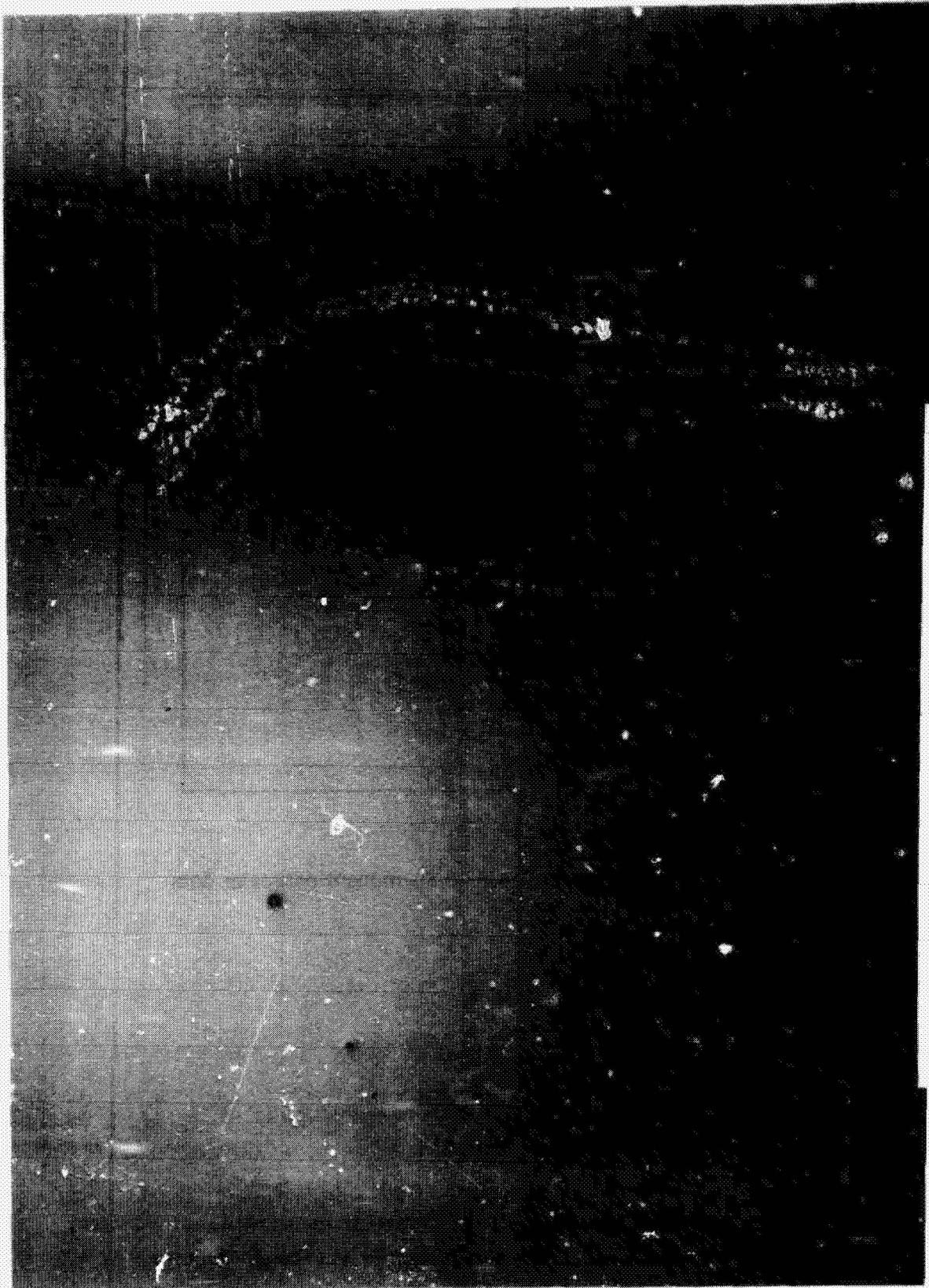
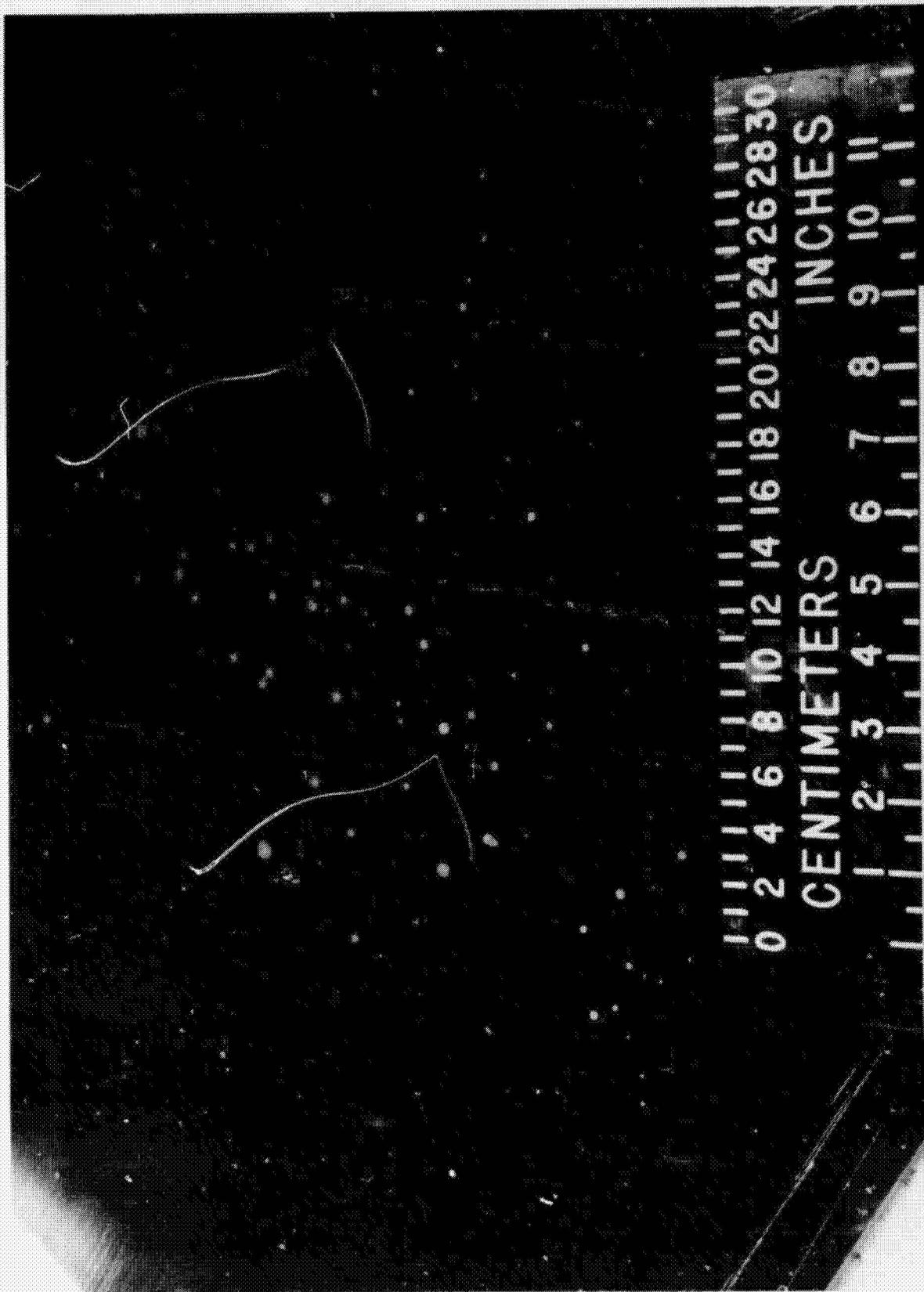Figure 6.- Typical bubbles trapped in cured epoxy surface.

Figure 7.- Typical area of epoxy surface after protrusions due to trapped bubbles were scraped away.

Figure 8.- Section of incompletely cured epoxy being removed for repair.
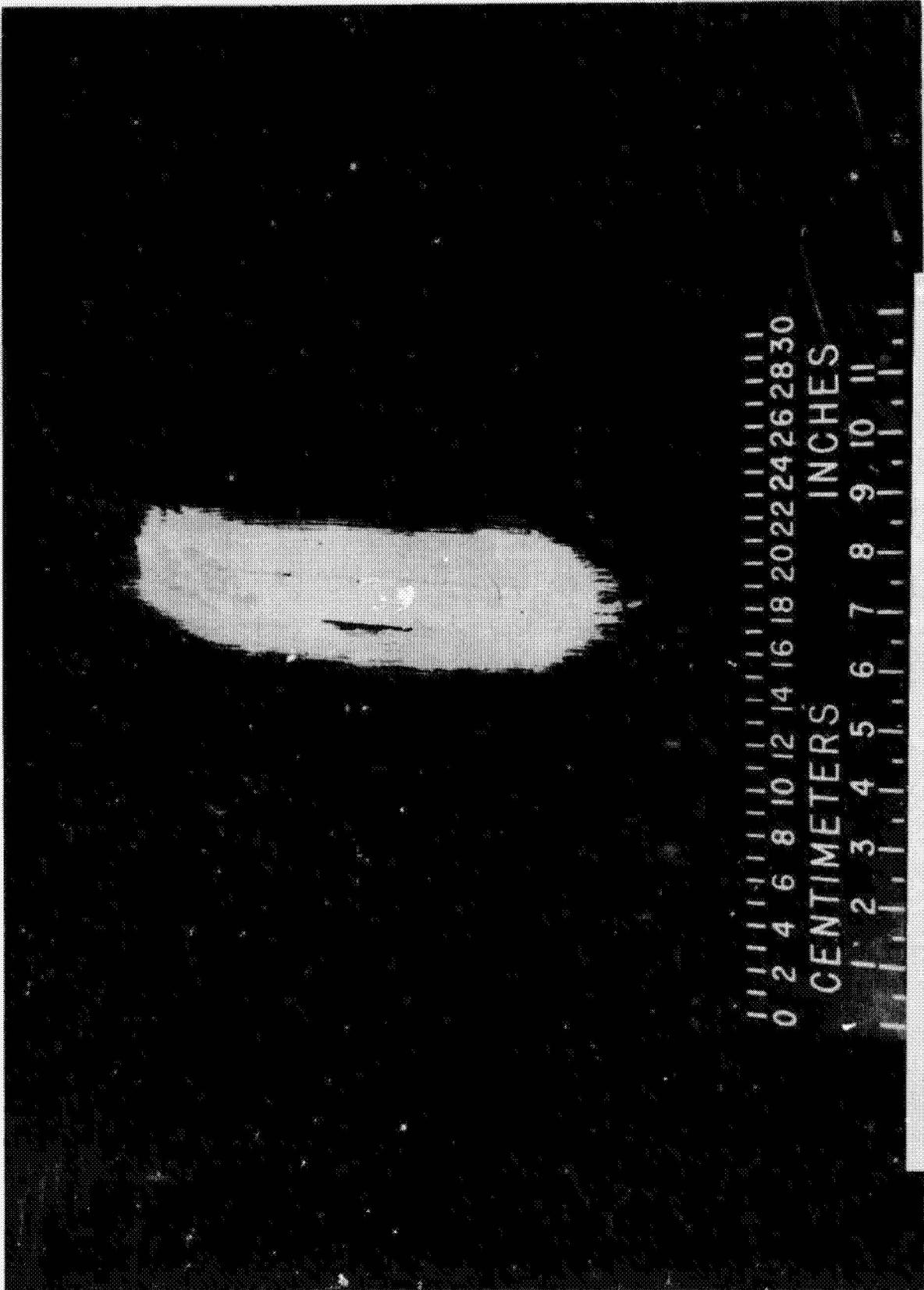
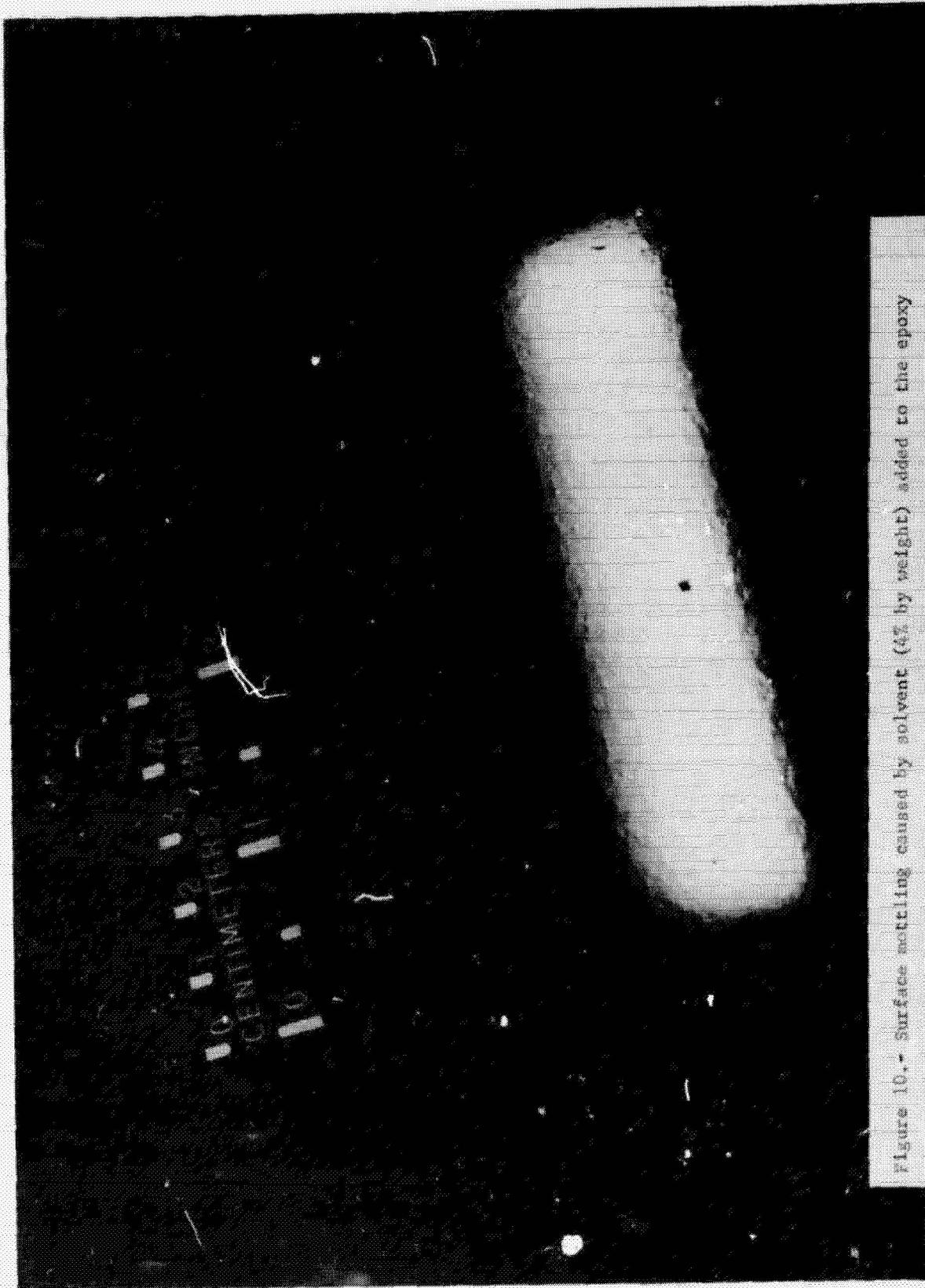Figure 9.- Typical finished repair where soft material was removed and replaced.

Figure 10.- Surface mottling caused by solvent (4% by weight) added to the epoxy for the final coating.

Figure 11.- Elevation data as read in inches from fourth surface. All values in inches, negative values are points lower than reference and positive values are higher than reference.

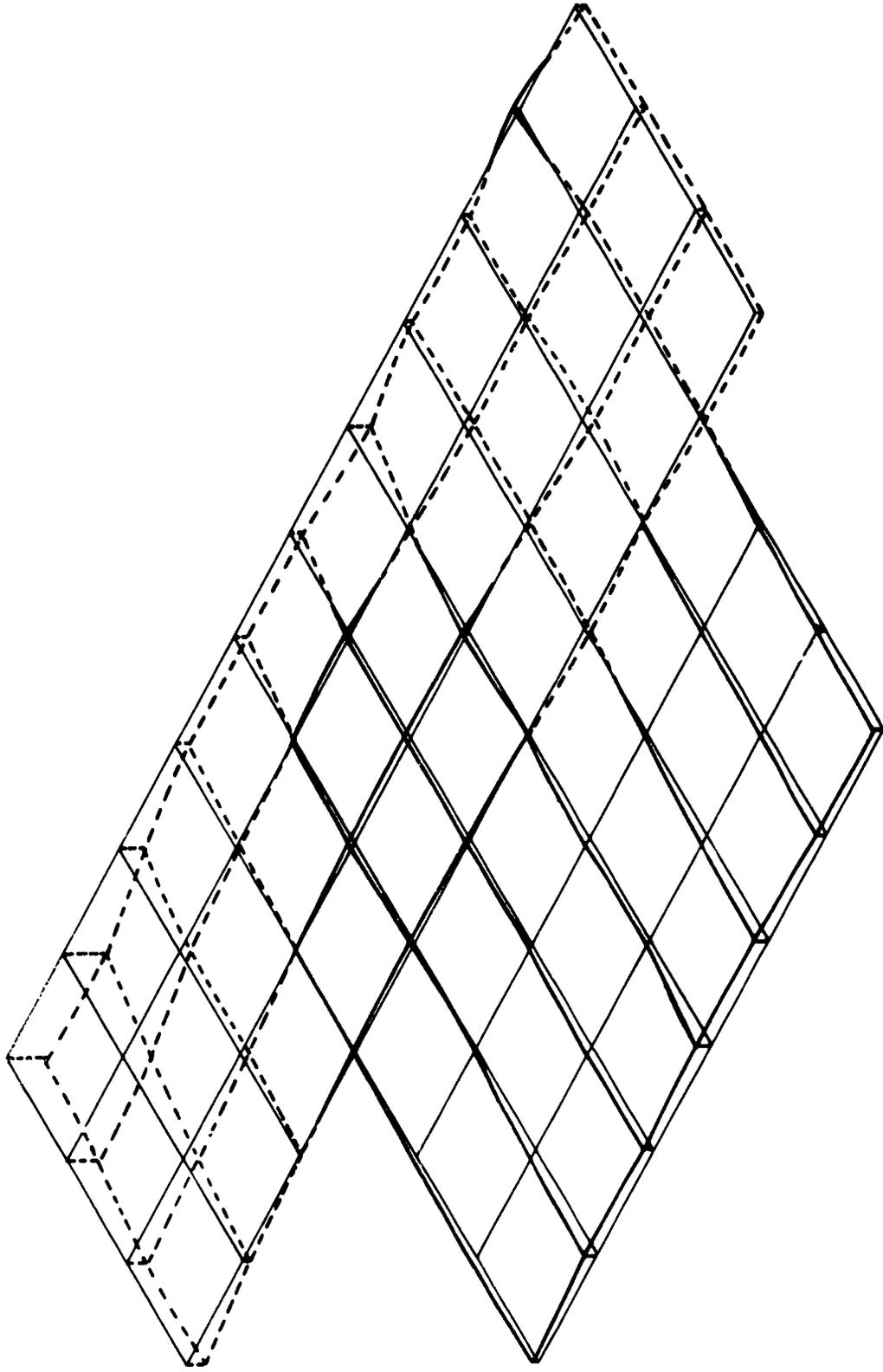|						
			-.005	-.005	-.008	-.010
			-.001	-.003	-.007	-.011
			.000	-.002	-.002	-.006
.002	.002	.001	.000	.000	-.001	-.003
.003	.002	.001	.001	.001	.001	-.003
.004	.001	.002	.000	.001	-.001	-.006
.003	.002	.001	-.001	-.001	-.002	-.002
.002 .002	.001	.001	.000	-.003	-.001	-.002
.001	.001	.001	-.001	-.002	-.002	.001 -.002

Figure 12.- Topographic representation of fourth surface based on data from Figure 10.

Figure 13.- Two sets of data as read in inches from third surface taken with precision tilting level using standard procedure for the instrument. Data were taken on successive days by same observer from same instrument set up.