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TECHNICAL REPORT
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CONSTRUCTION OF BALLISTIC MATERIAL SAMPLES FOR AIRCREW ARMOR SYSTEMS

by

R.A. Rodzen, C.F. Lamber,
F.C. Scribano and M. Burns

IIT Research Institute
Chicago, Illinois

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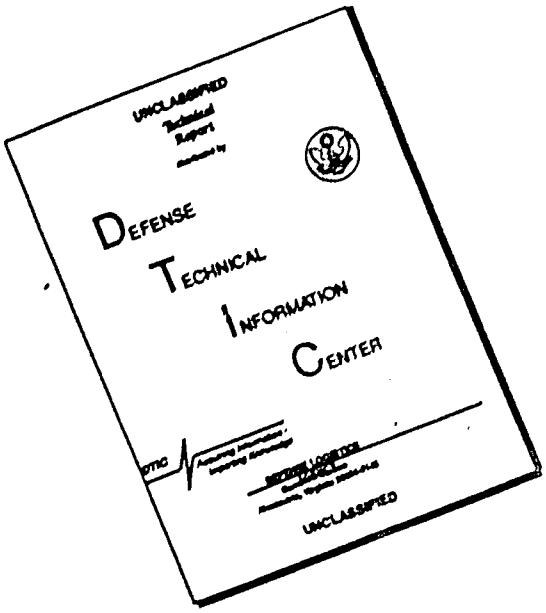

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January 1969

Clothing and Personal Life Support Equipment Laboratory
U. S. ARMY NATICK LABORATORIES
Natick, Massachusetts 01760

FOREWORD

This report describes the research and development effort necessary in constructing ballistic material samples for the aircrew armor developed under this contract. The report describes, in detail, the production analysis conducted for torso and leg armor configurations, and discusses the compromises which were necessary to make the armor compatible with existing production techniques.

The Project Officer, Mr. E. R. Barron, Armor Technologist for the U.S. Army Natick Laboratories, has provided valuable guidance and assistance which has substantially enhanced this phase of the total program effort.

These investigations were performed by the IIT Research Institute under Contract DA19-129-AMC-641 (N).

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ABSTRACT

This report describes the investigative, research, and experimental effort necessary to verify the commercial producibility of the aircrew armor configurations developed under this contract.

This was a cooperative effort with industry, to identify typical problem areas, solutions and compromises necessary to make such armor producible. Also described and illustrated are the ceramic samples which were fabricated to verify producibility of the armor configurations.

Manufacturing difficulties were encountered in fabricating standard aircrew armor from aluminum oxide ceramic material. In the sag molding process, the ceramic material tends to assume a catenary curve, making it difficult to manufacture rectangular shapes or curves in opposition to the normal catenary shape. Modifications made in the armor configurations have made production of armor from the ceramic material possible.

I. PRODUCTION ANALYSIS FOR BALLISTIC MATERIAL SAMPLES

General Considerations

Various ballistic ceramic materials are currently being utilized in the fabrication of personnel armor, i.e., aluminum oxide, boron carbide, and silicon oxide. Each of these materials is processed somewhat differently and possesses different physical characteristics.

Recently, the producers of aluminum oxide ceramic material have demonstrated the best capability for producing the compound curvatures characteristic of anatomical armor. The Coors Porcelain Company fabricated sample elements.

The Sag Molding Process

The process employed in fabricating the elements (sag molding) is one of isostatic pressing the ceramic powder (using a suitable binder) into a solid cylindrical shape. Wafers of proper thickness are sliced from the cylinder. These flat circular elements are trimmed to the desired peripheral shape of the armor. The trimmed wafer is then placed on a female mold form, and the combination is placed in a furnace. As the ceramic is heated, it is drawn by gravity into the mold and eventually assumes the shape of the mold surface.

There are some very striking limitations in the contours which can be produced with the sag molding process. The ceramic material, as it draws into the mold, tends to assume the shape of a catenary curve, very similar to a sagging string held loosely at the ends. Hence, it is difficult to manufacture a shape which is rectangular (a flat surface with perpendicular walls). Equally difficult to mold are inflection points (reverse curves) or changes in curvature which are in opposition to the normal catenary shape.

Some of the more difficult shapes can sometimes be made in stages (more than one pass). However, the reject rate generally goes up because of stress cracking. Therefore, in this production analysis it was necessary to modify the basic contours, and in some cases make major departures from the original anatomical contours to obtain

shapes that could be produced with a low reject rate. These points are further amplified and illustrated in the succeeding paragraphs.

Torso Armor Producibility Studies

Original anatomical torso mock-ups were prepared over the manikin in Figure 1. These contours are fairly representative of the medium range individual and are very similar to the contours of the U. S. Air Force manikins. The Air Force manikins, in fact, are slightly more angular and probably not as representative of real body contours, even though individual dimensions may be statistically more accurate.

In attempting to fabricate ceramic shapes conforming to the original contours, it was obvious that the reverse curve in the pectoral region in both the vertical and horizontal plane would be most difficult to accommodate. A manikin was constructed which was successively modified many times, to achieve a producible shape.

Figure 2 illustrates the final manikin which was utilized as a pattern for the prototype torso armor. It is apparent from viewing the modified manikin that the reverse curve in the suprasternum region has been completely eliminated, and the curvature in the substernum region has been substantially reduced to achieve as smooth a transition as possible.

Profile and Cross-Sectional Analyses

In order to graphically illustrate these changes, the various cross-sectional configurations are shown in Figure 3. In Section A-A the reverse curve was eliminated in the suprasternum region and the section was made virtually flat. In Section B-B, a change is made from a rectangular section to a shape which approaches the catenary curve, the latter being more amenable to the sag molding process. Similar changes were made in the vertical profile to substantially reduce the reverse curvatures which inhibit producibility.

It was necessary to accurately depict the curvatures at specific cross-sectional locations. Therefore, special forms were fabricated for the purpose of evaluating producibility in greater depth. Figure 4 shows a few of the typical forms which were fabricated, using the U. S. Army Natick Laboratories manikin, and illustrates the reverse curvatures and the rectangular configurations which were rejected in favor of the final manikin configuration depicted in Figure 2.

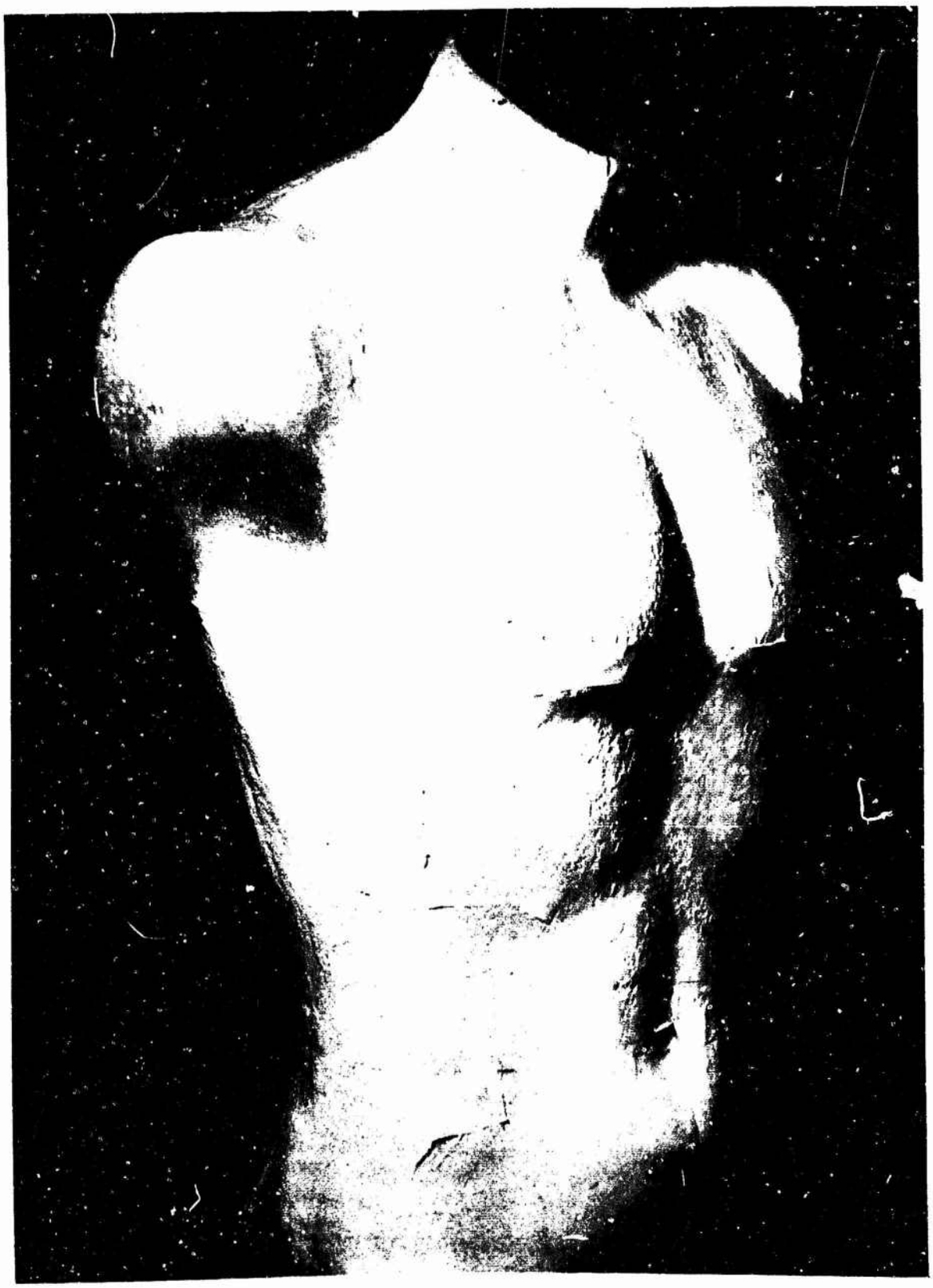


Figure 1. ORIGINAL TORSO MANIKIN FOR FORMING ANATOMICAL ARMOR

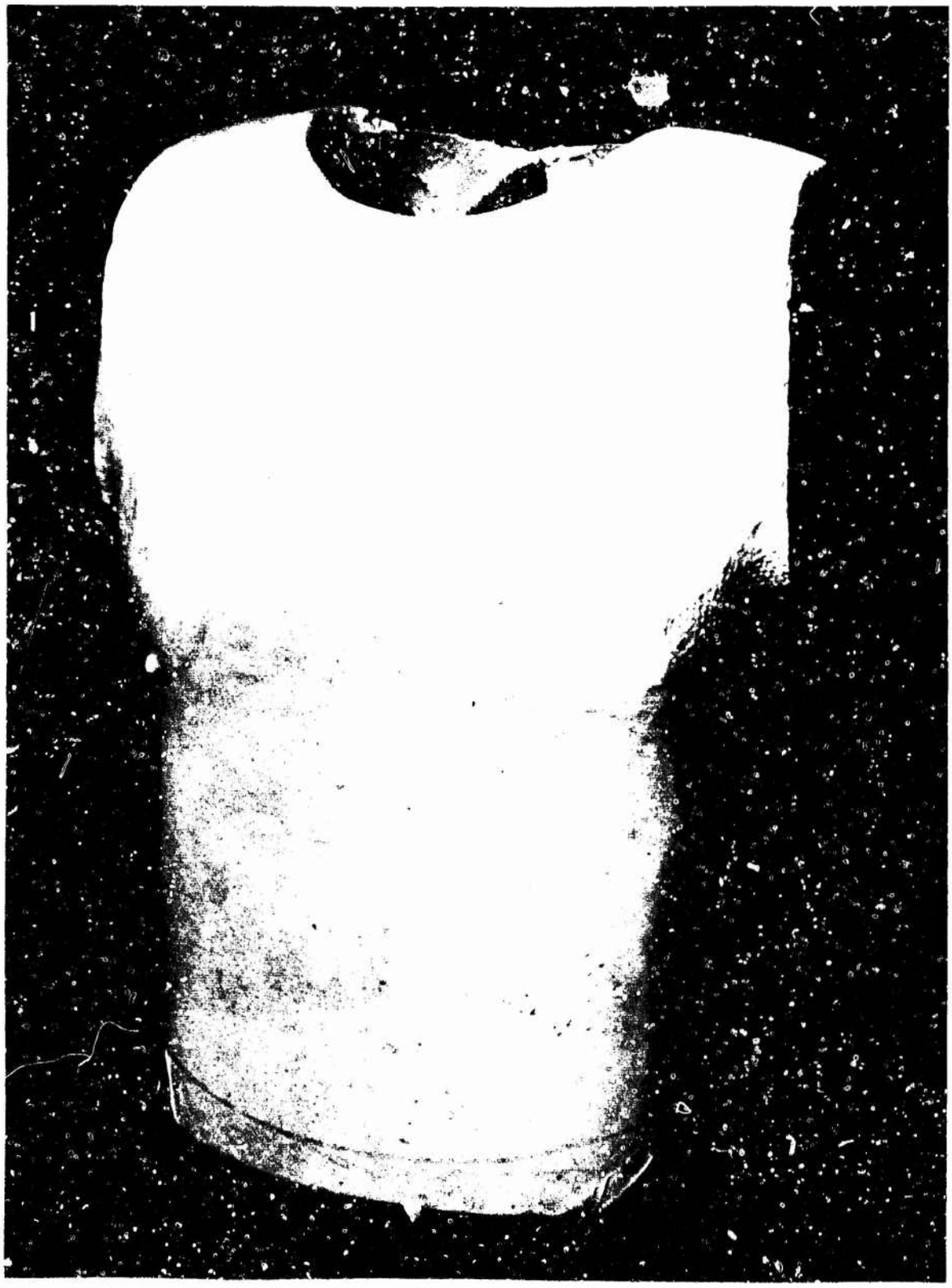
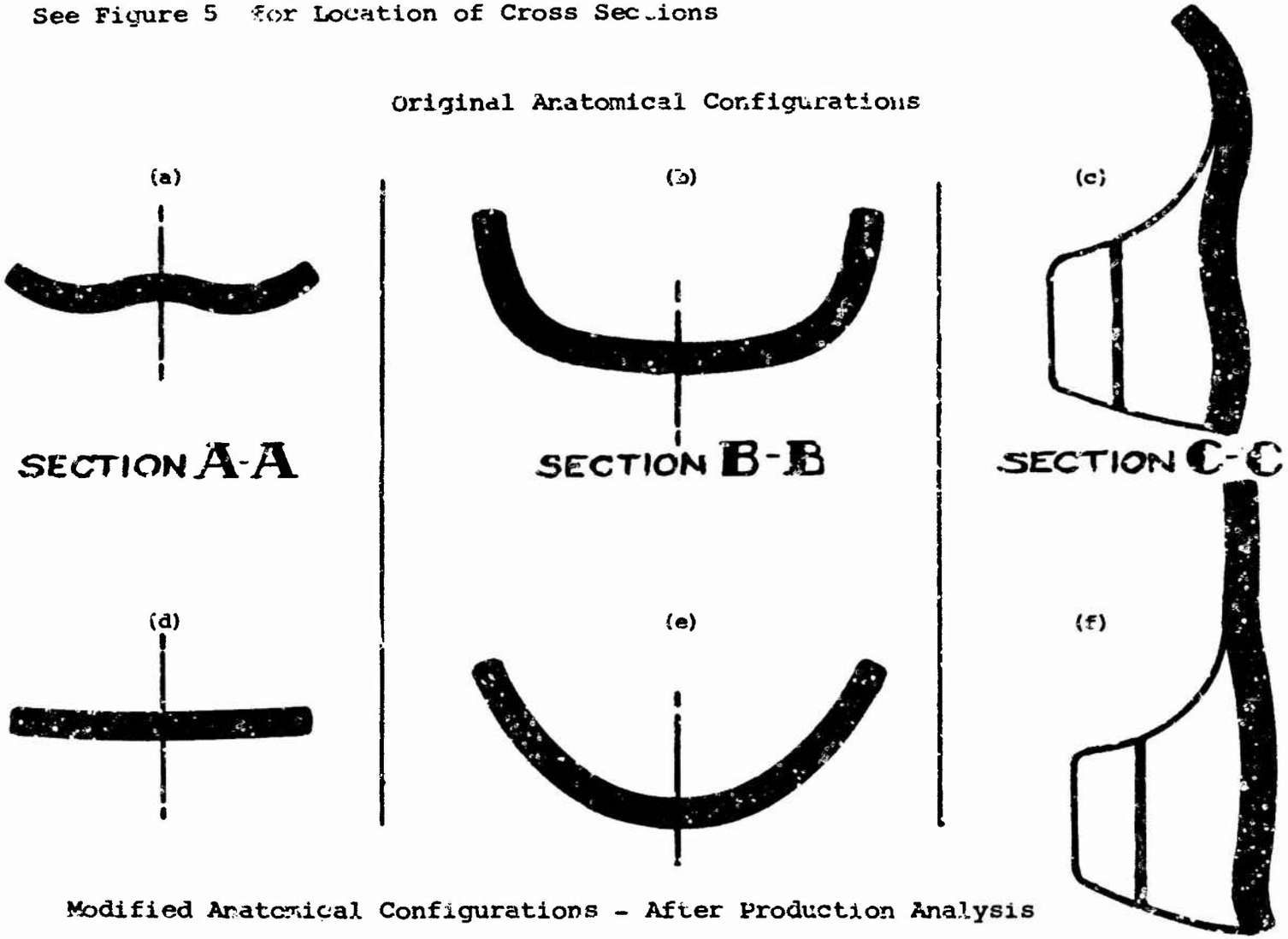


Figure 2. MODIFIED IITRI MANIKIN FOR FORMING FINAL PROTOTYPE ARMOR

Note: See Figure 5 for Location of Cross Sections

Original Anatomical Configurations



Modified Anatomical Configurations - After Production Analysis

Figure 3. CONTOUR MODIFICATIONS (Torso Armor)

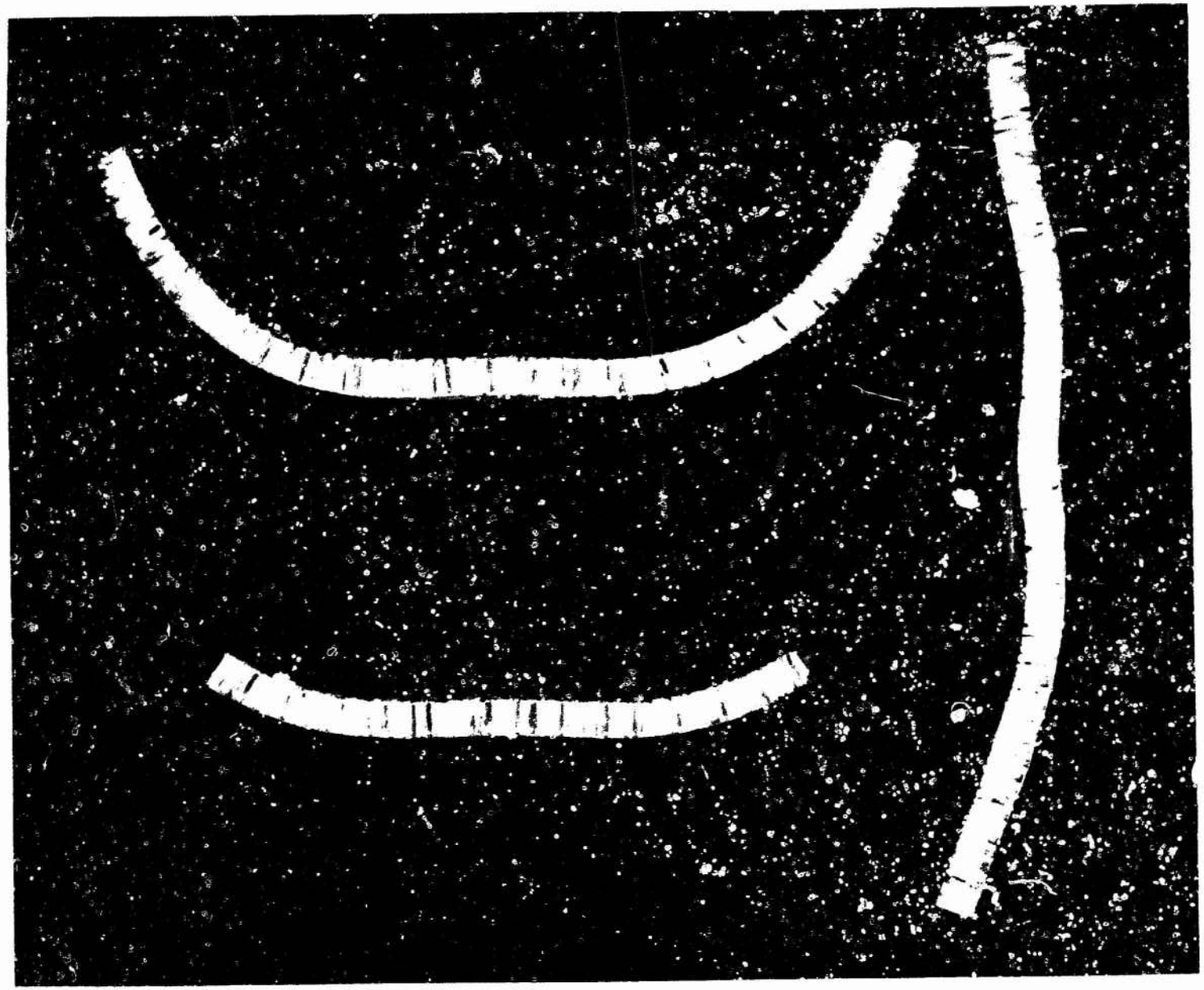


Figure 4. CROSS-SECTIONAL PROFILES OF ORIGINAL ARMOR PROTOTYPES

Modifications to Torso Armor

To clearly illustrate the extent of the changes which were necessary to assure producibility of the torso armor, it is necessary to inspect the original torso configuration. Figure 5 depicts the original theme in configuring the anatomical torso armor, and Figure 6 illustrates the actual mock-up which conforms to this shape. This class of anatomical armor employed deep reverse curves in both the vertical and horizontal planes. The producibility study strongly encouraged modification of these shapes, to eliminate reverse curvatures wherever possible, and to make certain other important modifications.

Figure 7 is an end view of the manikin showing the cross section at the waist level. The inner envelope (heavy dark line) represents the original shape of this manikin. The armor prototypes, which were fabricated over this manikin form, were anatomically correct but were not producible with the sag molding process. The reason for this is that the rectangular configuration of the armor (wrap around) at the sides, was not compatible with the ceramic manufacturing technique. Therefore, this torso manikin was modified to achieve a more continuous curve, approaching the catenary. The modifications affected both posterior and anterior sections of the torso manikin, corresponding with the front and rear torso armor elements. The final cross-sectional envelope is depicted by the line drawn around the outer periphery of the torso plane.

During each of the above stages, it was necessary to make additional mock-ups and contoured forms which could be checked in the laboratory for compatibility and fit. In reviewing the original shapes, the representatives from Coors indicated that the rectangular shapes could be tolerated to some extent if the wrap-around of the armor was kept to a minimum. In their terms, this meant that less material would have to be sagged into the mold. It was felt that side protection of the armor was significant, and to achieve a producible compromise, the cross-sectional curvatures were increased to better approach the catenary shape (Figure 7).

Figure 8 illustrates the final prototype armor shape. This armored element was fabricated over the modified manikin in Figure 7. The armor contours have been carefully blended to provide curvatures that are as continuous as possible. When compared with the earlier designs, it was obvious that significant compromises and modifications were necessary.

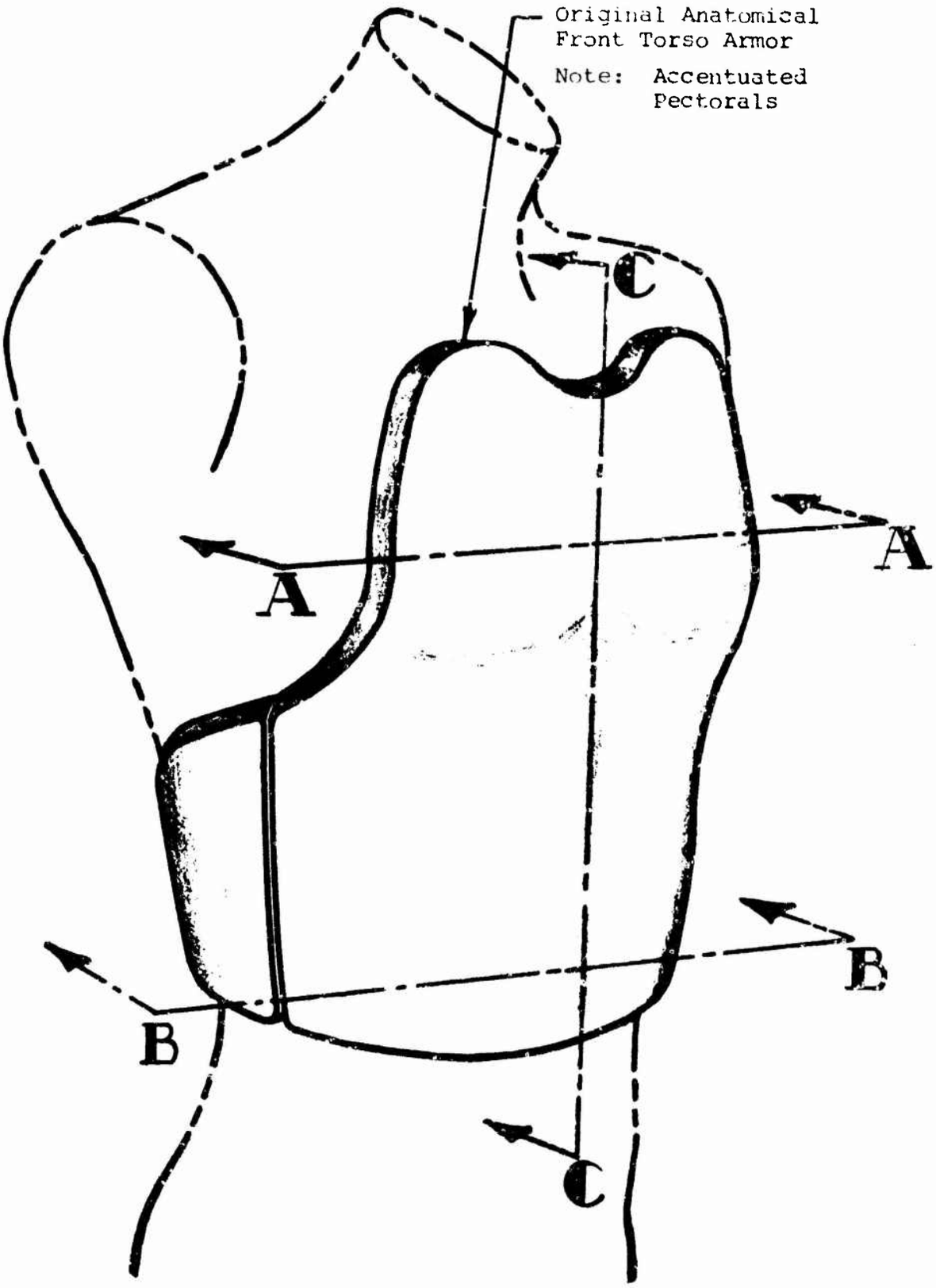


Figure 5. ORIGINAL TORSO ARMOR (Front)
ANATOMICALLY SHAPED

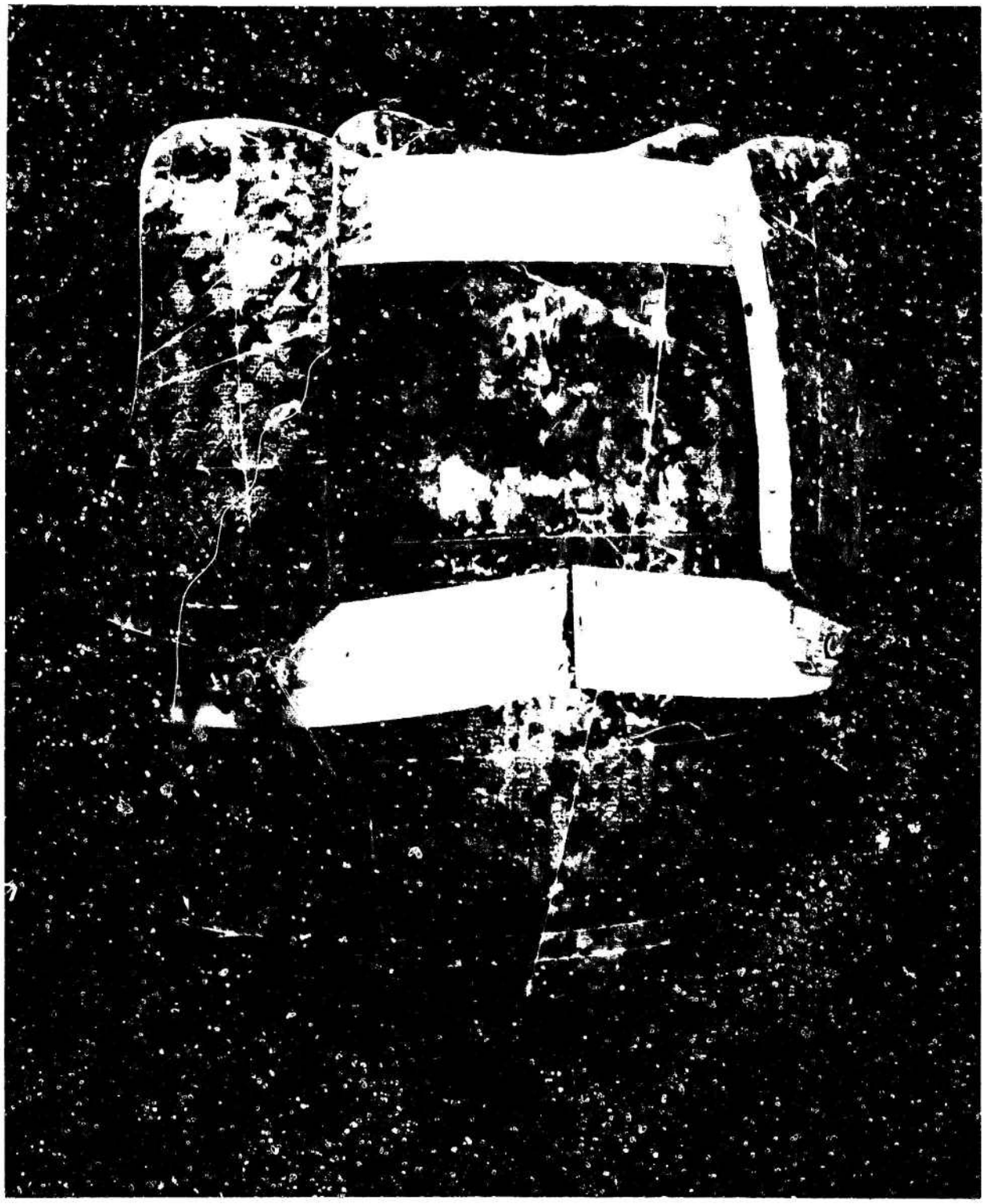


Figure 6. ORIGINAL ANATOMICAL ARMOR MOCK-UP

Figure 7. MODIFIED IITRI MANIKIN (End View)

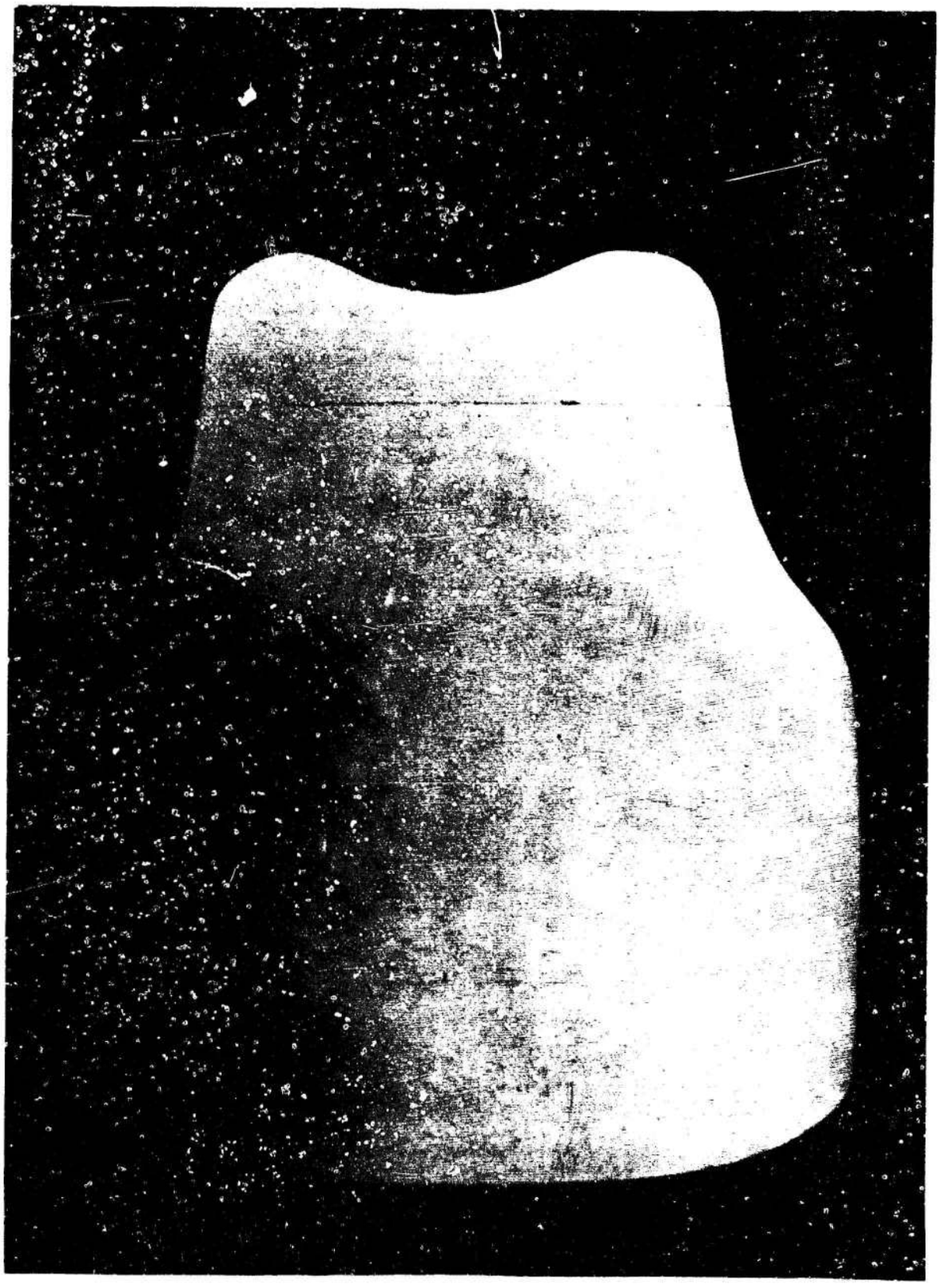


Figure 8. FINAL PROTOTYPE ANATOMICAL ARMOR

In enhancing producibility, the anatomical character of this armor was preserved in those areas where it was significant. To suit the needs of producibility, concessions were made to the extent that a functional shape could still be achieved without sacrificing the inherent effectiveness and good area coverage.

Leg Armor Producibility Studies

Cross-Sectional Profile Studies

The leg armor contours represented from the outset the most difficult problem with respect to producibility. Figure 9, Section A-A, illustrates the complexity of the curvatures associated with the leg armor. The changes in curvature at the knee require a fairly deep reverse curve (noted by the radius k_1). Radii r_1 and r_3 (viewed from the frontal plane) describe the contour of the armor at the outer and inner surface (above the calf). The width of the leg at this point is much smaller than the width at the calf and, therefore, requires a significant depression or reverse curve to precisely match the human leg contours.

The bell-shaped configuration at the knee presented a particular problem in production and Coors specifically requested a modification of the curvatures in this area. The effect of these changes is noted in Section C-C and Section D-D of Figure 9. Radii r_2, r_4, and k_2 were substantially increased to alleviate reverse curvature effect. These changes detracted somewhat from the anatomical appearance of the leg armor; however, it was felt that some of the appearance aspects could be compromised in favor of producibility. Several stages of development and laboratory testing were undertaken before the final contour was accepted.

Limits of Producibility

The original contours were favored from a functional and comfort standpoint, and the fact that it was easier to distinguish between the right and left leg. Departure from these anatomical contours meant that a greater premium was placed on the leg coupling device because the mating of the armor to the leg was less precise.

Since the leg armor curvatures were the most critical with respect to producibility, it was decided that ceramic samples of these elements should be fabricated to assure that these shapes could be manufactured. These ceramic samples are illustrated in Figure 13.

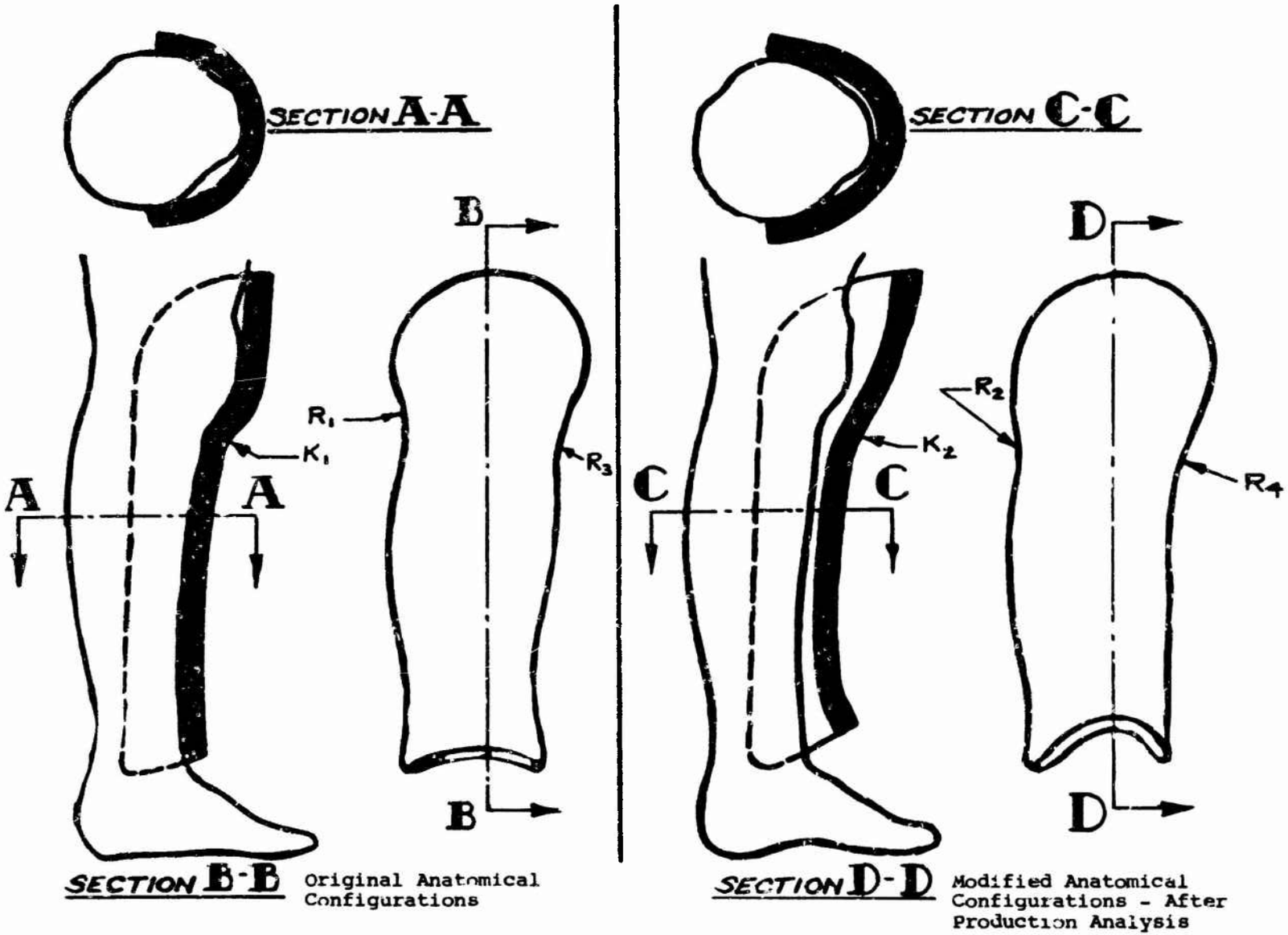


Figure 9. CONTOUR MODIFICATIONS (Leg Armor)

Modifications to Leg Armor Contours

Effects of Armor Contour on Production Reject Rate

It is important to inspect the original leg armor so that the modifications incorporated to enhance producibility can be clearly visualized. Figure 10 illustrates the anatomical leg contours representative of the original prototypes. The deep bell-shaped effect at the knee and the sharp reverse curvatures in the area where the outer calf contour meets with the knee are characteristic of this design. Attempts to produce this shape in the ceramic materials resulted in high reject rates and a lack of reproducibility.

The challenge was to make necessary modifications to permit producibility, and yet retain the anatomical character of the leg. The first step in this direction was to reduce the curvature in the knee area and permit the bell-shaped knee to assume a slightly forward angle with respect to the vertical. This had the effect of increasing armor weight because of increased clearances between the armor and the leg, but this was felt to be tolerable to assure producibility.

Final Compromises to Assure Producibility

Figure 11 shows the final prototype leg armor comprising the final modifications for producibility. The departures from the original contours (noted in Figure 10) are quite significant. The final contours were used in manufacturing the ceramic prototype elements.

Figure 12 shows the leg pattern that was used for the final prototype leg armor. The attempt to eliminate reverse curvatures is clearly apparent, and this pattern corresponds with the final ceramic elements which were manufactured.

There can be little question from viewing the final prototype elements that the primary changes in contour were for the purpose of obtaining a form that could be produced with a minimum reject rate.

Ballistic Sample Construction

The extensive producibility studies conducted resulted in modified armor configurations, as described in the preceding paragraphs.

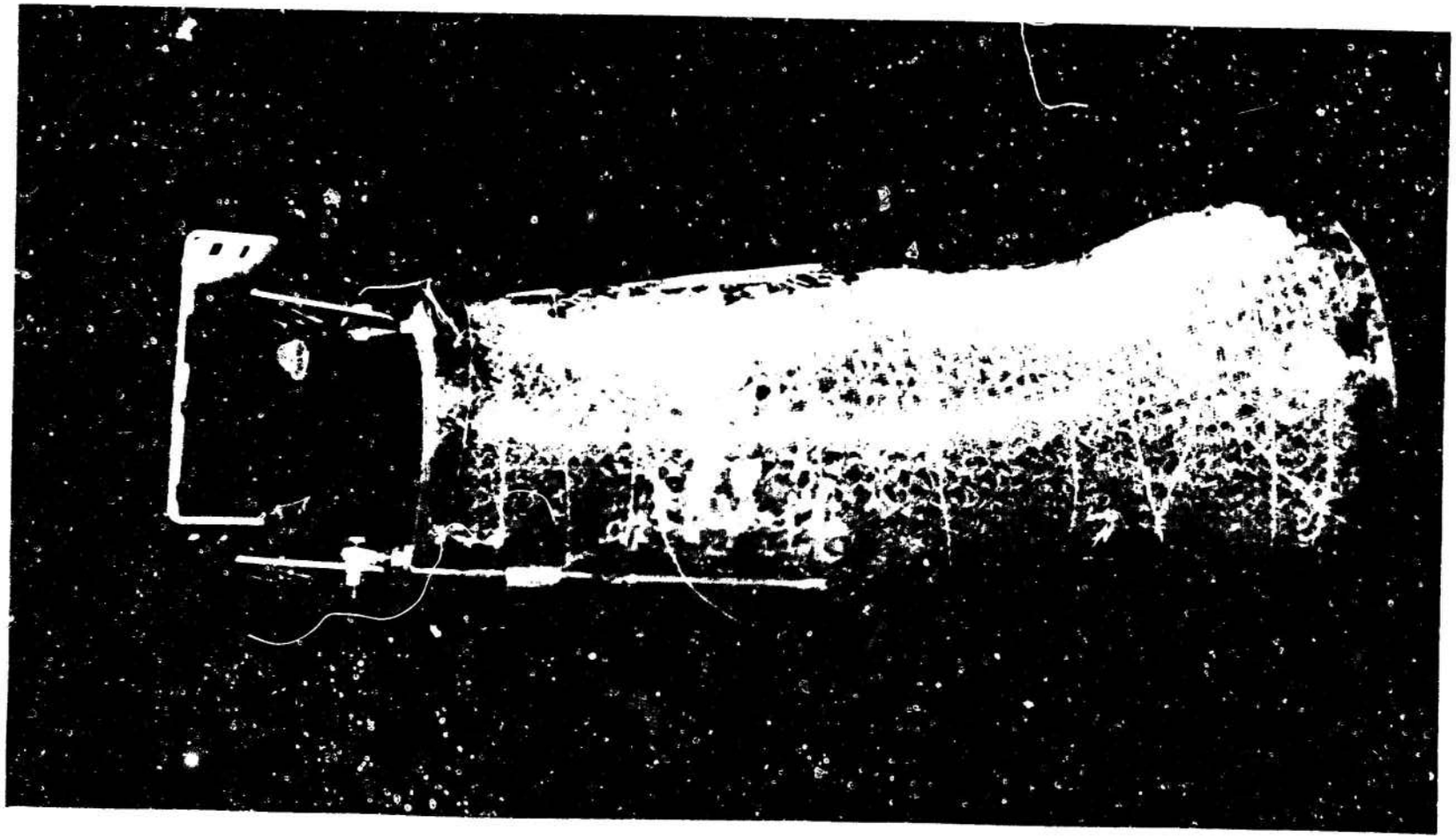


Figure 10. ORIGINAL ANATOMICAL LEG ARMOR MOCK-UP

Figure 11. FINAL PROTOTYPE LEG ARMOR

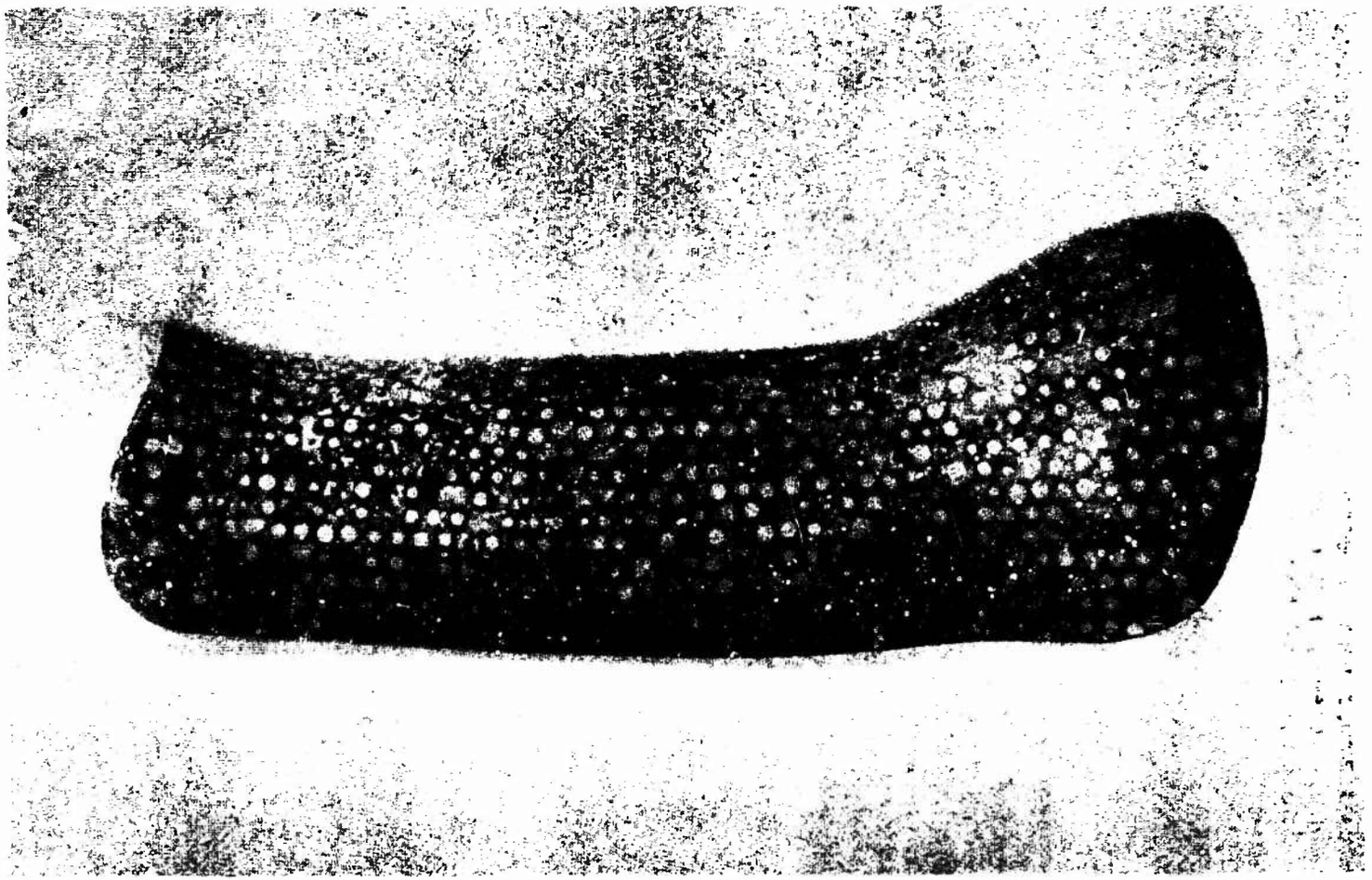


Figure 12. FINAL PROTOTYPE LEG PATTERN

The leg armor was selected as the most representative for the sample items, since production of these shapes would be indicative of the most complex manufacturing processes.

Figure 13 shows the ceramic leg armor elements which were fabricated.

II. CONCLUSION

The final armor configurations generated during this phase of the research effort have been shown to be commercially producible. These shapes represent a compromise to achieve the best anatomical qualities, with minimum manufacturing complexity. This approach has been consistent with the manufacturing resources and ceramics technology currently available.

This type of research/manufacturing study should be a continuing effort in all subsequent armor development programs, so that armor configurations can be fully optimized in the future.

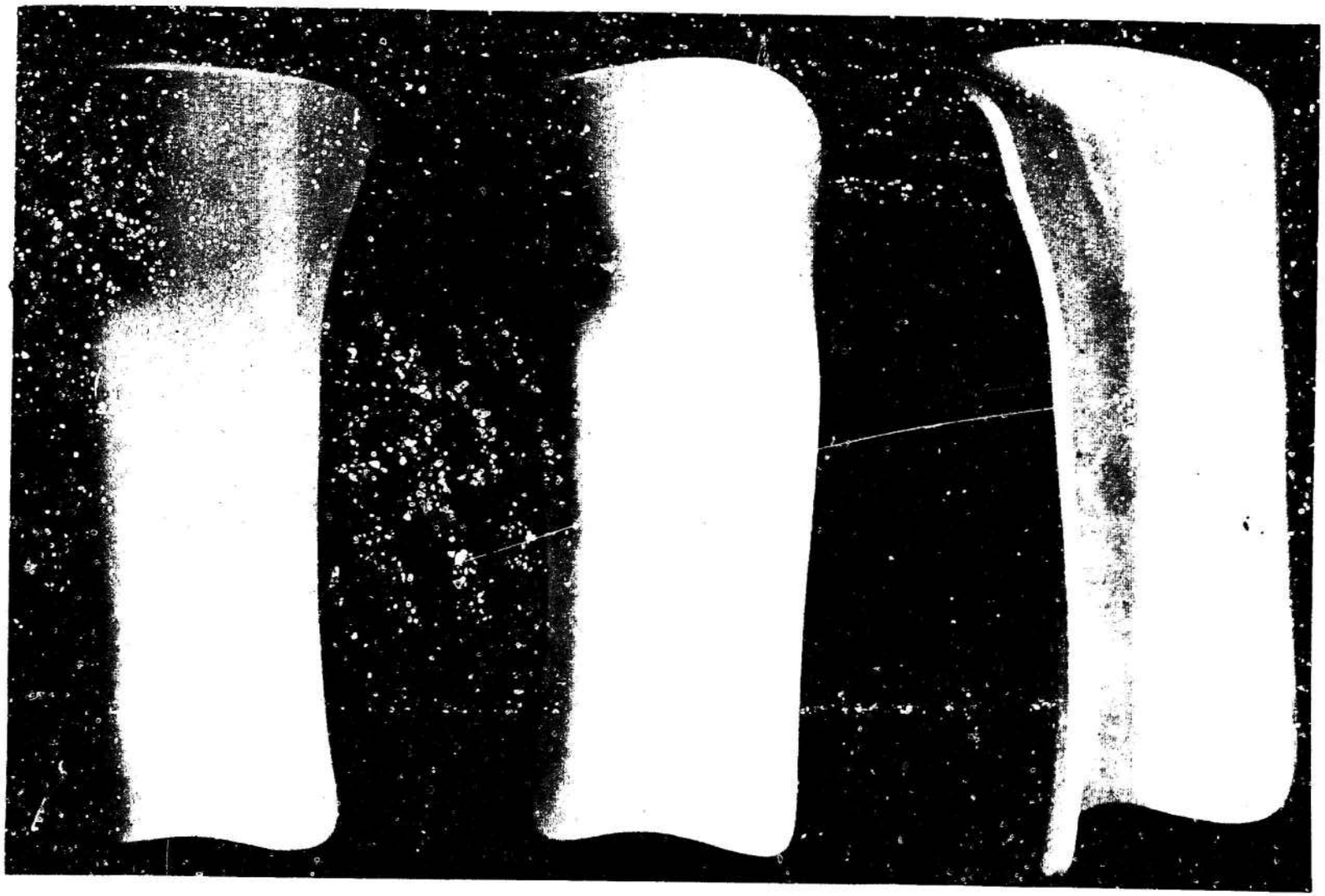


Figure 13. BALLISTIC CERAMIC SAMPLES OF LEG ARMOR

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