

1988

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GROUP TECHNOLOGY IN MANUFACTURING ADVANCED COMPOSITES

by

Glenn P. Livi

A Thesis

Presented to the Graduate Committee

of Lehigh University

in Candidacy for the Degree of
Master of Science

in

Manufacturing Systems Engineering

Lehigh University

1988

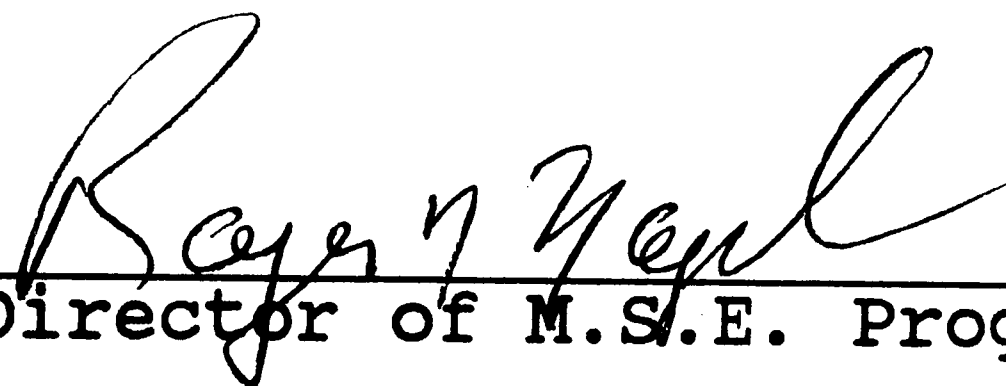
CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

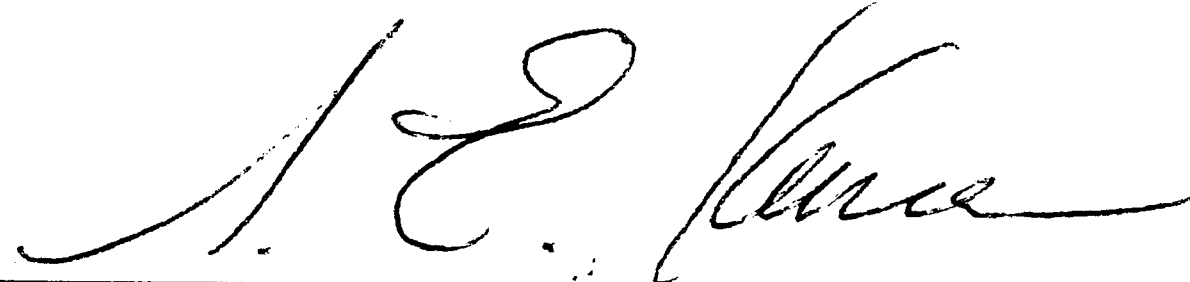
May 10, 1988
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Professor in Charge



Director of M.S.E. Program



Chairman of I.E. Department

ACKNOWLEDGEMENTS

I would like to first thank my thesis advisor, Dr. Keith M. Gardiner, for his inspiration, guidance and concern for my time limitations. I must also thank my project coordinator and close friend Orapong Thien-Ngern, without whom this thesis could not have been written. And most of all I thank my future wife Geri whose love and support continuously inspires me to work at the best of my ability.

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ABSTRACT

Advanced (fiber reinforced) composite parts are manufactured in a labor intensive batch-type process. Manufacturers who employ advanced composites in product designs are faced with the high cost of human labor and long manufacturing lead times. In addition inaccuracies in the fabrication process lead to appreciable waste of materials and poor quality.

As a result the composites industry is turning toward techniques such as Group Technology to solve these problems. Group Technology is a manufacturing philosophy applied to multi-product, small-lot-sized (batch-type) production to achieve some of the benefits associated with mass production. It is also a technique which can facilitate the introduction of automation into non-automated production processes. When linked to a computerized classification system Group Technology can lay the foundation for an integrated manufacturing system.

This thesis describes the development of a Group Technology application in the Aerospace industry. A classification system which incorporates the processing and property variables of advanced composites was computerized. This system will be used to improve design

techniques for composites, and as an aid to the introduction of automation into the manufacturing process.

1.0 INTRODUCTION

1.1 Group Technology

Group Technology (GT) is a method for recognizing and exploiting similarities in manufacturing in three distinct ways: (1) by performing like activities together; (2) by standardizing similar tasks; and (3) by efficiently storing and retrieving information about recurring problems. Group Technology is a manufacturing philosophy which can be applied to alleviate numerous inefficient engineering practices.

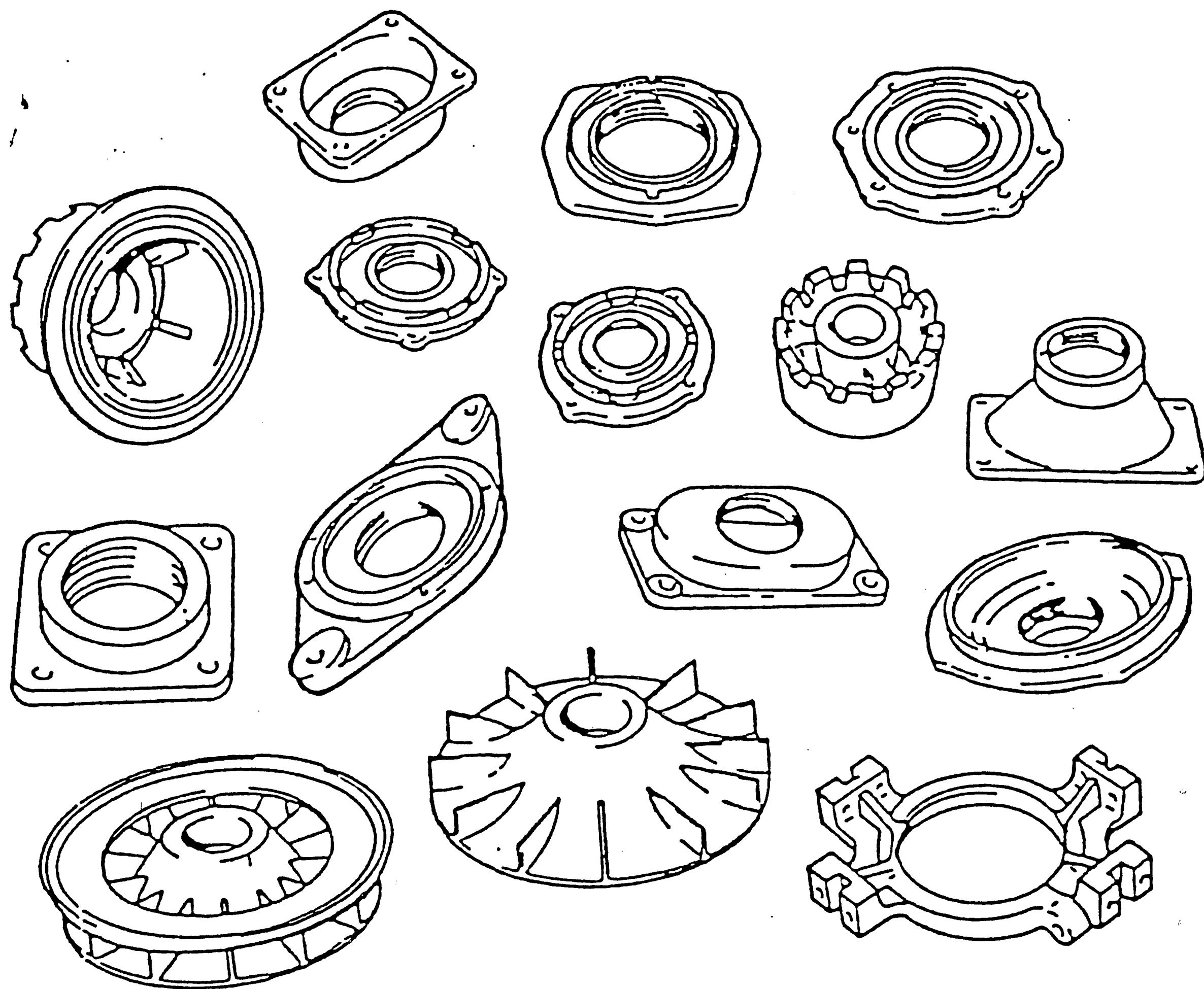
As a procedure to gain efficiency in engineering methods GT identifies and groups parts according to inherent similarities of their design, manufacturing process, or both. In batch-type manufacturing each part is considered a unique form in its design and production requirements. Group Technology, however, takes advantage of the fact that many new part designs share similarities with existing designs. With the ability to access this information about design practices and manufacturing requirements the task of creating new parts becomes much more efficient.

As a support system to a design organization a computerized GT system can reduce design proliferation by

providing a data base of all existing part designs. With a GT system the first step in designing a new part becomes accessing the system to inquire about similar part designs. In a significant number of cases a match may be found and used with little or no modifications. This technique reduces "reinventing the wheel" and helps create design standards.

As a methodology, GT creates efficiency in batch-type manufacturing, by allowing parts to be grouped into part "families". A part family is a group of parts which share similarities in their geometrical shape or manufacturing process (see Figure 1). Because of these similarities a part family may be manufactured with minimum change of tooling machinery and material handling. It also allows machinery and processes to be utilized more efficiently with less time between operations.

GT facilitates the grouping of machinery into "Group Technology Cells" which are each dedicated to a part family. This is in contrast with the traditional factory layout, where machines are grouped according to their function (for example all milling machines are grouped together). The GT cells can then be situated appropriately to form a flow-line. In this way GT enables the conversion of batch-type systems to a more continuous



PART FAMILY BASED ON MANUFACTURING PROCESS
(Each part possessing a round central hole)

FIGURE 1

line. There are many associated benefits, including reduced work-in-process and cycle time, and standardization of tooling and fixtures.

1.2 Why Group Technology

Group Technology maximizes production efficiency by capitalizing on the similarities between discrete items or processes. The implementation of GT simplifies and rationalizes the manufacturing aspects of a business, and has great potential to influence the productivity and thus competitiveness of an enterprise.

Between the end of World War II and the oil shortage in the early 1970's, U.S. manufacturers enjoyed a clear advantage in manufacturing capabilities. Because of this, virtually no emphasis was placed on developing new manufacturing technologies. Most organizations viewed design engineering as the crucial function. Today perspectives are changing. More emphasis is being placed on manufacturing innovations and flexibility with reduced manufacturing costs as the issue.

Today manufacturers are recognizing the importance of integrating the design/manufacturing process. In the traditional U.S. manufacturing organization a distinct

wall exists between design development and the manufacturing process. It is not uncommon to see designs created which do not reflect the manufacturing capabilities of a company. This is caused by the lack of a common method of communication which can integrate both functions. A computerized GT system with an engineering data base can be the basis of this important missing link.

Using this common system both groups may work as a team to achieve products that are both well designed and can be manufactured readily. However, there are other benefits attained by interdepartmental team work. Project teams work more productively as the product and the manufacturing line are developed congruently. In addition project teams remain responsible for a product from its inception through the end of its life cycle and thus provide consistent and experienced support.

1.3 Developing a Group Technology System: Classification and Coding

To help implement the GT philosophy a classification and coding method is usually employed to process and store all the information required about parts and manufacturing processes. Classification is a technique of organizing

data according to desired principles. The structure of a classification system conveys the logic of how data is divided and grouped according to selected parameters. Coding is a method of assigning a symbol (numeric, alphabetic or both) which signifies specific information. When the coding system is integrated with the classification method this becomes a useful tool for GT applications which can be computerized and linked with a data base. There are many different types of classification and coding methods and systems. However, it is not within the scope of this paper to discuss these in detail.

Although some GT users choose to develop their own system, approximately 2/3 of all users choose from the wide variety of classification and coding systems which are available commercially [Hyer, 1987, pg. 34]. Most of these systems, with their accompanying software, allow the user to tailor the system according to the application. In this way the user decides which characteristics need to be classified. Depending on the type of application these may be based on; part geometry, part function, manufacturing process, material, dimensions, etc.

With the system, similar parts may be retrieved and grouped to gain an advantage in manufacturing or retrieved

to aid the design or planning process. A GT retrieval system provides a valuable resource to the engineer, aiding decision making about new designs and manufacturing procedures.

The structure of the classification and coding system is a key factor in efficient data manipulation. A well designed system incorporates just enough detail to allow part families to be retrieved and grouped effectively while remaining quick and efficient. The system must also be flexible enough to allow easy coding and data entry and accommodate growth.

1.4 The History of Group Technology

Although the term Group Technology is of relatively recent origin, the ideas of grouping parts by their similarity in design or manufacturing requirements, and using flow-line methods for batch production are not new. In fact F. W. Taylor, one of the first proponents of scientific manufacturing methods, suggested the use of mnemonic classification for industrial management purposes in the late 1800's. The present principles of GT have evolved from what were previously many scattered ideas and techniques.

In the early 1920's manufacturing in the United States began employing concepts such as; product standardization, product dedicated equipment and machinery, minimal routing paths and visual control of work. In 1925 a paper was presented by R. E. Flanders to the American Society of Mechanical Engineers which presented factual data supporting these new revolutionary concepts [Hyde, 1981, pg. 25].

In 1949, Arn Korling, a Swedish engineer presented a paper entitled "Group Production and its Influence on Productivity" [Hyde, 1981, pg. 27]. In it he states:

"The principles of group production are an adoption of line production to machine-shops working on batch production...this implies radical decentralization into small independent production units or groups, each comprising the machines and everything needed for the complete manufacture of a special category of parts."

This statement clearly reflects the present concept of GT and one of the objectives of the GT project presented in this thesis.

Wide interest was also generated by a book entitled "The Scientific Principles of Group Technology" by S. P. Mitrofanov, published in 1959, and by the publications of Opitz, who formalized GT principles into a working methodology. The OPITZ Classification System for machined

components, developed in the 1960's, is still one of the most popular systems used in Western Europe.

There are several reasons why the industrial climate was ready for these developments [Gallagher, 1973, pg 9]:

- (1) The growth in complexity of manufacturing created difficulties with part numbering and filing systems.
- (2) There was a desire to reduce manufacturing costs, using variety reduction on a greater scale.
- (3) A rapid growth in the use of electronic data processing was demanding a closer scrutiny of classification and coding systems.
- (4) There was a desire to have the savings of mass-production extended to small batch jobbing work.

In the late 1960's and 1970's interest among U.S. manufacturers expanded widely as large companies such as Allen-Bradley, Allied-Bendix, Boeing, Caterpillar, John Deere, General Electric, IBM, and Lockheed, all started large scale GT programs. Today the GT concept has become a standard methodology, but continues to evolve into new industries and applications.

The early applications of GT were primarily in the metals industry. In the 1960's the Langston Division of Harris-Intertype Corporation in Camden, New Jersey, took

Polaroid snapshots of every seventh of some 21,000 metal machined parts. When inspected from a production processing point of view, it was discovered that about 93% of the sample could be allocated into five part families. Based on this information, a machine cell was created to handle each of the part families. The benefits of their program included a 50% increase in parts produced per man hour, a reduction in floor space of 20,000 square feet (22%) and a greatly reduced through put time: from 30 to 45 days down to 2 to 5 days [Burbridge, 1979, pg. 31]. The success of this single GT application became widely publicized and spawned a revolution in the metals industry.

Slowly the GT methodology spread to other industries involved in batch-type manufacturing. In the early 1970's, the Kansas City Division of the Bendix Corporation successfully applied GT to manufacturing electromechanical components [Walton, 1985, pg. 3]. Other companies such as IBM applied GT to injection molded plastic parts. Today with the revolution in the electronics industry there are extensive programs to apply GT to printed circuit board and surface mount manufacturing. Applications of GT continue to evolve as new product and material innovations occur.

1.5 Group Technology in the Aerospace Industry

The aerospace industry is evolving from small-lot-size or batch-type production processes to more automated line-type systems. At the same time however, there are inherent difficulties in this industry as modern aircraft employ a wide range of materials which have complex manufacturing requirements. One widely accepted class of materials are advanced composites, and are used extensively for structural components and skin panels. Although there are clear benefits for employing advanced composite parts in an aircraft design, such as high strength and low weight, there is one substantial drawback. Composite manufacturing is still in its infancy as most fabrication processes are accomplished manually.

As a result, there is competition within the aerospace industry to develop new automated processes to fabricate advanced composite parts and offset the increasing cost of human labor. One such manufacturer of military helicopters is faced with the need to develop a design/manufacturing system which can compete cost effectively with other military contractors. This thesis will examine the needs of this manufacturer and the application of Group Technology to address this challenge.

2.0 Background

Advanced composite materials and the associated manufacturing process must first be examined before the application of Group Technology and the requirements of this aircraft manufacturer can be discussed. The manufacturer is planning full-scale production of a military helicopter in the early 1990's. One of the first of its kind to be mass produced, the helicopter incorporates advanced composites extensively in the design of the airframe, fuselage, empennage (tail assembly), wings, rotor blades, landing gear, cockpit and skin panels. The manufacturer is currently in the development and pre-production planning stage and is designing the manufacturing line for the aircraft.

2.1 Advanced Composite Materials

A composite material is a combination of two or more physically distinct and mechanically separable materials that are mixed in such a way that the dispersion of one material in the other can be done in a controlled way to achieve optimum properties. The properties are superior to the properties of the individual materials. The type of composites used in aircraft construction are composed

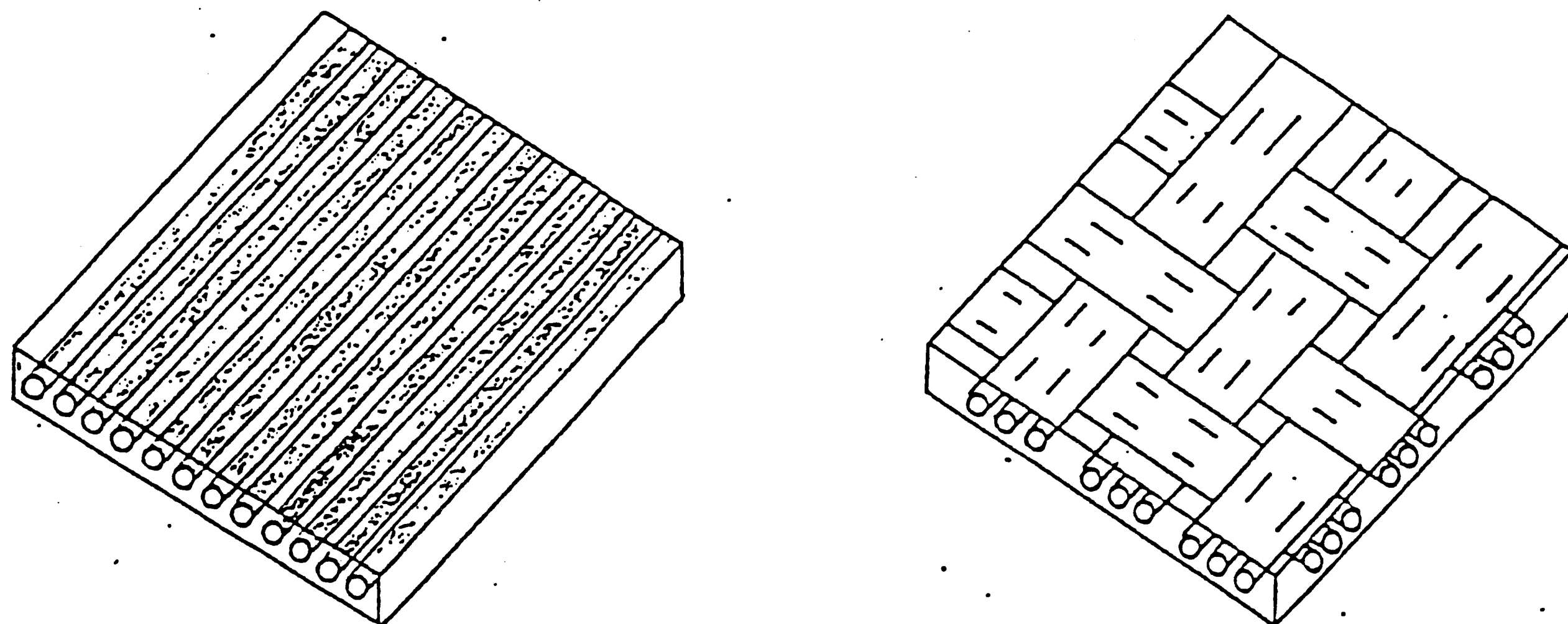
of load-bearing fibers embedded in a binding epoxy matrix. The bulk material produced has a strength and stiffness close to that of the fibers together with the chemical resistance of the epoxy.

There has been rapid growth in the use of fiber reinforced materials for engineering applications in the last few years. The growth has been achieved mainly by the replacement of traditional materials, primarily metals. On the basis of strength and stiffness alone, fiber reinforced composite materials do not have a clear advantage particularly when it is noted that their elongation to fracture is much lower than metals with comparable strength. The advantages of composite materials appear when the modulus of elasticity per unit weight (specific modulus) and strength per unit weight (specific strength) are considered. The higher specific modulus and specific strength of materials means that the weight of components can be reduced, and thus the reason they are used in aircraft construction.

Besides the benefits in strength and in weight, composites can often be tailored in ways not possible with unitary materials. By forming composites into large, intricate structures, many parts can often be consolidated into a single unit, saving both assembly time and material

cost.

Presently there are two primary types of composite parts used in the aircraft. Each type has unique manufacturing requirements. The first is composed of flat sheets of fibers which are pre-impregnated with an epoxy resin (pre-preg). A sheet of this material is called a lamina or a ply and is partially cured. A ply may have its fibers lie in one direction (unidirectional) or may have its fibers woven together at specific angles (90 degrees, 45 degrees, etc.) (see Figure 2).



UNIDIRECTIONAL

WOVEN (90 degree)

POSSIBLE FIBER CONFIGURATIONS

FIGURE 2

A unidirectional lamina is an-isotropic and is orthotropic, meaning that it has three mutually perpendicular planes in which the elastic and strength properties differ. For example, a unidirectional lamina is strongest in the direction parallel to its fibers. The benefits arise when many laminae (more than one lamina) are combined with different fiber orientations (bias). These can achieve properties that are much better than any metal. A ply that has woven fibers is also an-isotropic, however, its properties become much more difficult to predict in a component because of the combination of fiber orientations.

The second type of part is one that is composed of narrow strips of pre-preg material (tape) or a bundle of fiber (roving) which is mixed with epoxy in the fabrication process. The shape of the composite parts are formed when the tape or roving is placed on a mold by either a winding process (for cylindrical shaped parts) or a placement head.

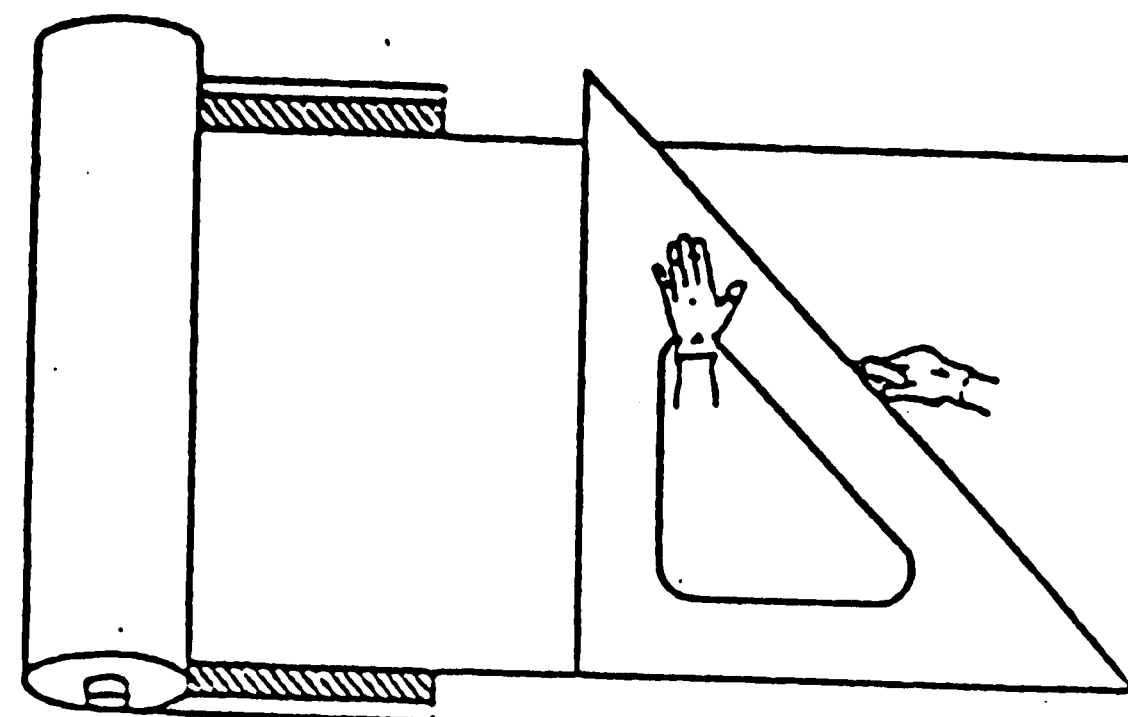
Since the design of advanced composite components involves a calculated mixture of laminae with different fiber orientations and inter-lamina resin to bind the system together, it is necessary for the designer to have a detailed conception of fabrication requirements.

Therefore it is imperative that the designer also define process details for manufacturing engineering. Unlike procedures with earlier metal products, it is not possible to "throw a design over the wall" and leave it to manufacturing to ponder how to make it, composites are very process sensitive.

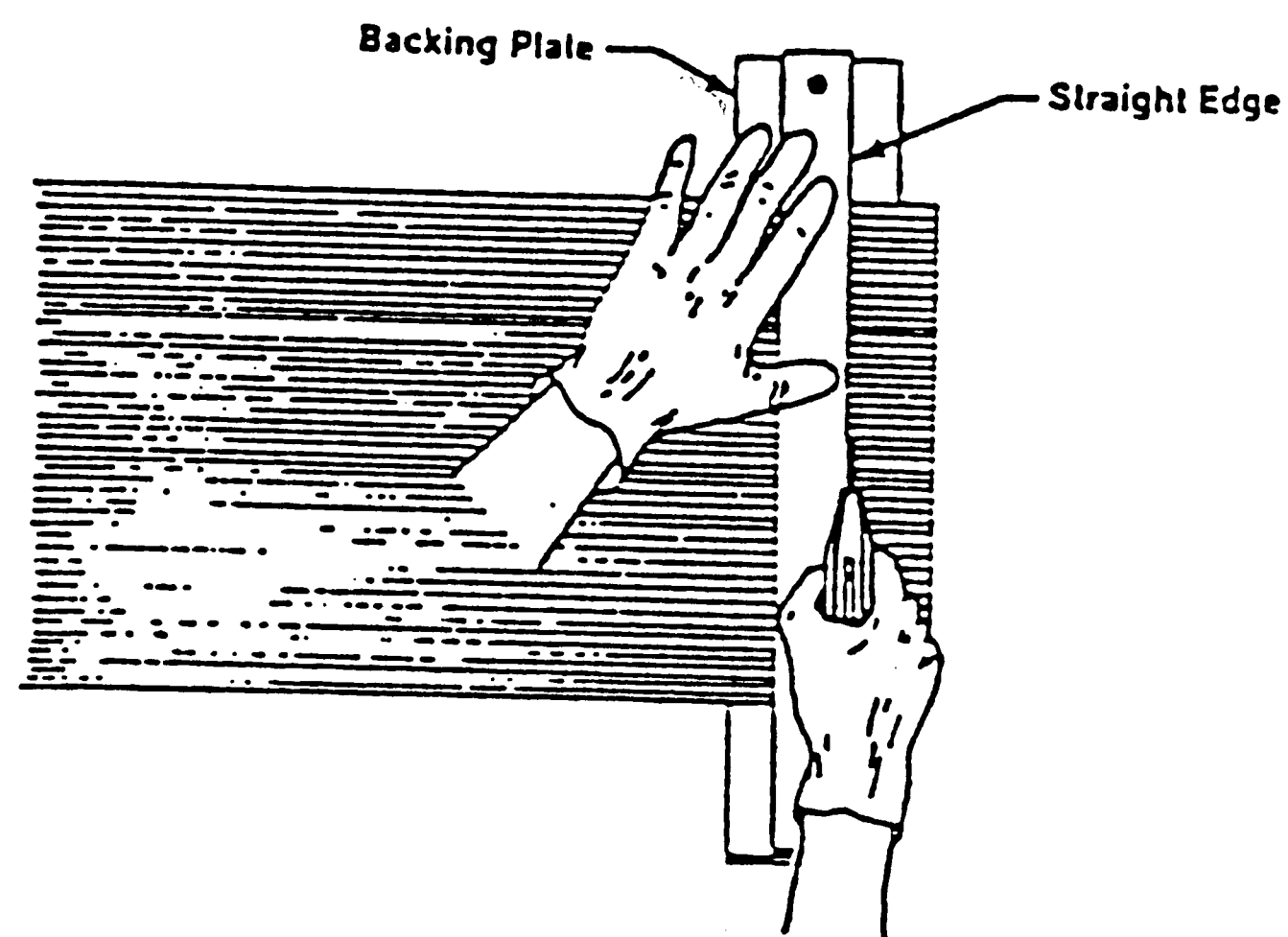
2.2 Manufacturing Advanced Composite Components

The most common form of composite fabrication in this aerospace company is hand lay-up (see Figure 3). Hand lay-up is an extremely labor intensive process of fabricating components, which are made up of layers of lamina, into laminates. In the first step of the process individual pre-impregnated partially cured (β -stage) plies are measured and cut from a large roll of material on an automated machine, called a Gerber Cutter. These plies are then delivered to the lay-up stage. At this point a worker peels the paper backing off the ply which covers the resin and places each ply over a mold with the orientations specified on the engineering drawing. Between each ply a thin layer of epoxy may be applied. Pressure is then applied to the surface with special tools such as a roller. When the plies are built up to the specified

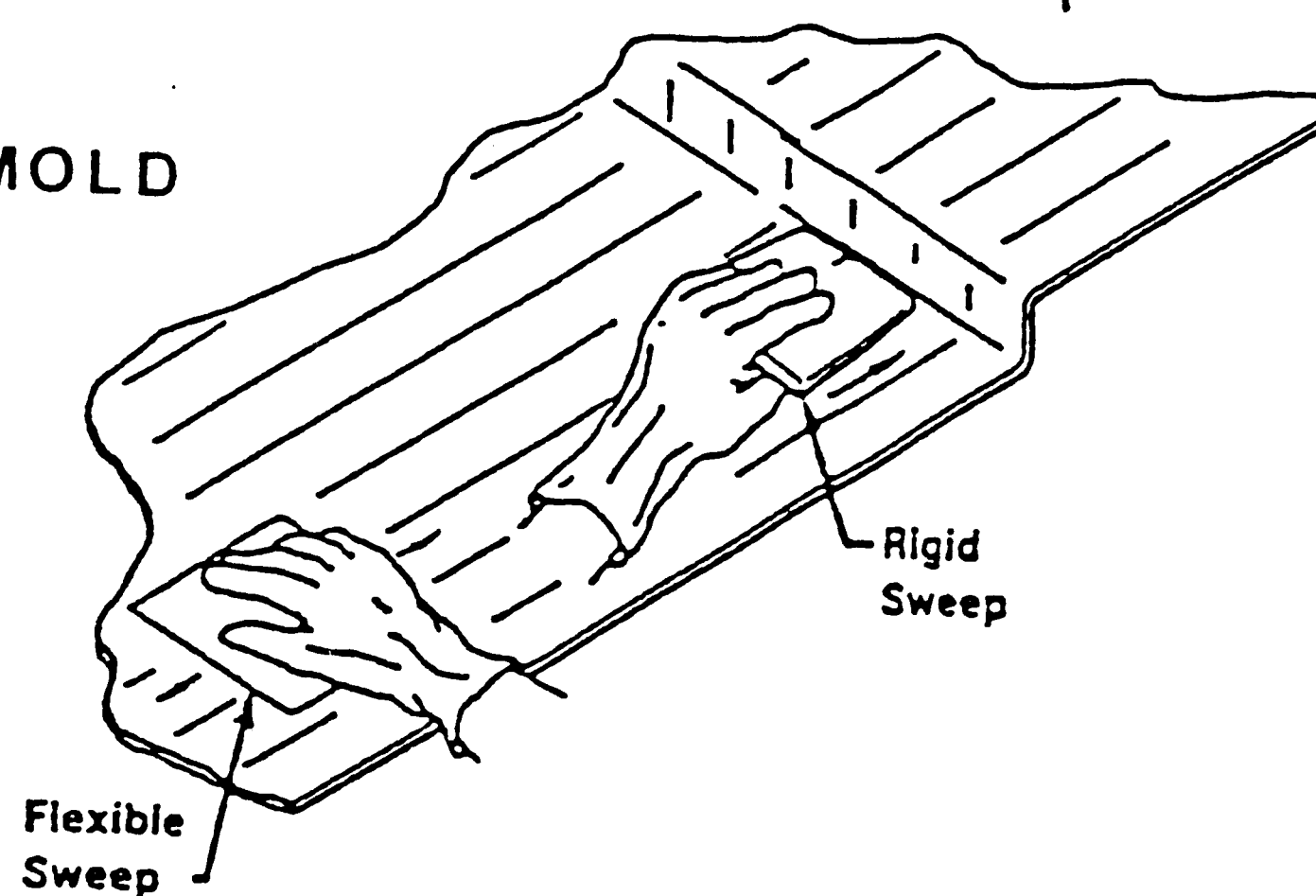
1. MEASURE PLY



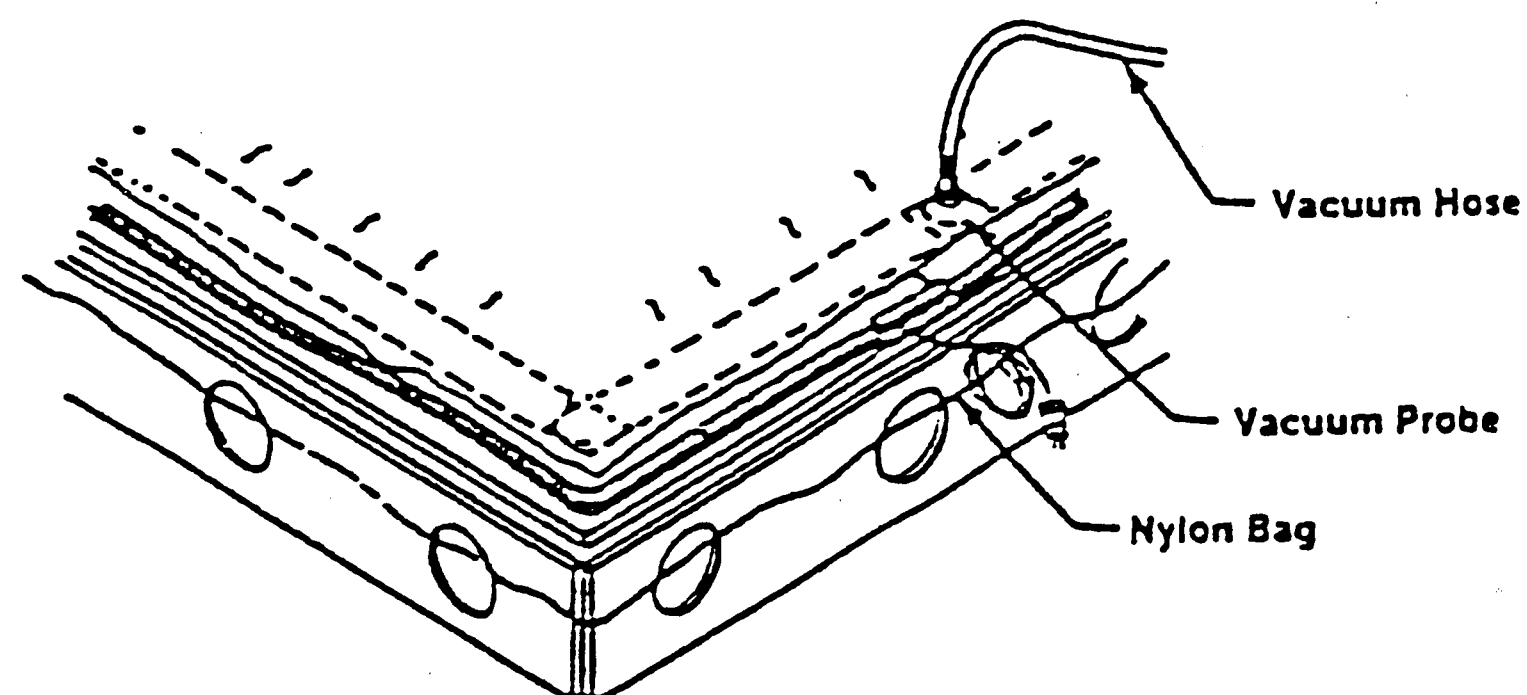
2. CUT PLY WITH KNIFE



3. LAY-UP PLY OVER MOLD



4. INSTALL PRESSURE BAG OVER MOLD



HAND LAY-UP PROCESS

FIGURE 3

thickness and shape of the part, a flexible plastic pressure bag is placed over the mold. A vacuum is then applied to force the plies together and remove any voids (air bubbles) which might exist. In some cases pressure is also applied in a press. The entire assembly is then placed in an autoclave where the final curing process takes place. After the autoclave, parts are cooled and are then ready to be trimmed and cut to final size. At this point the cured parts may be assembled to the aircraft or become part of a bonded assembly jig (BAJ). A bonded assembly jig is a device in which an assembly of cured parts and uncured components are fastened with epoxy and placed into the autoclave for final curing. When the assembly is taken out of the autoclave it exists as a single part which is then fastened to the aircraft.

Presently there is confusion with assigning part numbers both with cured parts and the uncured components which become an assembly. This problem has been solved by Group Technology and will be discussed later. It should also be noted that all material handling, from the ply cutting stage to the final assembly of the aircraft, is performed manually, and there is great difficulty tracking components through the process. This also complicates the accountability of the shelf life of work-in-process.

Another existing method of manufacturing is filament winding. This is an automated process used to fabricate rotational parts. A pre-impregnated composite tape is fed over rollers and wound, using a computer controlled machine, onto a mandrel at pre-determined angles. This winding process can also be performed using rovings with the placement head dispensing resin along with the fibers. The part is then removed from the mandrel and placed in the autoclave for final curing. This automated system is ideal for rotational parts. Unfortunately the number of these type parts on the aircraft is low.

2.3 Requirements of the Group Technology System

To produce an aircraft competitively the manufacturer is in need of automated systems and possibly new manufacturing methods. However, to design these new systems the manufacturing requirements of the entire set of part designs must be studied. With existing methods this task would require thousands of man hours.

The solution is a formal GT system which classifies and stores the information associated with every composite part design, together with the manufacturing requirements which become inherently part of the coding structure. The

system should also incorporate the intrinsic characteristics of existing production methods and the new processes which are currently being developed. Such a classification system will allow the retrieval of data based on process requirements of families of parts. This information will be used to identify new process requirements and to verify the need for machines and equipment being developed.

The classification system will aid the design function in two important ways. It will serve as a data link between manufacturing engineering and the designers. It will also facilitate the development of standard design methods. This is accomplished by allowing designers to examine the inconsistencies in design practices.

Nonstandard design methods complicate the manufacturing requirements. For example, parts designed for identical load requirements utilize different fiber orientations (called bias) and stacking sequence. There are certain bias patterns repeatedly used for specific applications (such as: $90^{\circ}/0^{\circ}/0^{\circ}/90^{\circ}$ or $+45^{\circ}/0^{\circ}/-45^{\circ}$). Standardizing these design techniques would simplify the fabrication procedures.

As manufacturing procedures become standardized for families of parts the system will also assist the process

planning function. The GT system will support process planning in communicating with the design and manufacturing groups. Presently, information flows in one direction from design engineering to process planning, and then to manufacturing engineering. Process planning receives information from designers in drawing form and transfers data to manufacturing via process plans (routings). However, with a standard communication system and language, vital information can flow in both directions.

By supplying the information on manufacturing requirements the system also provides the basis for tooling and fixture designs. Since the system establishes part families it will also facilitate the development of common tooling and fixtures for each family.

In addition to assisting both the design and manufacturing functions the GT system can identify material needs for each part family and thus assist material purchasing and planning. In this way it will assist accounting and financial planning.

In these ways the system will provide vital information to the designers of the new manufacturing line. It will also improve the operational structure of the organization.

2.4 Review of Manufacturing Processes

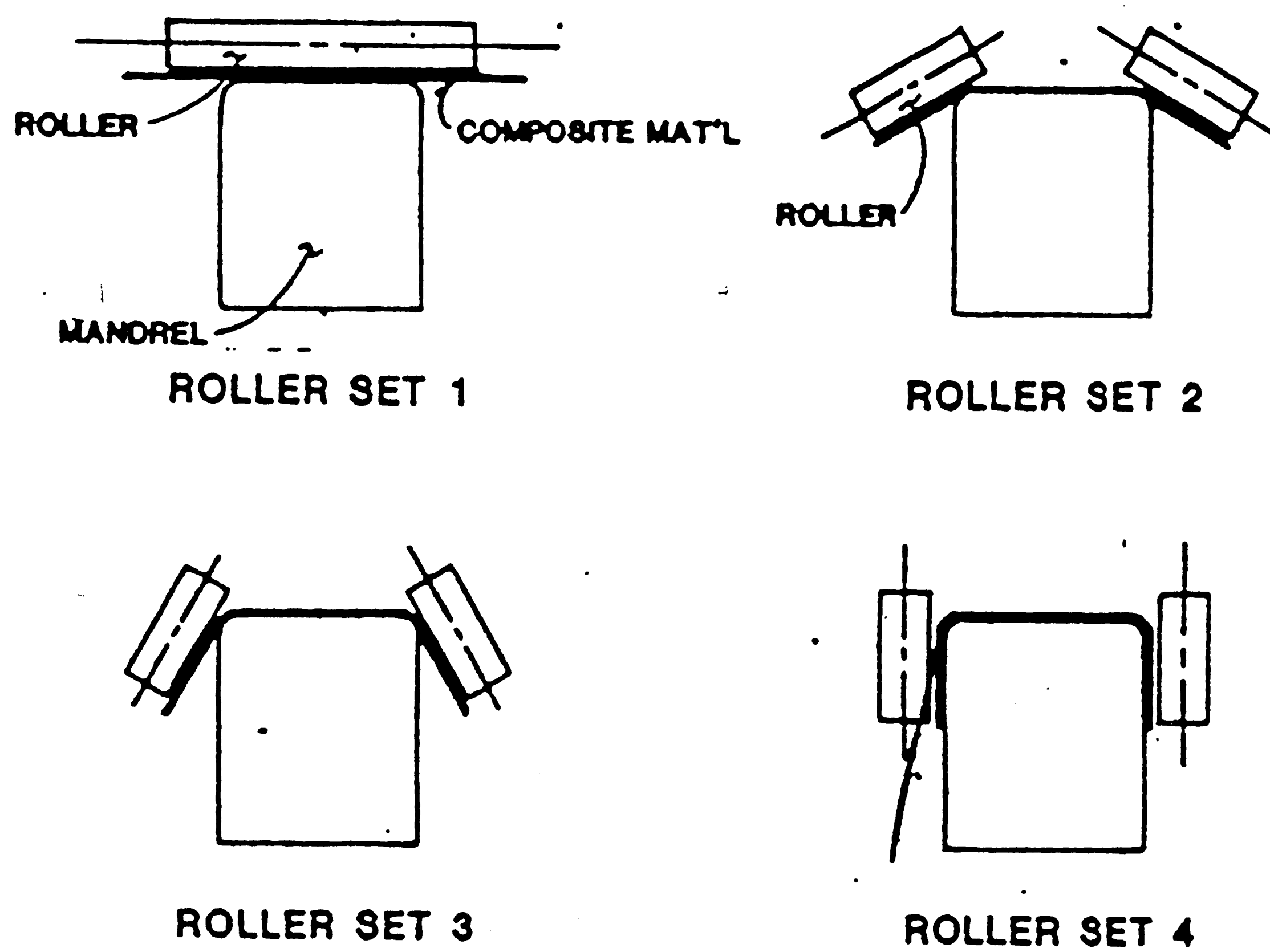
Four manufacturing processes will be presented to explain the structure of the classification system and the type of information required in it. These processes will be used in examples throughout the paper.

COMPOSITE ROLL FORMING SYSTEM (CRFS)

This system eliminates hand work, ensures configuration stability, and improves quality with reduction in cost. This will be accomplished by a series of compliant rollers which shape the pre-impregnated composite materials progressively over a male mandrel (see Figure 4). The compliant rollers must be capable of radially forming the legs of a composite angle as well as radially forming channel webs and/or flanges. Figure 5 shows an example of shapes which can be produced by the CRFS. The CRFS eliminates a hot pressure compaction step required during hand lay-up, thus through-put time reductions of 75 to 80 percent are anticipated.

AUTOMATED ELEMENT LAY-UP MACHINE (AELM)

The AELM is a five axis tape and roving placement machine which is under development. A roving is a bundle



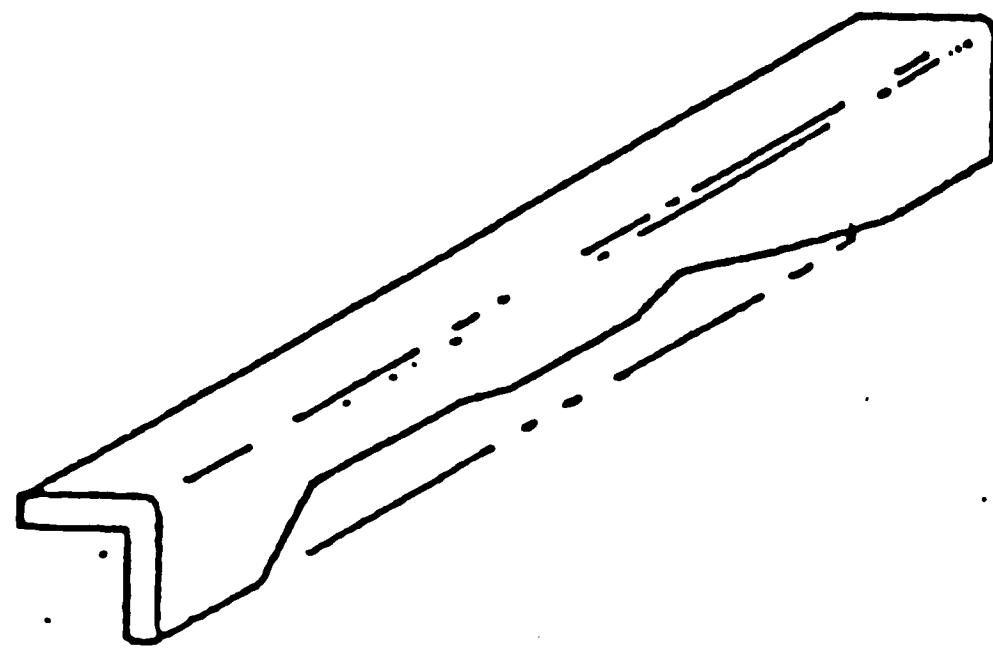
COMPOSITE ROLL FORMING SYSTEM

FIGURE 4

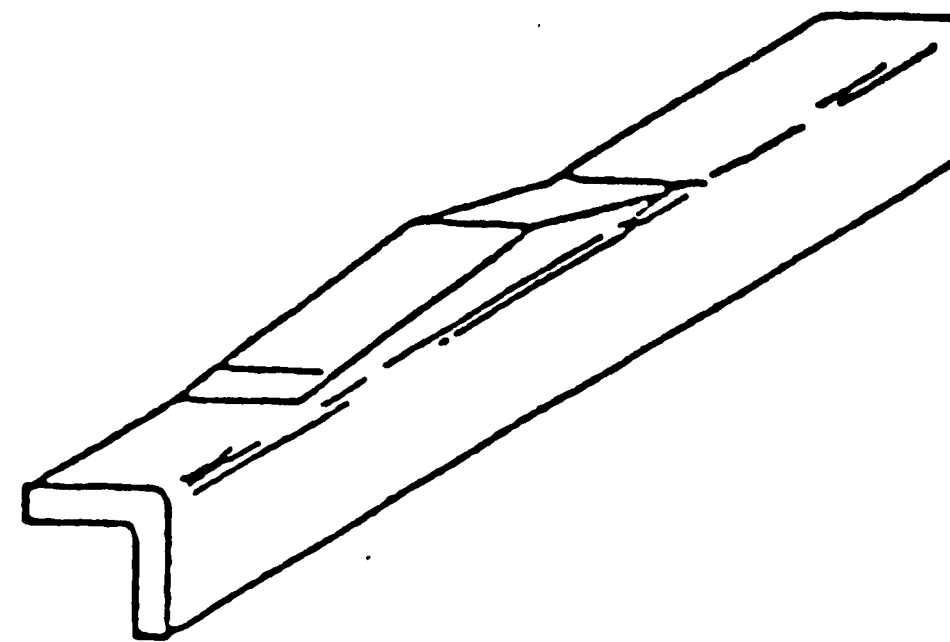
of fibers which is impregnated with epoxy as it is placed over a mold. The work envelope is 40 inches wide, 40 inches high and 40 feet long. The tape placement head is equipped with dual material supply reels which can be loaded with the same or different materials in laying up the laminate. The tape placement head places pre-impregnated composite tapes 3, 6, and 12 inches wide (see Figure 6).

The tape placement head is equipped with a fixed position cutter which cuts the pre-impregnated composite tape perpendicular to the tape path. In conjunction there is an automatic feed system which advances the tape for the start of the next tape path (see Figure 7). Pre-impregnated composite tapes can also be placed ply on ply without cutting the tape at the end of each ply (see Figure 8). A significant cost reduction is possible using this technique and the process saves 3 seconds per ply.

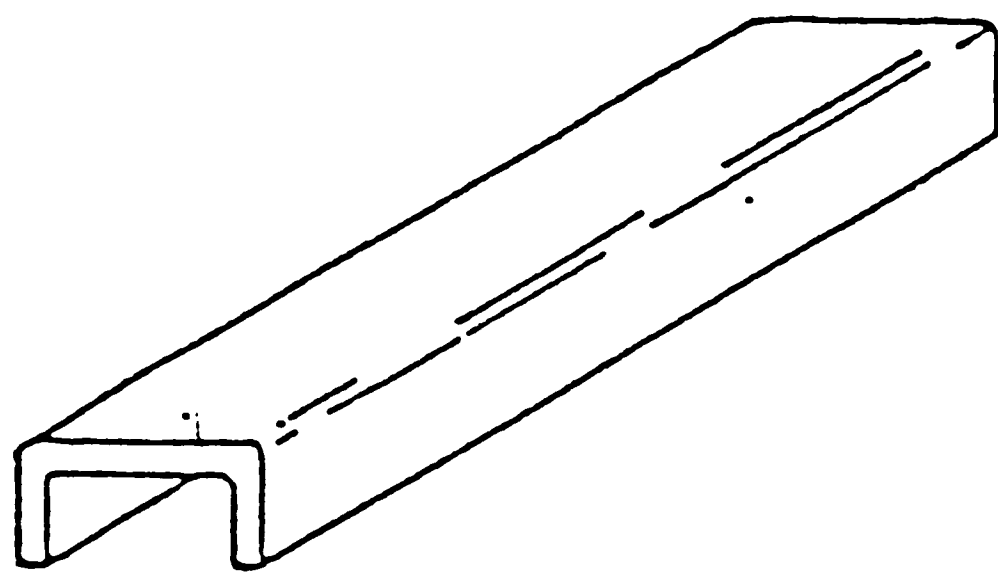
The AELM also has the capacity to fabricate parts by laying up rovings and wetting them with resin in the same process. The roving placement head combines 24 rovings to produce a 3 inch wide pass. Because each of the 24 rovings pay out at the same or different rates, laminates can be produced in complex serpentine configurations on flat or contoured convex surfaces. Some typical examples



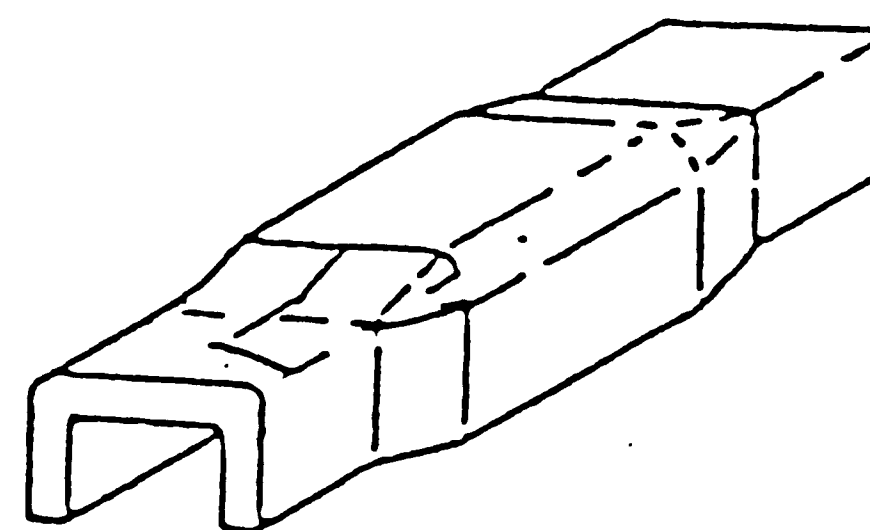
CONSTANT CROSS SECTION
LEGS TRIMMED STRAIGHT OR
TO SHAPE



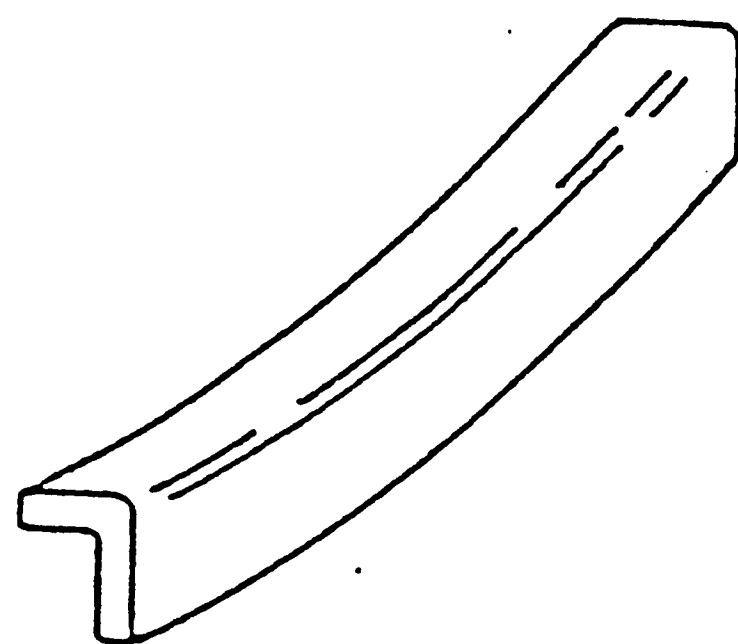
VARIABLE CROSS SECTION
ONE LEG OR BOTH



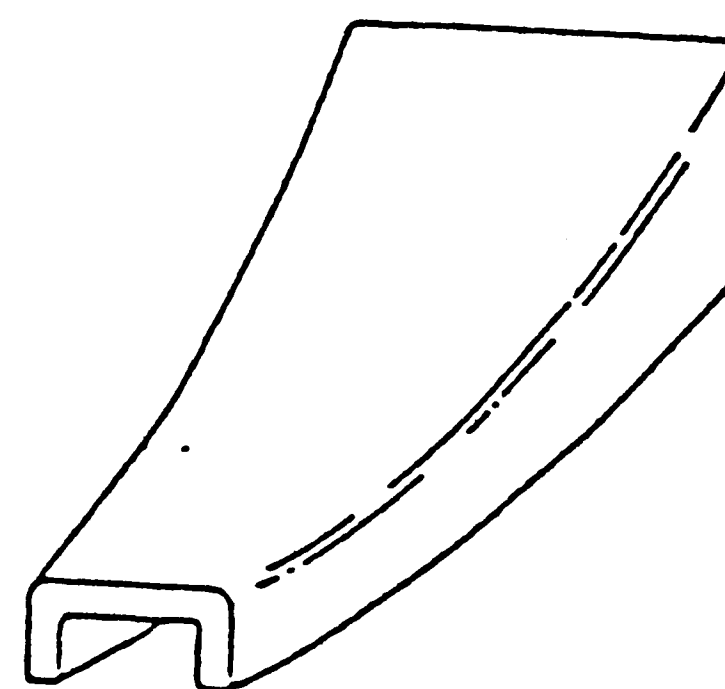
CONSTANT CROSS SECTION



VARIABLE CROSS SECTION
WEB & FLANGES
OR EITHER



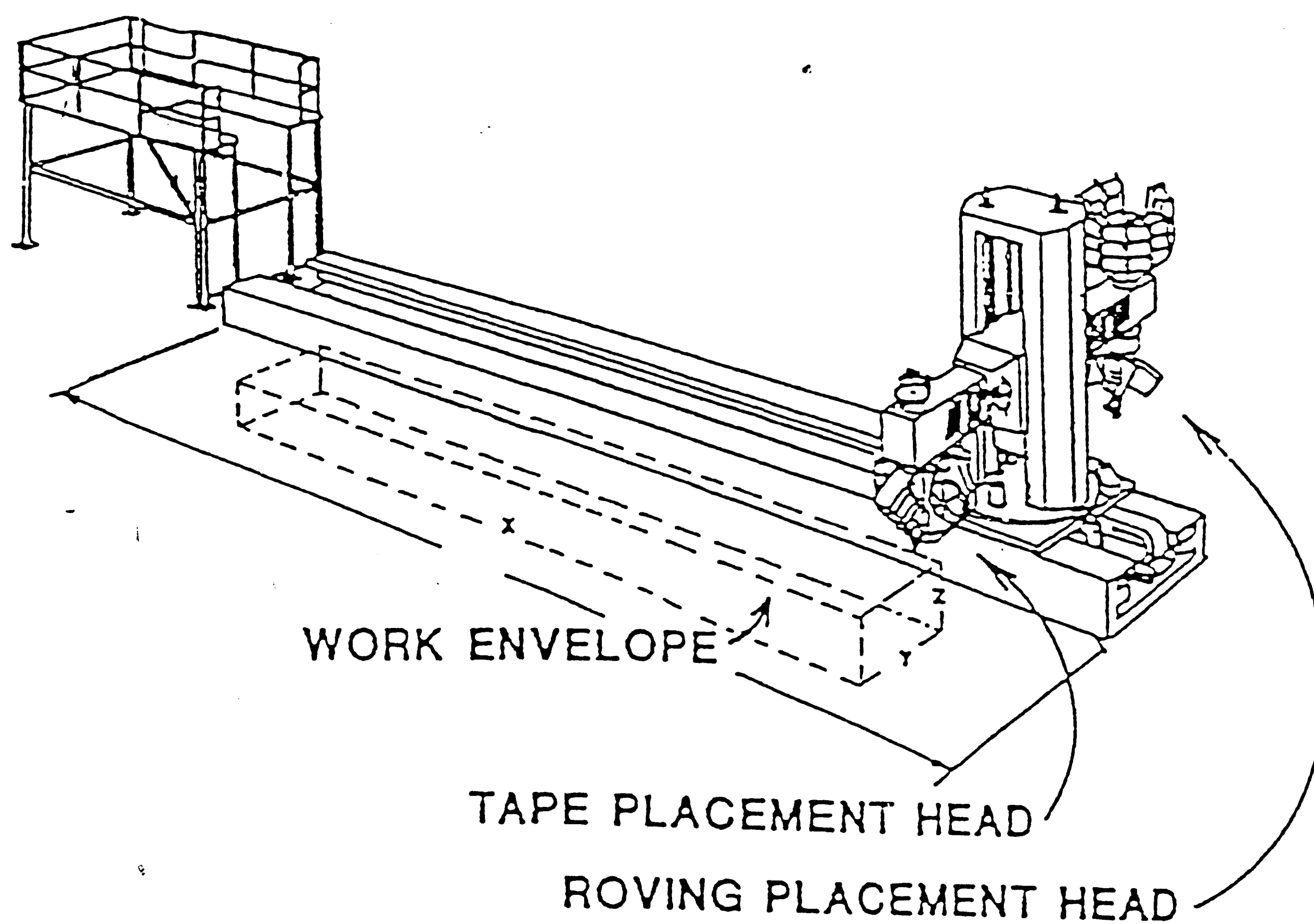
CURVED SECTIONS
CONSTANT CROSS SECTION
OR VARIABLE CROSS SECTION



VARIABLE SHAPES
SHAPED IN TWO PLANES

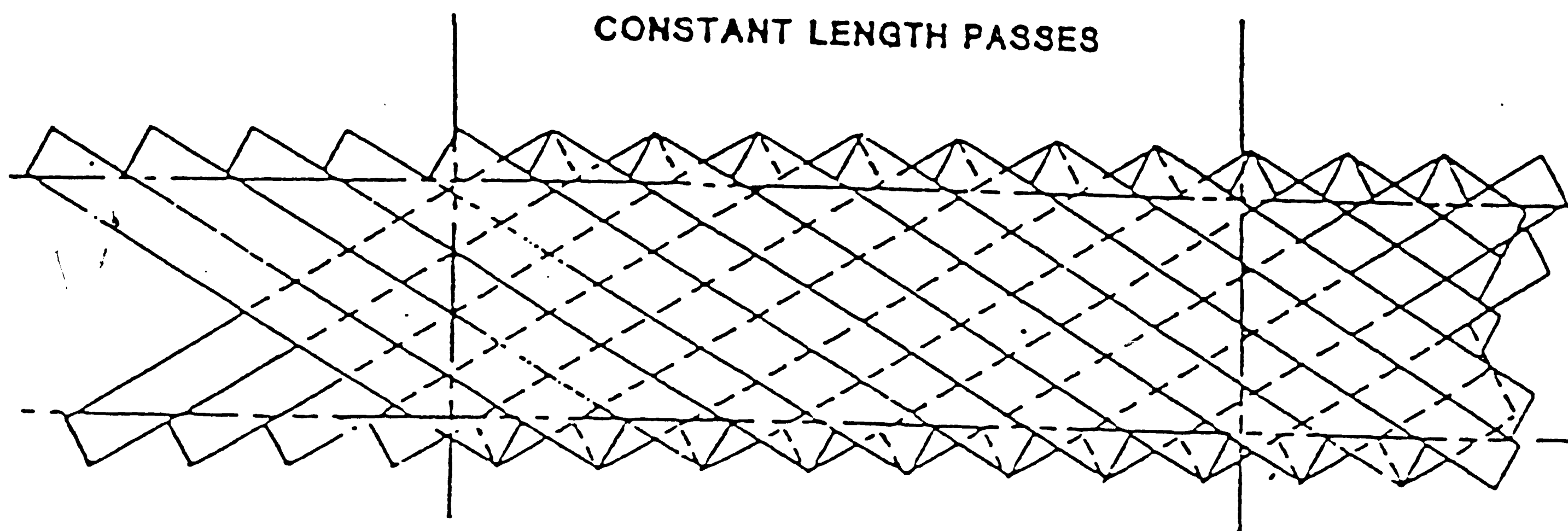
CRFS CAPABILITIES

FIGURE 5



AUTOMATED ELEMENT LAY-UP MACHINE (AELM)

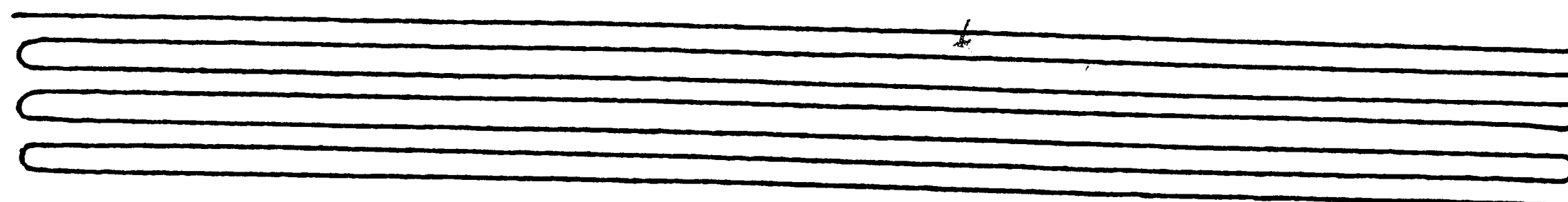
FIGURE 6



TAPE PLACEMENT

FIGURE 7

FINISH



START

CONSTANT PLY STACKING

FIGURE 8

of AELM capabilities is shown in figure 9.

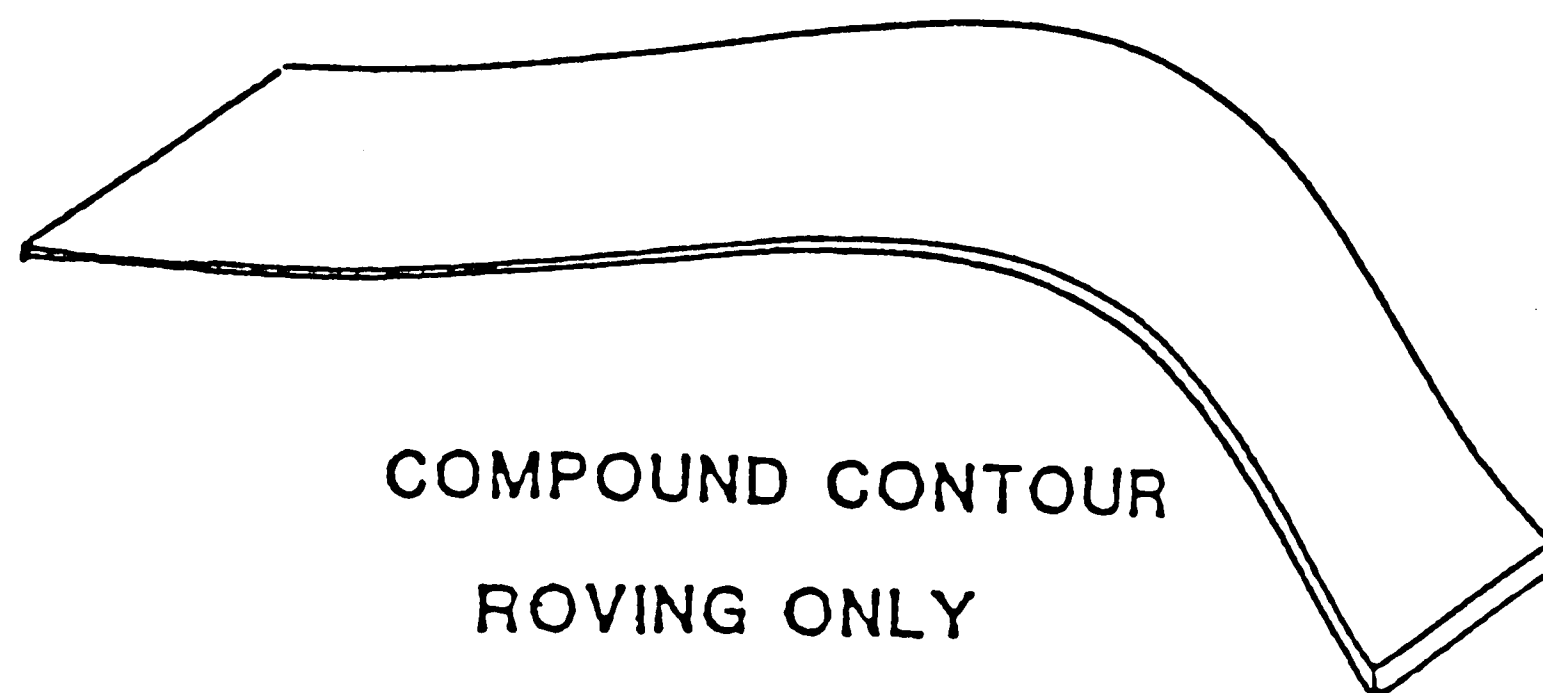
PULTRUSION (PULT)

Pultrusion is a process of fabricating long straight sections such as I-beams or tubes. A continuous feed of fibers in pre-selected orientations, is impregnated with resin and pulled through a heated die to give the shape of the final section. A partial or complete cure occurs during passage through the die.

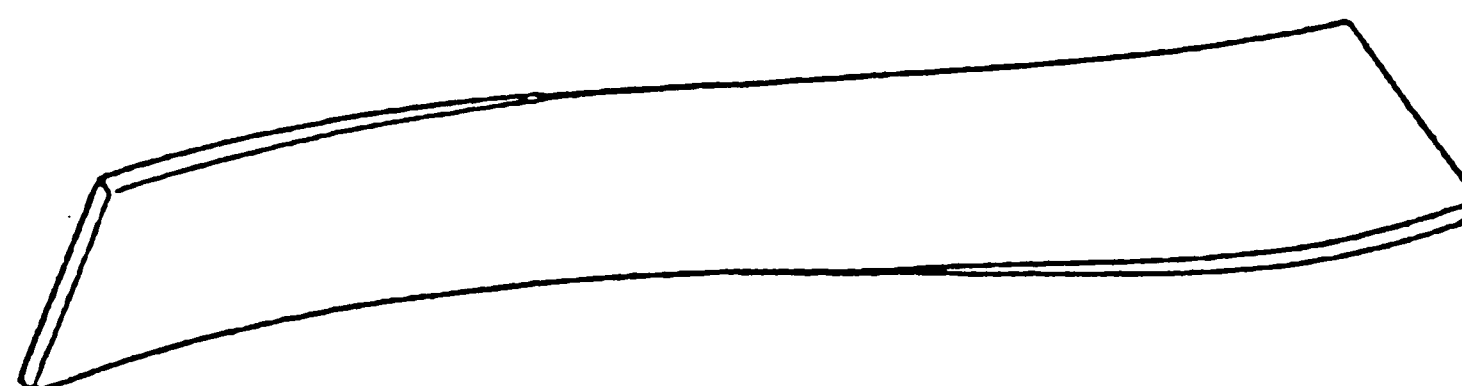
PATLM

PATLM is an automatic tape layup machine. It is limited to 7.5 inch wide tape and does not possess a feed system or cutter. Automatic lay-ups are limited to constant width. Like the AELM system plies are layered on top of each other and not cut. The machine can handle only one type of material at a time. It is also limited to a maximum 30 degree slope of changing thickness.

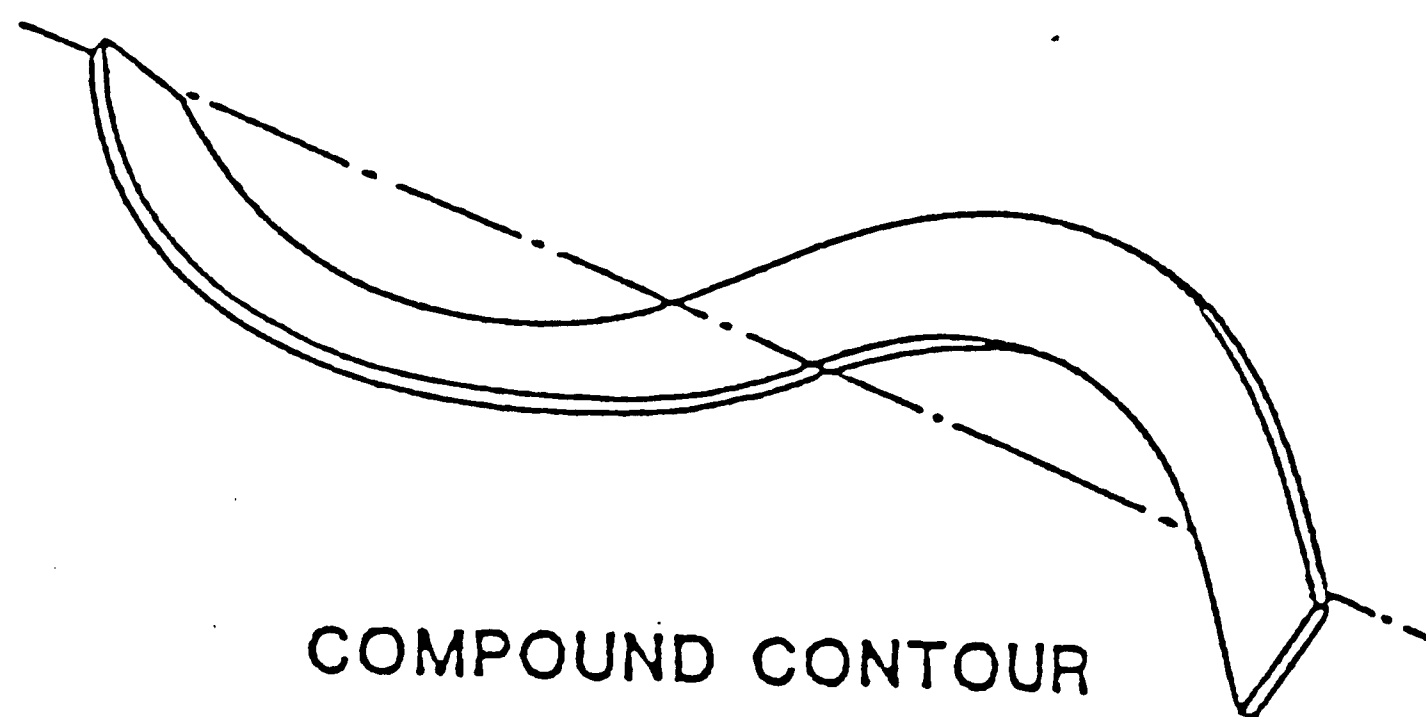
The classification system should incorporate these process variations in its scope. It must also include the material capabilities of each process. For example the AELM can process Fiberglass or Kevlar unidirectional plies or rovings.



COMPOUND CONTOUR
ROVING ONLY



GEODESIC PATH
TAPE/ROVING



COMPOUND CONTOUR
ROVING ONLY

TYPICAL EXAMPLE OF AELM LAMINATES

FIGURE 9

3.0 THE PROCLASS SYSTEM: DESIGN AND DEVELOPMENT

3.1 The Development Plan

When the requirements for a GT system were firmly established it was necessary to gain management approval. A comprehensive plan was then developed to ensure a proper development/implementation sequence. Because the system was developed for production applications it became known as PROCLASS; for Production Classification System.

The initial task was to identify the system requirements. Once the primary parameters were defined a PC-based (IBM-XT) pilot system was developed which modeled the full scale system. The pilot system was demonstrated using sample data. Following approval this became the prototype of the full scale system. It also served as a test of the computer software and hardware capabilities.

The requirements of the system were re-evaluated and refined using the pilot system. Testing was accomplished by coding sample parts, storing the data and then retrieving part families based on certain parameters. Success of the PC-based pilot effort paved the way for the full scale system.

The pilot program confirmed the need for and identified the type of information to be classified,

stored and manipulated. However, the structure of the system, that is, the procedure for data entry, storage and retrieval, was far from completion. This phase of development required long deliberations between the computer programming team and the future systems users. At the same time an investigation took place to find the most suitable computer hardware (mainframe) to run the full scale system.

After a long development stage of testing, evaluating and adjusting the logic structure of the program, the final version of the system emerged. With the classification system finalized, the classification method was recreated on paper. This version of the system became known as a data form. Each data form lists the same questions which PROCLASS sequences during a data entry session. (Appendix A illustrates the data form classification method.) A group of "coders" were assembled to study part drawings and classify each part using the data forms. With these prepared forms data entry can be accomplished much faster at each work station.

Concurrently, an IBM 9370 computer with four work stations was acquired on loan from IBM. During the twelve month term of the loan the 9370 will be evaluated and

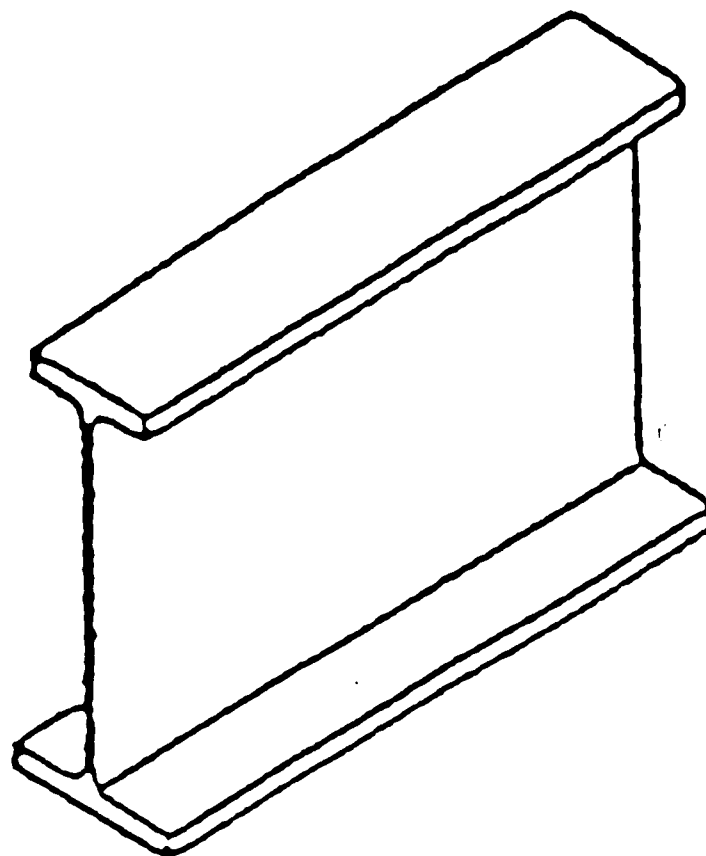
judged for running the PROCLASS system.

The GT project is currently in the implementation stage. The PROCLASS computer program has been installed on the mainframe and a relational data base is being evaluated. Once this is in place the data forms may then be used to load the data base.

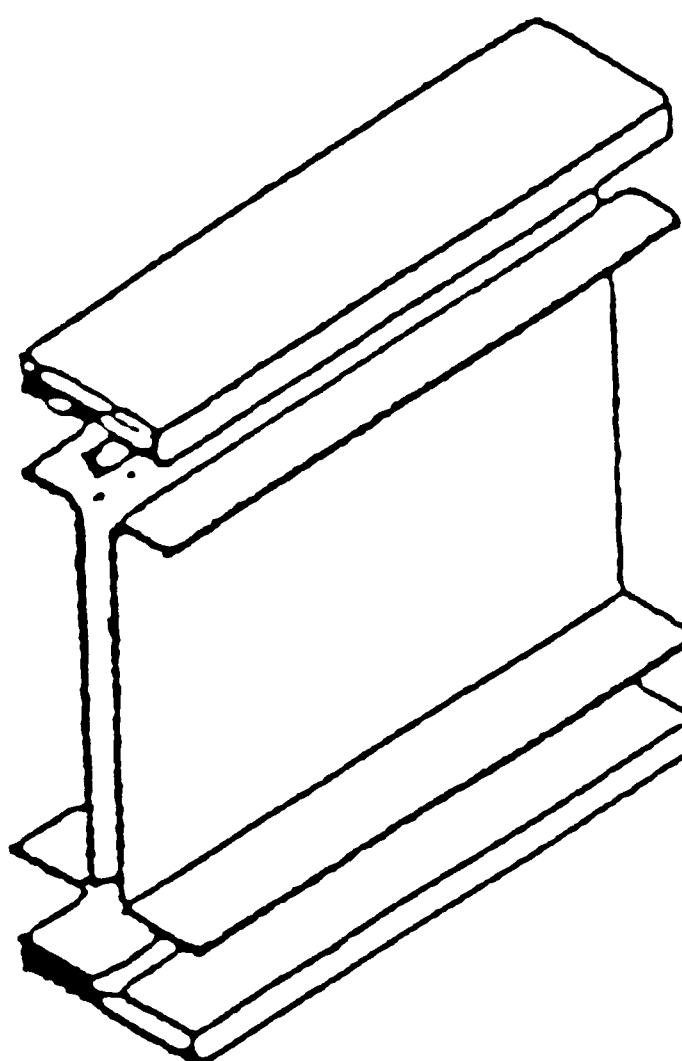
3.2 The Classification System

The classification system must identify composite manufacturing requirements for composite parts on each level of the operation, from cutting out individual plies to secondary operations performed on final cured parts. Every component must be identified by the state in which it exists at each point in the manufacturing sequence. The intrinsic complexity of the manufacturing process made the structure of the classification system difficult to design.

The new classification technique developed divides composite parts into four major states or levels of the manufacturing process, called "process levels" (see Figure 10 and 11).



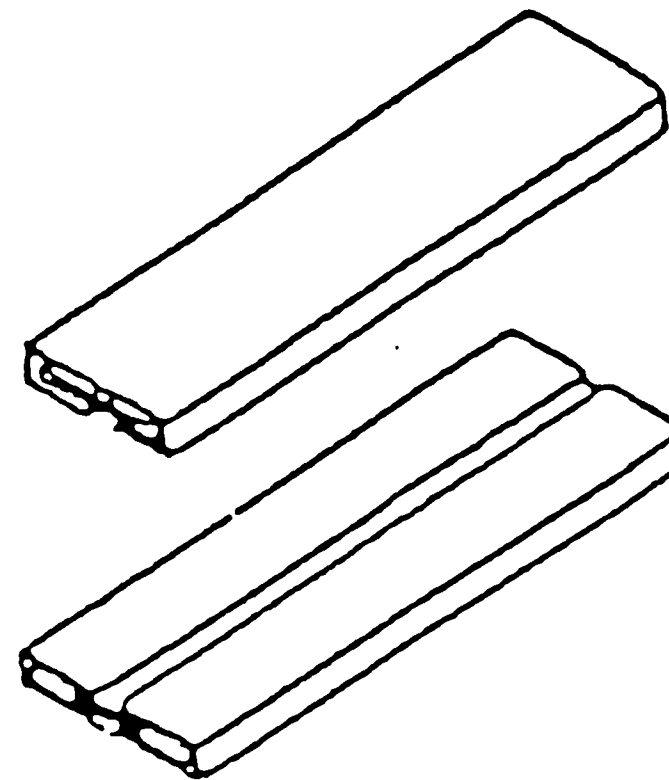
PART LEVEL - A final cured part ready for secondary operation.



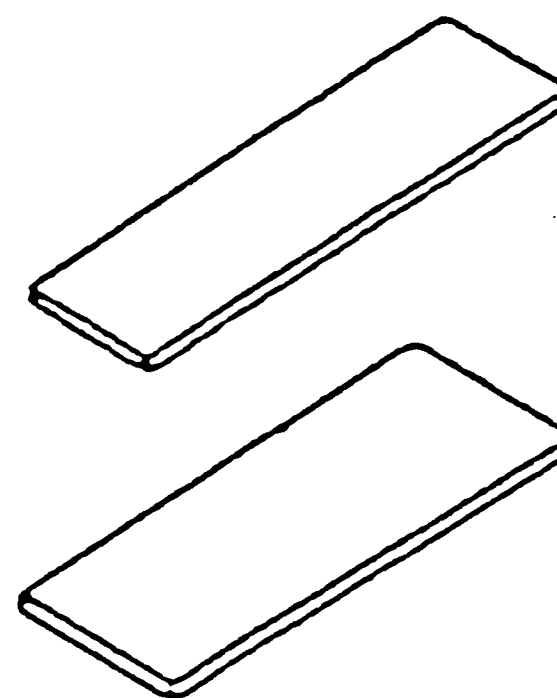
PLY PACK ASSEMBLY LEVEL - A group of ply packs assembled outside the bonded assembly jig prior to any curing process.

THE PROCESS LEVELS

FIGURE 10



PLY PACK LEVEL- A group of plies that cannot be reduced to simpler shapes other than the plies themselves.



PLY LEVEL - An individual ply

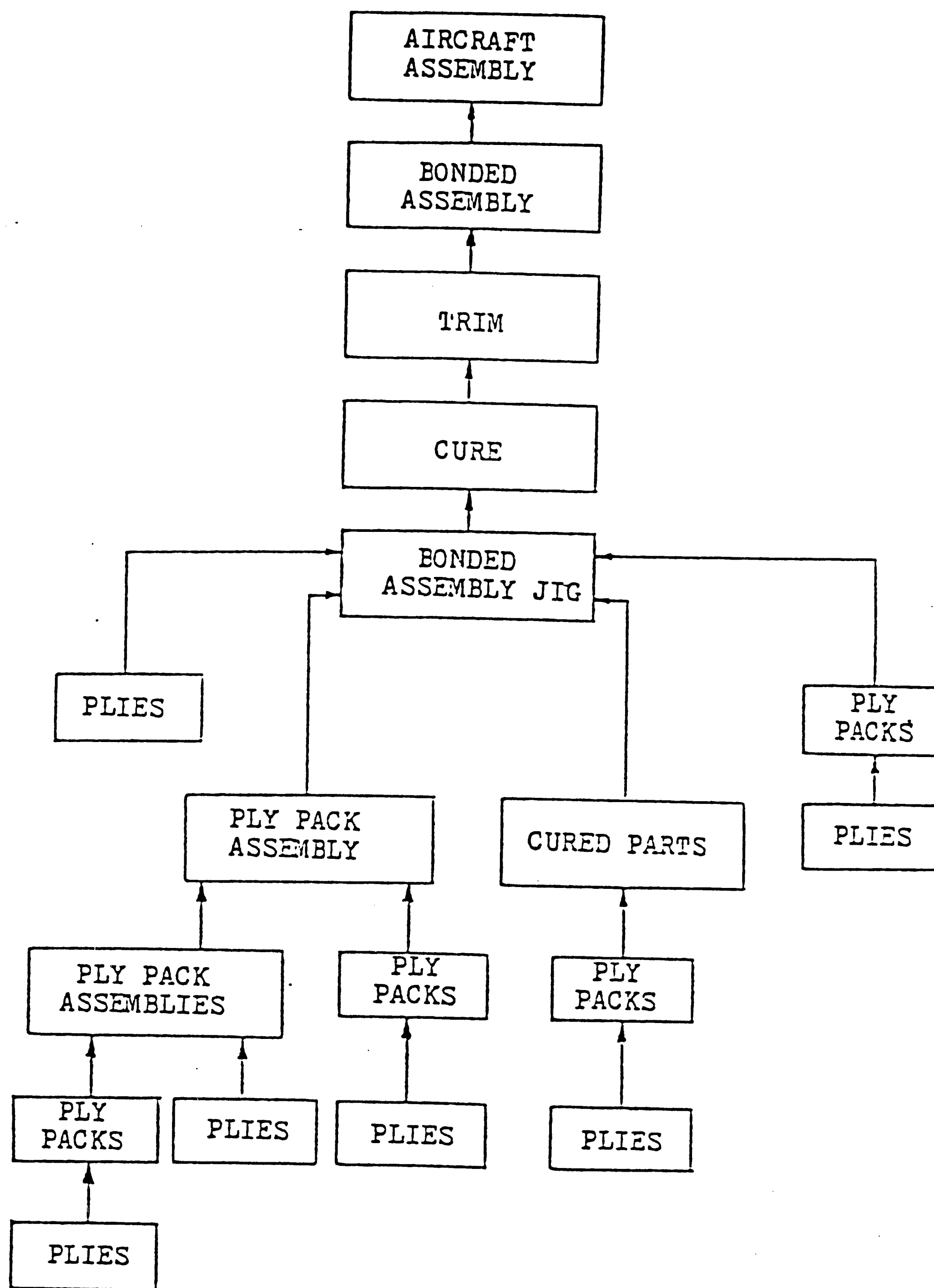
THE PROCESS LEVELS

FIGURE 11

A bonded assembly is an assembly of any combination of the four types (see Figure 12). The constituents are assembled in a bonded assembly jig and are cured together in an autoclave.

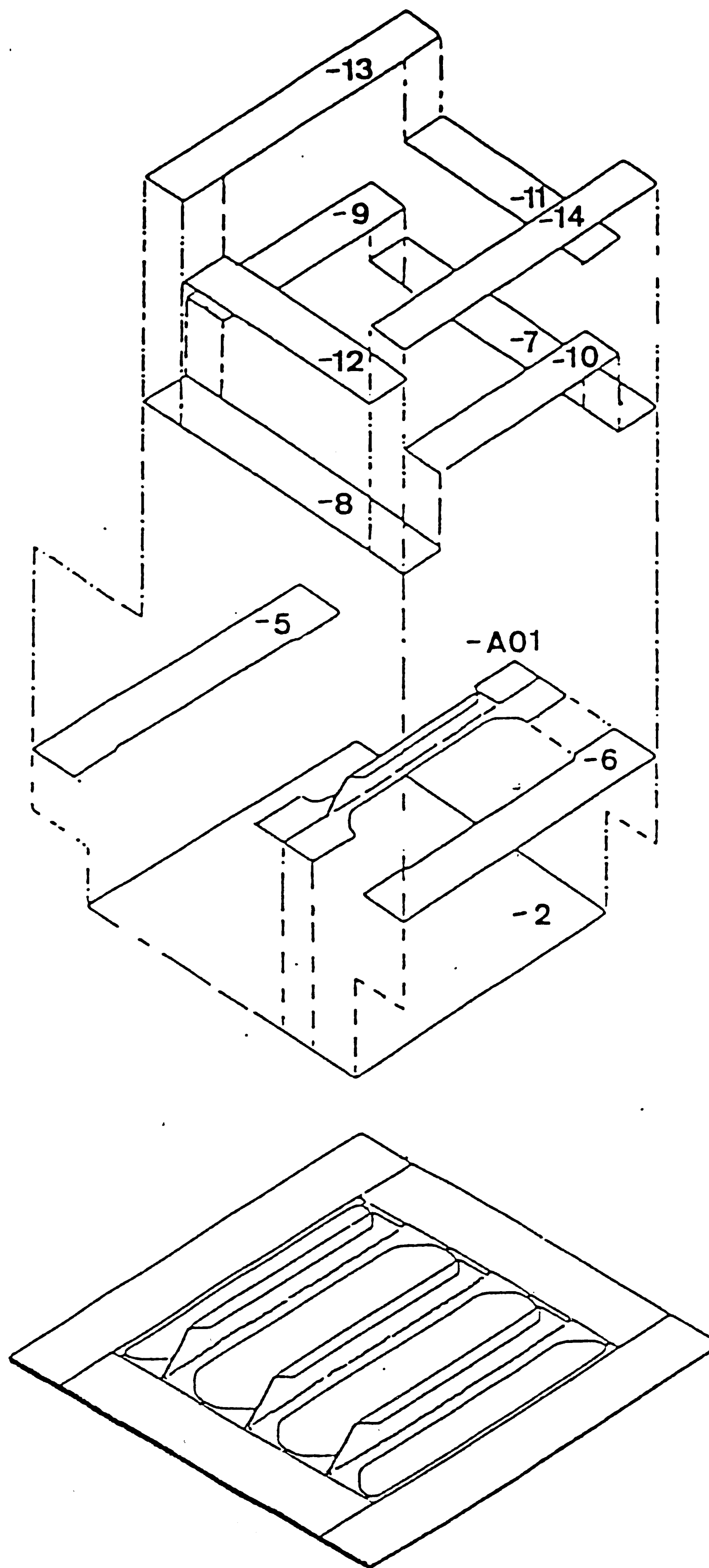
The PROCLASS system is structured around the four process levels. Each level is considered distinct and requires its own classification method for identifying unique features and attributes. Each composite component is classified at the Part Level and is then classified according to subsequent process levels. At this point a part can usually be broken down into ply pack assemblies, ply packs or a combination of both. Each ply pack assembly is broken down into ply packs and individual plies and then each ply pack is broken down into its individual plies.

For example, Figure 13 illustrates the breakdown of a test panel. (The test panel is a common type part found in the structure of the aircraft.) In the top diagram the test panel is broken down into individual plies (-7 through -14), ply packs (-5, and -6) and ply pack assemblies (-A01). The (-A01) stiffeners are ply pack assemblies which can be broken down into ply packs and individual plies. Accordingly each ply pack can be broken down into its individual plies.



BONDING ASSEMBLY

FIGURE 12



BREAKDOWN OF TEST PANEL

FIGURE 13

In comparison, the test panel is a relatively simple part, many parts have hundreds of individual plies. As parts become more complicated the method of labeling and tracking their constituents for the purpose of coding can be very difficult. A tracking chart technique was devised to assist the coding process. Tracking charts are based on the structure of the classification system. In Figure 14 another simple test panel is depicted along with its tracking chart. Each part has an existing part number. The new technique assigns a dash number for each ply pack assembly (beginning with the letter A) and each ply pack.

For Example:

Part ID Number

SK27050 - 1 - A01

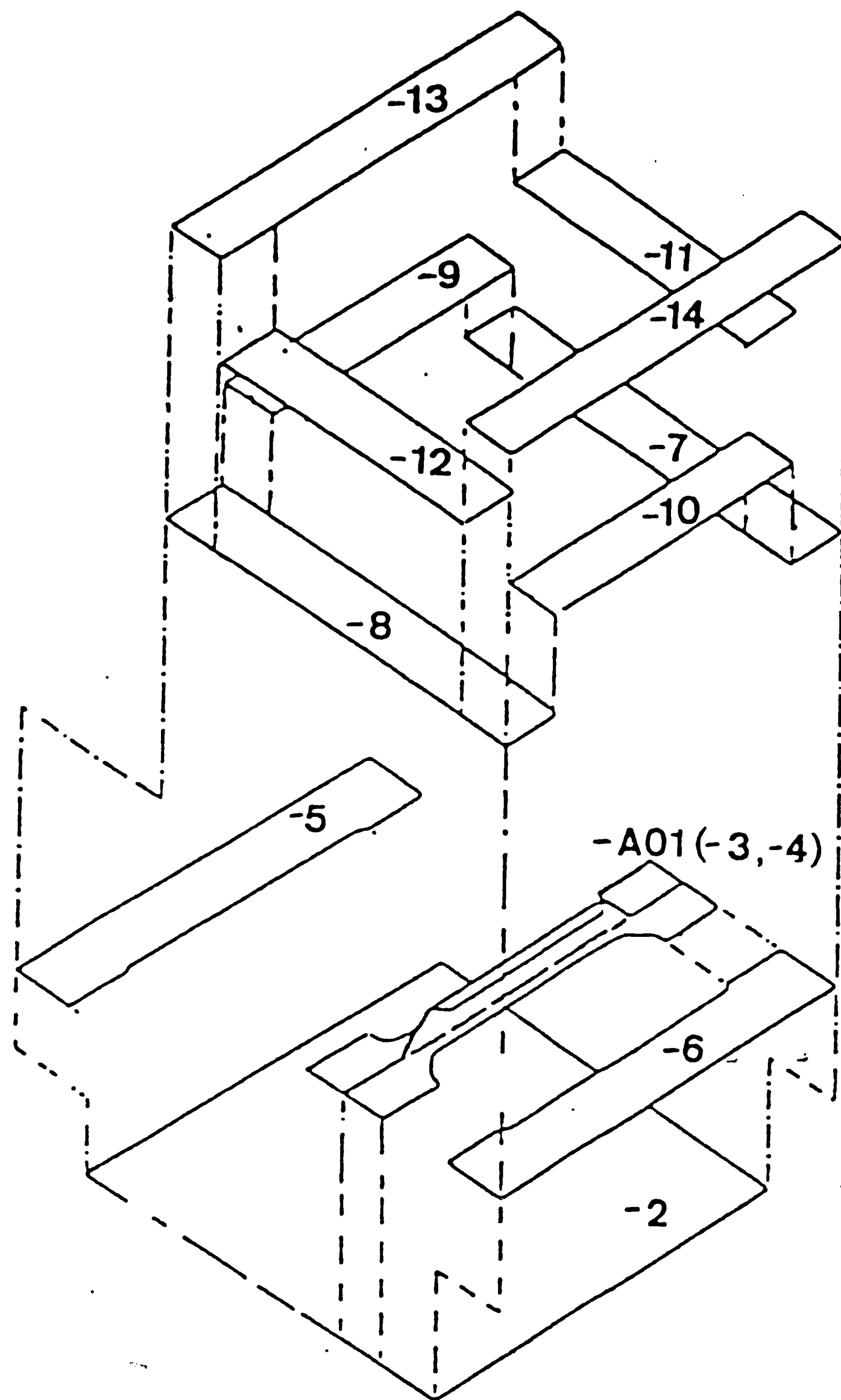
↑
Ply Pack Assembly on
part SK27050

SK27050 - 1 - A01 - 3

↑
Ply Pack in Ply Pack
Assembly A01

SK27050 - 1 - 5

↑
Ply Pack on part SK27050 - 1



TRACKING CHART

TEST PANEL SK27050

PLYPACK ASSEMBLY

PLYPACKS

-A01

-3

-4

-2

-5

-6

-7

-8

-9

-10

-11

-12

-13

-14

TEST PANEL WITH TRACKING CHART

FIGURE 14

There is no need to assign dash numbers to individual plies because they are simply numbered in order, for each ply pack assembly and ply pack, on their data forms. In the case of an individual ply being part of a bonded assembly it is treated as a ply pack in the tracking chart.

With this technique a coder begins the task of preparing data forms by first drawing a tracking chart for each part. The coder then uses the tracking chart as a check list and a guide to follow as data forms are created for the numerous constituents.

After the classification process, the tracking chart and the data forms are packaged for each part and transferred to the data entry operation. Since the tracking chart and the data forms correspond exactly to the method of data entry in PROCLASS, the classification/data entry process can be performed quickly and efficiently. The method also improves the accuracy of the data entry operation and allows verification of the data before it is entered into the computer.

3.3 The Computerized PROCLASS System

There are vendor supplied GT software packages which come equipped with their own internal data storage systems. One such package, called DCLASS (developed at Brigham Young University), was chosen for this application for several reasons. The first was that the engineering consulting team from Lehigh University was experienced and adept with the software. The second was its ability to run on a personal computer, which made the development process easier and served as the foundation for the pilot program. And the last, but most important, DCLASS is highly flexible, as the user may structure the program to match the application. Most GT software packages are inherently biased towards traditional metal machining applications and are thus more rigid than DCLASS. Furthermore, DCLASS allows programs written in Fortran to be linked to the program, which provides even more flexibility. The flexibility issue was crucial because classification of advanced composite parts is much more complex than that for metal components.

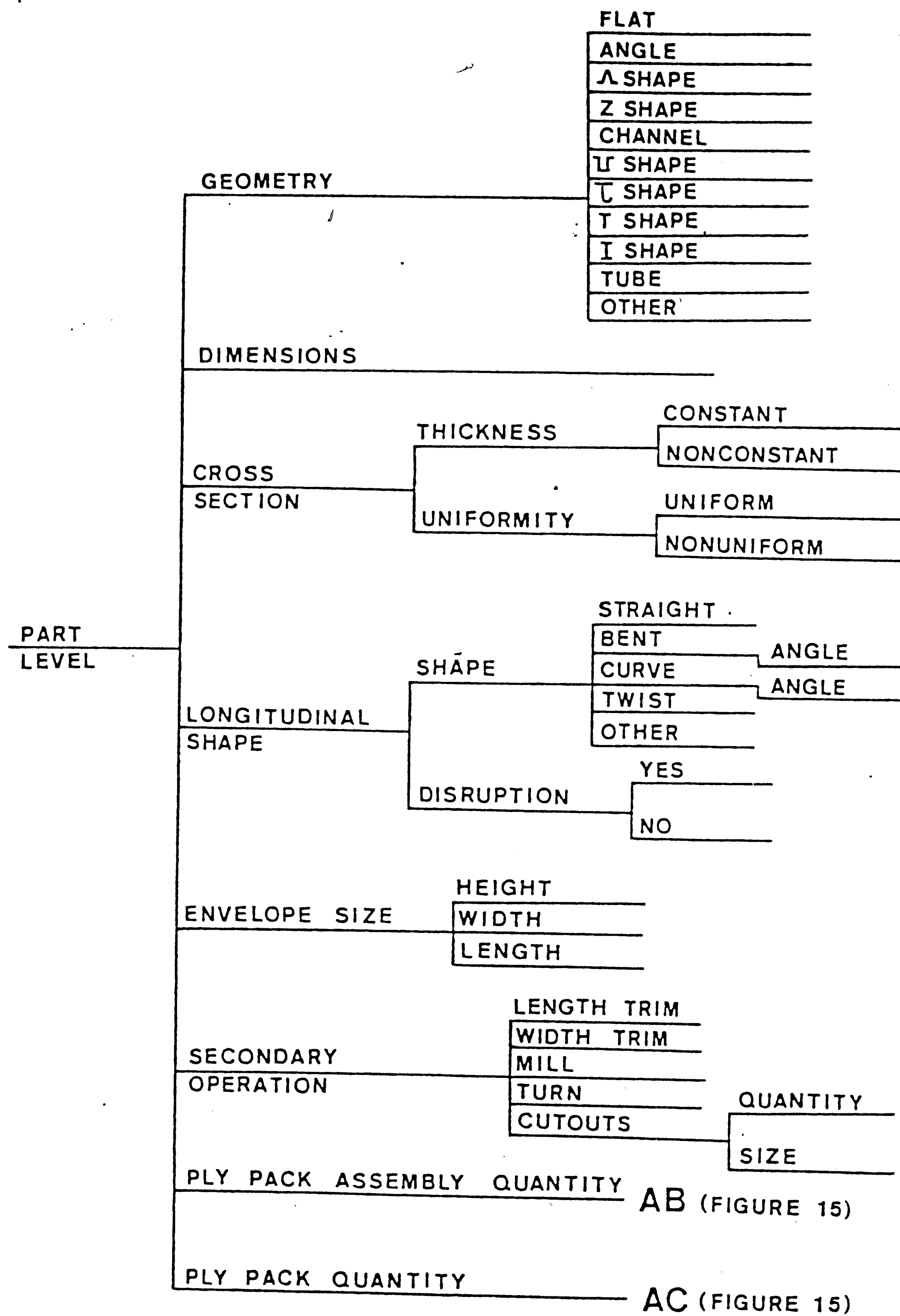
One of the requirements of PROCLASS was accessibility to both Design Engineering and the Manufacturing Research and Development Departments. Therefore, the framework of the system had to be based on their terms, definitions

and needs. An interdepartmental team was organized to work with the PROCLASS development team to ensure that the system integrated all of the separate requirements.

Some of the details cannot be presented here for proprietary reasons, but the principal concepts of the system may be understood in Figures 15 and 16. The schema is depicted as a main tree with a series of subtrees and branches that represent classification into families of information.

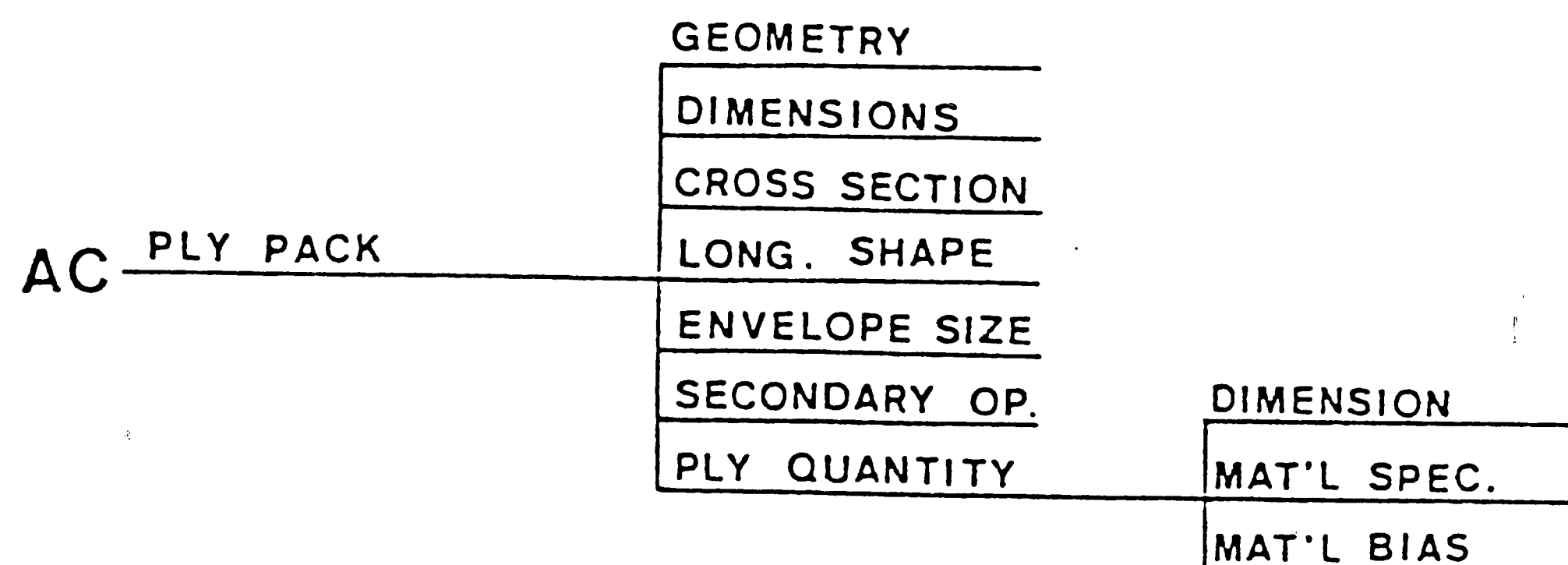
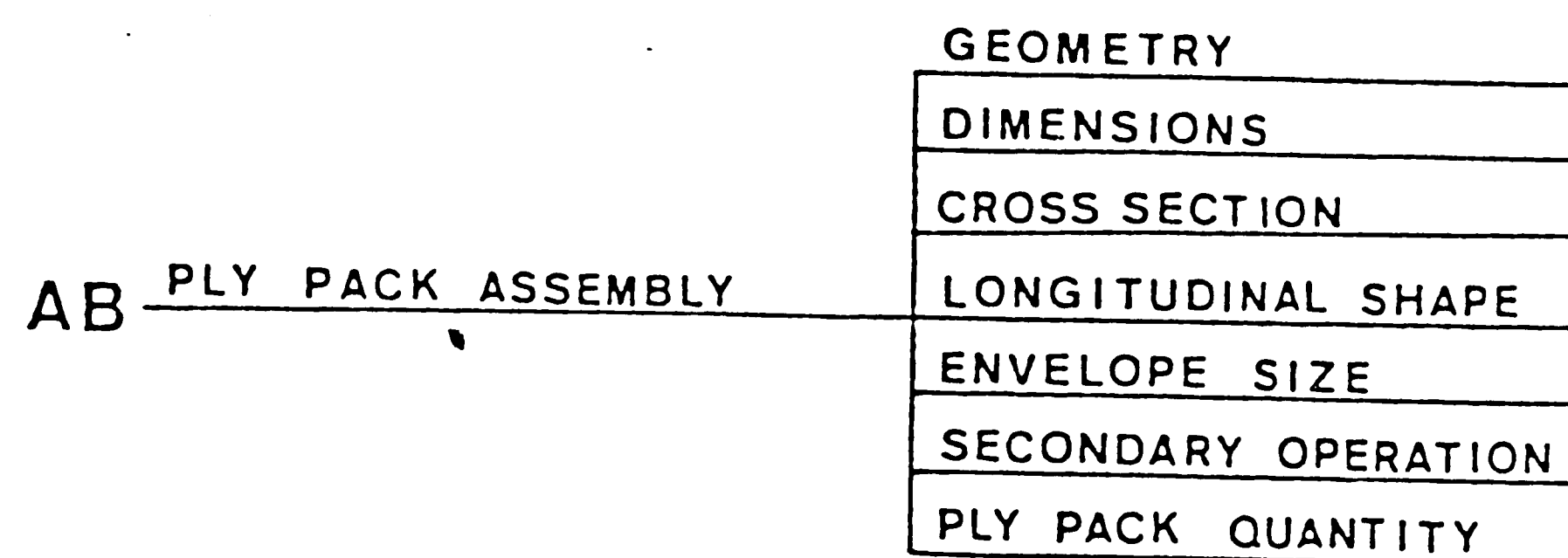
A data entry session begins at the part level with the entry of the part identification number. All of the part numbers and associated dash numbers (of ply packs and ply pack assemblies) are manipulated by a separate Fortran program which keeps track (like the tracking chart) of storing the data for the different process levels. The program then traverses the tree and accepts the specified information. In the tree a "%" sign signifies that all of the branches of the immediately following subtrees should be traversed. A "1" signifies that one branch of the following subtree should be chosen or answered.

After the part tree has been traversed the last two branches prompt for the number of ply pack assemblies and the number of ply packs on the part (but not those that



PROCLASS LOGIC TREE

FIGURE 15



PROCLASS LOGIC TREE

FIGURE 16

make up a ply pack assembly). If there are ply pack assemblies in the part the program will traverse subtree AB (Figure 16). The information required on the ply pack assembly level is similar to the questions asked on the part level. The last branch prompts for the number of ply packs in the ply pack assembly. The program then traverses subtree AC (Figure 16) until it reaches the last branch. The last branch requires the entry of the number of plies and the ply subtree will be traversed for each ply specified. With this ply pack completed the program returns to subtree AC until all ply packs are classified. The program then returns to subtree AB until all ply pack assemblies have been entered and returns to subtree AC to classify each of the ply packs specified back at the part level. Each part's features are classified and entered into PROCLASS in this way.

All of the information depicted in the Logic Tree is defined in Appendix B. Each piece of data is stored by PROCLASS in a data base and can be retrieved. This process will be discussed in the next section.

4.0 APPLICATIONS OF PROCLASS

4.1 Data Retrieval

PROCLASS was developed as a classification and retrieval system, to identify inefficiencies in composite part designs and to enable the improvement and recognition of manufacturing capabilities. The identification process is performed by retrieving families of parts according to desired criteria. Benefits can then be derived based on the information about part families.

The PROCLASS system was designed so that data may be retrieved by two different types of selection criteria. Following the classification technique, certain characteristics of a component are fixed by definition and some are variable. Fixed characteristics may be the specific geometry or shape of a component. Variable characteristics can then be the material, ply, bias or dimension specifications. For example, a specific geometry such as a channel may be composed on any material (within bounds) and can be any size. For the purpose of retrieval, fixed characteristics are identified by the system as key words and variable characteristics are identified by their variable name and value.

When selecting the retrieval criteria on the

computerized version of PROCLASS, a choice appears on the screen for entering key words and/or variable names. After selection the system prompts the user for the specific information. If a variable is being selected the system may list the possible values. For example if the variable name "BIAS" is entered the following list will appear:

```
BIAS:          0 DEGREE
               +45 DEGREE
               -45 DEGREE
               90 DEGREE
               0/90 DEGREE
               +/-45 DEGREE
               OTHER
```

In this case more than one bias may be required to represent the combination of the bias configuration of a part, ply pack or ply pack assembly.

4.2 Part Family Formation

In the beginning of every retrieval session PROCLASS prompts the user to identify the Process Level of the part or group being retrieved. Key words and variables are then selected reflecting the specific characteristics of the part or group. PROCLASS then searches the data base and lists all of the part identification numbers (and dash numbers) which match the selection. All of the components

in the list together make up a part family.

A part family retrieval operation is shown in Figures 17 and 18. These families were produced with the pilot system, which had a very limited data base. Each example illustrates the selection criteria beginning with the identification of the Process Level. Next, a geometrical key word is listed and following are the chosen variables. On the bottom of the figure the part family is listed along with the sample size represented in the pilot data base.

This small scale representation of the ability to group parts based on any selection criteria reveals the strength of the PROCLASS system. Statistical analyses may be performed on families of parts with the system to identify the need for certain processing capabilities and machine requirements.

For example, suppose the data base of composite parts has been studied and a large family of parts is found with manufacturing requirements not readily satisfied by existing equipment. This result may warrant the development of a new fabrication machine. The next step is to identify the ranges for specification of the machine's capability. These are measured by studying the characteristics of the part family. These requirements

PART FAMILY: Channels

SELECTION CRITERIA

PROCESS LEVEL: Ply Pack Assembly

KEY WORDS: Geometry - Channel

VARIABLES:

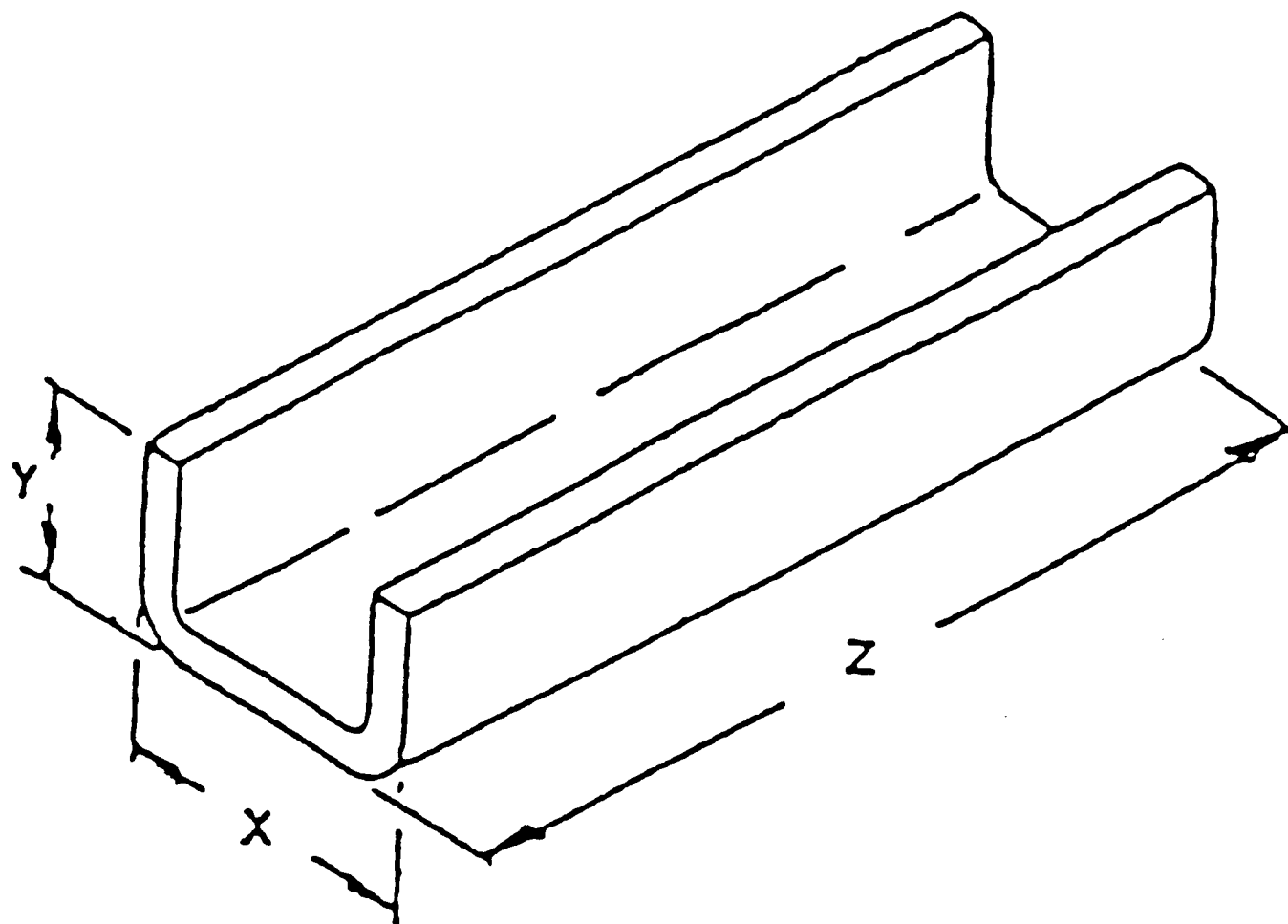
Bias - 0/90

Material - 7370

Cross Section - Constant Thickness
- Uniform

Longitudinal Shape - Straight
- No Disruption

Dimensions - Y from 1.0 to 1.42 (in)
X from 0.8 to 1.0 (in)
Z from 12.0 to 21.2 (in)



RETRIEVAL (From sample size of 75 Ply Packs)

ID NUMBERS

901-030-456-115-2
-116-1
-117-1
-119-2
-457-119-1

ID NUMBERS

901-030-458-107-1
-113-1
-125-3
-127-1
-129-4
-131-2

PILOT PROJECT RESULTS

FIGURE 17

PART FAMILY: Clips

SELECTION CRITERIA

PROCESS LEVEL: Part Level

KEY WORDS: Geometry - Angle

VARIABLES:

Bias - +/-45, 0/90

Material - 7250

Cross section - Uniform

- Constant Thickness

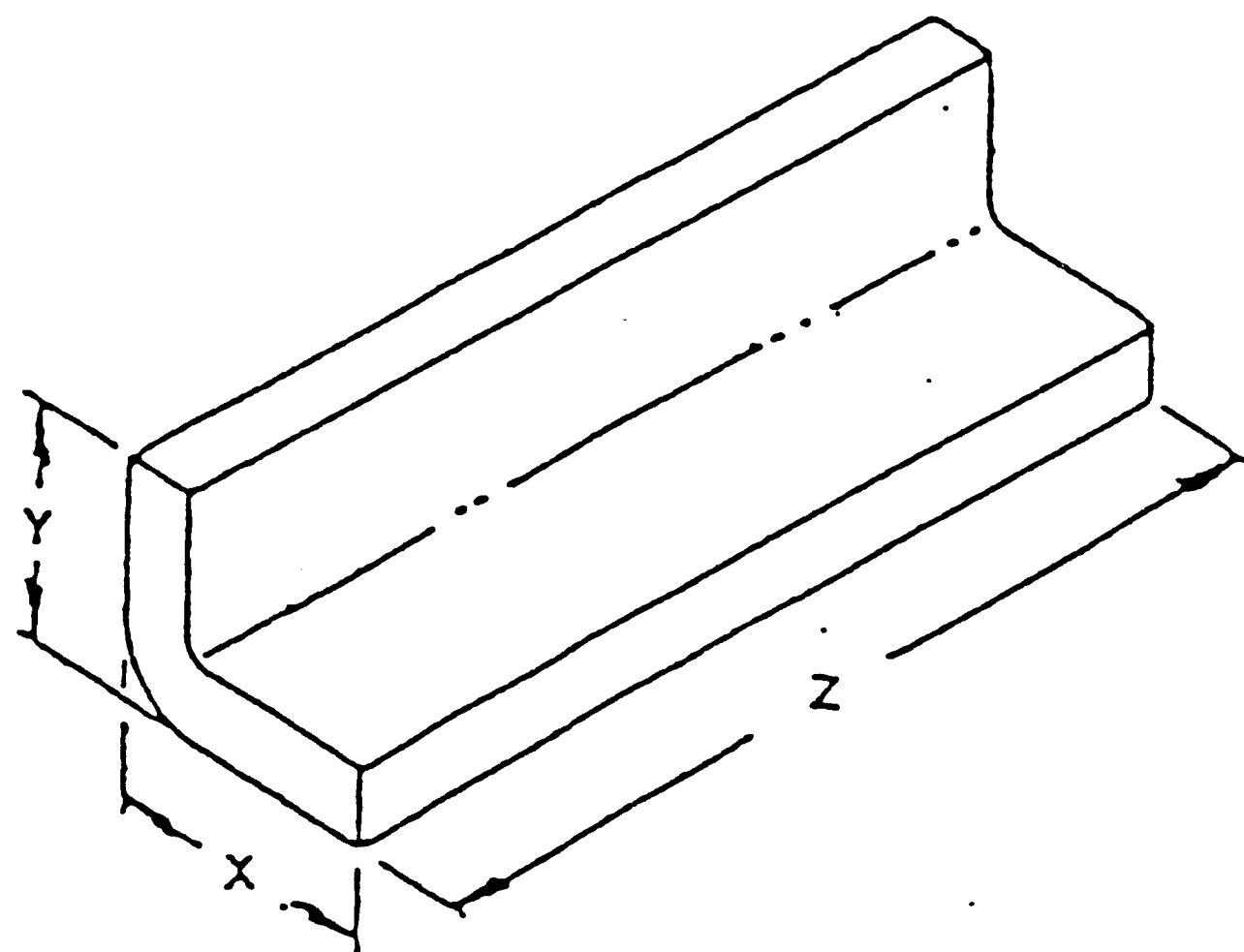
Longitudinal Shape - Straight

- No Disruption

Dimensions - X from .5 to 1.05 (in)

Y from .5 to 1.0 (in)

Z from 1.0 to 12.2 (in).



RETRIEVAL (From sample size of 20 Parts)

ID NUMBERS

901-030-119-111

-113

-117

-118

-119

-121

-131

PILOT PROJECT RESULTS

FIGURE 18

may be based on bias configurations, cross-sectional bends, changing thickness, and the process envelope size for the machine.

Another advantage of the system is the ability to group parts into "Machine Families". A Machine Family is a list of all parts which can be processed on a particular machine. A machine family is retrieved by selecting the criteria which represents the limits of the machine's operating capabilities. Figure 19 illustrates the retrieval of Machine Families. The machines listed were described in section 3.

4.3 Design Standardization

Designed as a pre-production planning tool, PROCLASS allows the manufacturer to study the similarities in part designs. This ability facilitates the standardization of design practices as well as improving the manufacturability of part designs. There are several composite design features which can be standardized with the PROCLASS system.

The first is the stacking sequence or the order of individual plies with a specific bias and material type. This sequence is configured based on the loading

COMPOSITE ROLE
FORMING SYSTEM

(CRFS)

PULTRUSION

(PULT)

AUTOMATED
ELEMENT LAY-UP
MACHINE

(AELM)


901-030-119-111	901-030-325-113	901-030-114-101
901-030-119-113	901-030-325-114	901-030-114-102
901-030-119-114	901-030-326-101	901-030-114-103
901-030-119-116	901-030-326-102	901-030-114-106
901-030-119-117	901-030-333-101	901-030-114-121
901-030-120-111	901-030-333-103	901-030-121-101
901-030-120-112	901-030-333-104	901-030-121-102
901-030-120-113	901-030-333-105	901-030-121-103
901-030-121-101	901-030-333-106	901-030-121-104
901-030-121-102	901-030-456-101	
901-030-121-103	901-030-765-101	
901-030-121-104	901-030-765-111	
901-030-121-105	910-030-765-232	
901-030-121-106	901-030-987-101	
901-030-121-107	901-030-987-102	
901-030-121-108	901-030-987-103	
901-030-121-109		
901-030-121-110		
901-030-121-111		
901-030-121-122		
901-030-122-101		
901-030-122-102		
901-030-122-103		
901-030-122-104		

MACHINE FAMILIES

FIGURE 19

conditions of the component. However, each designer has the freedom to configure the plies in any sequence as long as the requirements are met. There may be dozens of possible orders for the stacking sequence. This variability complicates both the process planning function and the manufacturing procedures. In fact it is imperative to standardize stacking sequences if automated systems are to be implemented in the manufacturing process.

An example of the variability in stacking sequences is illustrated in Figure 20. This chart which reports the order of ply bias and material, is produced by PROCLASS in the retrieval process. Both parts in the figure were designed to meet similar load conditions, are the same geometry, and have the same number of plies and material configuration. The only difference between both components is that -177 has two 0 degree bias plies between its two 90 degree plies in the center, and lacks a 0 degree ply just below the top and the bottom ply. As shown by the arrows both parts would have identical ply sequences if ply 4 and 15 were moved between plies 9 and 10.



PART: 901-830-003-177

PART: 901-830-003-125

<u>PLY#</u>	<u>BIAS</u>	<u>MATERIAL</u>	<u>PLY#</u>	<u>BIAS</u>	<u>MATERIAL</u>
1	+45	7250	1	+45	7250
2	0	7150	2	0	7150
3	0	7150	3	0	7150
4	+45	7150	4	0	7150
5	-45	7150	5	+45	7150
6	0	7150	6	-45	7150
7	0	7150	7	0	7150
8	90	7150	8	0	7150
9	0	7150	9	90	7150
10	0	7150	10	90	7150
11	90	7150	11	0	7150
12	0	7150	12	0	7150
13	0	7150	13	-45	7150
14	-45	7150	14	+45	7150
15	+45	7150	15	0	7150
16	0	7150	16	0	7150
17	0	7150	17	0	7150
18	+45	7250	18	+45	7250

VARIATIONS IN STACKING SEQUENCE

(The arrows indicate the change in stacking sequence to achieve standardization.)

FIGURE 20

If this technique were performed for the entire data base of components, standard stacking sequences could be developed. This would assist the design function and could improve manufacturing in a dramatic way. If components were grouped into families based on their stacking sequence, material and geometry, they could be scheduled to be fabricated on machines in groups with minimal set-ups, programming changeovers, and tooling requirements. In fact, if a large enough family exists, dedicated machinery can be justified for the family. In this way PROCLASS is an invaluable tool for the development of automated manufacturing systems.

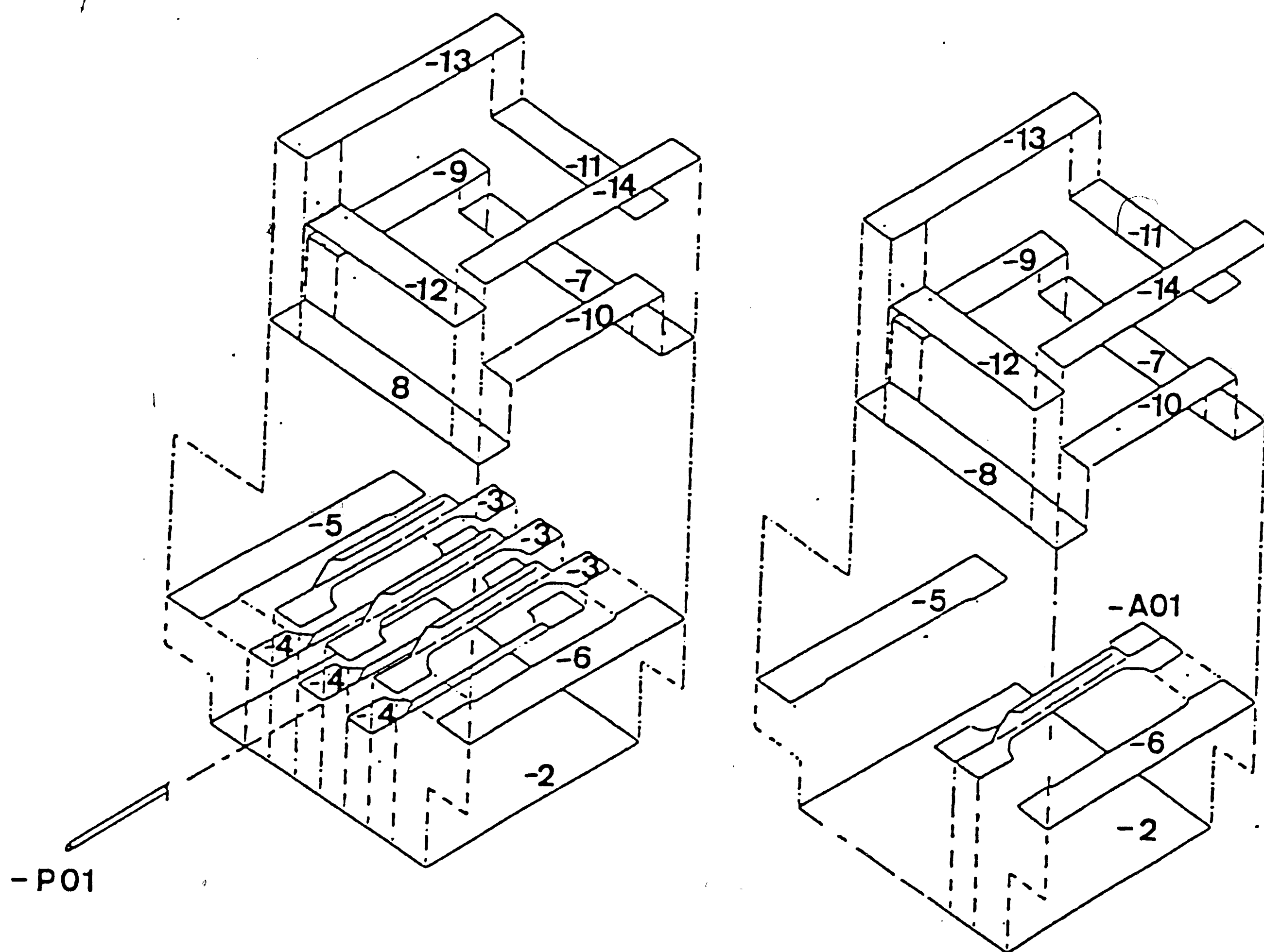
In a similar way, strength or load bearing properties may also be standardized. The strength of a composite component is determined by the relationship between geometry, bias, thickness (number of plies) and material type. The strength of a composite material is determined by the strengths of the fibers, matrix and the interface between them.

A new PROCLASS function is being developed currently which will estimate the load bearing capability of a component based on geometry, thickness, bias configuration and material; this will then be part of the data generated when a ply pack, ply pack assembly or a part is

retrieved. The value is only an estimate but will aid in the creation of design standards.

Another area which should be standardized is the application of ply packs and ply pack assemblies in a part design. Figure 21 illustrates two similar test panels which are alike except for the number of reinforcing stiffeners. There is a difference in the manufacturing requirements however.

The reinforcing stiffeners are similar in geometry, material and load bearing capabilities, although they are fabricated in two different ways. The stiffeners of test panel 1 are formed by joining 3 ply packs in a BAJ. In fact, test panel 1 is an assembly of only ply packs. The stiffener in test panel 2, on the other hand, is a ply pack assembly as its three ply packs are assembled before placement onto the BAJ. This is a subtle example yet it illustrates the lack of a standard fabrication process. Since PROCLASS classifies ply packs and ply pack assemblies separately, they can be retrieved to reveal these inconsistencies in design and manufacturing techniques. In these ways the PROCLASS system will aid the recognition of nonstandard design practices which complicate the manufacturing process and production planning.



TEST PANEL 1

TEST PANEL 2

PLY PACK ASSEMBLY AND PLY PACK APPLICATIONS

FIGURE 21

4.4 Machine Windows

One of the benefits derived in developing PROCLASS is that it forced the identification and definition of the operating capabilities of each machine. The "PROCLASS language" is being adapted to describe machine capabilities. This new methodology is called "machine windows" and is illustrated in Figure 22.

Machine Windows are important for several reasons. First, they illustrate the existing manufacturing capabilities thus assisting the identification of future processing needs. Second, they provide designers with a method of recognizing relationships between design features and manufacturing capabilities. Machine Windows can also be used as the selection criteria for the retrieval of part families discussed in section 2. Finally, they provide the organization with a uniform method of comparing processes and capabilities.

4.5 Benefits of the PROCLASS System

Group Technology can change the operating philosophy of an organization. The PROCLASS system has broad ramifications that will ultimately influence all functions.

FEATURES	MACHINE			
	AELM	PATLM	PULT	CRFS
SHAPE:				
Z shape			X	
J shape			X	X
U shape			X	X
L angle			X	X
- Flat	X	X	X	X
CROSS SECTION THICKNESS				
Constant	X	X	X	X
Nonconstant	X		X	
UNIFORM CROSS SECTION				
Uniform	X	X	X	X
Nonuniform	X	X		X
LONGITUDINAL SHAPE				
Straight	X	X	X	X
Bent	X			X
Curve	X			X
Twist	X			
Other	X			
DISRUPTION				
Yes	X			X
No		X	X	
ENVELOPE SIZE				
Max X	40"	7.5'	12"	5'
Max Y	40"	2'	12"	12'
Max Z	40'	20'	-	20'
REPEAT PLIES				
Yes		X	X	
No	X			X
MATERIAL FORMS				
All	X			X
Limited (no adhesive no copper screen)		X	X	

MACHINE WINDOWS

FIGURE 22

One of the tangible benefits of the system will be its future use in the engineering design function. As the PROCLASS data base grows to encompass all part designs it will become a library of existing designs. In fact, retrieval of existing designs which may satisfy newer requirements will be the first step in any design activity.

Table 1 is from the 1987 Hyer and Wemmerlov study of 53 U.S. manufacturing facilities currently using GT [Hyer, 1987, pg. 40]. The table illustrates some of the advantages expected of PROCLASS. The study found that 1/5 of existing part designs can be reused in a new application with no modifications. Further results indicate that 1/2 of existing designs can be used in some way (as is, with slight modifications, or with extensive modifications).

Table 2 (also from the Hyer and Wemmerlov study), shows a substantial reduction in the time to create a new design, number of total part numbers, number of design errors, number of designers needed, and the cost to create a new design. In effect, PROCLASS has the potential to establish new methods of engineering design and enable faster results.

TABLE 1

BENEFITS FROM GROUP TECHNOLOGY APPLICATIONS

	<u>REPORTED AVE</u>	<u>REPORTED MAX</u>
<u>REDUCTIONS IN:</u>		
Time to create a new design	24.00%	75.00%
Number of unnecessary items designed	22.40%	80.00%
Number of part numbers	9.00%	20.00%
Number of new designs per year	9.50%	20.00%
Number of stored designs	7.50%	10.00%
Number of items which must be designed from scratch	6.67%	10.00%
Time required to retrieve an existing design	32.50%	50.00%
Number of design errors	30.00%	50.00%
Cost to create a design	7.50%	10.00%
Number of designers needed	10.00%	10.00%
Cost to store and retrieve a part design	5.00%	5.00%

From the Hyer and Wemmerlov study of 53 U.S. manufacturing facilities using Group Technology (1987).

TABLE 2

THE USE OF GROUP TECHNOLOGY IN DESIGN RETRIEVAL

	<u>AVERAGE VALUE</u>
Percentage of instances in which an existing part is used, as is, in place of a new part	20.44%
Percentage of instances in which an existing part is modified slightly to create a new part	18.32%
Percentage of instances in which an existing part is modified extensively to create a new part	12.00%
Percentage of instances in which a new part is created from scratch	49.40%

From the Hyer and Wemmerlov study of 53 U.S. manufacturing facilities using Group Technology (1987).

PROCLASS also affects the process planning function. With the ability to form part families based on manufacturing requirements, it is possible to develop a standard process plan for each part family. The task of creating new process plans can be completed as quickly as classifying a part into one of these part families. Standardization will increase the number of process plans incorporating the preferred manufacturing methods, and it will also decrease the number of totally new process plans.

5.0 CONCLUSION

5.1 The Future of PROCLASS

PROCLASS has the potential to accelerate the evolution toward automation in manufacturing composites. However, the system must adapt continuously to technological advances in manufacturing procedures, design techniques and operating conditions within the organization. Likewise classifications and codes must keep abreast of composite technologies and changes within the aerospace industry.

PROCLASS was designed and structured to be flexible to accommodate future developments. New forms of data manipulation may be devised without effecting the storage structure, and new definitions or classification methods may be incorporated without rewriting the application programs. Thus PROCLASS has the ability to evolve with the technology of composite manufacturing.

Future applications of the PROCLASS system are currently being investigated. The next version of the system could have the ability to make machine selections for each component retrieved. This is the first step toward automated process planning.

Other applications are planned to aid the design

activity. For example, PROCLASS could recommend a particular geometry, material specification and stacking sequence, based on loading conditions and the functions of a particular part. It could also recommend certain standard ply pack or ply pack assembly configurations based on these application conditions.

When these capabilities are available PROCLASS will have the attributes of an expert system. Expert systems provide pertinent data for decision making, and can be useful in manufacturing/business related activities. Ultimately, in addition to its primary functions, PROCLASS could support financial planning, accounting, and material resource planning.

5.2 PROCLASS and Manufacturing Systems Integration

The PROCLASS system was conceived as the first step in developing an integrated manufacturing system. To this end, PROCLASS will serve two functions. The first is as a classification system which identifies inconsistent design methods and inefficient manufacturing techniques. In this way PROCLASS will support the development of new automated manufacturing procedures and will facilitate the integration of the manufacturing process.

The second function of PROCLASS is as a communication

and data format that can integrate the efforts of separate departments. In this way the system will provide a common information source so that different groups within the organization can work concurrently towards a common goal. For example, Design Engineering, Manufacturing Engineering, and Process Planning will each have access to a common data base, eliminating the need for manual data exchange. In addition PROCLASS will interface with the corporate-wide Group Technology Standards System and ultimately support the interdivisional exchange of information associated with the design and manufacturing techniques of advanced composite parts. With a common Group Technology standards system, interdivisional projects may interface with a higher degree of accuracy.

The benefits of Group Technology in the field of advanced composites manufacturing have been identified. Group Technology systems such as PROCLASS can substantially improve a manufacturing process and the efficiency of an organization. The manufacturer discussed in this thesis has taken an important step toward the development of a world class manufacturing facility.

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APPENDIX A

DATA FORM CLASSIFICATION

PART LEVEL

PART ID: SK27050

DESCRIPTION: TEST PANEL

GEOMETRY

DIMENSIONS

Flat	X 23.5	Y 1.8	Z 23.5	R ₁	θ ₁
Angle					
Channel	X ₁	Y ₁	Z	R ₂	θ ₂
T -shape					
J -shape	X ₂	Y ₂		R ₃	θ ₃
I -shape					
Z -shape	X ₃	Y ₃		R ₃	θ ₄
V -shape					
Tube					
Other	SKIN				

CROSS SECTION THICKNESS

CROSS SECTION UNIFORMITY

Constant _____
Nonconstant X

Uniform _____
Nonuniform X

LONGITUDINAL SHAPE

ENVELOPE SIZE

Straight X
Bent--angle: _____
Curved--angle: _____
Twist _____
Other _____

Width: 23.5
Height: 1.8
Length: 23.5

SECONDARY OPERATIONS

None _____
Length Trim X
Width Trim X
Mill _____
Turn _____
Cutouts _____
Angle: _____
Size: _____

Number of Ply Pack Assemblies:
1
Number of Ply Packs:
11

PLY PACK ASSEMBLY LEVEL

PLY PACK ASSEMBLY ID: SK27050-A01

DESCRIPTION: STIFFENER ASSEMBLY

GEOMETRY

DIMENSIONS

Flat	X	Y 1.75	Z 23.5	R ₁	θ ₁
Angle					
Channel	X ₁ .75	Y ₁	Z	R ₂	θ ₂
T-shape					
J-shape	X ₂ 2.68	Y ₂		R ₃	θ ₃
I-shape					
Z-shape	X ₃ .75	Y ₃		R ₃	θ ₄
V-shape					
Tube					
Other					

CROSS SECTION THICKNESS

CROSS SECTION UNIFORMITY

Constant X
Nonconstant

Uniform
Nonuniform X

LONGITUDINAL SHAPE

ENVELOPE SIZE

Straight X
Bent--angle:
Curved--angle:
Twist
Other

Width: 3.43
Height: 1.75
Length: 23.5

NUMBER OF PLY PACKS:

3

PLY PACK LEVEL

PLY PACK ID: SK27050-A01-3

DESCRIPTION: STIFFENER (C)

GEOMETRY

DIMENSIONS

Flat	X 1.75	Y	Z 23.5	R ₁ .12	θ ₁ 90
Angle					
Channel	X ₁	Y ₁ 2.68	Z	R ₂ .12	θ ₂ 90
T-shape					
J-shape	X ₂	Y ₂ .75		R ₃	θ ₃
I-shape					
Z-shape	X ₃	Y ₃		R ₃	θ ₄
V-shape					
Tube					
Other					

CROSS SECTION THICKNESS

CROSS SECTION UNIFORMITY

Constant X
Nonconstant

Uniform
Nonuniform X

LONGITUDINAL SHAPE

ENVELOPE SIZE

Straight X
Bent--angle:
Curved--angle:
Twist
Other

Width: 1.75
Height: 2.68
Length: 23.5

SECONDARY OPERATIONS

None
Length Trim X
Width Trim X
Mill
Turn
Cutouts
Angle:
Size:

NUMBER OF PLIES:

6

PLY LEVEL

PLY PACK ID: SK 27050-A01-3

<u>PLY #</u>	<u>BIAS</u>	<u>MATERIAL</u>	<u>LENGTH</u>	<u>WIDTH</u>
1	45	7250	23.5	5.2
2	0	7250	23.5	5.2
3	45	7250	23.5	5.2
4	45	7250	23.5	5.2
5	0	7250	23.5	5.2
6	45	7250	23.5	5.2
7				
8				
9				
10				
11				
12				
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34				
35				

PLY PACK LEVEL

PLY PACK ID: SK 27050-A01-4

DESCRIPTION: STIFFENER (ANGLE)

GEOMETRY

DIMENSIONS

Flat	<u> </u>	X	<u>2.68</u>	Y	<u>.75</u>	Z	<u>23.5</u>	R ₁	<u> </u>	θ ₁
Angle	<u>X</u>									
Channel	<u> </u>	X ₁		Y ₁		Z		R ₂		θ ₂
T -shape	<u> </u>									
J -shape	<u> </u>	X ₂		Y ₂				R ₃		θ ₃
I -shape	<u> </u>									
Z -shape	<u> </u>	X ₃		Y ₃				R ₃		θ ₄
V -shape	<u> </u>									
Tube	<u> </u>									
Other	<u> </u>									

CROSS SECTION THICKNESS

CROSS SECTION UNIFORMITY

Constant X
Nonconstant

Uniform
Nonuniform X

LONGITUDINAL SHAPE

ENVELOPE SIZE

Straight X
Bent--angle:
Curved--angle:
Twist
Other

Width: 2.68
Height: .75
Length: 23.5

SECONDARY OPERATIONS

None
Length Trim X
Width Trim X
Mill
Turn
Cutouts
 Angle:
 Size:

NUMBER OF PLIES:

6

PLY LEVEL

PLY PACK ID: SK27050-A01-4

<u>PLY #</u>	<u>BIAS</u>	<u>MATERIAL</u>	<u>LENGTH</u>	<u>WIDTH</u>
1	45	7250	23.5	3.5
2	0	7250	23.5	3.5
3	45	7250	23.5	3.5
4	45	7250	23.5	3.5
5	0	7250	23.5	3.5
6	45	7250	23.5	3.5
7				
8				
9				
10				
11				
12				
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33				
34				
35				

PLY PACK LEVEL

PLY PACK ID: SK27050-2

DESCRIPTION: SKIN

GEOMETRY

DIMENSIONS

Flat <u>X</u>	X <u>23.5</u>	Y	Z <u>23.5</u>	R ₁	θ ₁
Angle <u> </u>					
Channel <u> </u>	X ₁	Y ₁	Z	R ₂	θ ₂
T-shape <u> </u>					
J-shape <u> </u>	X ₂	Y ₂		R ₃	θ ₃
I-shape <u> </u>					
Z-shape <u> </u>	X ₃	Y ₃		R ₃	θ ₄
V-shape <u> </u>					
Tube <u> </u>					
Other <u> </u>					

CROSS SECTION THICKNESS

CROSS SECTION UNIFORMITY

Constant X
Nonconstant

Uniform X
Nonuniform

LONGITUDINAL SHAPE

ENVELOPE SIZE

Straight X
Bent--angle:
Curved--angle:
Twist
Other

Width: 23.5
Height: .06
Length: 23.5

SECONDARY OPERATIONS

None X
Length Trim
Width Trim
Mill
Turn
Cutouts
Angle:
Size:

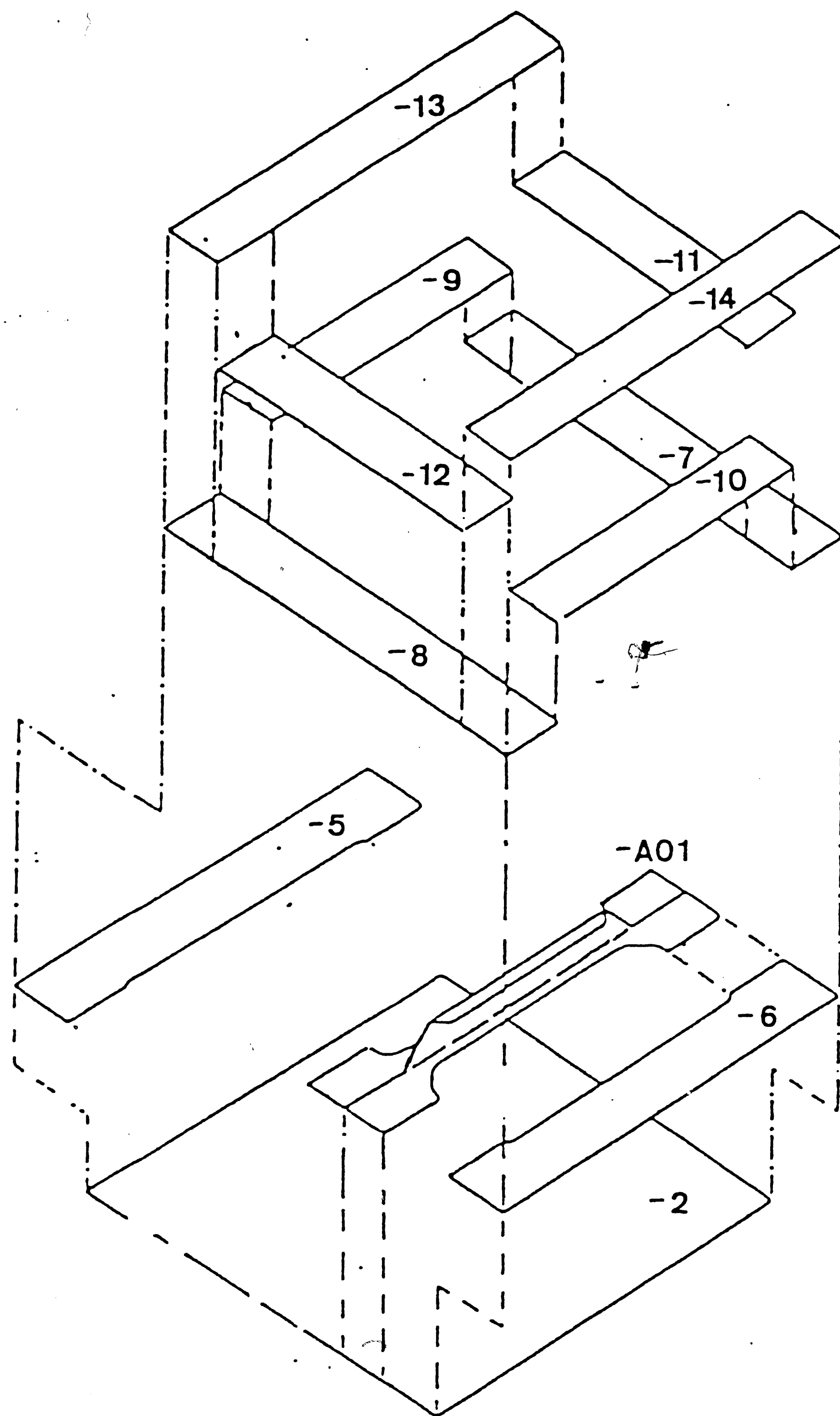
NUMBER OF PLIES:

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PLY LEVEL

PLY PACK ID: SK27050-2

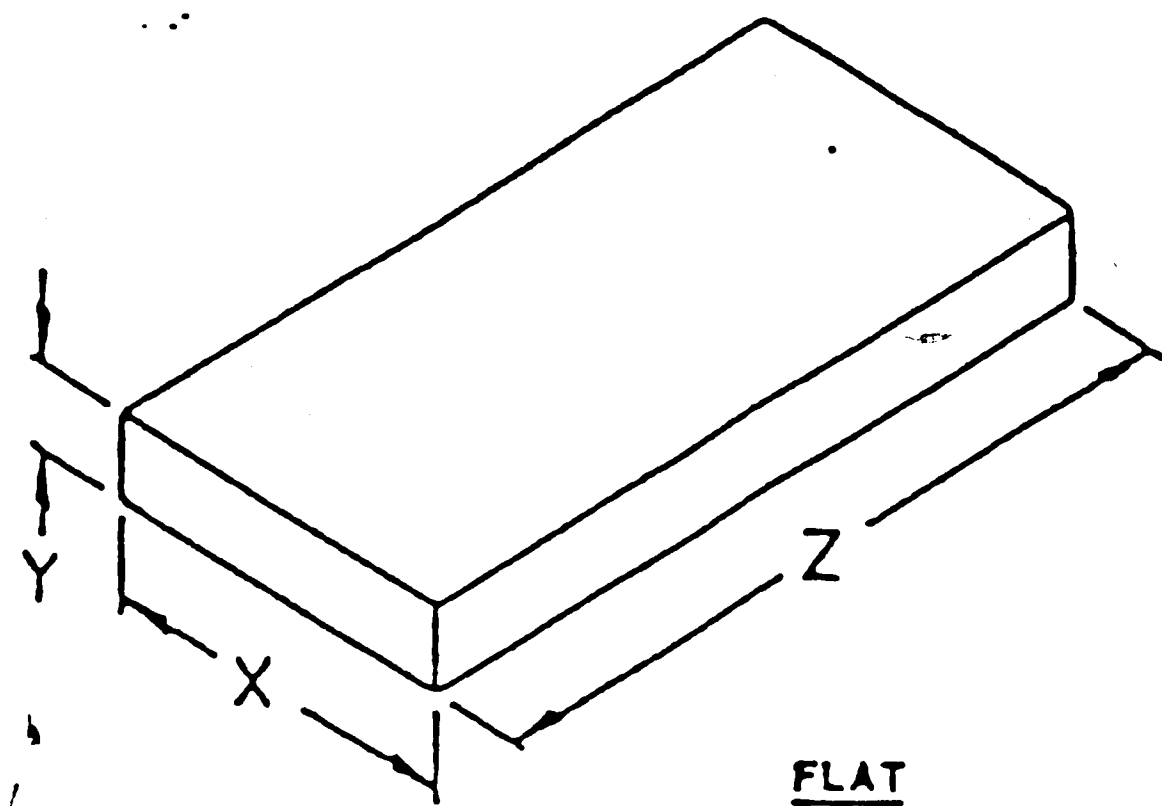
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5	45	7250	23.5	23.5
6	45	7250	23.5	23.5
7	45	7250	23.5	23.5
8				
9				
10				
11				
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34				
35				



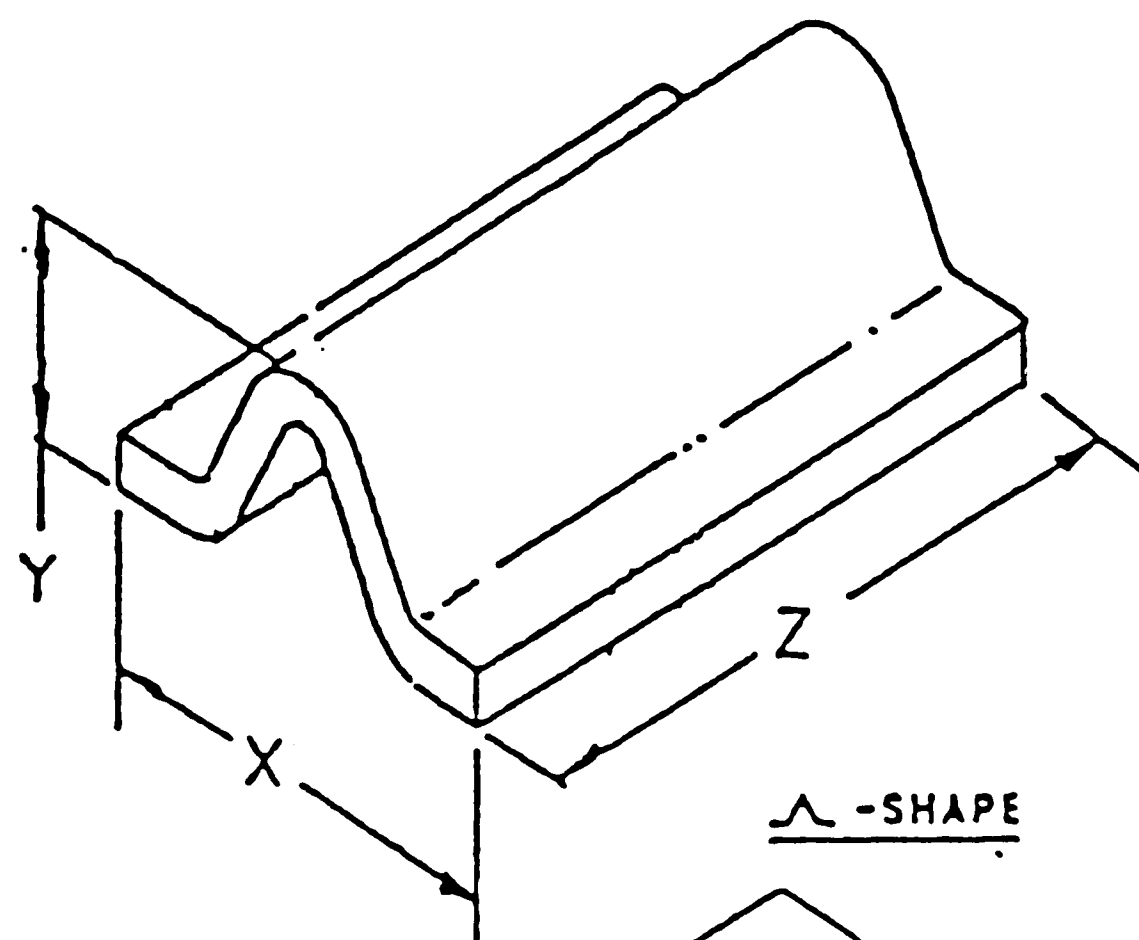
TEST PANEL (SK27050)

APPENDIX B

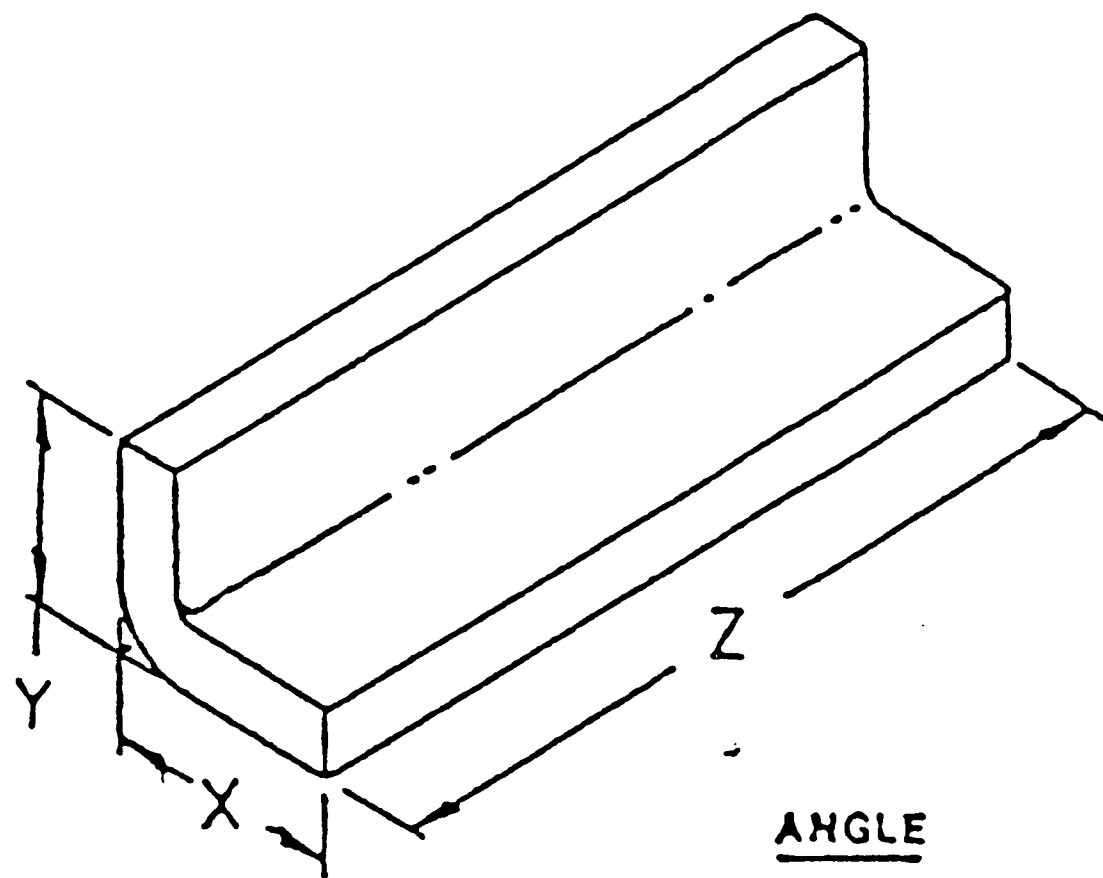
DEFINITIONS FOR PROCLASS LOGIC TREE



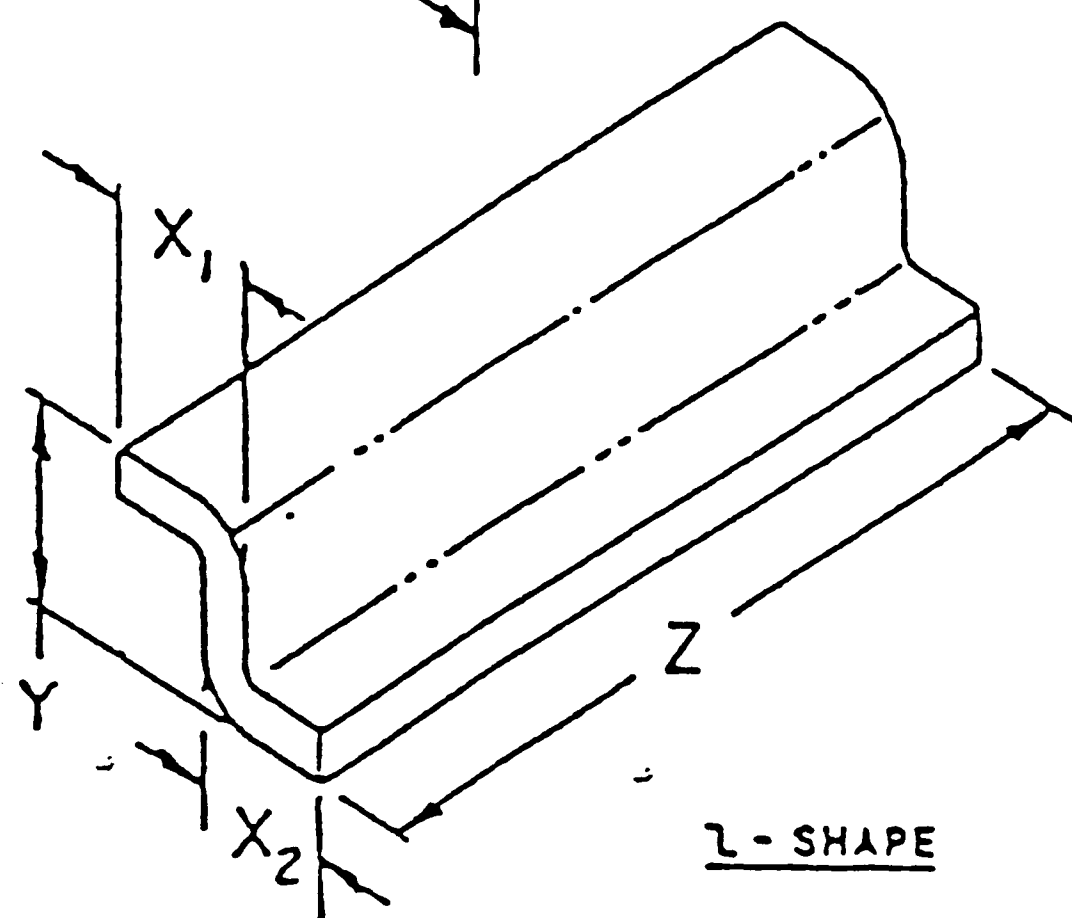
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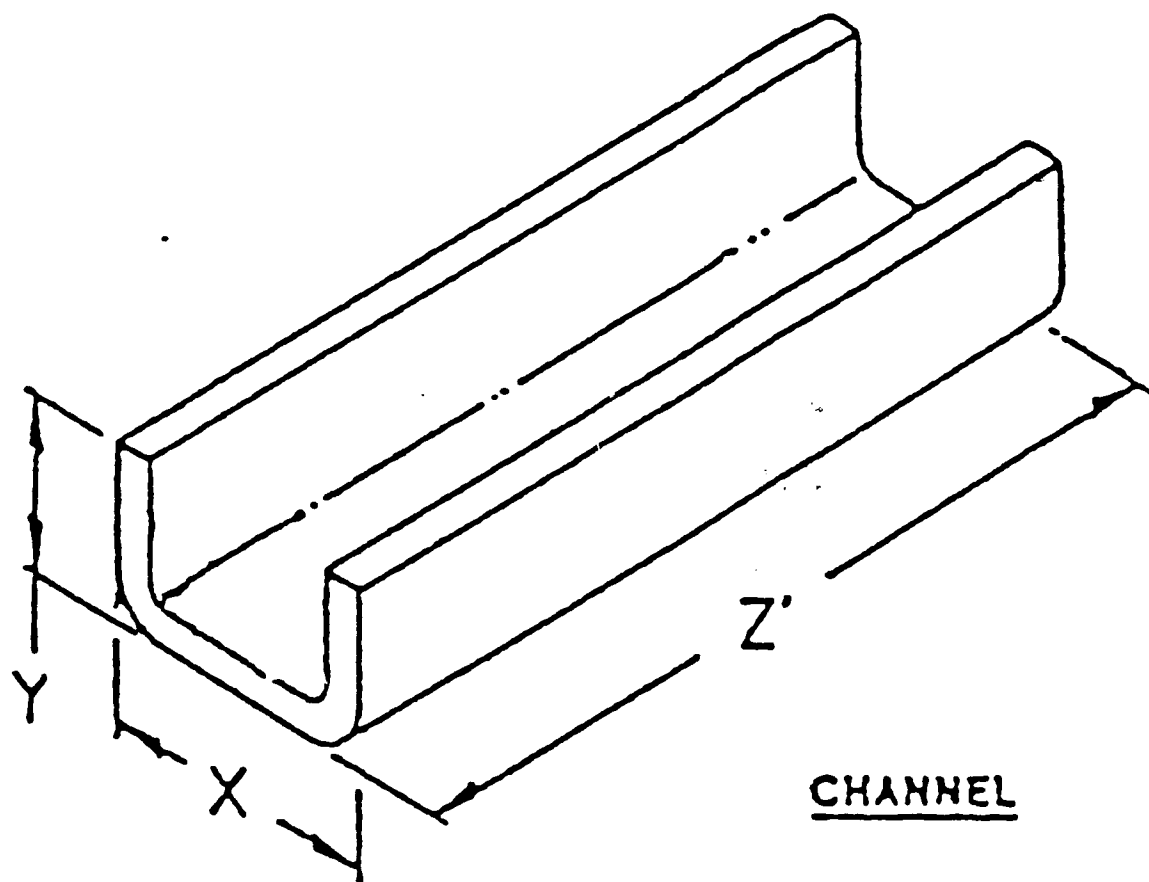
A-SHAPE



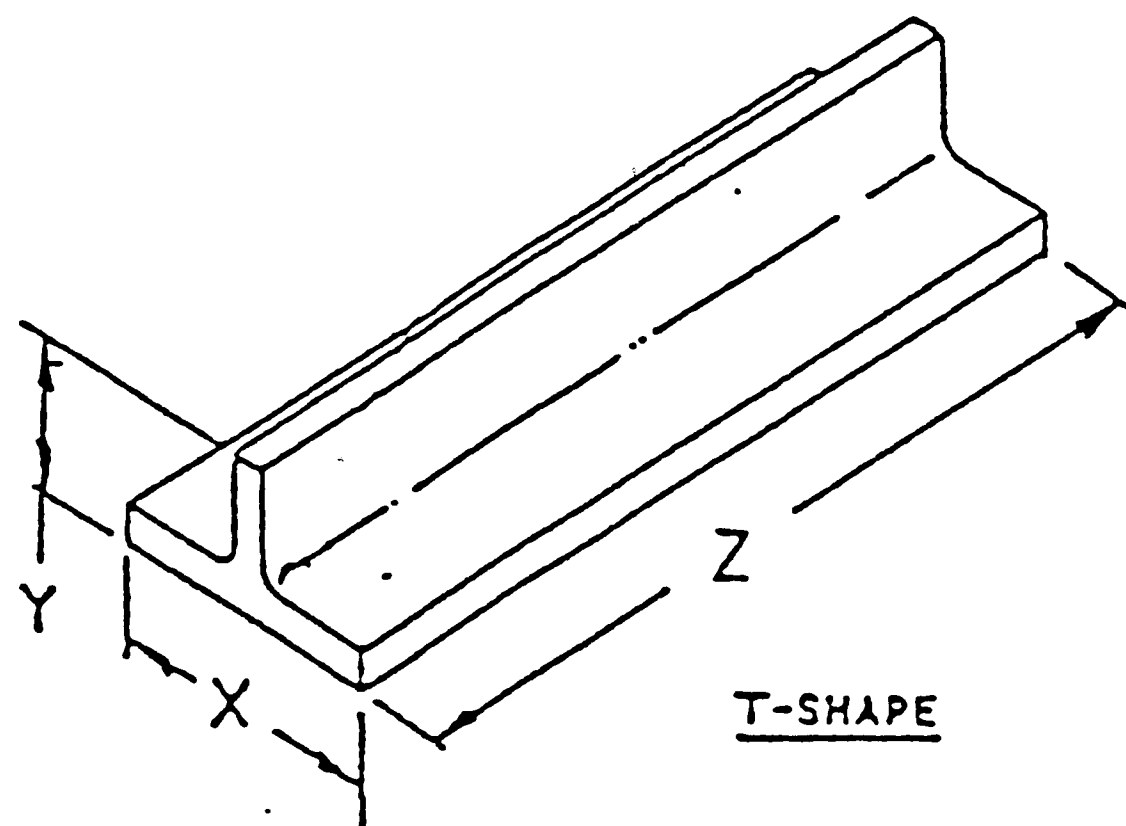
ANGLE



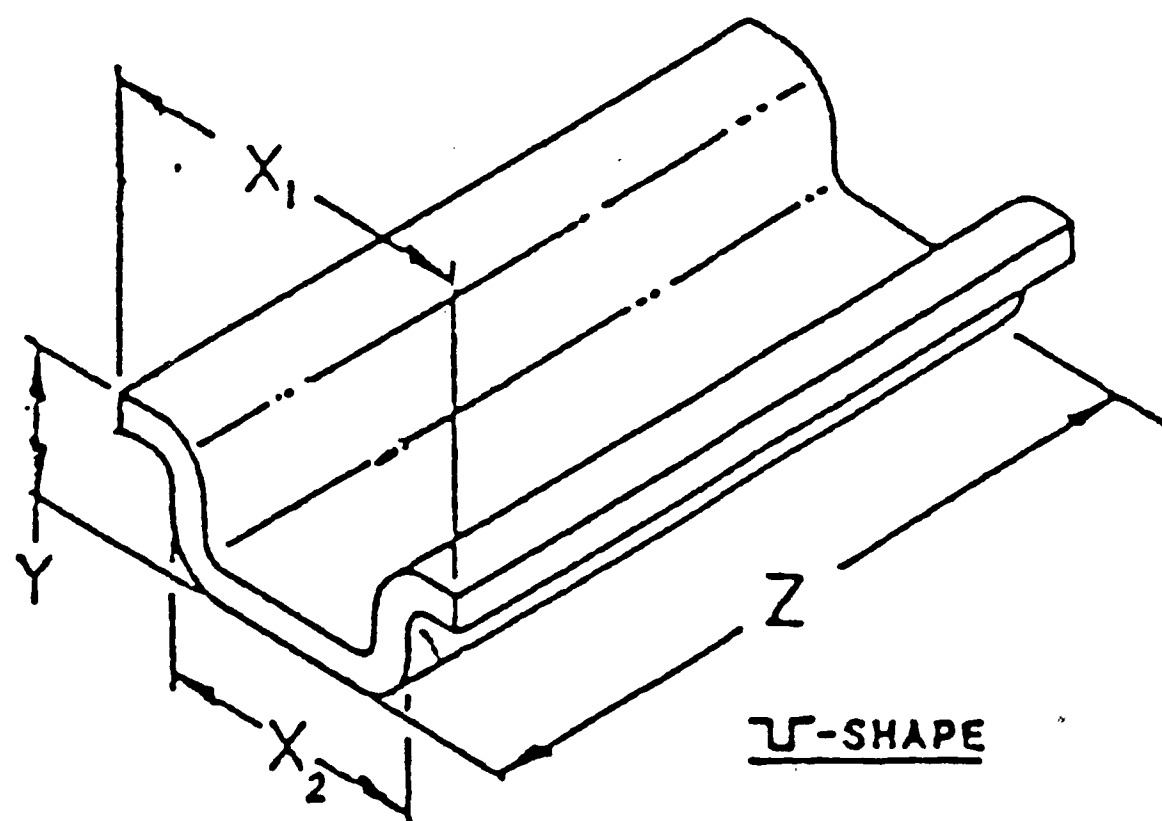
L-SHAPE



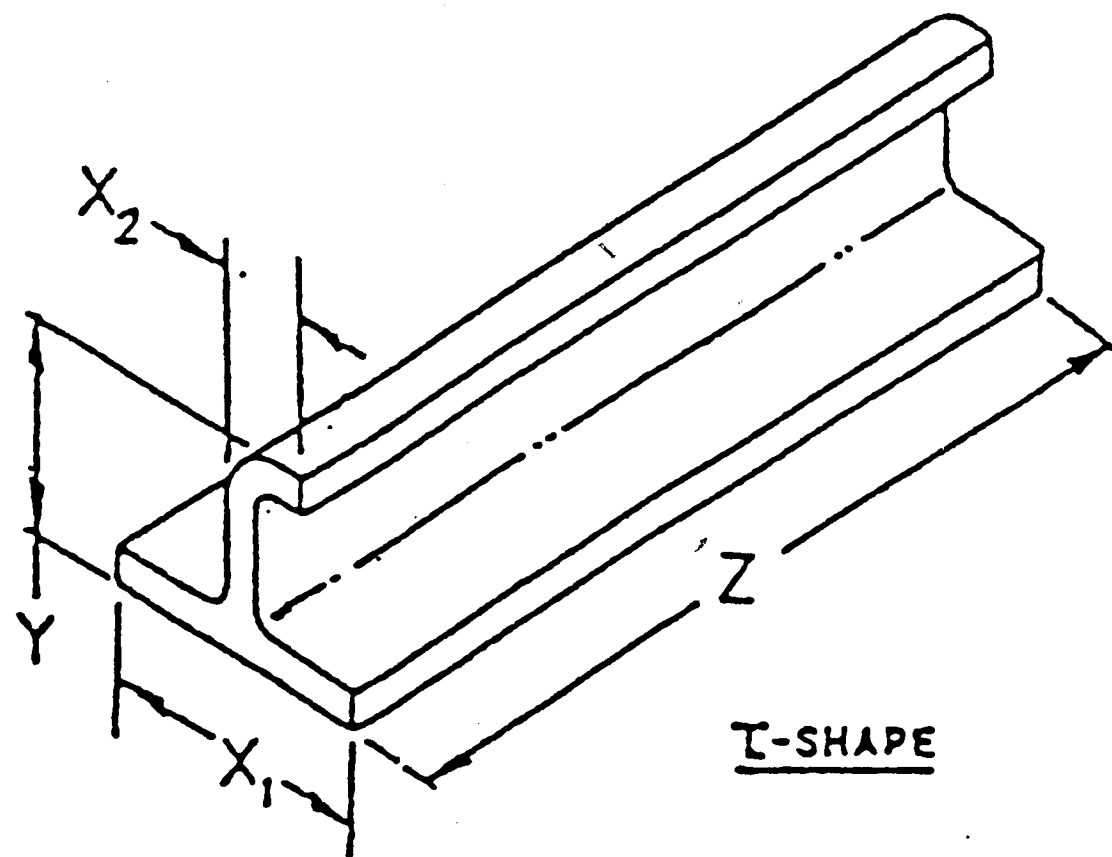
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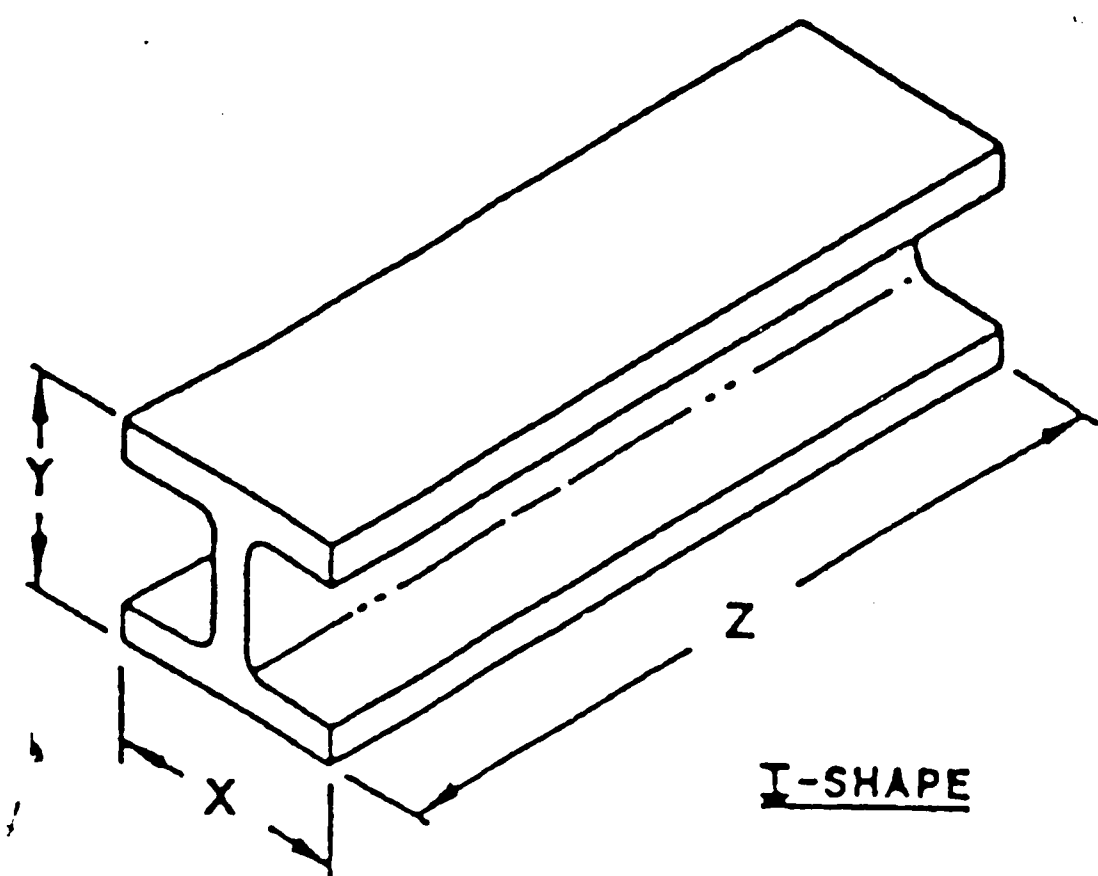
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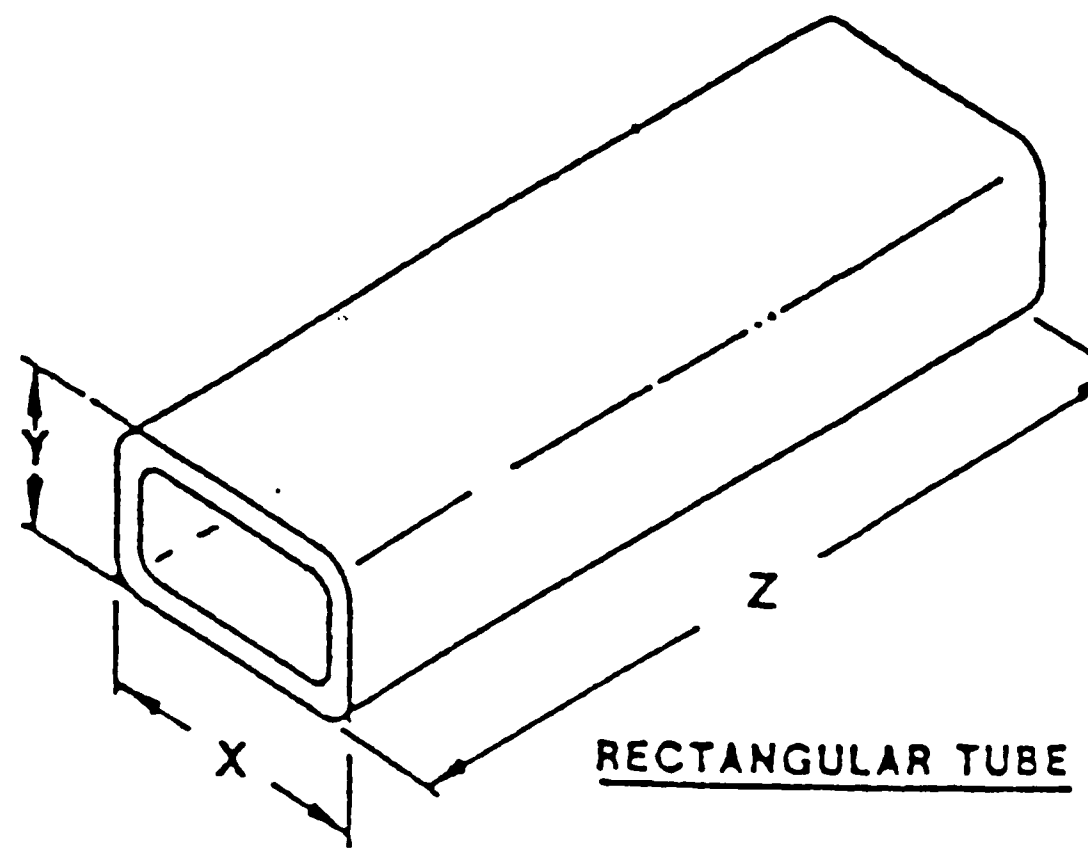
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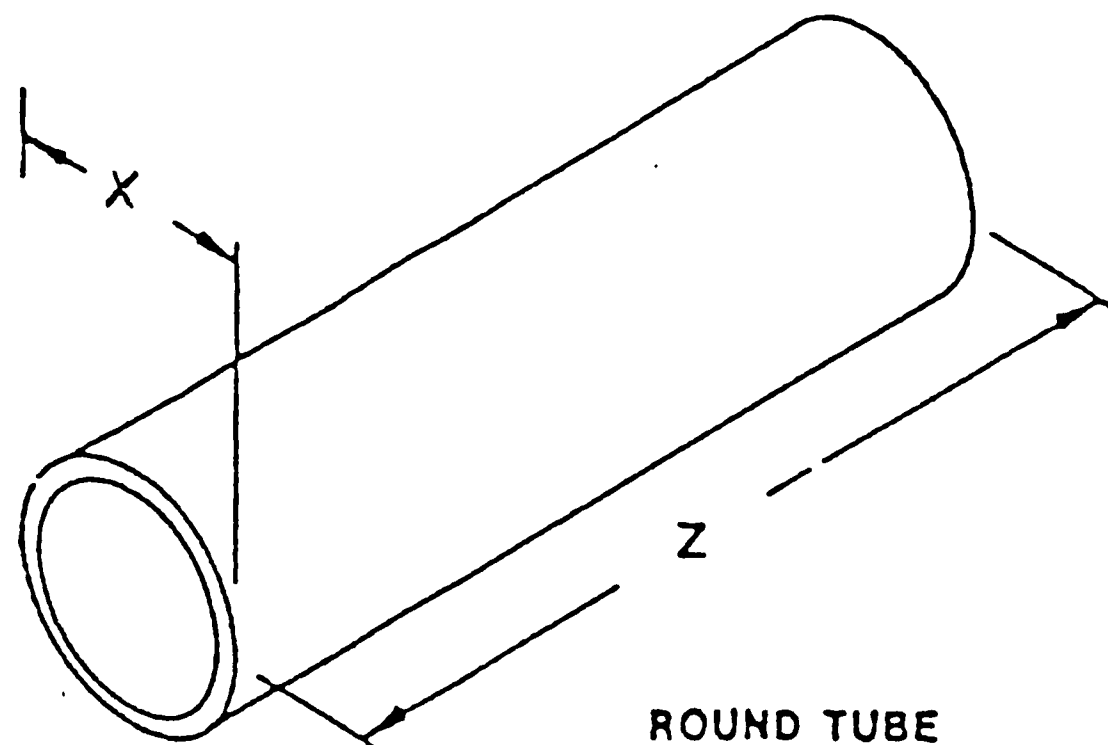
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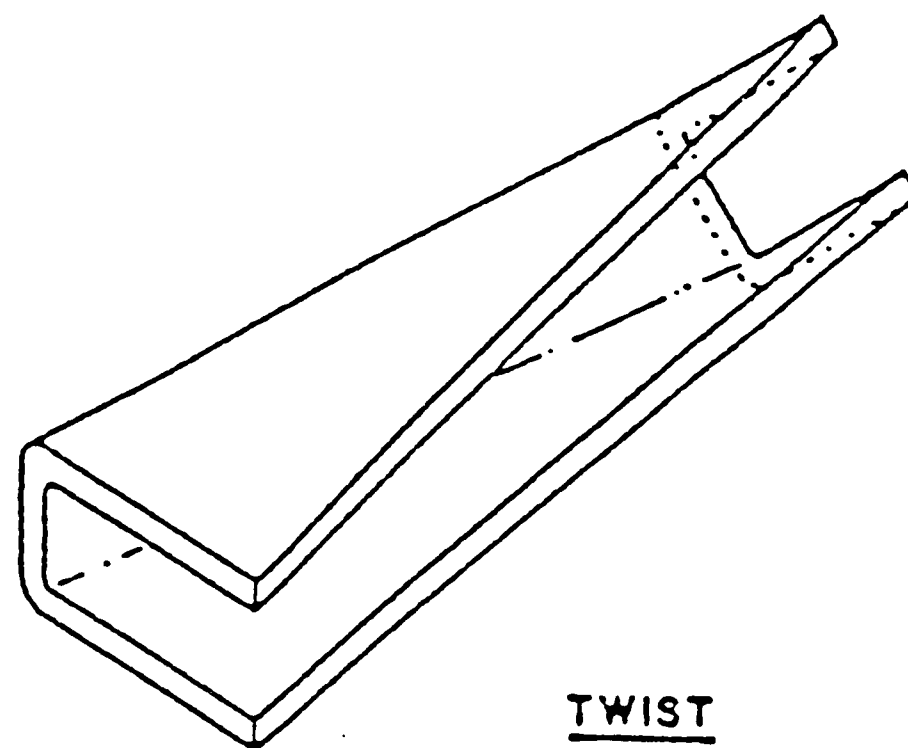
I-SHAPE



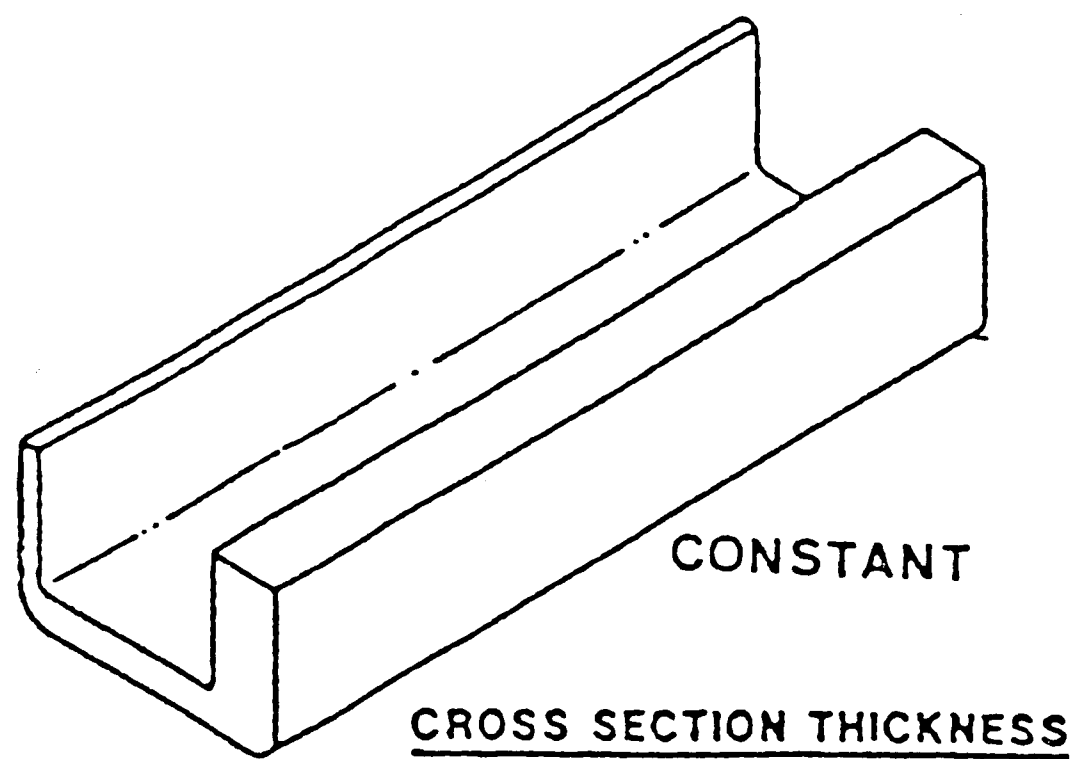
RECTANGULAR TUBE



ROUND TUBE

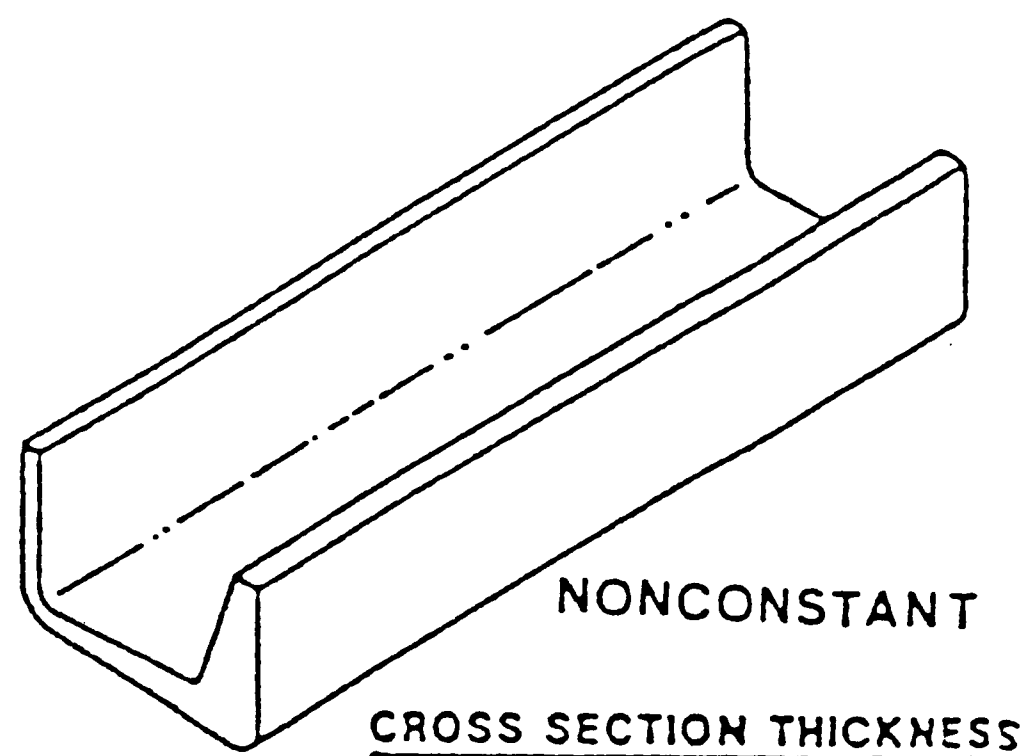


TWIST



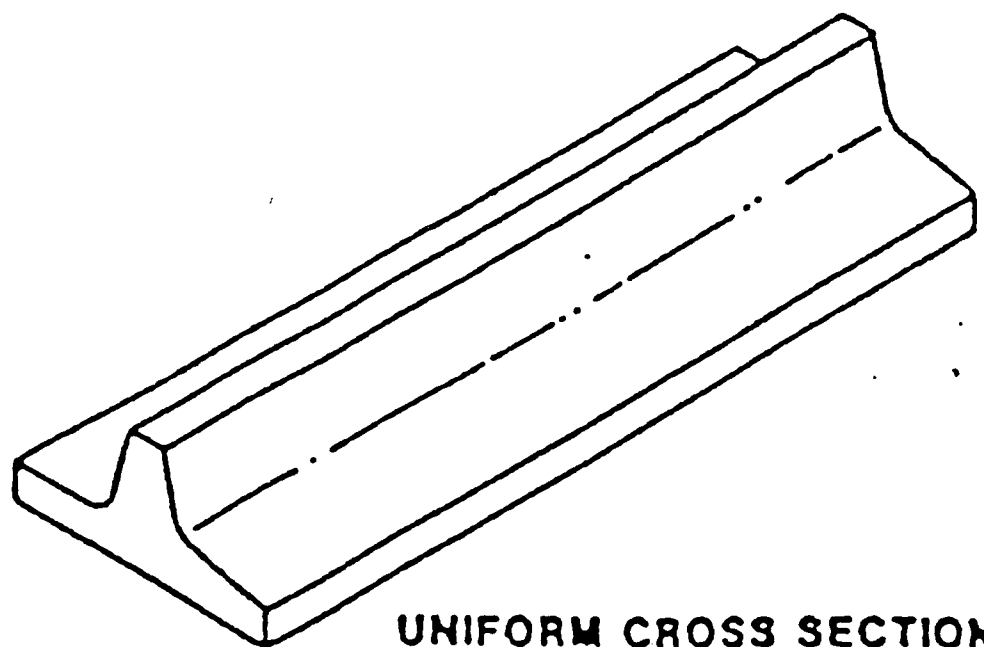
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CROSS SECTION THICKNESS

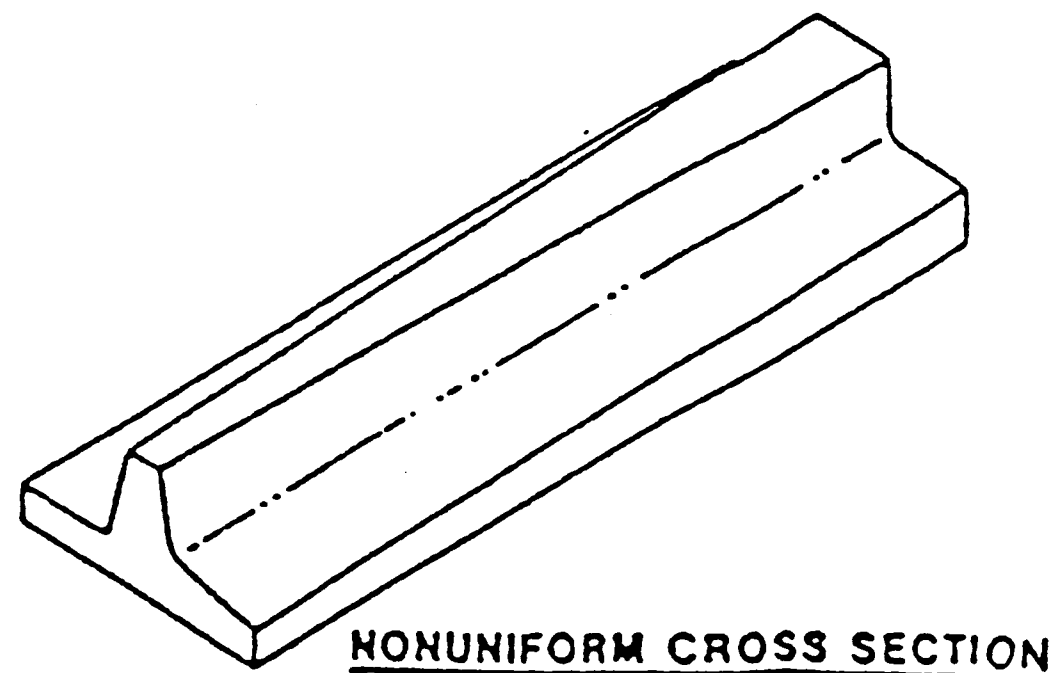


NONCONSTANT

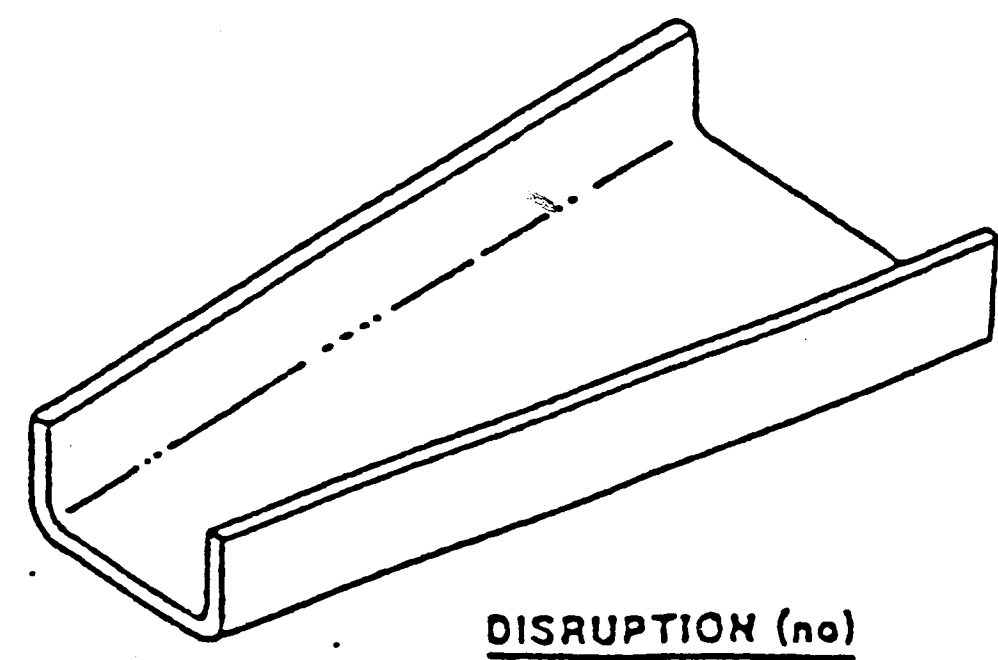
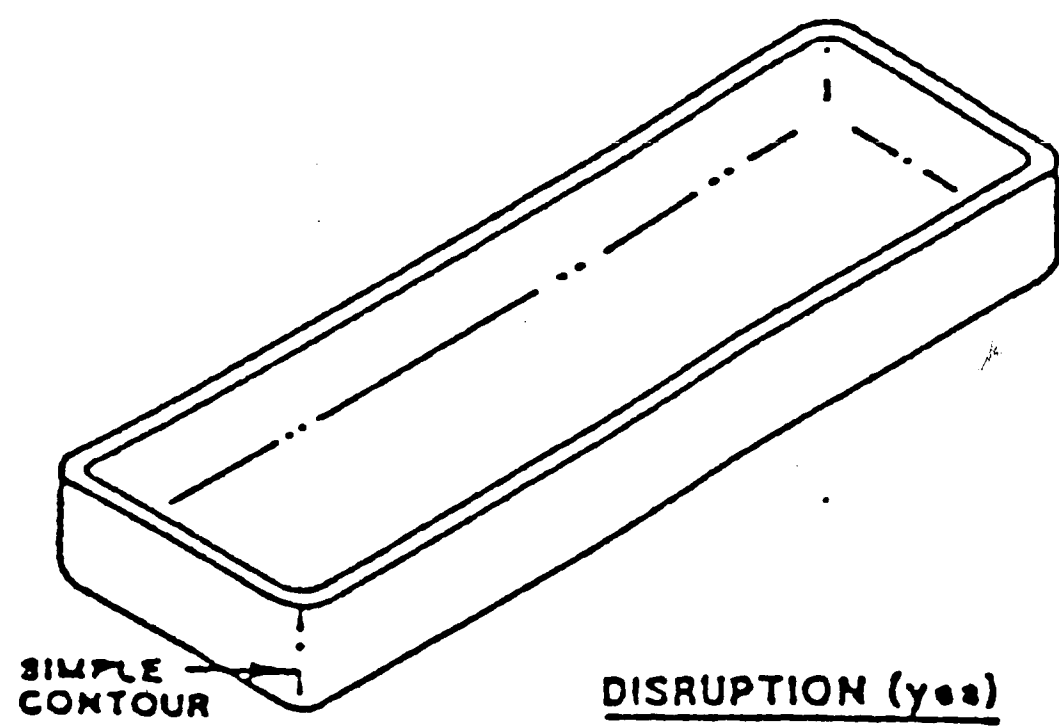
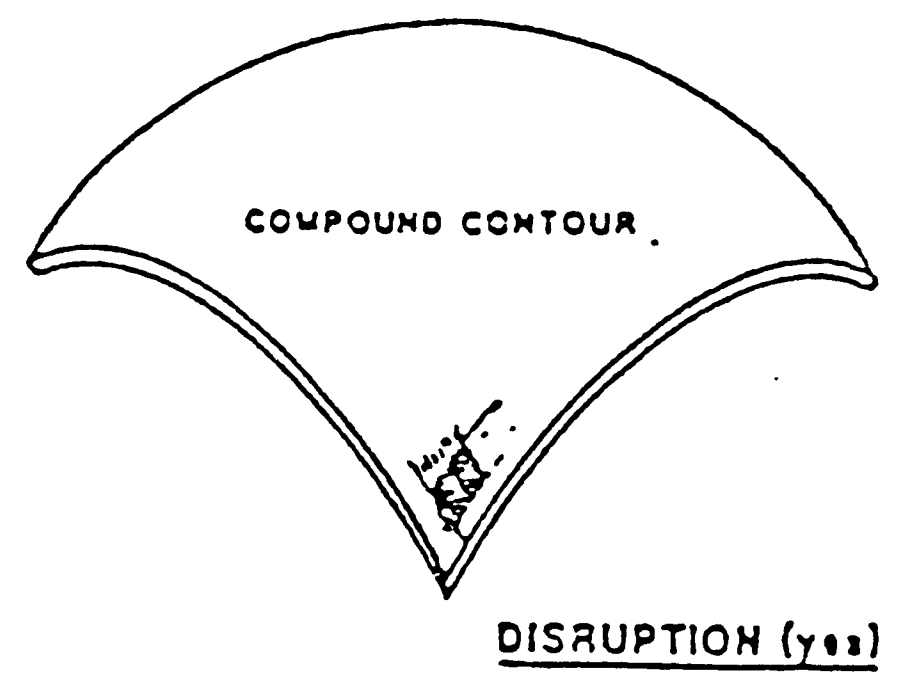
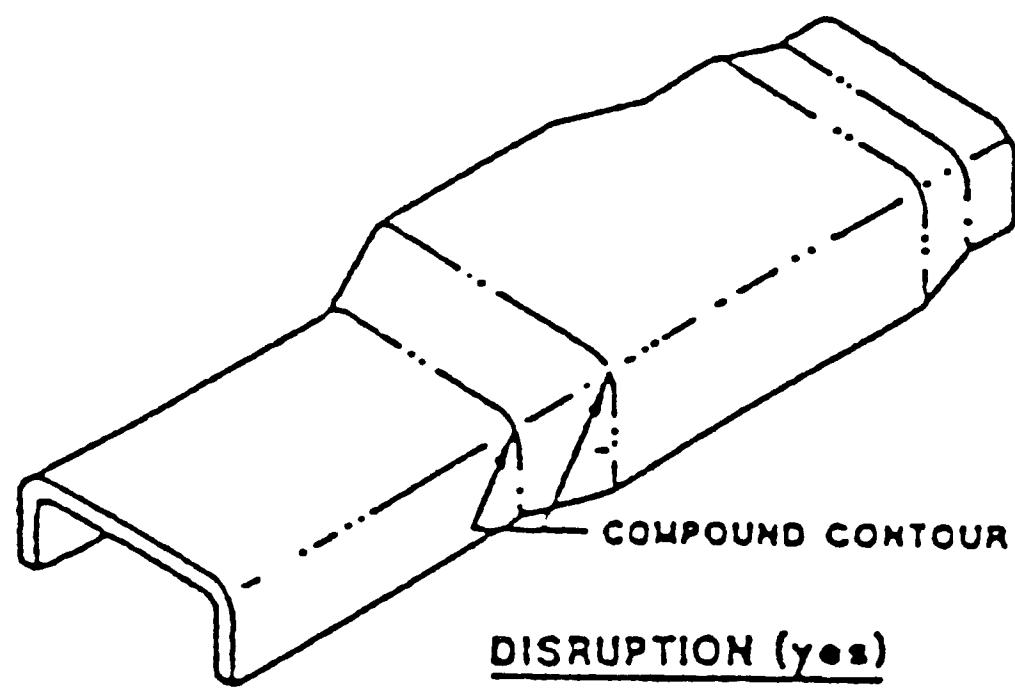
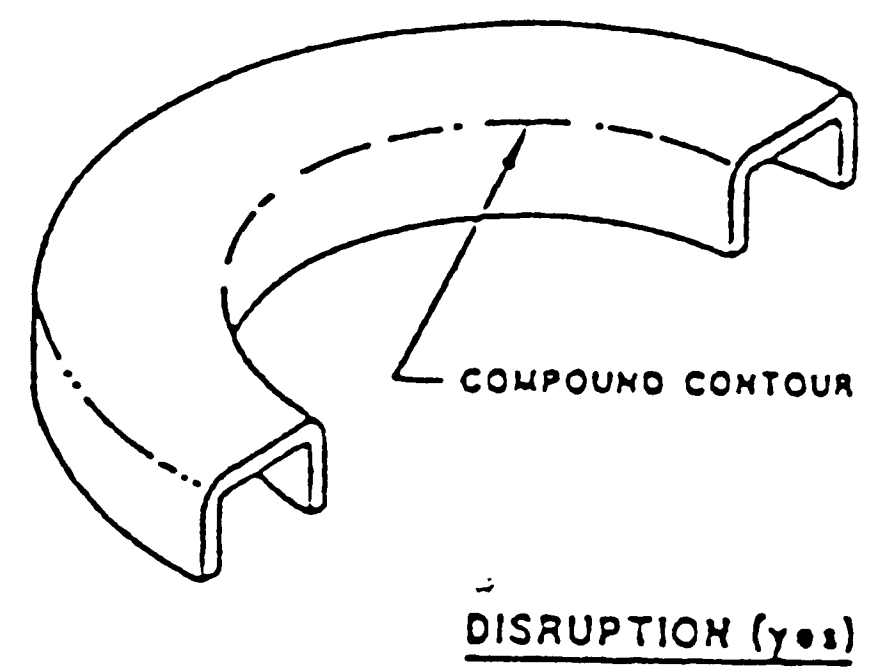
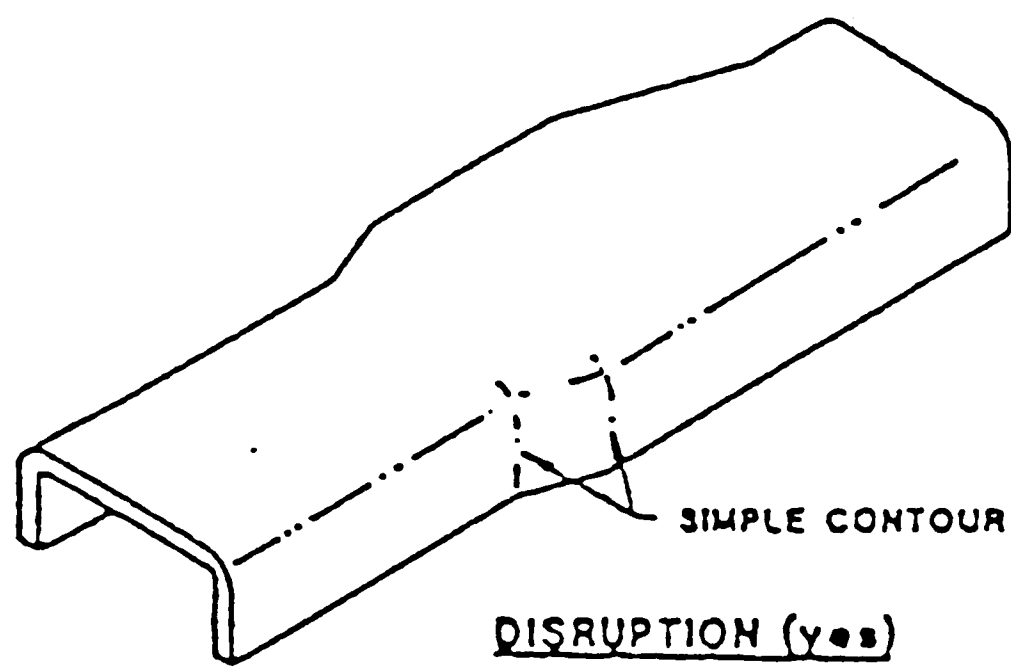
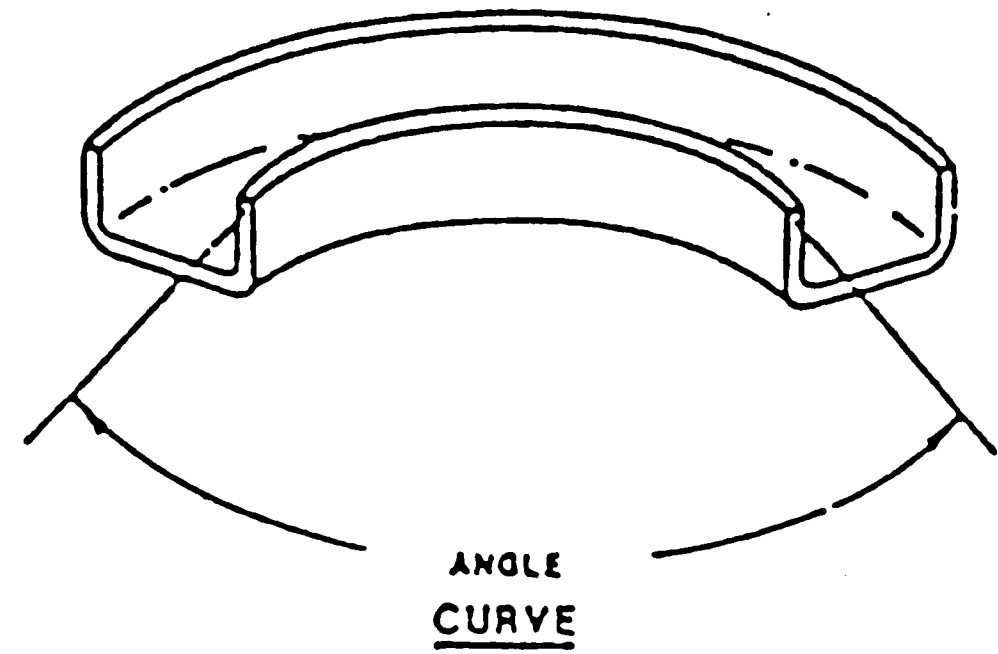
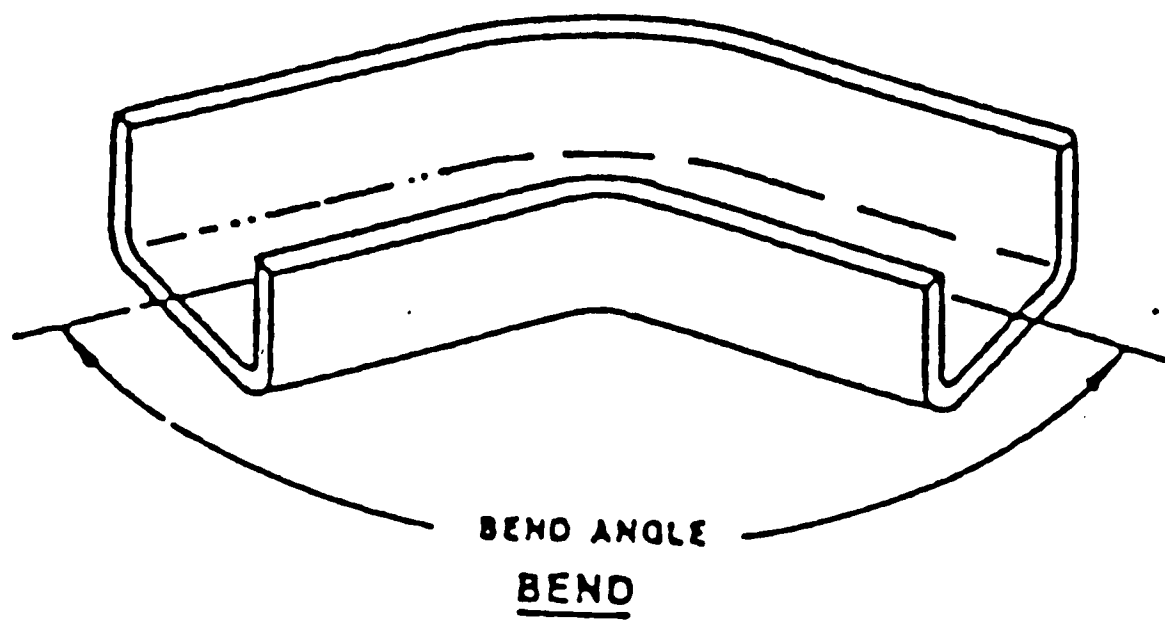
CROSS SECTION THICKNESS

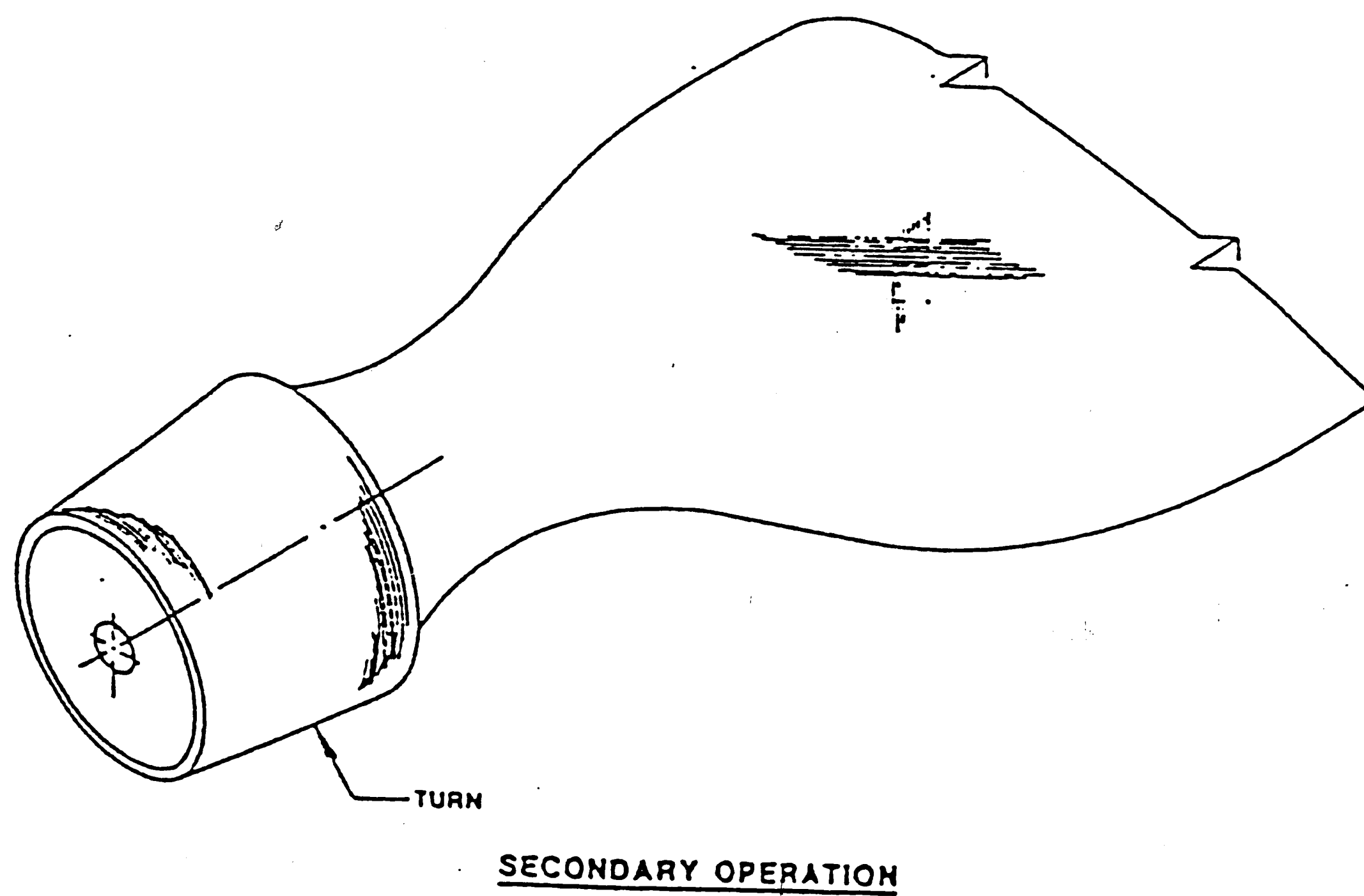
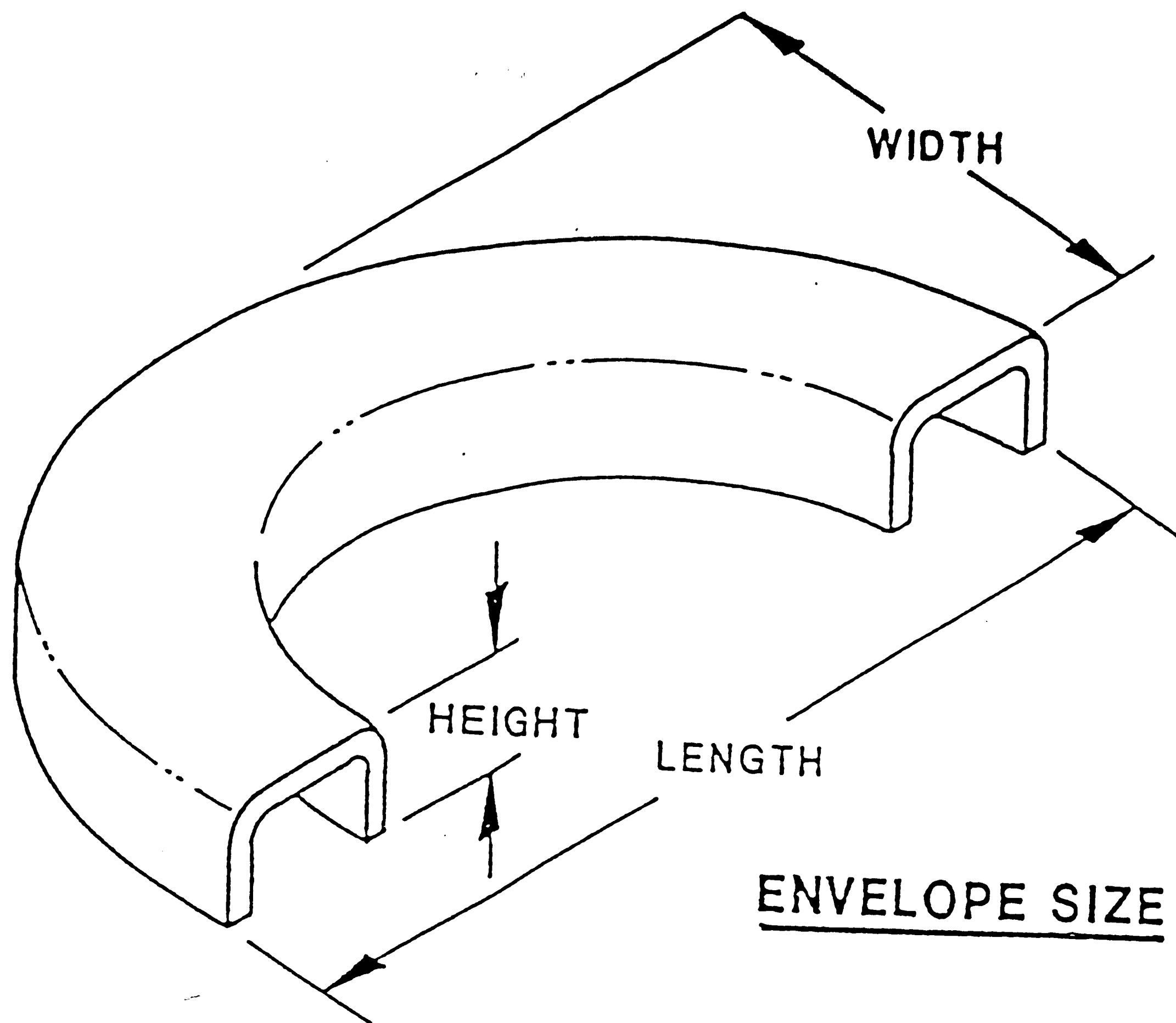


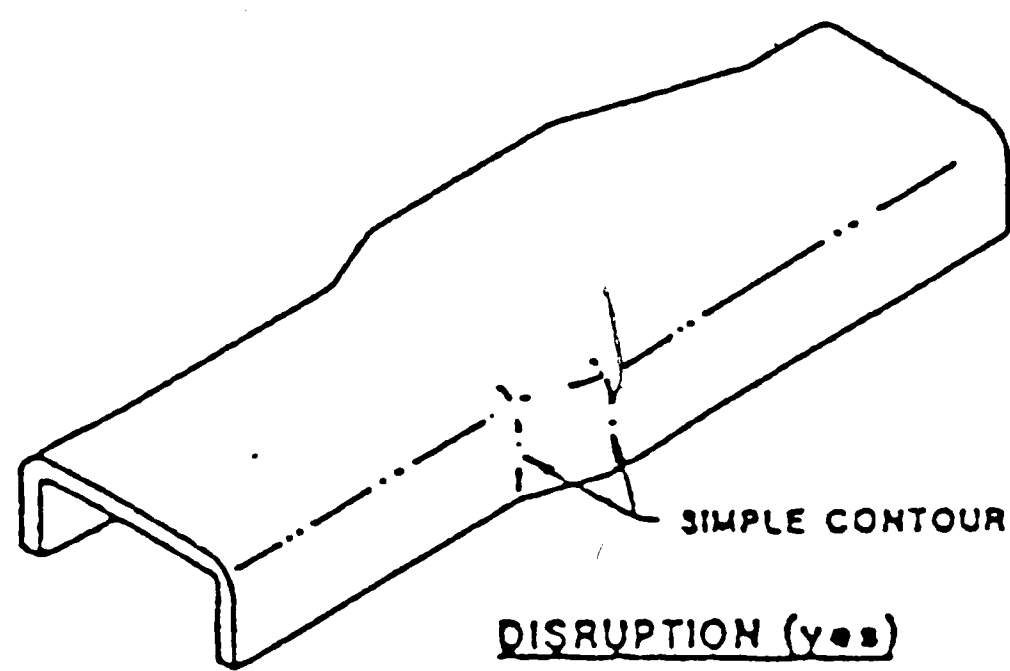
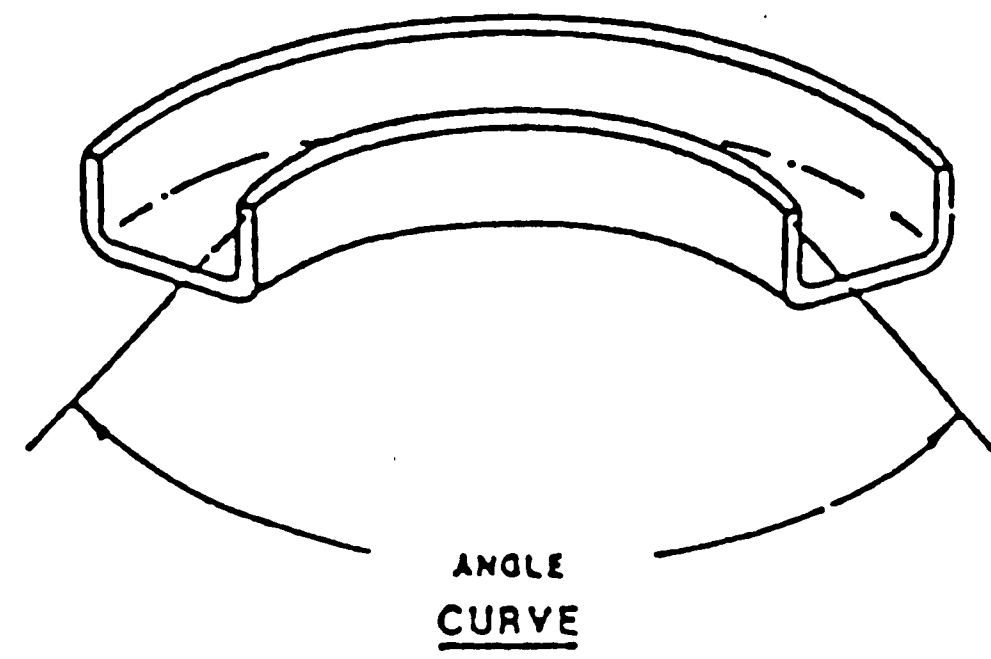
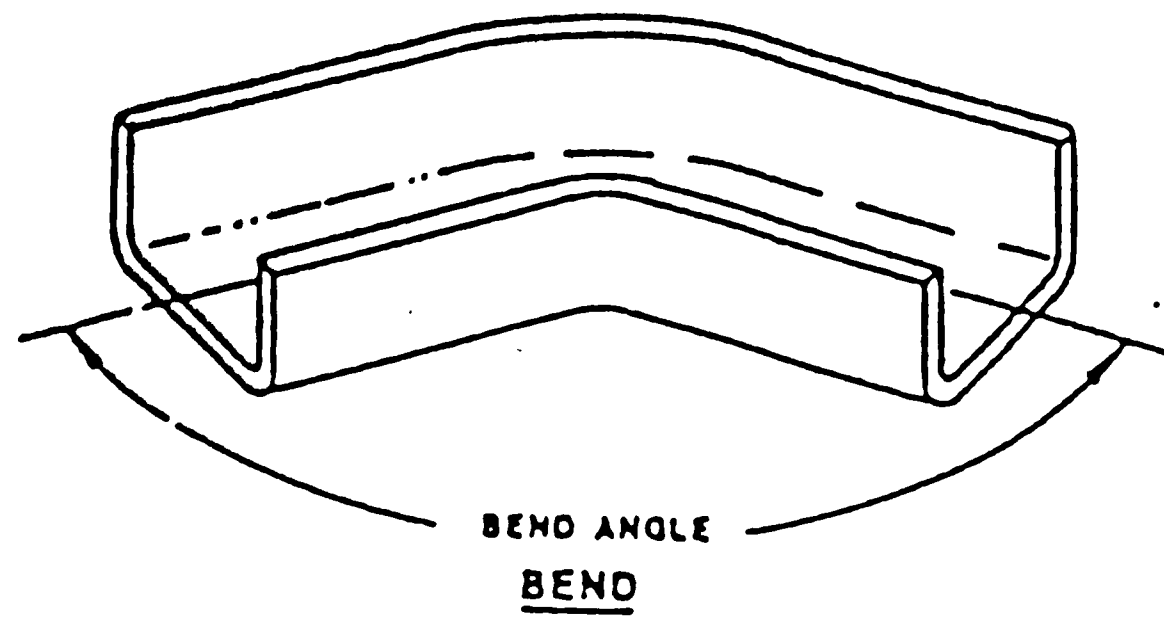
UNIFORM CROSS SECTION



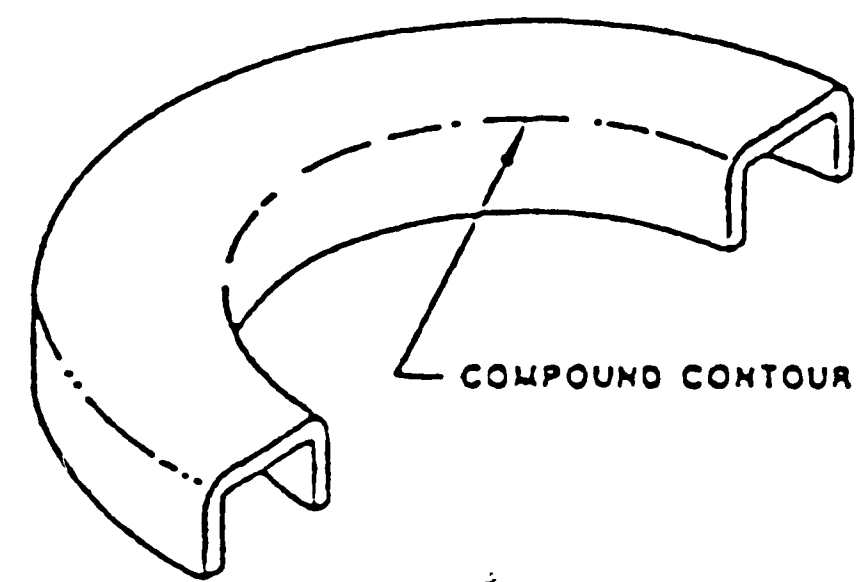
NONUNIFORM CROSS SECTION



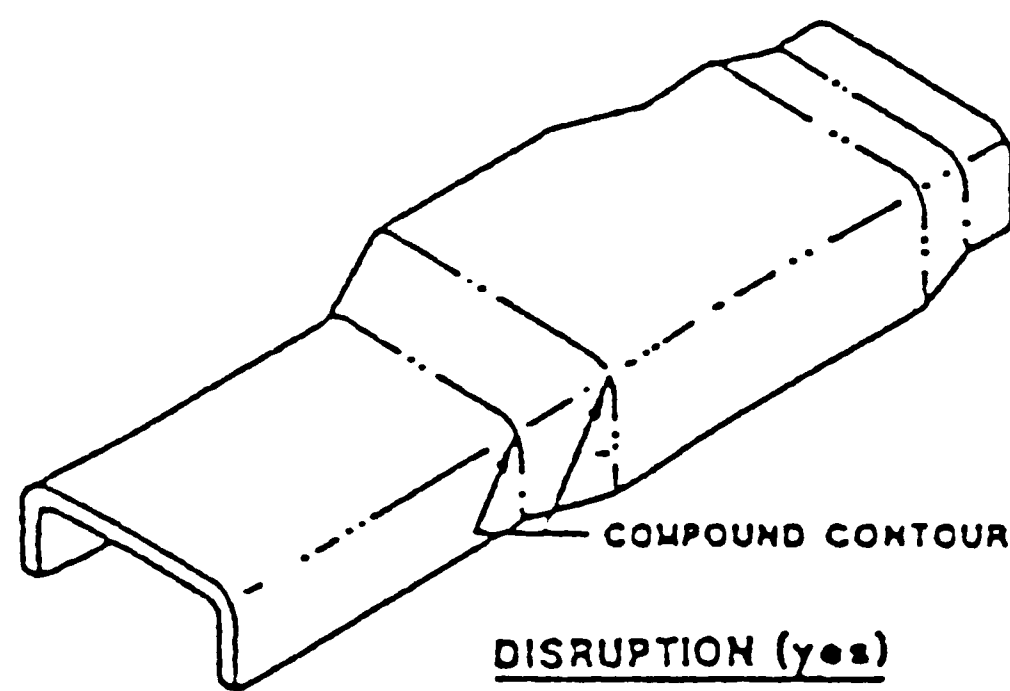




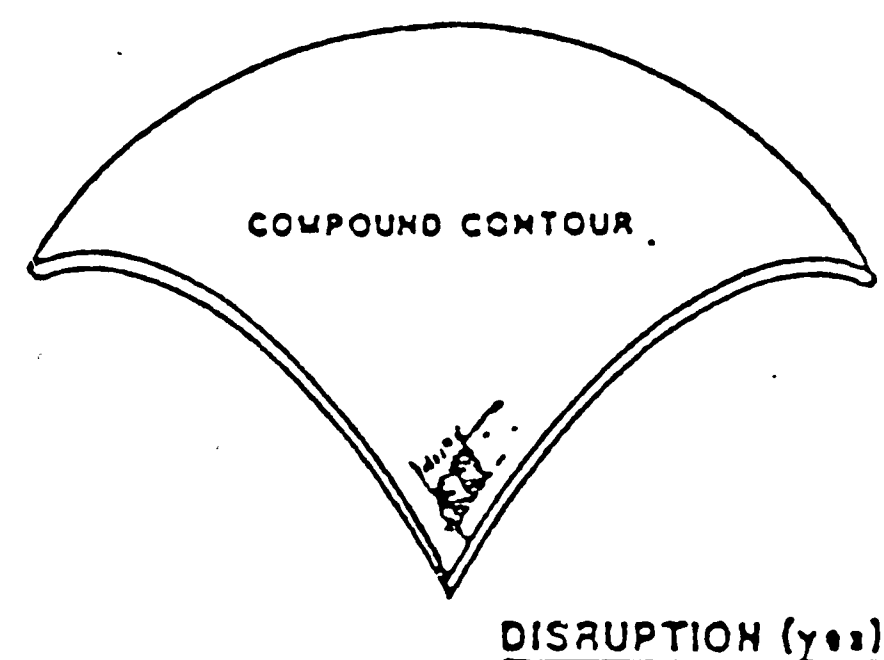
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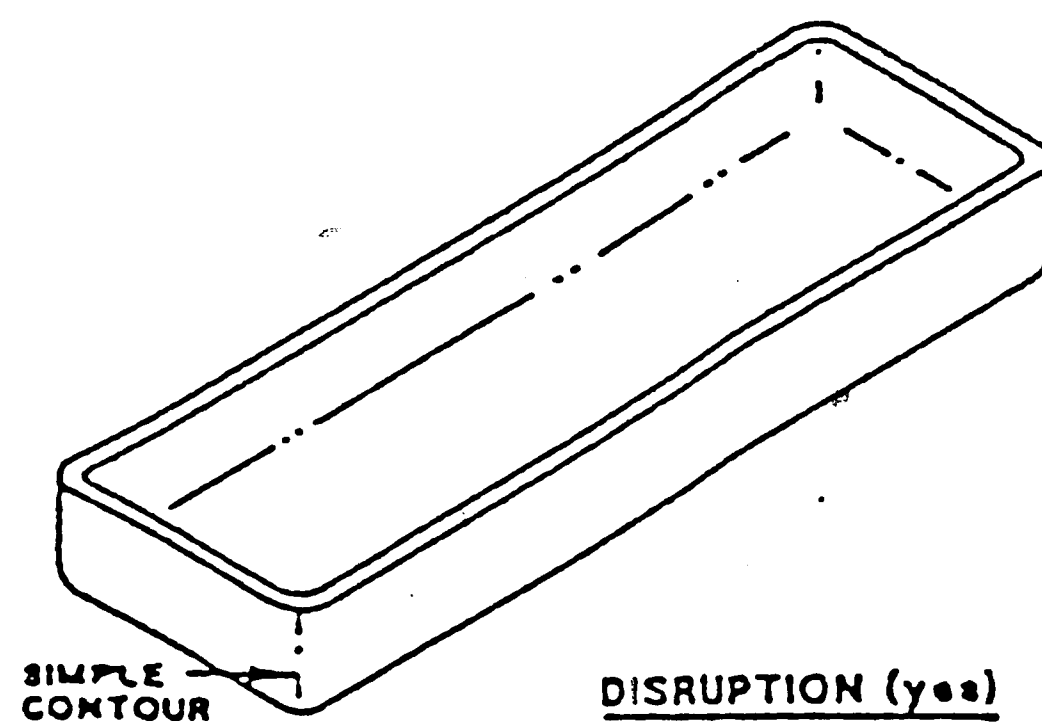
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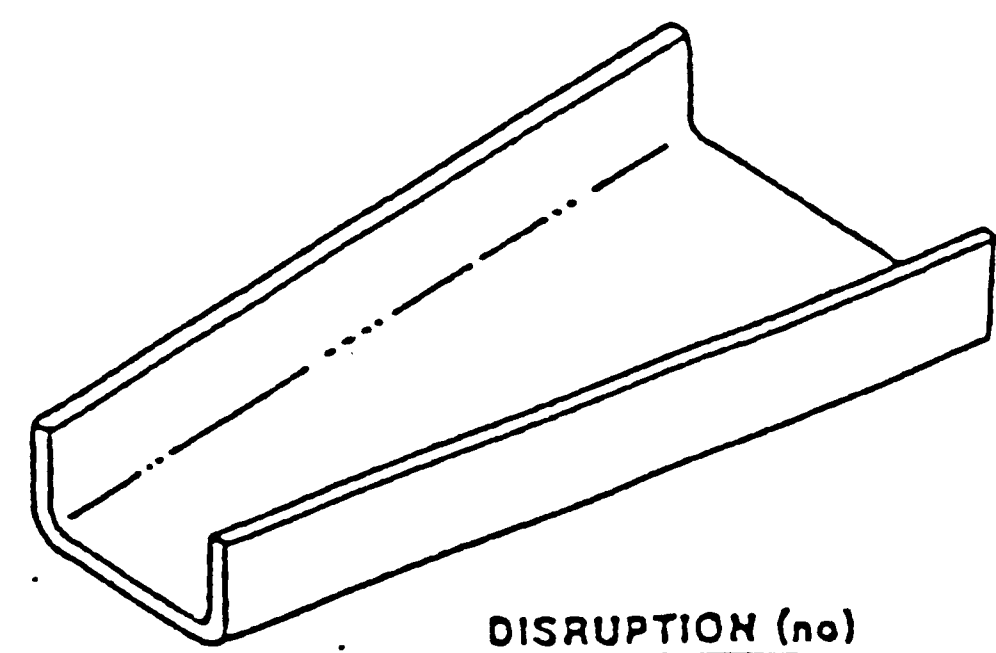
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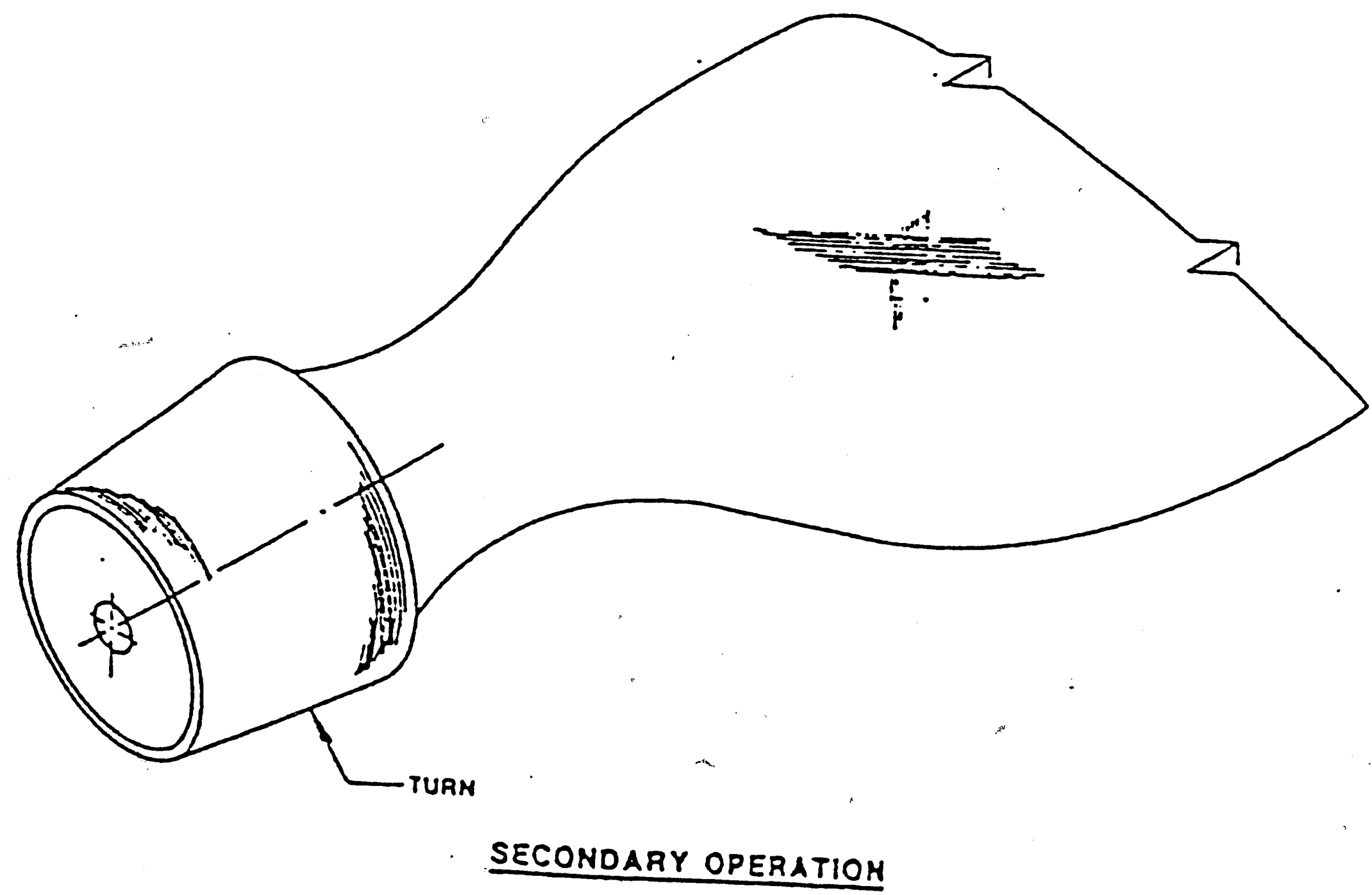
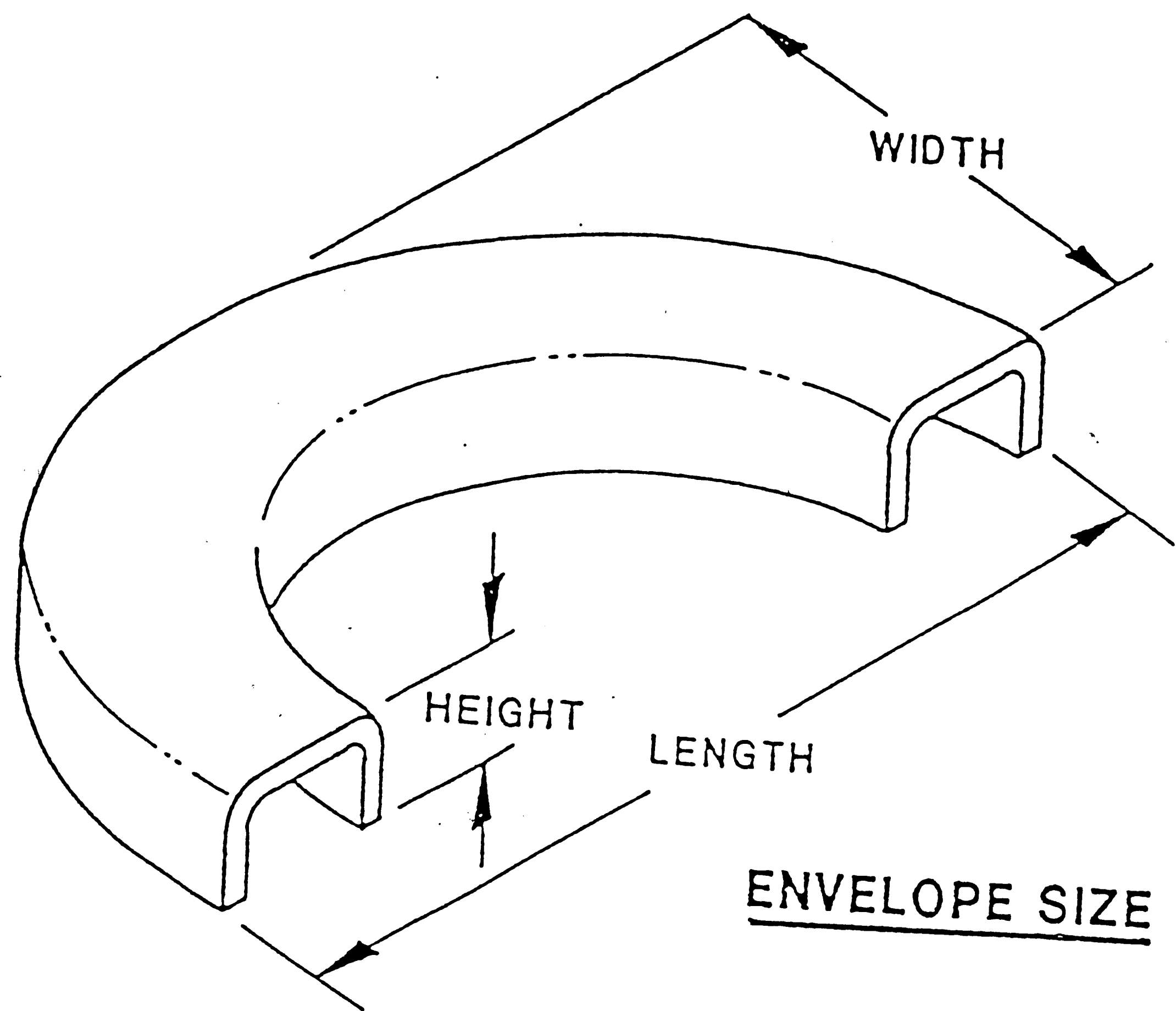


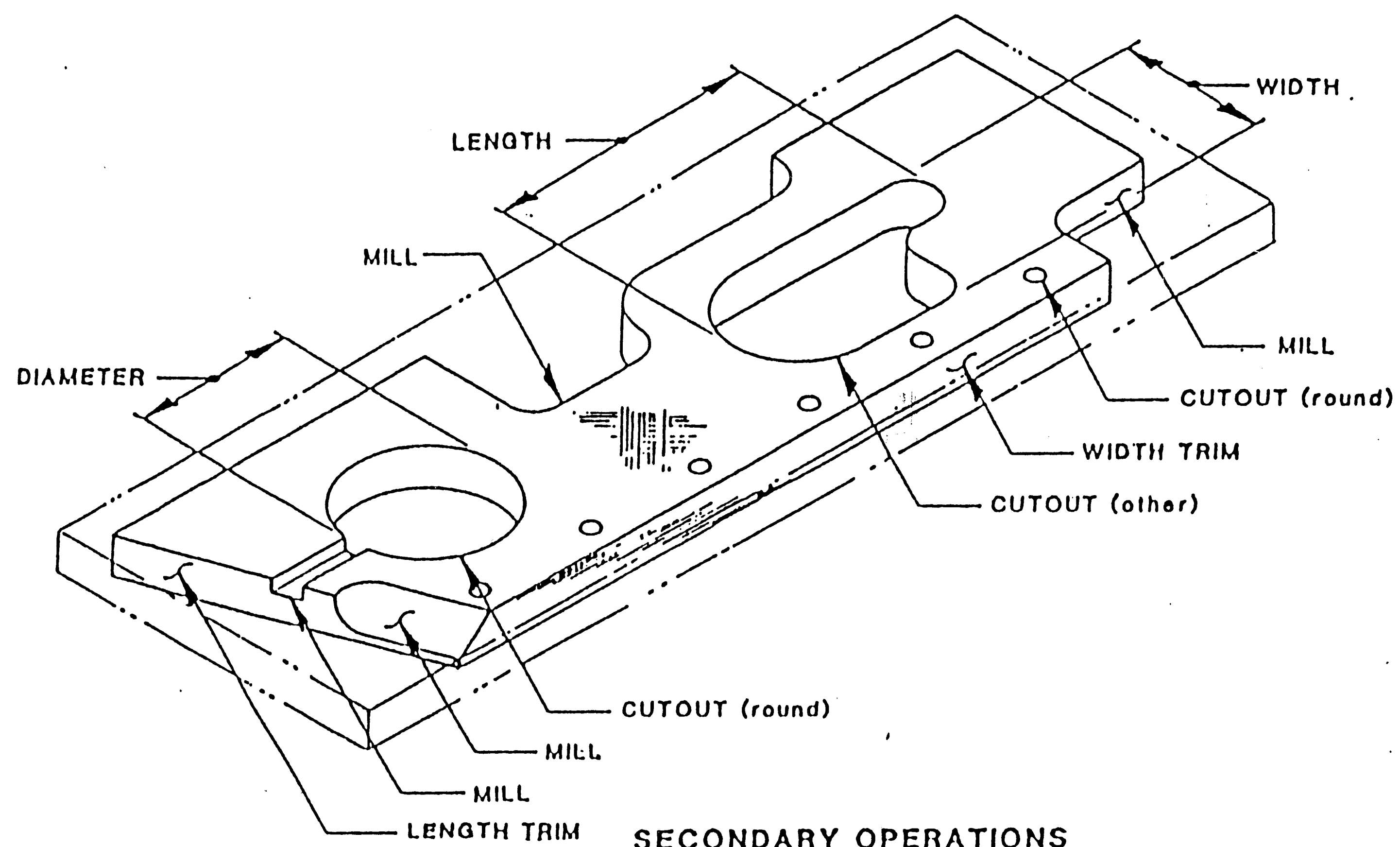
DISRUPTION (yes)



DISRUPTION (yes)







APPENDIX C

VITA

Glenn P. Livi was born in Hackensack, N.J. on July 18, 1962 to Mr. and Mrs. George I. Livi. Glenn attended Seton Hall University in South Orange, N.J. where he earned a Bachelor of Arts in Economics in 1985 and a Bachelor of Science in Physics in 1986. As a student at Seton Hall he was inducted into Omicron Delta Epsilon, The International Honor Society of Economics and Sigma Pi Sigma, The Honor Society of Physics. Glenn then entered the masters program at Lehigh University where he earned a Master of Science in Manufacturing Systems Engineering in the Spring of 1988.