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AFWAL-TR-88-4049
Supplement

MANUFACTURING COST/DESIGN GUIDE (MC/DG) FOR CONCEPTUAL DESIGN

AD-B143 015

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WRIGHT RESEARCH & DEVELOPMENT CENTER

August 1989

Final Report for Period July 1985—May 1989

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Air Force Systems Command
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This technical report has been reviewed and is approved for publication.

DAVID JUDSON
Project Manager

15 April 90
Date

FOR THE COMMANDER

BRUCE RASMUSSEN, Acting Chief
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Manufacturing Technology Directorate

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A

3. DISTRIBUTION/AVAILABILITY OF REPORT: Distribution authorized to US Gov't agencies only; critical technology; May 1989. Other requests for this document shall be(cont)

4. PERFORMING ORGANIZATION REPORT NUMBER(S):

5. MONITORING ORGANIZATION REPORT NUMBER(S): AFWAL-TR-88-4049, Supplement

6a. NAME OF PERFORMING ORGANIZATION: Battelle-Columbus Division

6b. OFFICE SYMBOL (If applicable):

7a. NAME OF MONITORING ORGANIZATION: Wright Research and Development Center Manufacturing Technology Directorate (WRDC/MTIB)

6c. ADDRESS (City, State and ZIP Code): 505 King Avenue, Columbus, OH 43201-2693

7b. ADDRESS (City, State and ZIP Code): Wright-Patterson AFB, OH 45433-6533

8a. NAME OF FUNDING/SPONSORING ORGANIZATION:

8b. OFFICE SYMBOL (If applicable):

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F33615-85-C-5016

8c. ADDRESS (City, State and ZIP Code):

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
78011F	4504	10	68

11. TITLE (Include Security Classification): Manufacturing Cost/Design Guide (MC/DG) for Conceptual Design

12. PERSONAL AUTHOR(S): Bryan R. Noton

13a. TYPE OF REPORT: Final

13b. TIME COVERED: FROM July 85 TO May 89

14. DATE OF REPORT (Yr., Mo., Day): August 1989

15. PAGE COUNT: 231

16. SUPPLEMENTARY NOTATION: Export Control Restrictions & FEDD

17. COSATI CODES

FIELD	GROUP	SUB. GR.
01	03	
11	04 & 06	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Conceptual Design, Airframes, Sheet Metal Structures, Polymer Composite Structures, Computerization

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The "Manufacturing Cost/Design Guide" (MC/DG) volumes developed earlier are primarily intended for the detail design phase where the dimensions of the structural alternatives have been defined in some detail. However, manufacturing and inspection costs must be addressed by designers from the outset of the development of any aerospace component or system. This supplementary report to Technical Report AFWAL-TR-88-4049, therefore presents a comprehensive series of qualitative formats to guide designers in their decisions to reduce costs from the initial stages of development. The formats are in two categories; the first indicates the cost-drivers or hazards, and the second provides comparative information on the impact of various design decisions that influence manufacturing cost. The two sets of formats are intended to stimulate the development of innovative design configurations which use conventional, frequently lower cost, materials more effectively and advanced materials selectively to minimize cost.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS ☒

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL: Lt. Dean B. Griffin

22b. TELEPHONE NUMBER (Include Area Code): (513) 255-6976

22c. OFFICE SYMBOL: WRDC/MTIB

DD FORM 1473, 83 APR   EDITION OF 1 JAN 73 IS OBSOLETE.

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SECURITY CLASSIFICATION OF THIS PAGE

3. Continued

referred to WRDC/MTIB, W-PAFB, OH 45433-6533.

19. Abstract (Continued)

When conducting trade-off analyses, learning curves are necessary to determine total program cost. The problem areas hindering the achievement of the theoretical or ideal learning curve are indicated.

The data developed on manufacturing cost is adaptable to PC software. While very limited resources existed to explore software implementation, an initial step was made to enable cost-drivers and design/cost trade-off studies to be conducted on mechanically fastened assemblies. To support this report section, the results of a survey of designer needs, conducted at the outset of the design guide development, is included as an appendix.

A series of MC/DG volumes has been prepared under four Air Force contracts. Each of these volumes contains designer oriented formats or charts. To simplify retrieval of this data, format and ground-rule locators have been prepared and are included as an appendix.

FOREWORD

This supplementary report to the Air Force Final Technical Report AFWAL-TR-88-4049, covers work performed on conceptual design of airframes and an initial effort on computerization of mechanically fastened assemblies, conducted under Air Force Contract No. F33615-85-C-5016 from February 1, 1989 through May 31, 1989. The Air Force Technical Report AFWAL-TR-88-4049, dated May 2, 1988, was for the contractual period July 26, 1985 through September 30, 1987, and included the following subjects: airframe design, cost drivers, manufacturing cost, composite structures, mechanically fastened assemblies and superplastic forming of titanium alloys.

The contract was sponsored by the Computer Integrated Manufacturing Branch, Wright Research and Development Center. During the period of technical performance, initially the Air Force Project Manager was Lt. Eric J. Gunther and, later, Lt. Dean B. Griffin.

Battelle's Columbus Laboratories was the prime contractor. Mr. Bryan R. Noton was the Program Manager and Principal Investigator. Dr. David Pherson of Battelle conducted the work on computerization. The development of the data on which the "Manufacturing Cost/Design Guide for Conceptual Design" is based, was accomplished under a series of contracts. These contracts, design curves, etc., are listed in Appendix C. Performance of this work required organizing a number of teams. The participating aerospace companies and the project managers for various periods, were:

Industrial Subcontractors	Project Managers
General Dynamics Corporation, Fort Worth Division	Ben E. Kaminski Phillip M. Bunting James E. Schidler W. T. Trice
Grumman Aerospace Corporation	Vincent T. Padden Anthony J. Tornabe
Lockheed Aircraft Systems Company, California Division	Anthony J. Pillera John F. Workman
Metcut Research Associates, Inc.	Robert L. Carlton
Northrop Corporation, Aircraft Group	John R. Hendel Al P. Langlois
Rockwell International Corporation, North American Aircraft Operations	Ralph A. Anderson Kenneth A. Henn Leonardo Israeli
Rohr Industries, Inc.	James R. Woodward

TABLE OF CONTENTS

TABLE OF CONTENTS (Concluded)

Page

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION 1.0
INTRODUCTION

The performance and quality achieved by designers and manufacturers of defense and commercial aircraft and space systems, where the broad structural design objectives include strength, stiffness, fatigue, damage tolerance, reliability and maintainability, are impressive. The challenge today is to improve performance and quality, but with increased emphasis on cost. A number of aerospace systems with quite diversified missions are currently at the brief conceptual design phase. With these new systems, acquisition, operations and maintenance costs are emphasized as being equal in importance to performance and schedule. Meeting these requirements within the complex aerospace manufacturing environment presents a very difficult task for all disciplines in the systems development process. Characteristics of this environment include a cyclic industry, a substantial number of companies responding to the needs of a small number of customers, minimal automation and high technology orientation driven by the quest for product excellence. The difficulty in designing complex systems at low cost is evident. Certainly, additional innovations in design configurations, utilization of composite materials and superplastic formed titanium and manufacturing technology developments, including test, inspection and evaluation techniques, are required. Such innovations are most effectively accomplished during conceptual design.

Unfortunately, it is not unusual in aerospace programs that only a small percentage of the total development and production cost is allocated to this vital conceptual design phase. After all, the decisions that are "molded-in-place" during that phase impact the total, frequently multibillion dollar, operations and maintenance costs. We must also realize that the conceptual design phase or "window of opportunity" is where the leverage exists to not only respond innovatively to design objectives such as damage tolerance, but also, of equal importance, to minimize cost. As time and the design process progresses, the number of engineering decisions increases, but their impact decreases to an almost insignificant level. Thus, it is at the developmental phase that designers need to address the specific cost drivers related to performance, design, materials and manufacturing, including inspection, usually becoming evident when analyzing the aerospace system mission requirements. As with other design considerations, the structural configuration or concept can have the most significant impact on minimizing manufacturing, inspection and repair costs.

It is at this early phase that cost reducing features such as part consolidation, minimized fastener count, accessibility, interchangeability and repairability can be more easily introduced and, particularly important, subsequent costly engineering change traffic can be reduced. While manufacturing engineers experienced in composites are frequently involved at the conceptual design phase, thereby minimizing the number of these engineering changes, it is equally important that manufacturing technology engineers, experienced with other materials and processes, participate in all up-front decisions that impact their discipline. Conventional and advanced metals also contribute to meeting the system design requirements; for example, composite panels may be supported by low-cost metallic substructures. The economic benefits of improving design/manufacturing interaction cannot be overstressed; it is the key to affordable performance.

In the case of a proposed aerospace system, or in fact any other product, potential cost drivers in specific categories, such as performance, design, materials, manufacturing and inspection are likely to be apparent from the outset; i.e., when the first lines are drawn or are displayed on the computer graphics screen. Similarly, it is possible to identify potential cost drivers during the initial evaluation of a new composite material under development to improve, for example, producibility or elevated temperature performance. The curing, tooling, inspection and facility requirements soon become apparent and, when their cost implications are considered early on, they do not later appear as barriers hindering technology transfer to cost-competitive products. Cost is seldom, if ever, considered at the outset of material development.

The trade-offs between manufacturing cost and mission performance are extremely complex with supersonic and hypersonic vehicles. Again, it is vitally important to seek out potential cost drivers and to address these as soon as possible. Certain cost-driving features may be identified, such as the power plant being developed parallel with the airframe, avionics escalating in cost, high-performance accessories (also providing opportunities for advanced materials), double curvature and tapered structural elements and assemblies, special purpose fasteners, butt joints and limited use of automated assembly. However, with these high performance systems, it is unlikely that performance will be significantly downgraded to minimize acquisition cost.

On the other hand, the performance of a higher volume production, low-speed aircraft is more likely to be compromised in design to reduce cost. The features of such an aircraft are that an existing engine, avionics and accessories are expected to be specified. The airframe may be characterized by a constant section fuselage, constant section control surfaces, interchangeable components, lap joints, common use tooling, and maximum use of automatic riveting.

Because of the impressive progress, service experience and subsequent designer and management confidence in several families of polymer-matrix composites, these engineering materials have for some time been considered by designers as cost-competitive candidates with aluminum and titanium. Therefore, it is important to stress the significance of the conceptual design phase leverage for maximizing the impact of decisions; for identifying, analyzing and addressing cost drivers with materials, manufacturing technology and systems; and for ensuring that interaction is achieved not only between design and manufacturing for composites, but also for all other candidate materials and manufacturing technologies. When this is accomplished, the cost of engineering change traffic, that can be responsible for 20 to 30 percent of the cost of the first production system, and expensive redesign and rework of tooling, will be substantially reduced. Cost must be reduced by identifying cost drivers and promoting interdisciplinary interaction from day one!

To accomplish cost driver avoidance from day one, a "Manufacturing Cost/Design Guide" (MC/DG) has been assembled for use in the conceptual design phase. This MC/DG for conceptual design is presented with two categories of charts of formats. These are firstly, those that show the cost trends or hazards and are presented in a manner which enables the designer to rapidly achieve an overview for both materials and manufacturing methods, and the second category of formats provide relative or qualitative cost comparisons between materials, manufacturing, inspection and dimensional alternatives. To conduct trade-off studies providing the total manufacturing and inspection cost for each design solution to the system performance and other objectives or, to determine the total system and program cost, designers must consult References 5, 7 and 8 describing earlier phases of these Air Force contracts.

A computerized MC/DG can be utilized by designers to perform many tasks determining the impact of often critical information that would otherwise be time consuming, intricate and bothersome, if these effects have to be determined through design charts. Potential applications of a computerized MC/DG in design is to determine the impact of price fluctuations typical with material shortages, energy problems, inflation and the introduction of production methods which result in changes in the utilization rate of materials and, therefore, the capability to utilize accurate current and/or projected material costs. This is particularly true at the conceptual and preliminary design phases where attempts to meet the performance objectives are made by utilizing significant quantities of advanced materials, which are initially expensive.

The determination of the impact of the location on the learning curve of the production quantity under consideration for trade-off studies is important. The current MC/DG data are based on unit 200, but the prototype development of aircraft requiring, for example, trade-off studies for five aircraft only, would have a much higher manufacturing cost based on the learning curve. At the other end of the scale, is a large production contract with obvious implications.

A computerized MC/DG would also be of use in determining the impact of lot release size, especially for those of less than 25 units. For most manufacturing technologies, beyond 25 units, the impact of lot size is negligible for the purpose of typical trade-off studies; but lot sizes below 15 units have, in most cases, a dramatic impact on cost.

The computerized design guide would be an invaluable aid in extrapolating and interpolating dimensional data of airframe parts and assemblies. The function of the computerized MC/DG is, in reality, more of a necessity than of a convenience, because it is not possible for the hard copy to contain all possible dimensions of aerospace parts. In order to conduct a trade-off study, the designer must be able to input the part dimensions.

Another useful feature of a computerized MC/DG would be the ability to retrieve earlier design trade-off details in a readily usable and recognizable form. This would allow the designer to quickly evaluate past designs and determine what features would be applicable to the present problem and what cost drivers to avoid. This feature would be helpful to designers in preparing presentations to management detailing how the chosen configuration for the part under study was developed based on past experience, forecasts and, thus, imparting confidence to the trade-off study conducted.

In summary, a computerized MC/DG can also be utilized by designers to:

- Determine the impact of material price fluctuations
- Determine the impact of learning curve base, i.e., aircraft quantity ordered
- Determine the impact of lot size other than current data for the detail ground rule of 25
- Determine the impact of labor-rate increases
- Retrieve earlier design trade-off data in a readily usable and recognizable form
- Extrapolate and interpolate dimensional data of part and assembly manufacture.

The following are the principal features of the Air Force "Manufacturing Cost/Design Guide":

- Provides the design engineer with the capability to rapidly conduct, with high confidence levels, trade-off studies on cost vs. performance of conventional and emerging manufacturing technologies and materials vs. state-of-the-art technologies

- Enables design engineers to identify and avoid cost drivers when utilizing conventional and emerging materials and manufacturing technologies

- Provides the design engineer with a single comprehensive source of qualitative and quantitative (man-hour and cost) data related to several conventional and emerging materials and manufacturing technologies, instead of a large number of technical reports, each related to one specific technology or material and each based on markedly different ground rules

- The cost data provided in the guide are based on industry averages and not from a single company. The guide has been developed by a team and is, therefore, unbiased information conforming to accepted ground rules

- The guide is prepared in design engineer's language. The designer can, therefore, readily analyze and utilize the data required.

- Enables the manufacturer to validate, for the customer, cost proposals utilizing various materials and manufacturing technologies

- Provides actual cost data and cost avoidance information (qualitative) applicable at all design phases including for determining the cost impact of engineering changes

- One of the major deterrents to the introduction of emerging materials and technologies is a lack of comparative cost data. The MC/DG, by providing such manufacturing man-hour data, enables trade-off studies to be conducted and thus removes this deterrent

- Alerts design engineer to the fact that he or she may achieve increased performance using advanced materials and new manufacturing technologies at costs competitive with conventional materials and processes

- Promotes interaction between design and manufacturing engineering and the teamwork necessary to successfully ntroduce innovative structural configurations, new materials and manufacturing technologies

- Reduces necessity of down-stream changes by bringing to the attention of the design engineer the impact of decisions on designer-influenced cost elements (DICE) and other cost drivers, early in the design phase

- Provides cost drivers related to test, inspection and evaluation (TI&E) and tooling cost, as well as manufacturing cost, and therefore guides the designer in developing components and structures that are easier to inspect

- Provides manufacturing cost data in basic formats: cost driver effects, cost-estimating data and DICE, for discrete parts through subassemblies

- Companies wishing to apply new materials and manufacturing technologies have a source of industry developed cost data on which to base decisions.

SECTION 2.0
SPECIAL ASSIGNMENTS

2.1 CONCEPTUAL DESIGN PROCESS

This volume of the design guide enables designers to address acquisition costs. Designers are rated on their performance with respect to cost, weight and schedule in aerospace systems design, Figure 2.1-1. The design guide addresses, at this time, only acquisition costs. However, the designer must also be innovative with respect to design for reliability and maintainability (R&M), now considered as co-equals of acquisition cost, performance and schedule. Each of these cost factors must be considered from day one.

The decreasing leverage for cost savings is shown in Figure 2.1-2. A brief window of opportunity exists, during which only a small percentage of the total systems development and production cost is expended. However, the decisions then made will influence the cumulative program cost, which for many systems will be billions of dollars. Commitment decisions are made at the conceptual design phase influencing all investments. The exploratory phase may range from three to five years, and for the advanced development phase, an additional three to five years may be necessary. It is during this period that advanced technologies need to be applied to fully exploit the unique advantages of these materials or processes. Later in the development process, form, fit and function requirements will preclude utilizing all advantageous properties of emerging materials. At the beginning of the prototype phase, 90-95% of the total program cost may have been committed. In Reference 9, Mr. J. Gallagher, Chairman, Design Integration Subcommittee, Design Engineering Committee, American Institute of Aeronautics and Astronautics (AIAA), provided the following information illustrating the distribution and number of designers involved in the conceptual through support stages of a fighter aircraft:

	Conceptual Design	Preliminary Design	Development	Production	Support
Designers	10	50	250	100	100
Analysts	50	150	550	50	25

However, such comparisons may be complicated by some designers being analysts and drafters and vice versa. In the exploratory development

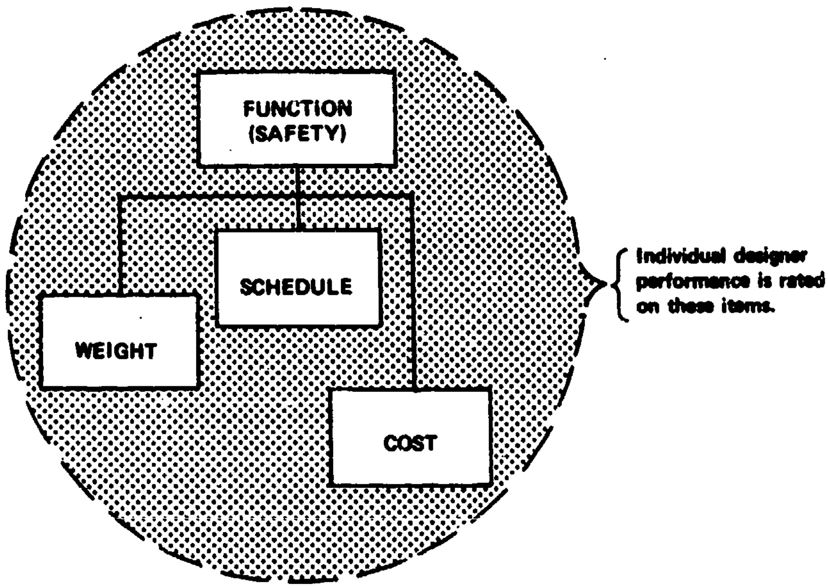

FIGURE 2.1-1 PRESENT AIRCRAFT DESIGN TEAM PRIORITIES

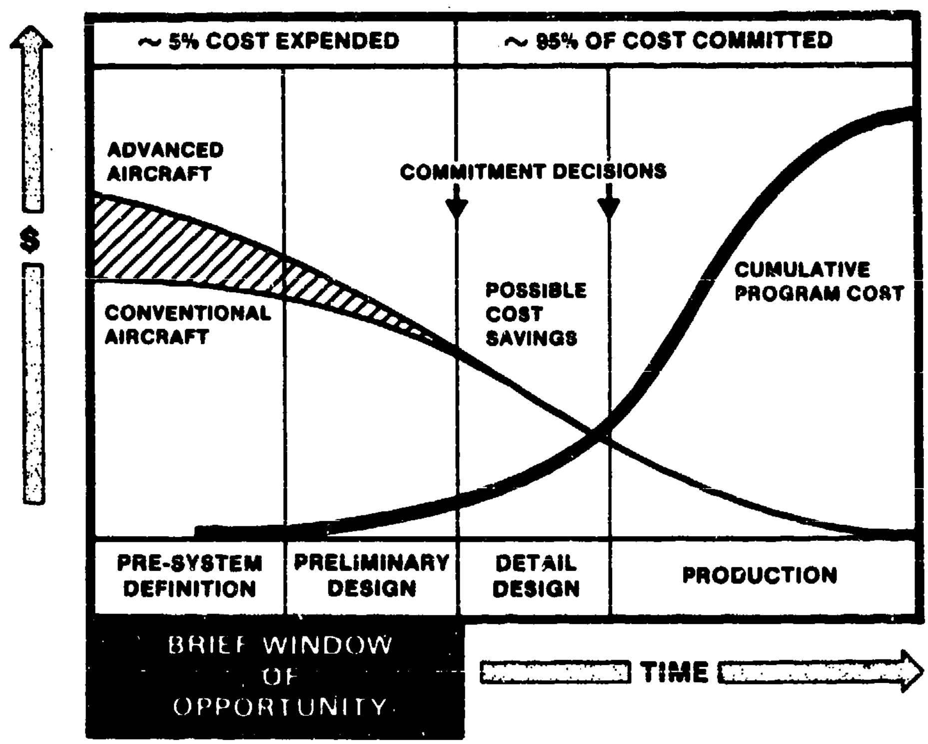

FIGURE 2.1-2 DECREASING LEVERAGE FOR COST SAVINGS

stages, even for extremely complex systems, such as intercontinental ballistic missiles, the number of conceptual designers may be only two or three and the length of the total program, which includes production, may run from two to three decades.

Typical decisions made from the preproposal through manufacturing phases are shown in Figure 2.1-3. This, of course, is a generic diagram and will not be applicable in all aerospace organizations. The abbreviations DTC and MTC refer to design-to-cost and manufacturing-to-cost, respectively.

During each design phase shown in Figure 2.1-3, tooling decisions are made. Tooling costs are normally cost-drivers. The life of the tools must be amortized throughout the duration of the program. Typical tooling decisions are shown in Figure 2.1-4. Again, this is a generic diagram and is not expected to apply to all aerospace companies. However, Figures 2.1-3 and 2.1-4 are useful in indicating to unseasoned designers the impact of other disciplines on their decisions and system objectives.

2.2 CONCEPTUAL DESIGN APPLICATIONS OF COST/DESIGN GUIDE

Seven volumes of the "Manufacturing Cost/Design Guide" (MC/DG) have been prepared to enable trade-off studies to be conducted at all phases of the design process. The conceptual designer must be aware of cost-driver hazards and the decisions that can alleviate or avoid them. Toward this end, the "MC/DG for Conceptual Design" provides timely analysis of the materials and manufacturing technologies currently in use in the aerospace industry.

As pointed out earlier in this report, designers must consider cost with weight and other performance critical factors from day one. However, trade-off studies of the types which precede each manufacturing technology section of the MC/DG volumes prepared, are not necessarily applicable at day one. For example, the MC/DG volumes in References 5, 7 and 8 are used when the number of frames, longerons and stringers and their geometries for a fuselage panel assembly have been determined. It is therefore appropriate to present first, an overview of the cost hazards for each of the technologies and materials analyzed in References 5, 7 and 8 and, second, comparative charts or formats showing the impact of manufacturing technologies, discrete part dimensions, etc. These two groups of formats or charts are presented in Sections 2.3.1 and 2.3.2, respectively, and are applied in the conceptual design phase where innovative structural design concepts need to be developed. It is at this time, that the manufacturing methods, including assembly techniques, are, in general, determined. In the case of a fuselage panel, the materials and configuration of skins, panels, frames and stringers (number and shapes), are determined.

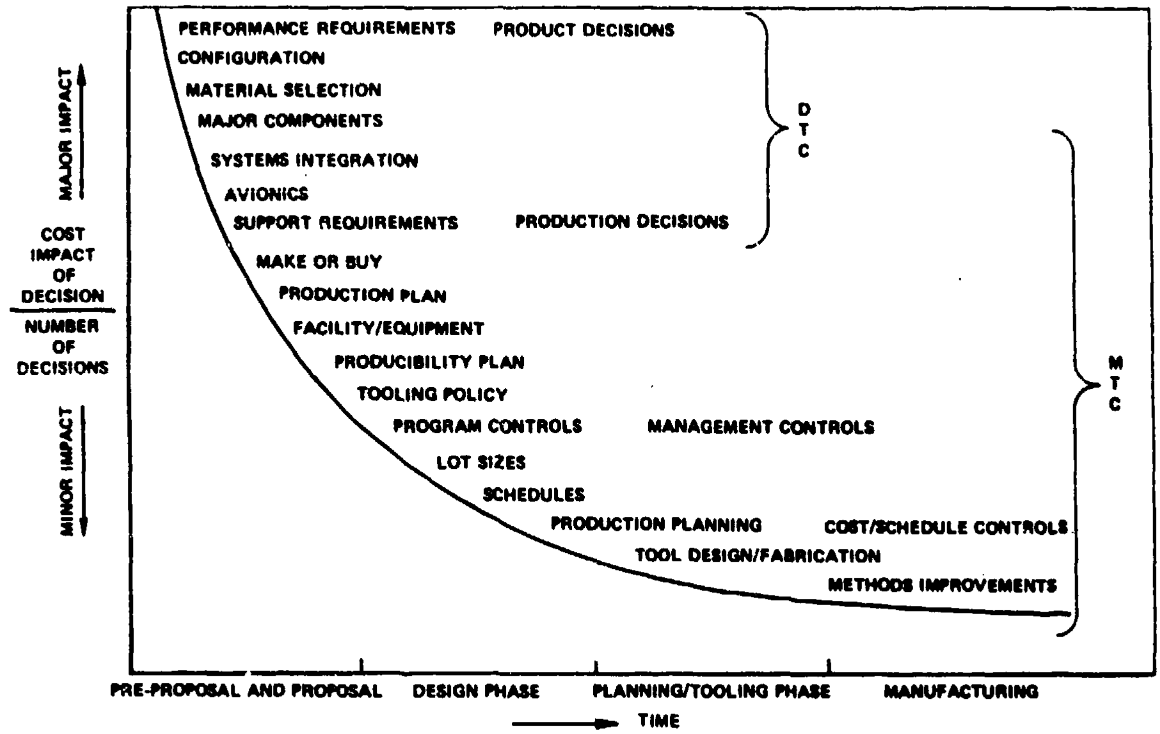

FIGURE 2.1-3 DECAYING IMPACT OF DECISIONS ON COST

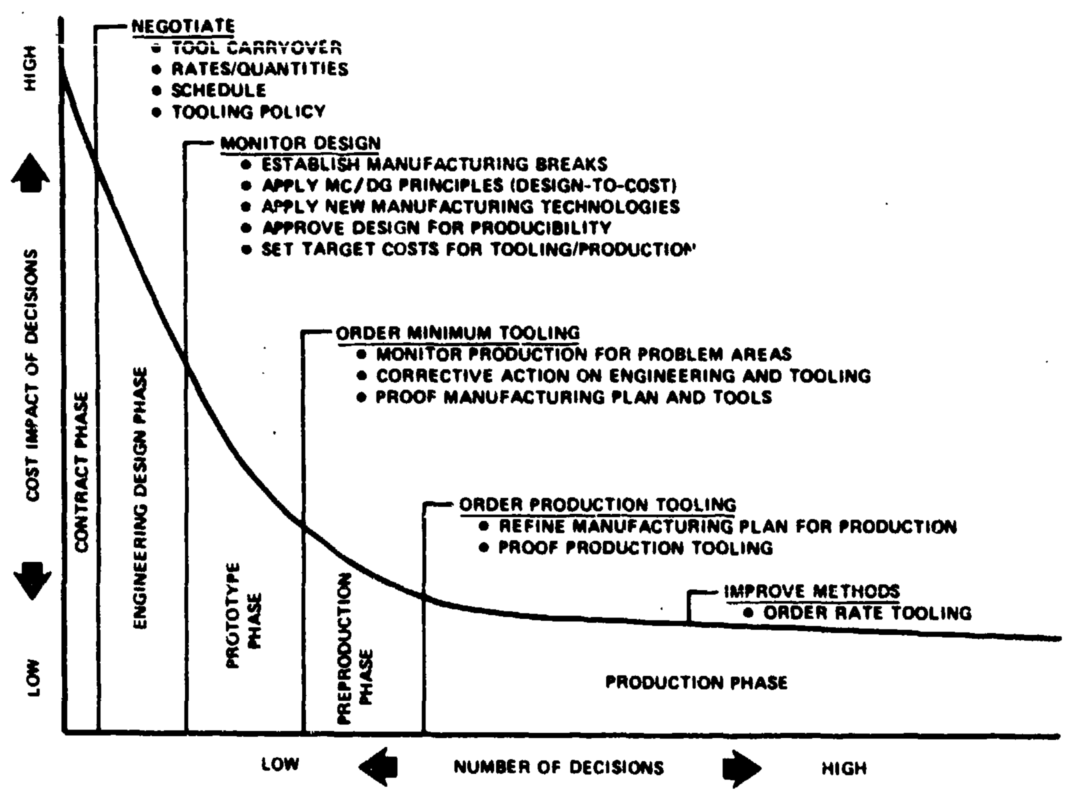

FIGURE 2.1-4 IMPACT OF COST ON EARLY DECISIONS CONCERNING TOOLING

The applicability of the two categories of conceptual design formats is shown in Figure 2.1-5. To determine the data on which these curves are based, a series of discrete parts, i.e., base parts with designer influenced cost elements (DICE) were analyzed using cost estimating methods generally accepted throughout industry. These methods are discussed in Reference 5, and typical parts analyzed are shown in Figure 2.1-6. The base parts, DICE and joining trade-off factors for sheet metal assemblies are shown in Figure 2.1-7 to indicate how a trade-off study is conducted. The interaction between the MC/DG and the design process is shown in Figure 2.1-8. In the latter figure, it will be noted that when selecting the material, etc., the designer must consider factors such as temperature, environment, galvanic compatibility, material allowables, heat treatment, damageability, fatigue life and available space.

The formats or charts are presented in such a way that the designer can identify and maximize the number of cost-drivers addressed during the design process. The illustrations are also intended to stimulate designer interest in reducing costs and are, therefore, structured to address the needs of the designer in a simple, not time consuming way.

In summary, the input at the conceptual design phase considerations will include quantity, aerospace system general configuration, loads, cost/weight relationships, maintenance and environmental factors. The output, using the "MC/DG for Conceptual Design", will be affordable conceptual designs, material systems, assembly configurations with some details and cost/weight-effective use of emerging materials and manufacturing technologies -- all leading to lower acquisition costs. However, it should be stressed that the complete series of MC/DG volumes can also be utilized to evaluate the production costs of various alternative designs, which not only respond to weight and similar performance requirements, but also to the maintenance and repair requirements of the life cycle of the system.

2.3 CONCEPTUAL DESIGN GUIDE ORGANIZATION

2.3.1 Cost Hazard Avoidance

Each format included in this section indicates the magnitude (relative or actual) of one or more cost-drivers. Due to the complexity of some of the manufacturing processes, diagrams have been prepared to quickly reveal potential cost hazards. For example, in the case of machining, the increase or decrease of cost, material removal rate, or material utilization, is presented as a function of the primary parameter in this diagram. The diagrams are prepared not only to guide the conceptual designer in the direction of low-cost structural assemblies and discrete parts, but also to provide guidance to manufacturing, procurement and management personnel, and indeed the customer, with a ready overview of these cost-drivers. By utilizing References 5,

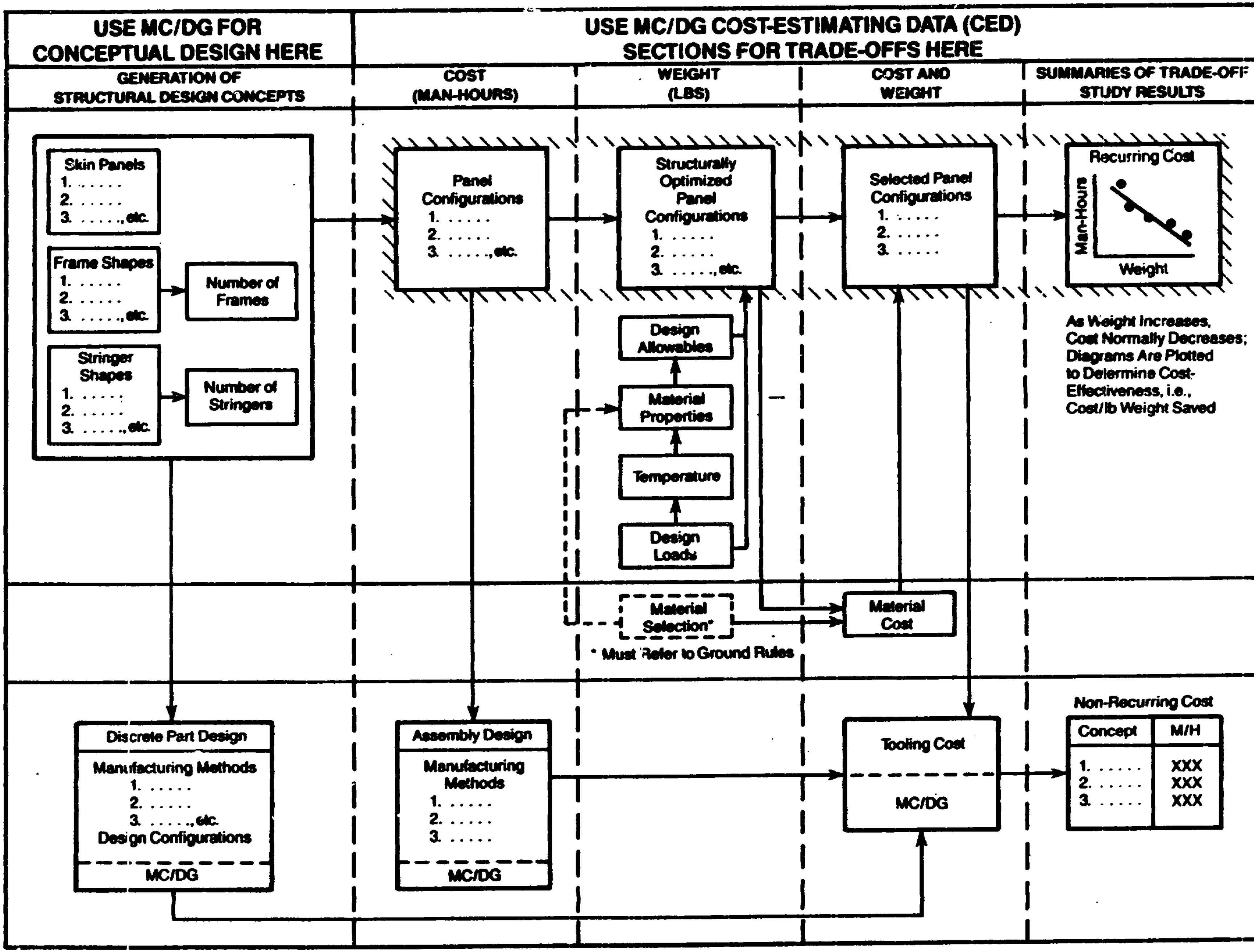

FIGURE 2.1-5 TRADE-OFF STUDY FLOW

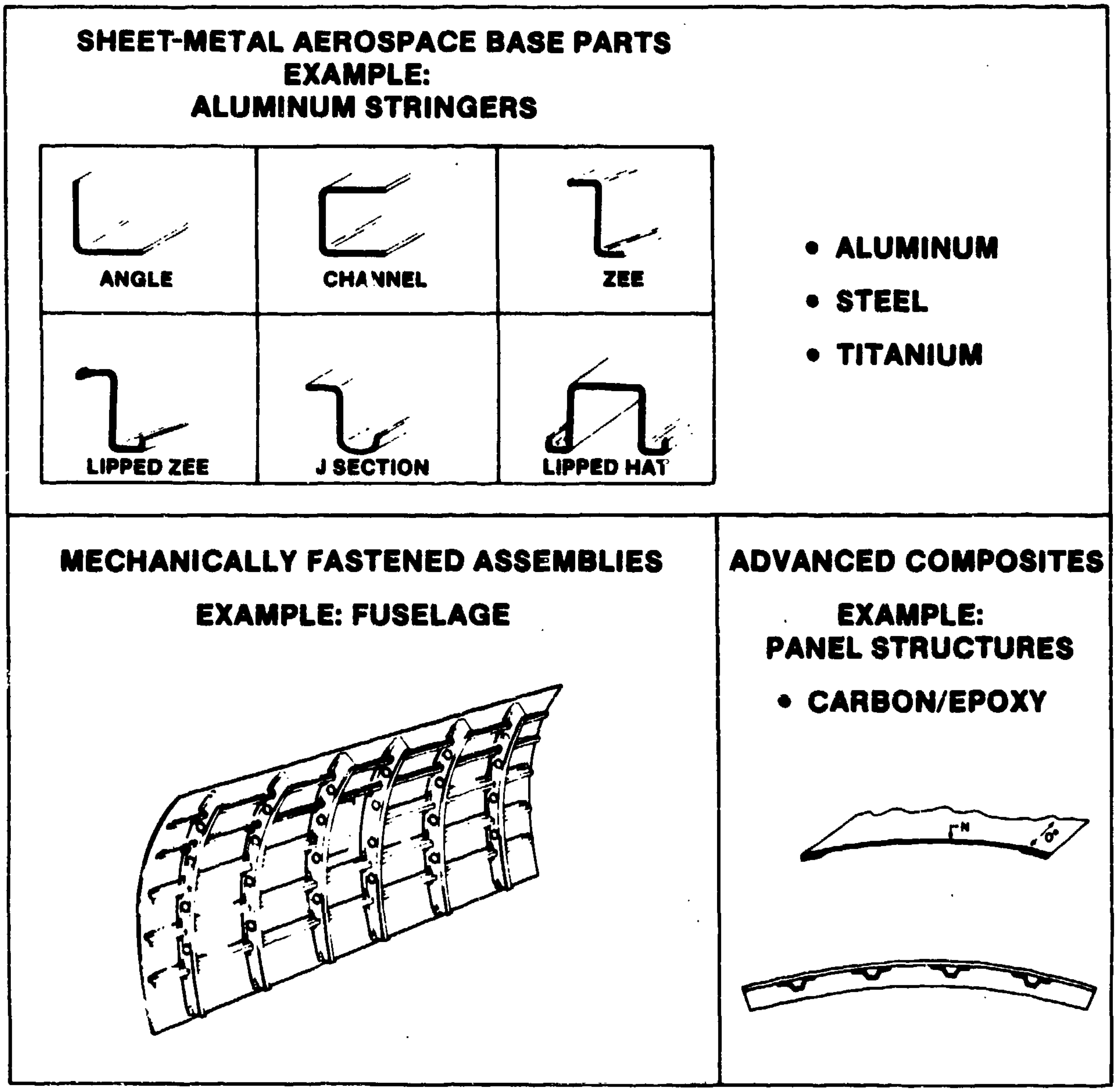

FIGURE 2.1-6 SAMPLE PARTS USED TO DERIVE COST DATA FOR MC/DG

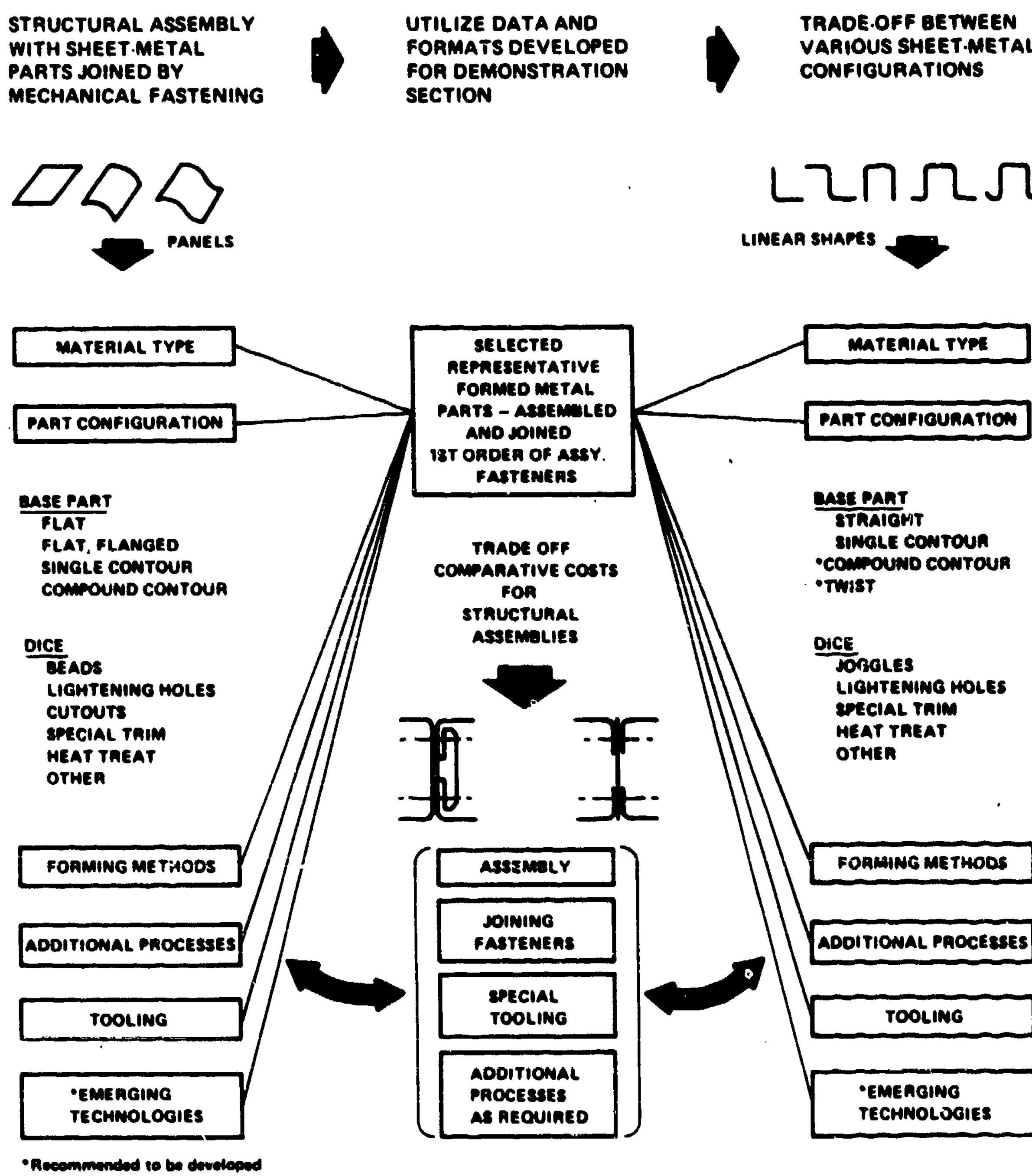

FIGURE 2.1-7 UTILIZATION OF MC/DG SECTIONS FOR SHEET-METAL AEROSPACE DISCRETE PARTS & MECHANICALLY FASTENED ASSEMBLIES

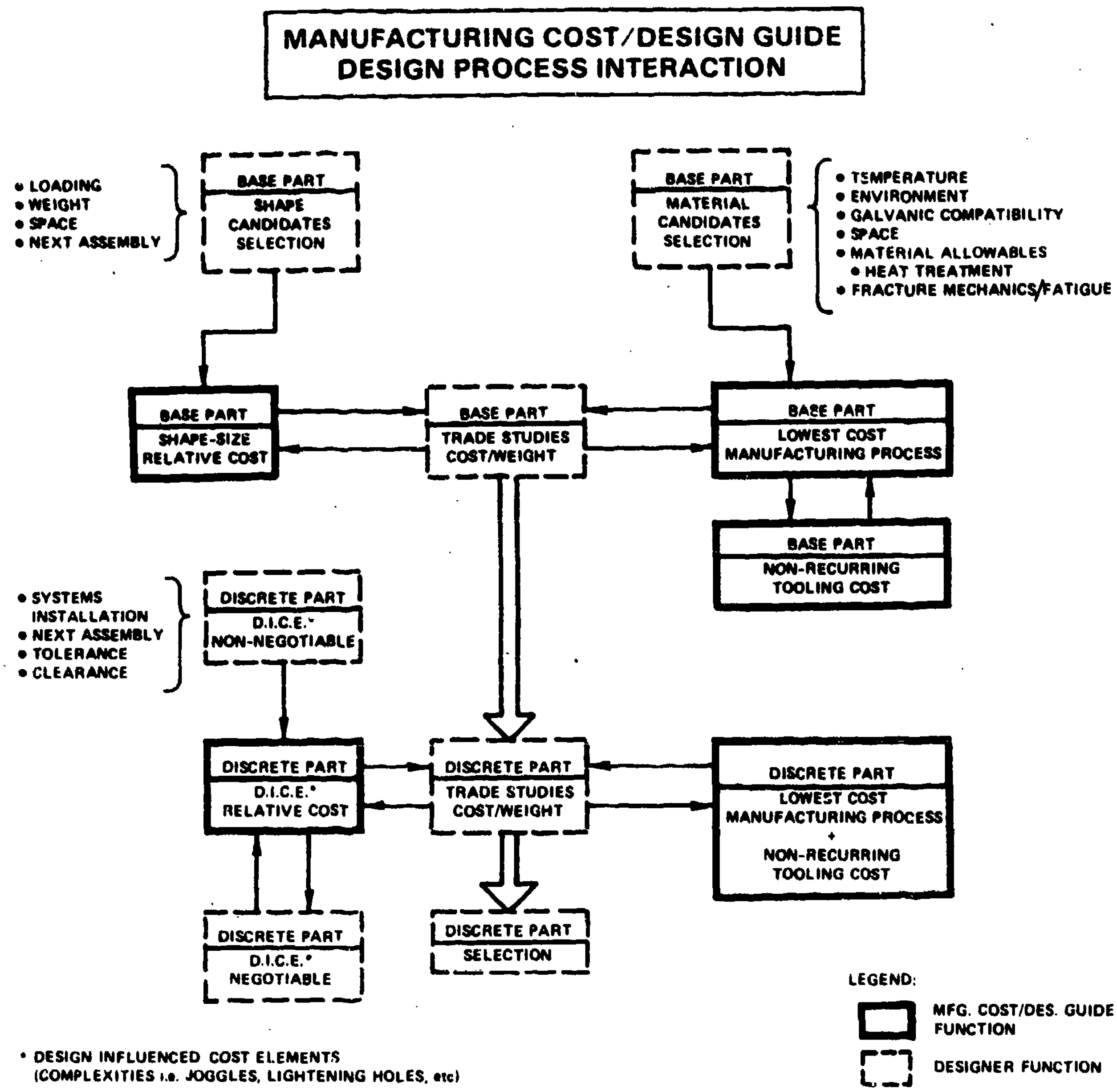

FIGURE 2.1-8 MANUFACTURING COST/DESIGN GUIDE AND DESIGN PROCESS INTERACTION

7 and 8, the designer can determine the man-hours of each cost-driver. Such guidance will prove to be very useful to inexperienced or unseasoned designers, who may not have shop experience or have been trained in design at the colleges or universities. Furthermore, these diagrams promote and encourage design/manufacturing interaction, so important in achieving lower cost aerospace systems that perform efficiently throughout their life cycle.

Serving as an example, let us study machining. The most significant cost-drivers are:

- Materials type and heat treat range
- Volume of material removed
- Surface finish requirements
- Dimensional tolerances.

When designing machined bulkheads, frames, ribs or spars, the designer must address the following cost-drivers:

- Size
- Material removed
- Pockets or slots
- Internal stiffeners
- Varying flange angles
- Boring and drilling of holes
- Varying corner radii and schamfers

Further, in the case of machining, the following are a series of designer influenced cost elements (DICE) which must be consider:

- Taper
- Pockets
- Blind holes
- Webs/flanges
- Tolerances
- Surface finish.

It is again important to emphasize that material selection for an airframe is a complex process that does not relate only to cost. Factors frequently involved in finalizing, for example, an alloy selection and which may precede cost considerations are:

- Tensile and compressive strengths
- Bearing strength
- Fatigue strength
- Damage tolerance

- Corrosion avoidance
- Available space for the part.

2.3.1.1 Manufacturing Technologies

This report section addresses the manufacturing technologies which have been earlier analyzed and provides the designer with an overview of significant cost-drivers, many of which need to be addressed at the outset of system development. The majority will eventually be considered in trade-off studies until the production go-ahead is given. These manufacturing technologies considered here are for:

- Sheet metal
- Extrusions
- Castings
- Forgings
- Machining (metals)
- Mechanically fastened assemblies
- Composite methods
- Superplastic forming.

2.3.1.2 Test, Inspection and Evaluation

In many trade-off studies, the man-hours involved in the complex test, inspection and evaluation (TI&E) processes are seldom evaluated or included in the analysis. In some cases, results of the trade-off studies will not be meaningful or of sufficient accuracy unless the man-hours for TI&E are included. In this section, a series of illustrations are presented to guide the designer with respect to TI&E. The technologies included are:

- Casting
- Forging
- Composites
- Assembly.

2.3.2 Cost-Driver Effect Design Charts

2.3.2.1 Manufacturing Technologies

The objective of this section of the "MC/DG for Conceptual Design" is to provide the relative cost of various cost drivers, materials and manufacturing technologies, for the following:

- Sheet metal
- Extrusions
- Castings
- Forgings
- Machining (metals)
- Mechanically fastened assemblies
- Composites
- Superplastic forming (SPF)
- Test, inspection and evaluation (TI&E).

Again, these formats are not used for trade-off studies, but are intended to guide the designer, from the outset, in the development of lower-cost discrete parts, structural design configurations and assemblies. In several instances, the designer influenced cost elements (DICE) are also presented to indicate to the designer the potential cost of certain design refinements normally specified. By reviewing these qualitative formats, the designer will be able to make high-confidence decisions leading to low-cost designs, while also meeting the other design requirements mentioned earlier, e.g., ease of repair. In each case, the formats have been based on calculations in accordance with detailed and general ground rules published in References 5, 7 and 8.

2.3.2.2 Test, Inspection and Evaluation

The need for qualitative and quantitative data for test, inspection and evaluation (TI&E) was discussed in Section 2.1.1.2 of this report. The formats showing relative trends for sheet metal, composites and machining are included in the second category for conceptual design use. However, the user should also refer to the cost-driver effect (CDE) volumes (References 5, 7 and 8) for additional information useful to design for ease of inspection.

2.4 FORMAT AND GROUND RULE LOCATORS

A large number of designer-oriented formats or charts have been prepared under four Air Force contracts from 1975 through 1988. These contracts are:

- F33615-75-C-5194
- F33615-77-C-5027
- F33615-79-C-5102
- F33615-85-C-5016.

The series of volumes contain both formats and ground rules for manufacturing technologies applicable to both metallic and composite materials and structures.

To aid designers in retrieving this data, a series of format and ground rule locators have been prepared. These locators are included in this report as Appendix C.

2.5 LEARNING CURVES

2.5.1 The Theoretical Curve

During the application of the MC/DG for conducting trade-off studies between structural performance (which also includes such considerations as damageability, corrosion, etc.) and manufacturing cost, it is necessary to refer to typical aerospace industry learning curve factors such as shown in Table 2.5-1.

In referring to the ground rules for the various manufacturing technologies in References 5, 7, and 8, the designer needs to have some knowledge of those costs which are included or omitted in the ground rules under recurring and nonrecurring cost categories. These are indicated below:

a) Recurring Costs

- Rate or production tooling (tool design, numerically controlled programming, production planning, tool manufacturing)
- Tool maintenance (repair, realignment and refurbishment)
- Production labor
- Inspection labor (quality control)
- Material cost (raw material and procurement)
- Engineering changes (increase or decrease cost)
- Engineering maintenance (liaison, etc.)
- Manufacturing engineering (liaison)
- Production control
- Production planning (work orders, etc.)
- Industrial engineering
- Configuration control/verification
- Methods, studies and improvements
- Perishable or consumable tools (cutters/drills, reamers, etc.)
- Facilities and equipment maintenance
- Recruiting and training personnel.

TABLE 2.5-1 TYPICAL AEROSPACE INDUSTRY LEARNING CURVE VALUES

Manufacturing Category	Learning Curve Value
Assembly; Controls	85%
Assembly; Electrical	80%
Assembly; Hydraulics, Pneumatics	85%
Structural Assembly - Bench (Sheet Metal Parts)	85%
Structural Assembly - Floor	75%
Structural Assembly - Final	70%
Mechanism Assembly - Bench (Machined Parts)	80%
Functional Installation	65%
Machining; Conventional	80%
Machining; Numerical Control	95%
Filament Winding	85-90%
Pultrusion/Wrapping	85%
Sheet Metal Fabrication	90%
Composite Lay-up	85%
Adhesive Bonding	
- Assembly	75-80%
- Curing	90%
Brazing	75%
Welding	70-80%

b) Nonrecurring costs

- Basic engineering design/specifications
- Initial or basic manufacturing engineering costs (tool design, NC programming, production planning and tool manufacturing)
- Rearrangement costs for factory and facilities for new products and new equipment
- Tool inspection of basic and initial tooling
- Bidding/proposal cost
- Engineering testing and evaluation
- Original industrial engineering (time standard data/line loading, etc.)
- Quality control procedures/testing support.

A typical learning curve for military aircraft production is shown in Figure 2.5-1.

2.5.2 Actual Learning Curves

For any product to be competitive, learning must always be achieved. However, there are specific, frequently observed reasons for failure to achieve learning improvement, and these include:

- Basic cost estimating inaccuracies
- Inconsistent ground rules
- Economic order quantity not achieved throughout program (schedules may be stretched on large projects)
- Skilled labor turnover on multiyear projects
- Quality assurance costs are initially underestimated, especially for advanced materials and joining methods
- Significant engineering changes incorporated after production go-ahead

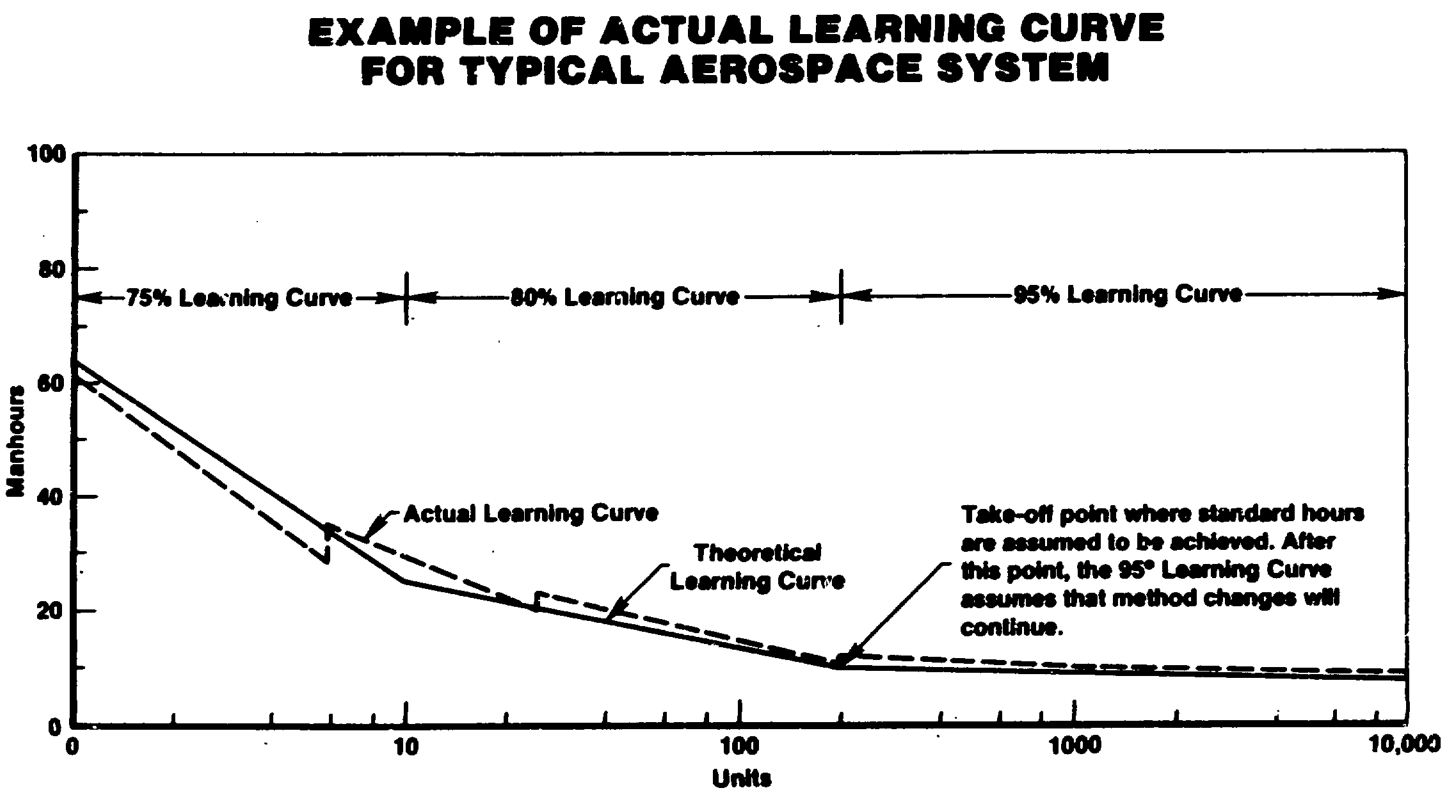

FIGURE 2.5-1 TYPICAL LEARNING CURVE FOR MILITARY AIRCRAFT PRODUCTION

- Past experience may not be carried over for all project types
- Lack of financial incentives
- Flow of materials and parts not optimized, e.g., group technology and computer integrated manufacturing system may not be widely used
- Cost schedule monitoring through manufacturing to output requirements inadequate
- Lack of emphasis on sustaining engineering to minimize high cost areas.

It should be noted that a larger number of formats or charts are included for superplastic forming (SPF) than for the other manufacturing technologies in the "MC/DG for Conceptual Design". For certain categories of aerospace vehicles, SPF is still considered to be an emerging technology. Probably the most effective way to achieve technology transfer of an emerging technology is to provide cost information at the outset of system's development. This enables the designer to establish realistic cost-effectiveness values of merit to justify the use of the technology. The data also enables the designer to address any cost-drivers with the emerging technology and to request assistance of manufacturing engineering and other associated disciplines.

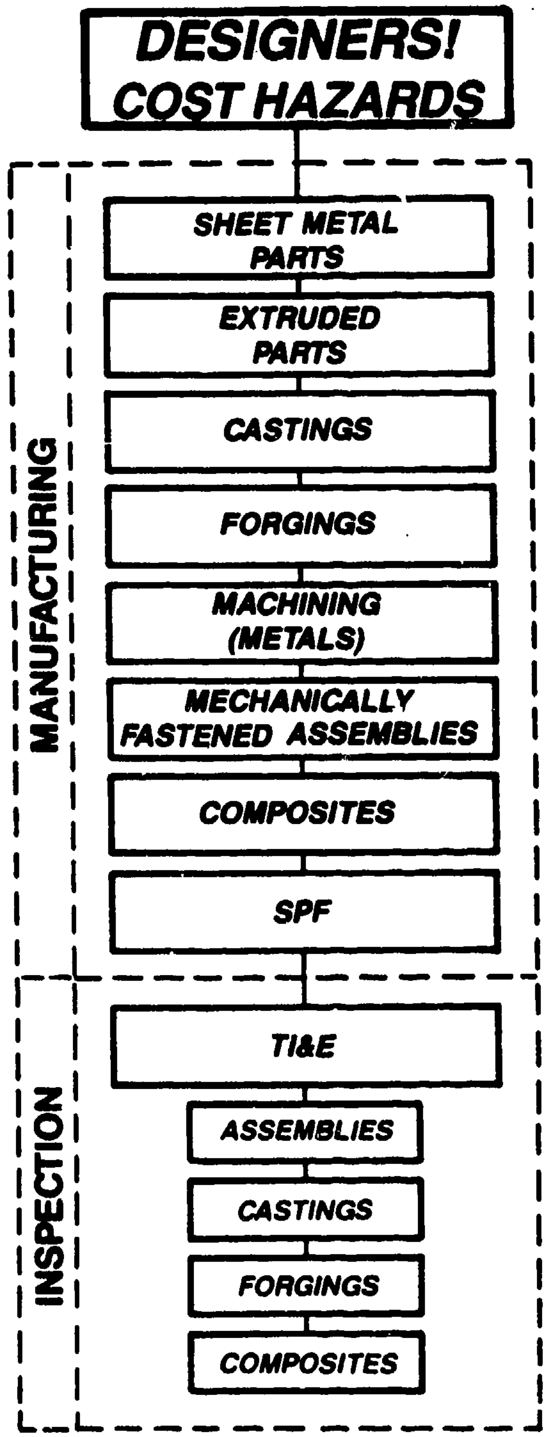

FIGURE 2.3-9 SELECTION AID FOR DESIGNER COST HAZARD ILLUSTRATIONS

DESIGNERS! COST TRENDS

MANUFACTURING
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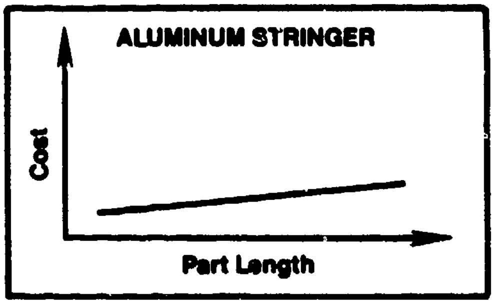
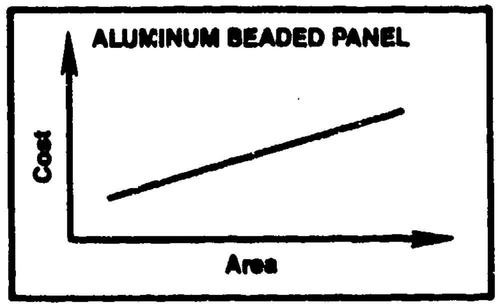
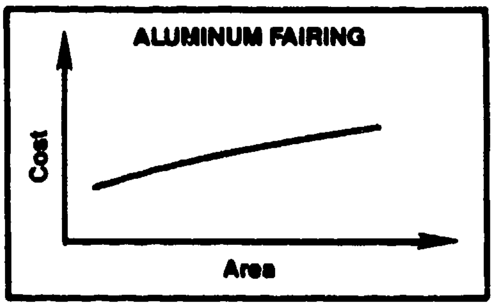
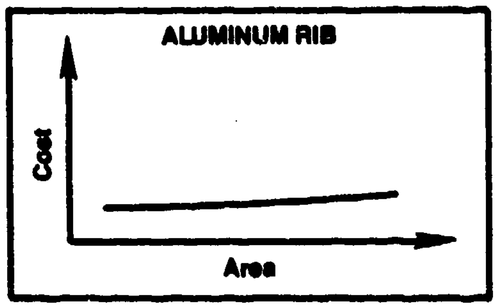
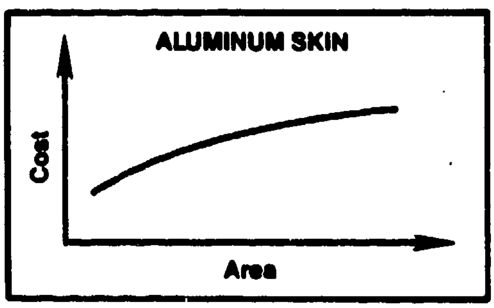
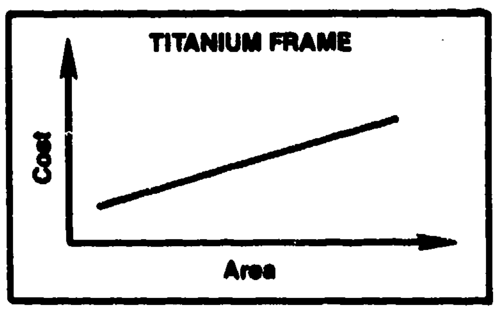


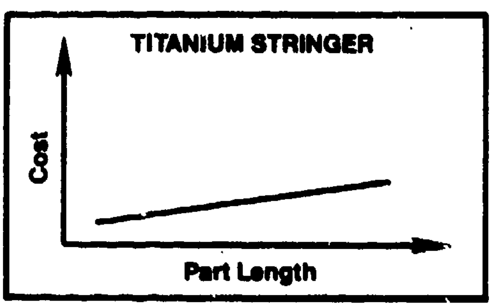


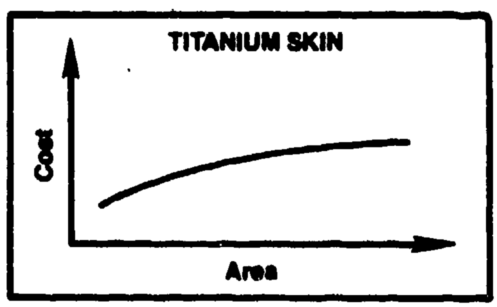








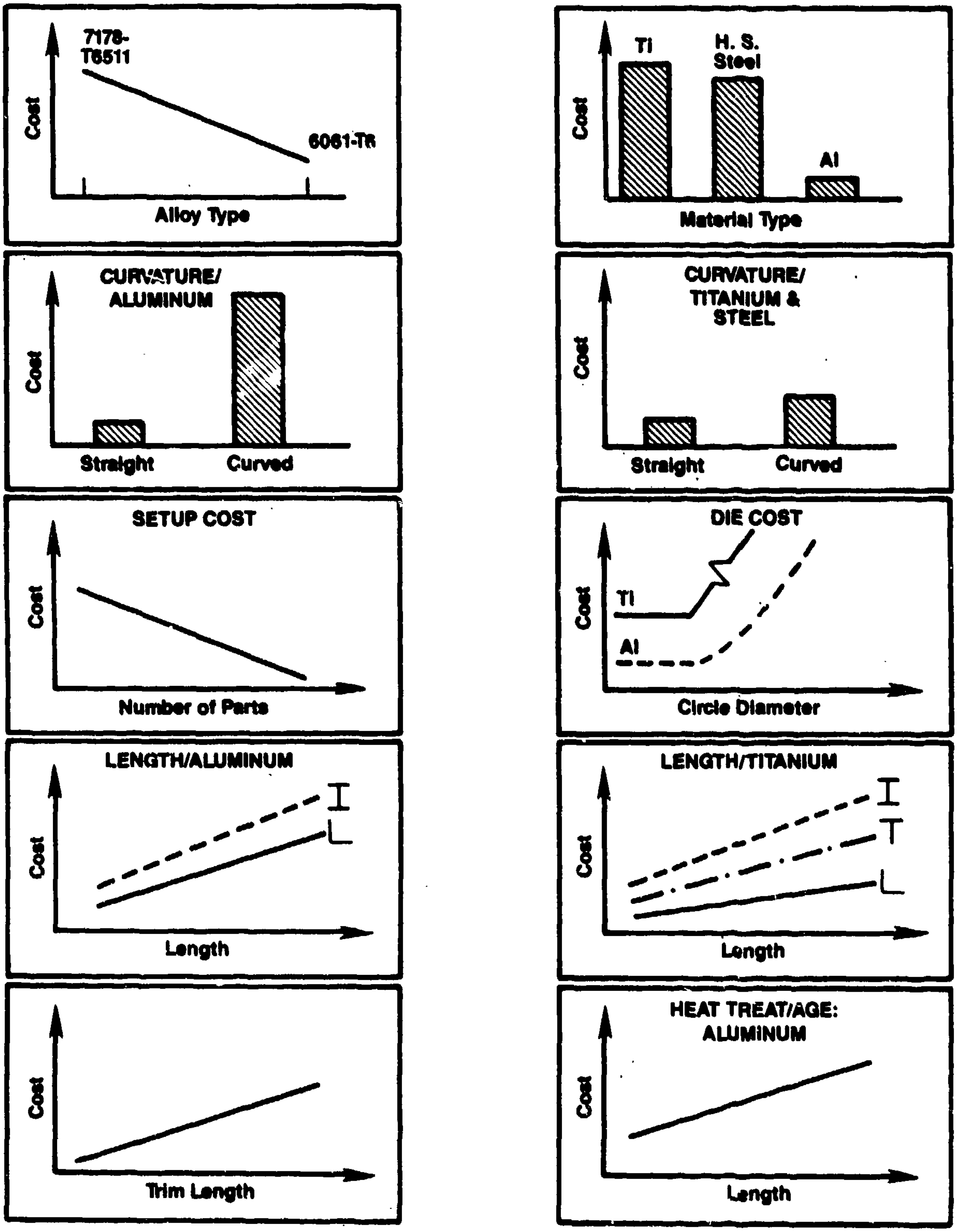




DESIGNERS! COST TRENDS

MANUFACTURING

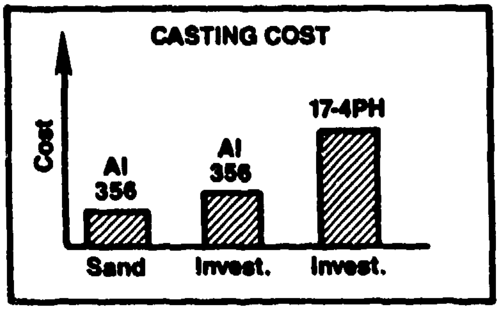
EXTRUSIONS:

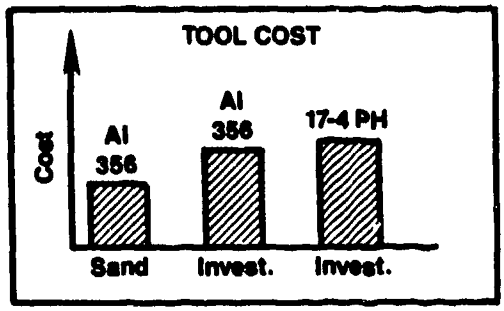


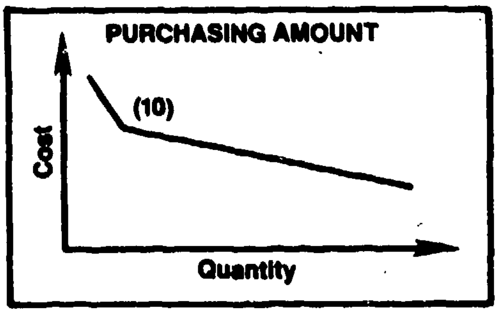
DESIGNERS! COST TRENDS

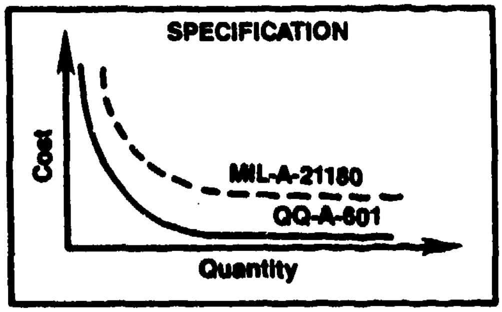
MANUFACTURING

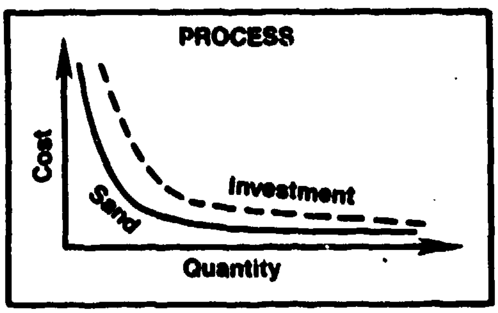
CASTINGS:

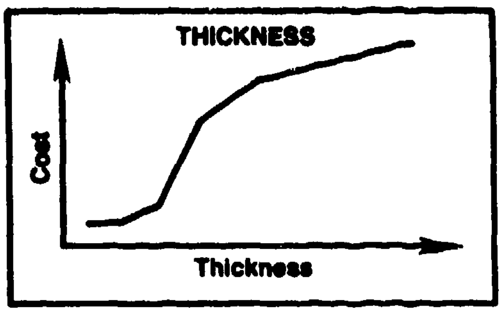


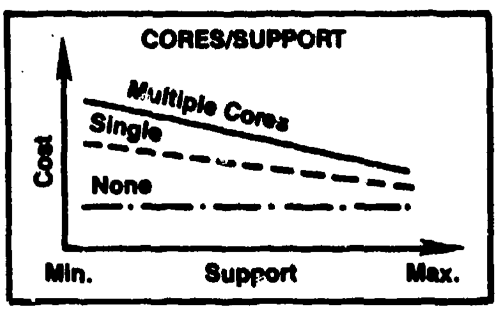


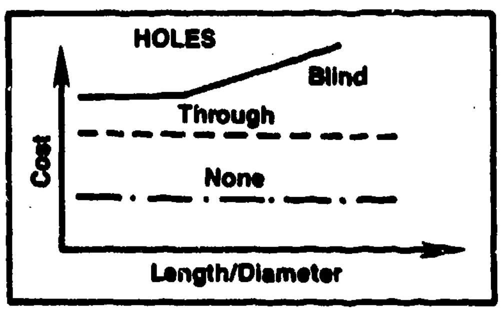








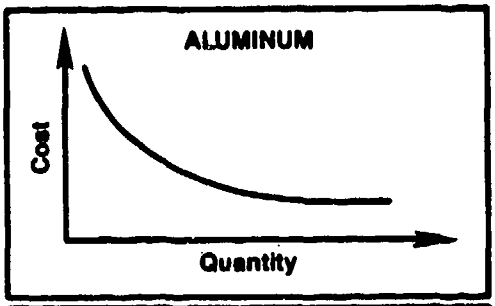


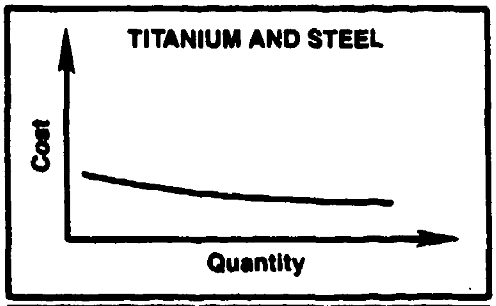


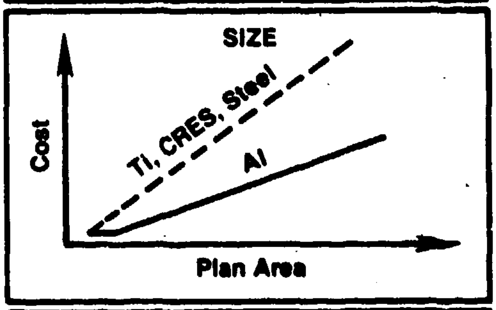
DESIGNERS! COST TRENDS

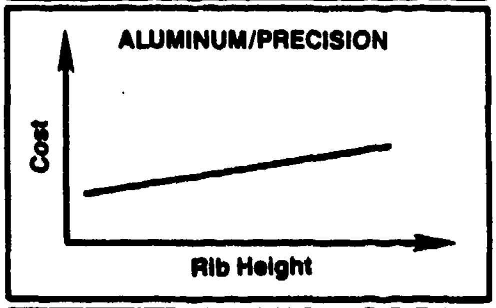
MANUFACTURING

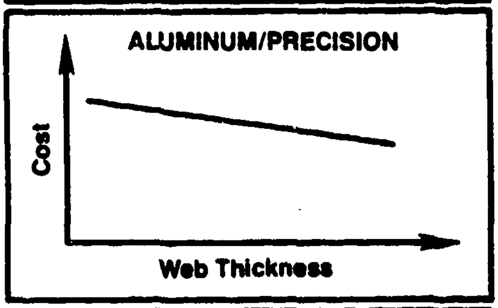
FORGINGS:

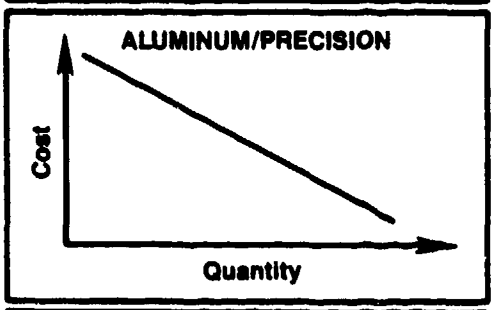


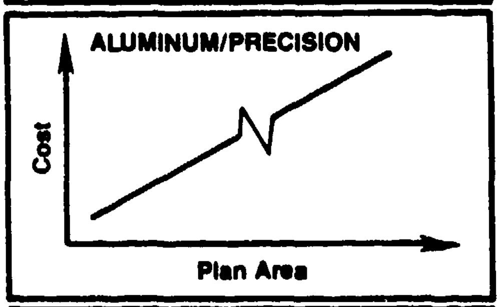


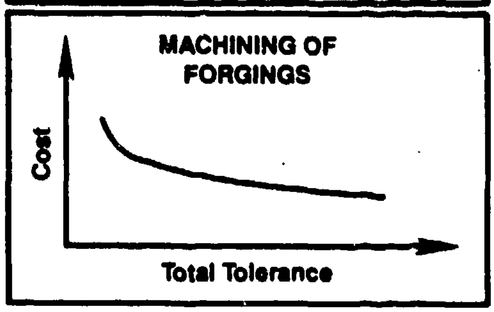


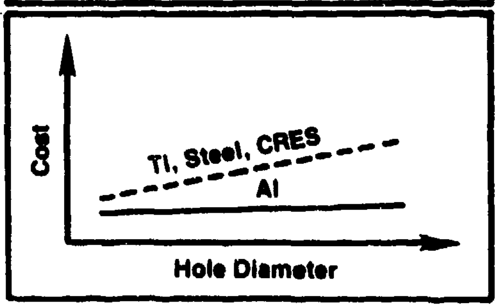








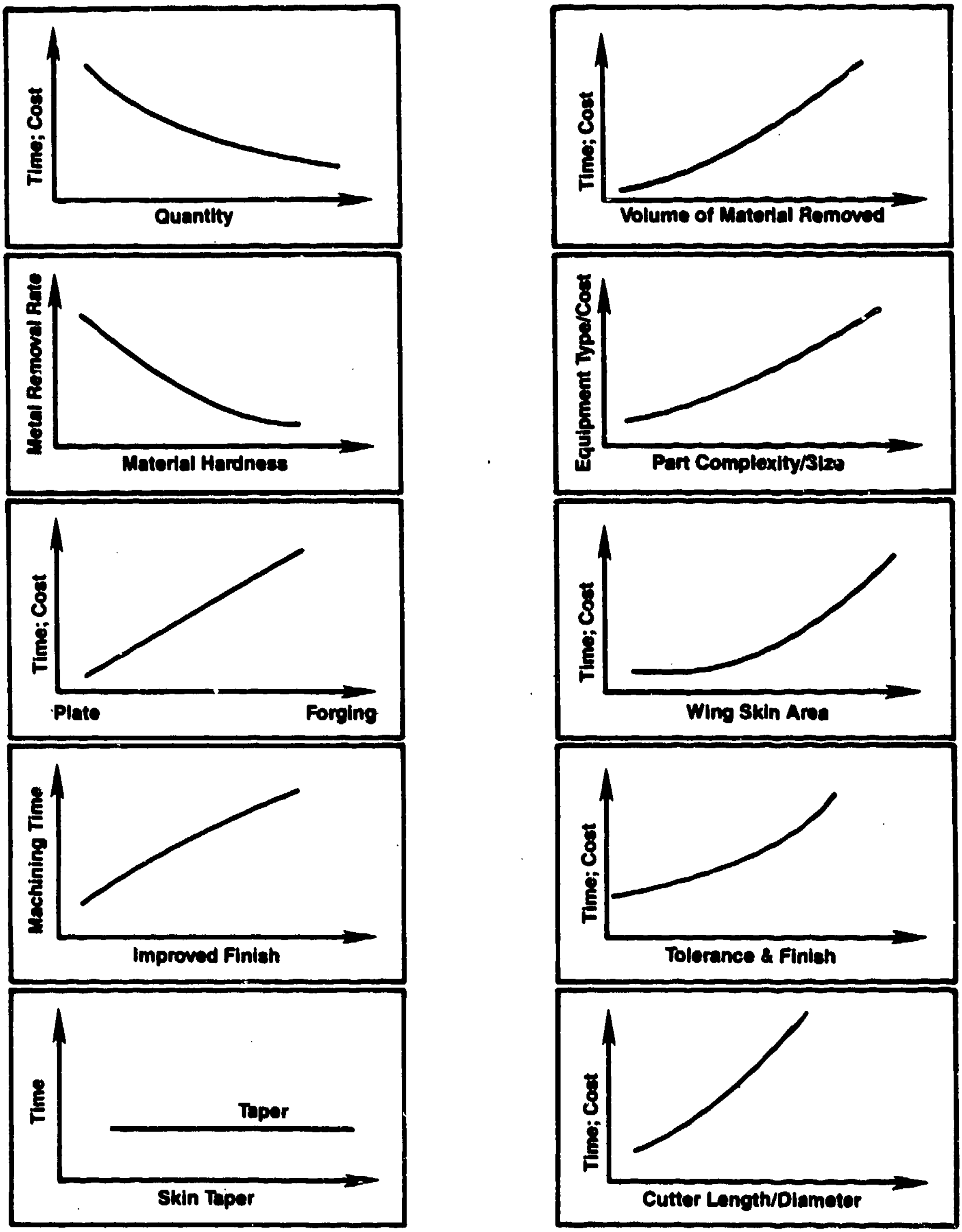




DESIGNERS! COST TRENDS

MANUFACTURING

MACHINING:



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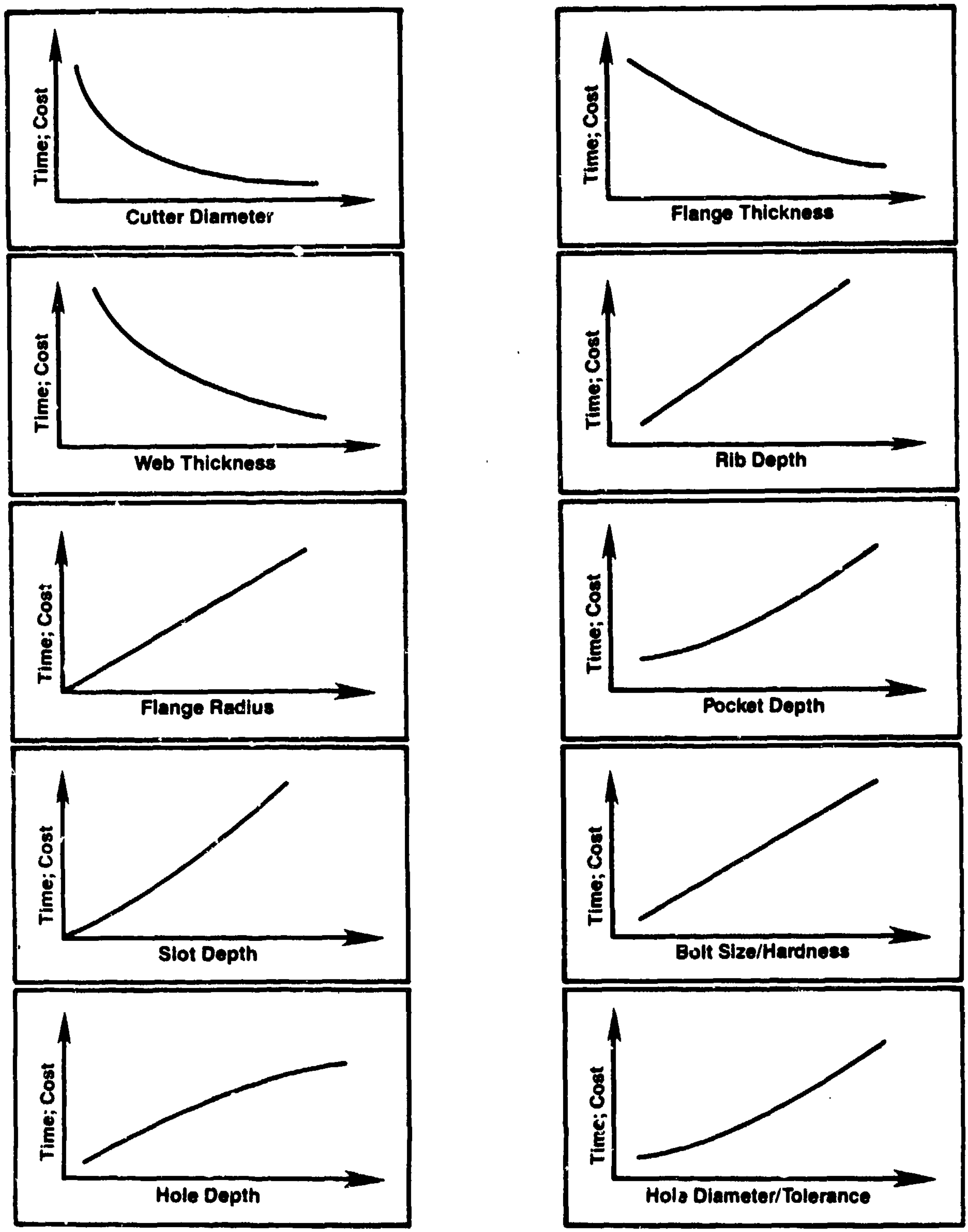

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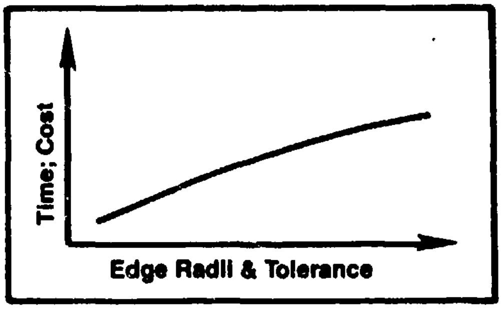

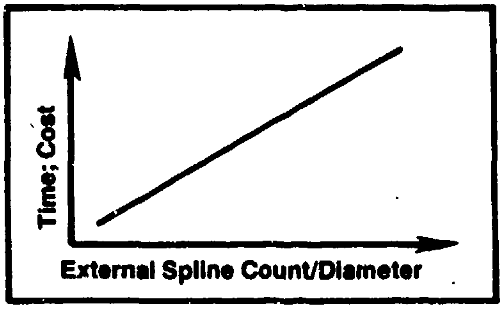

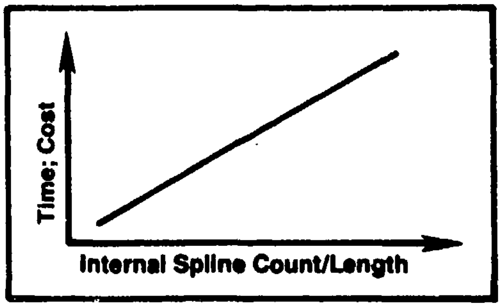

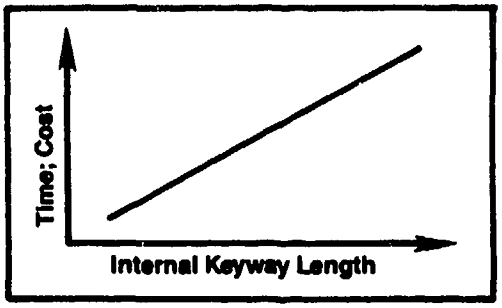

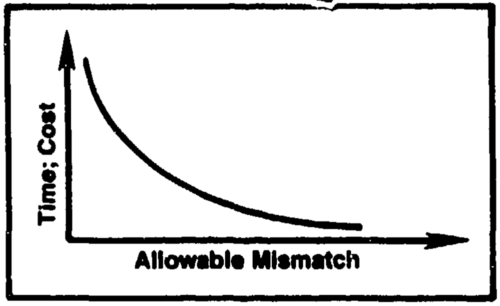

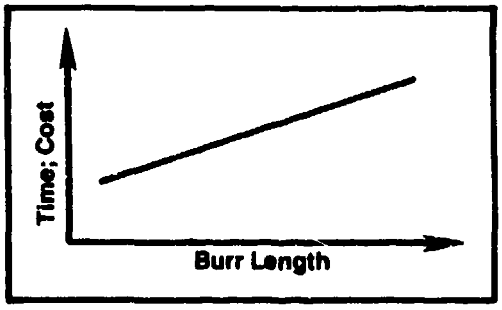

DESIGNERS! COST TRENDS

MANUFACTURING

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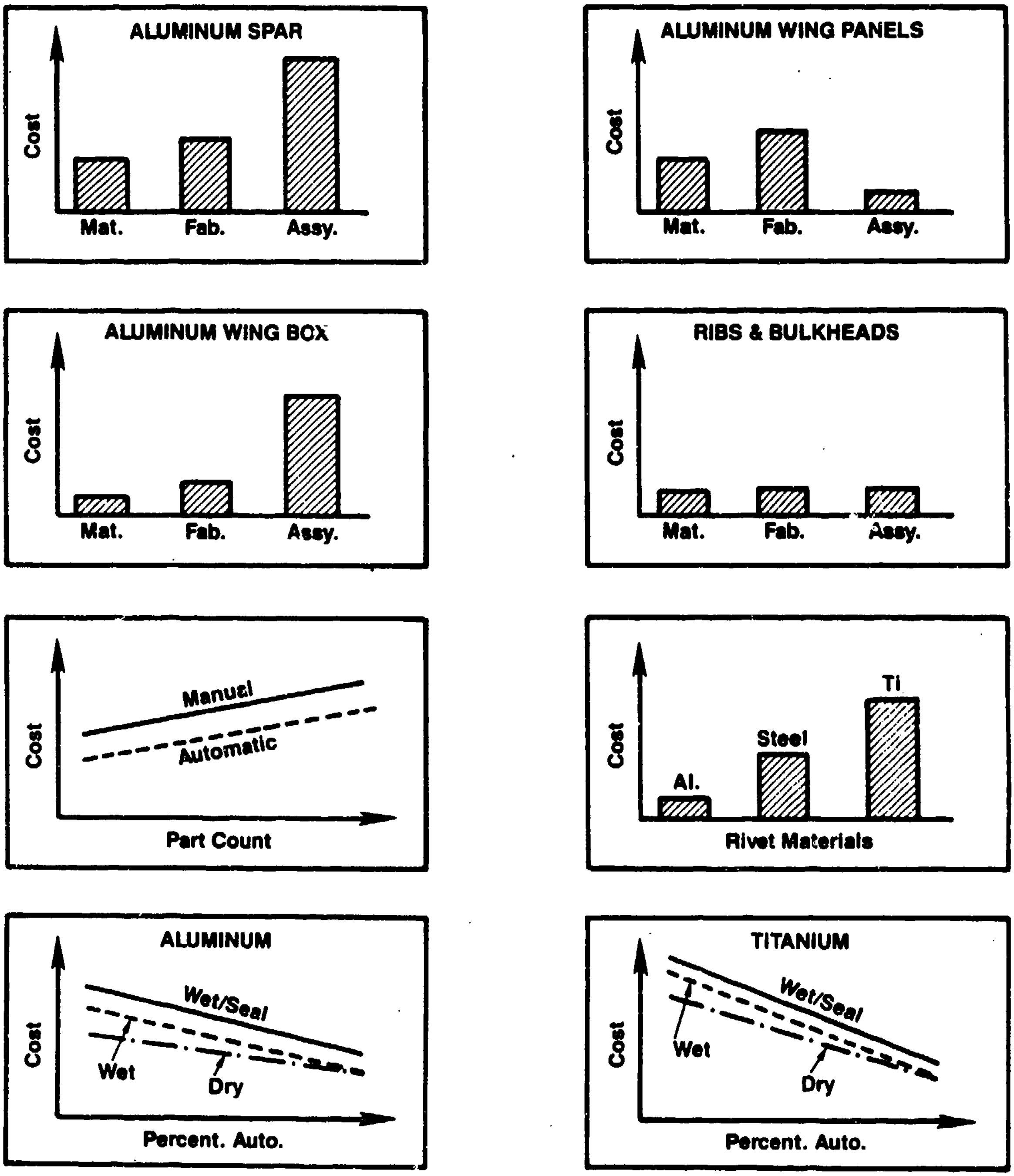
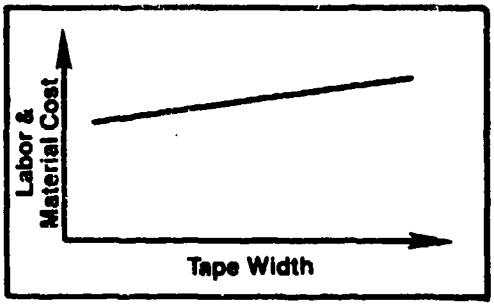
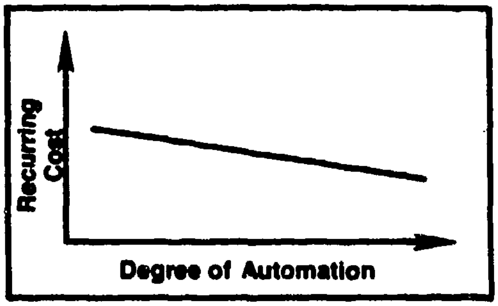


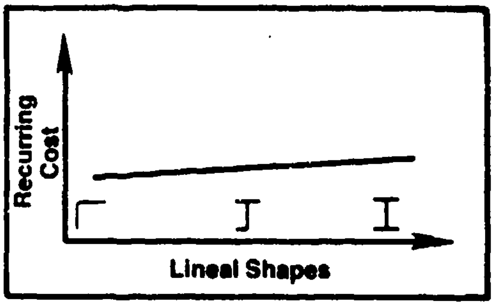
DESIGNERS! COST TRENDS

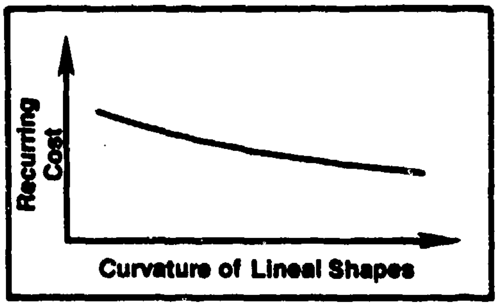
MANUFACTURING

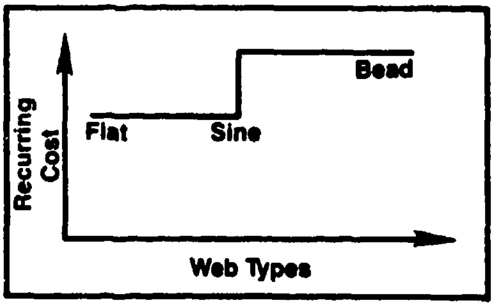
CARBON/EPOXY COMPOSITES:

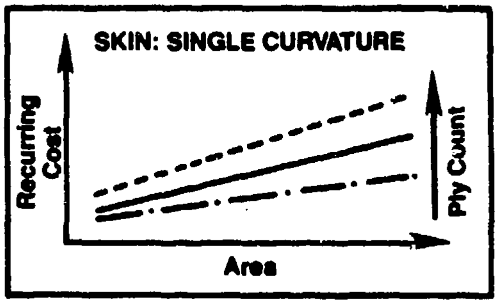


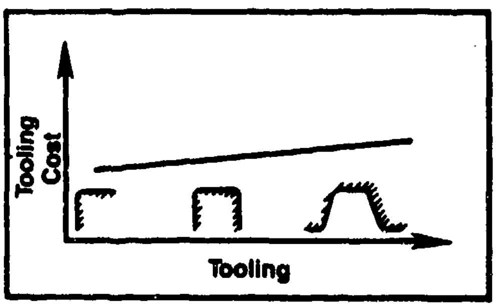


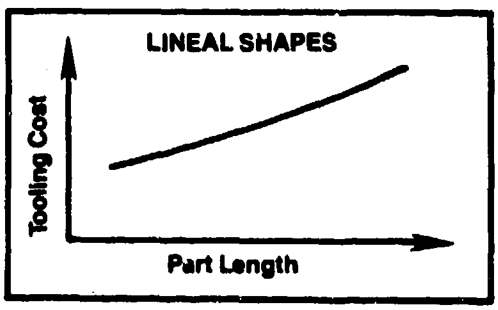








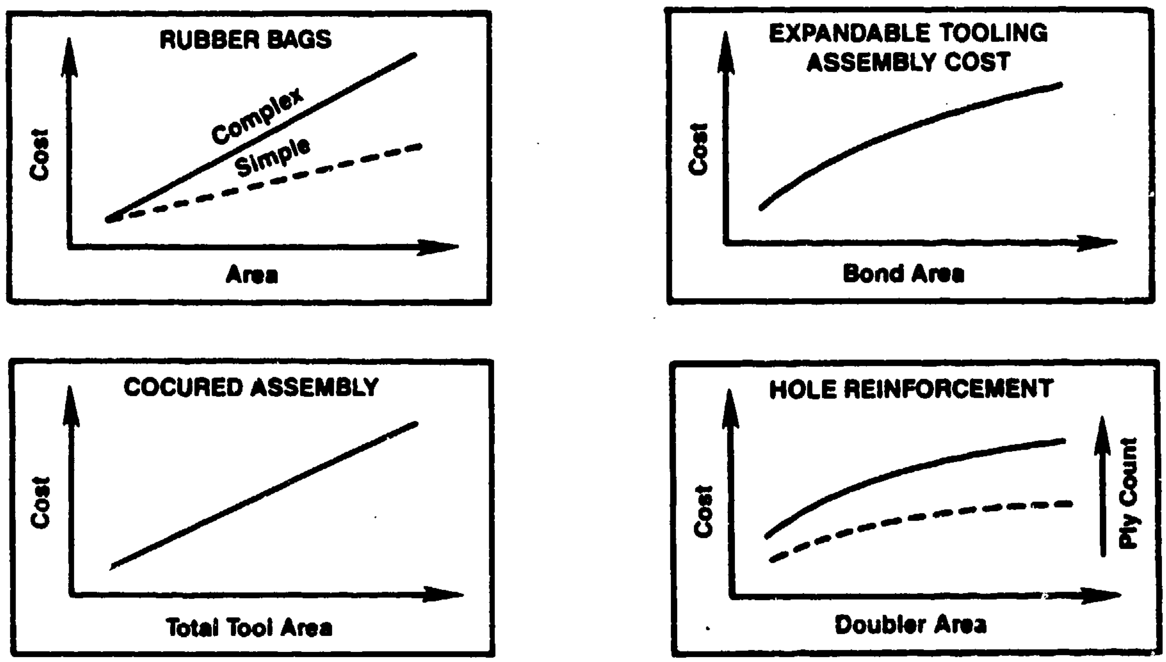




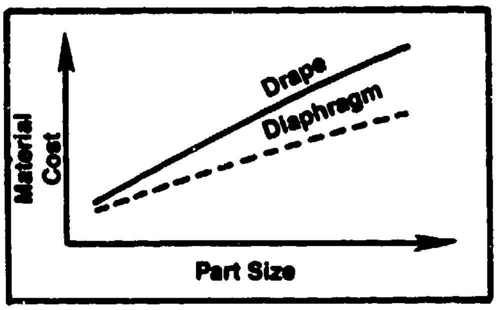
DESIGNERS! COST TRENDS

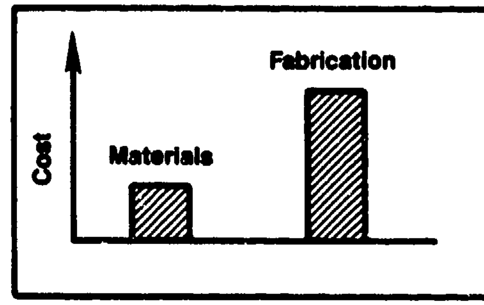
MANUFACTURING

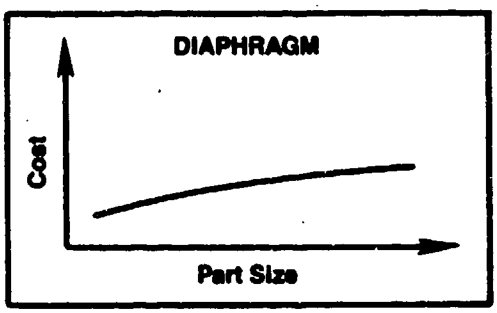
CARBON/EPOXY COMPOSITES:

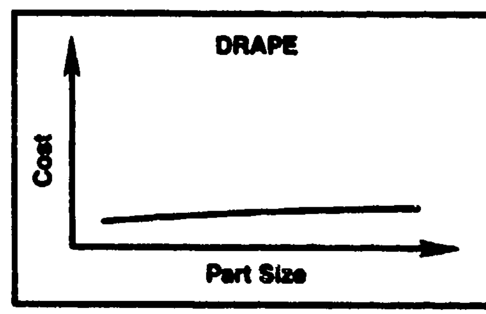


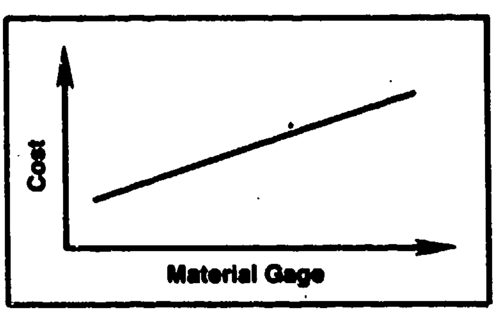
DESIGNERS! COST TRENDS
MANUFACTURING
SUPERPLASTIC FORMING / TITANIUM:

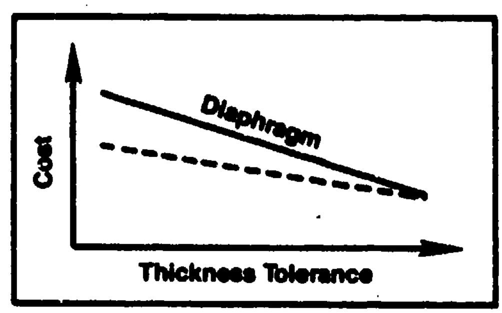


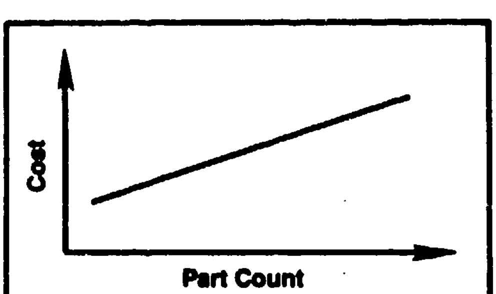


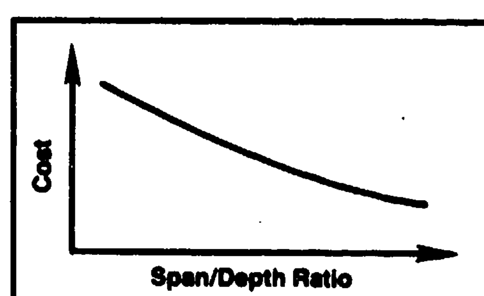








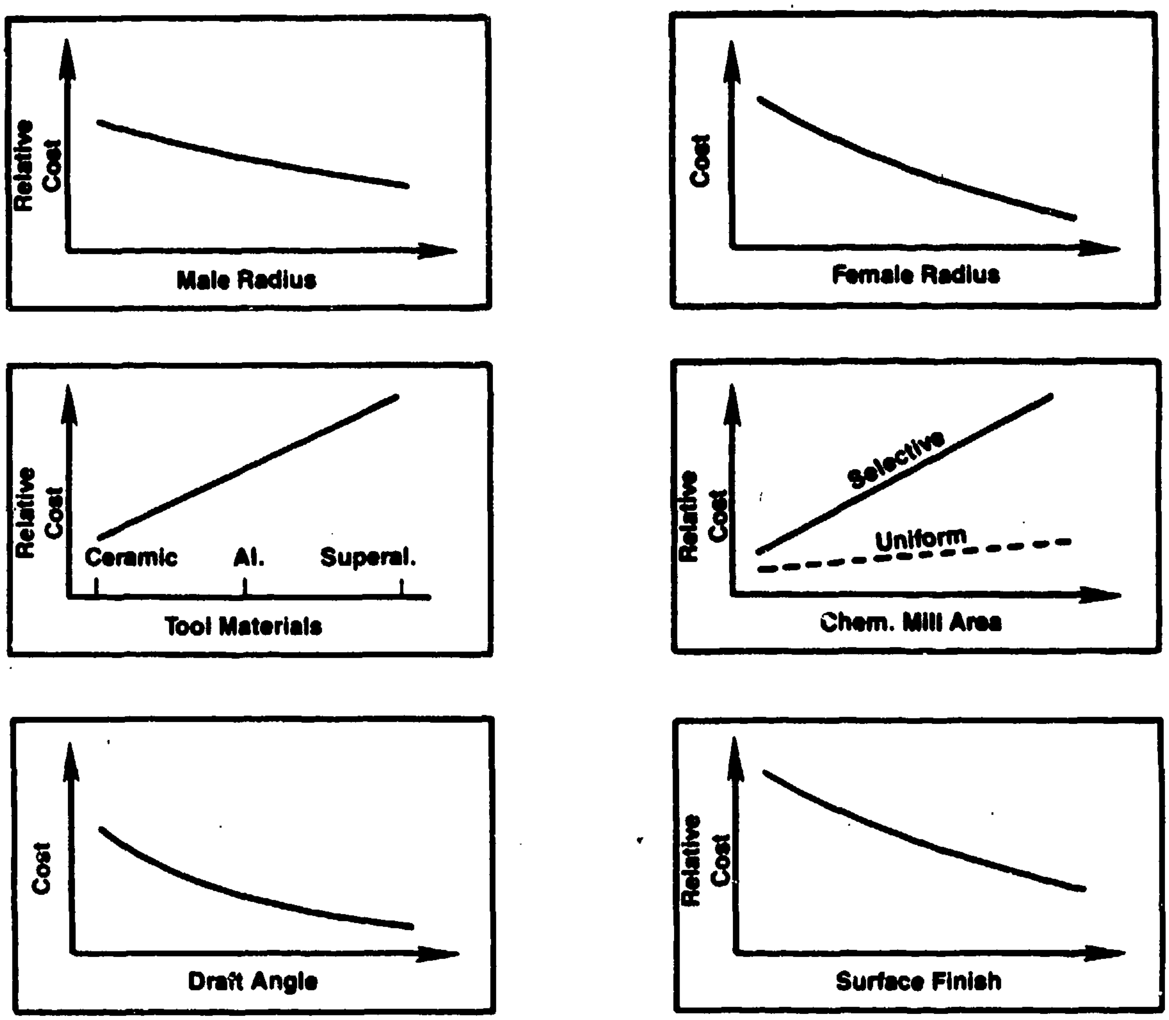




DESIGNERS! COST TRENDS

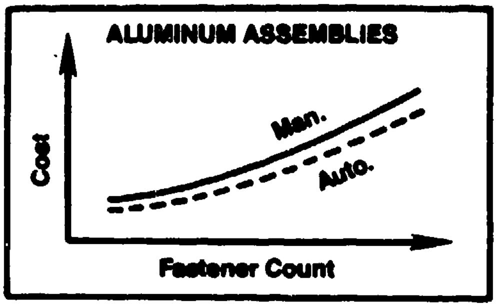
MANUFACTURING

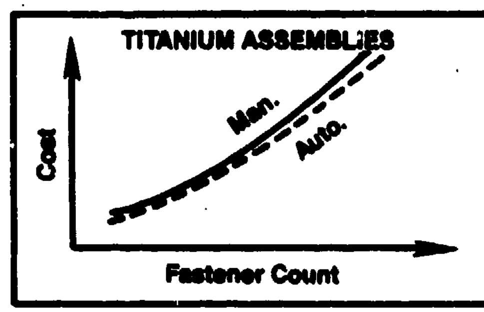
SUPERPLASTIC FORMING / TITANIUM:

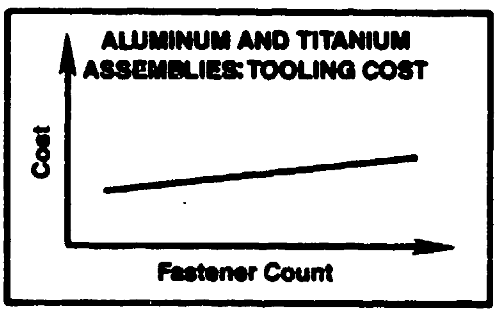


DESIGNERS! COST TRENDS

TEST, INSPECTION & EVALUATION FOR *ASSEMBLIES:*

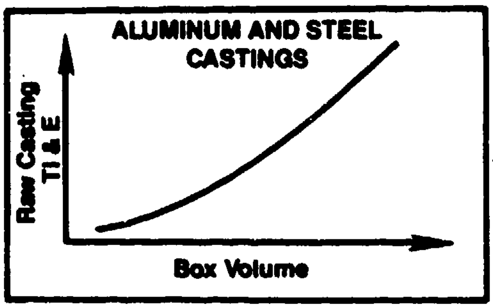


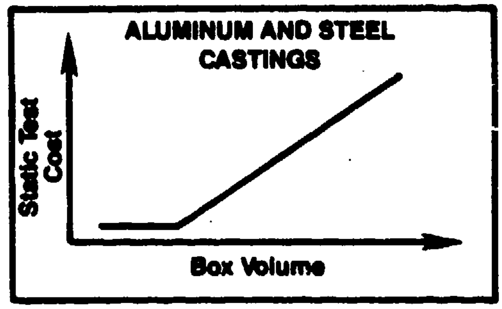


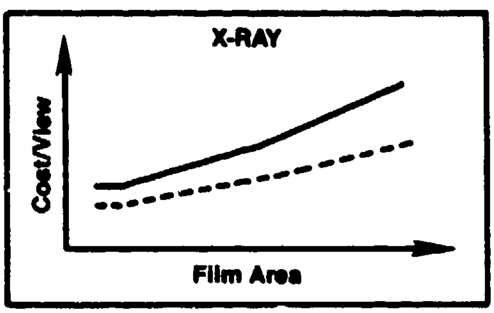


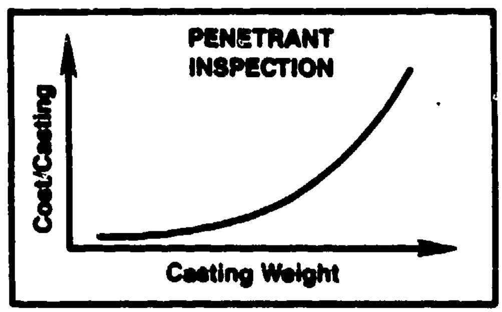
DESIGNERS! COST TRENDS

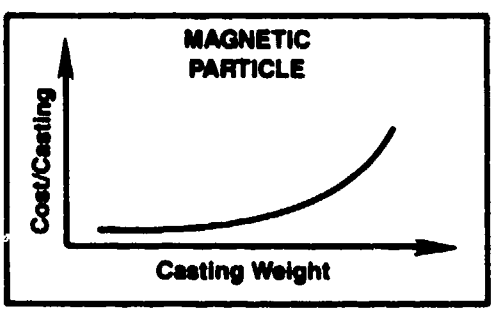
TEST, INSPECTION & EVALUATION FOR *CASTINGS:*





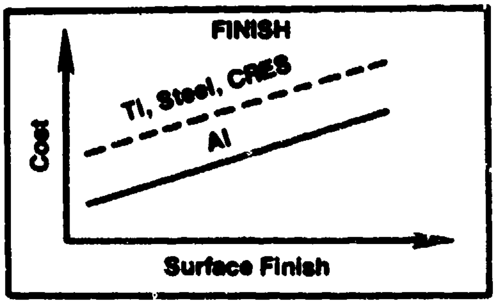


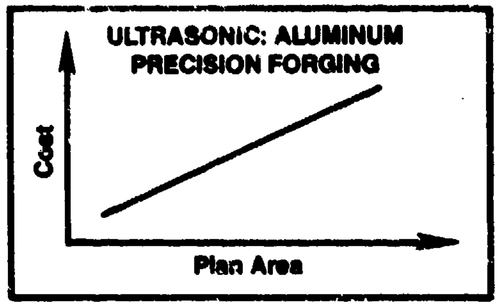




DESIGNERS! COST TRENDS

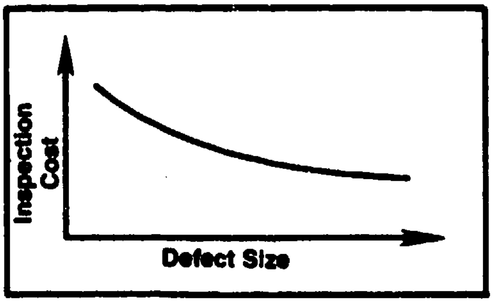
TEST, INSPECTION & EVALUATION FOR *FORGINGS:*

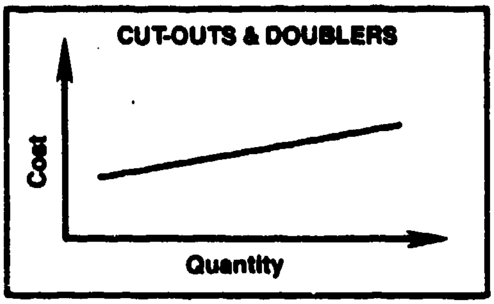


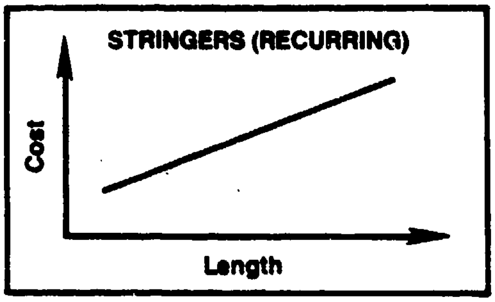


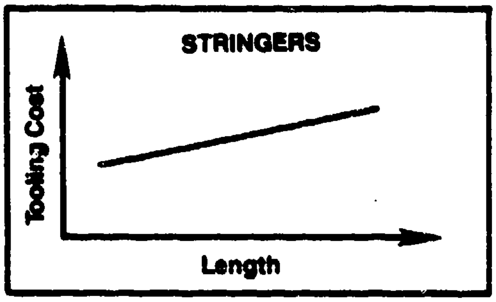
DESIGNERS! COST TRENDS

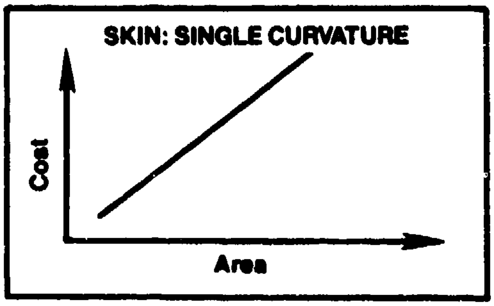
TEST, INSPECTION & EVALUATION FOR *CARBON/EPOXY COMPOSITES:*

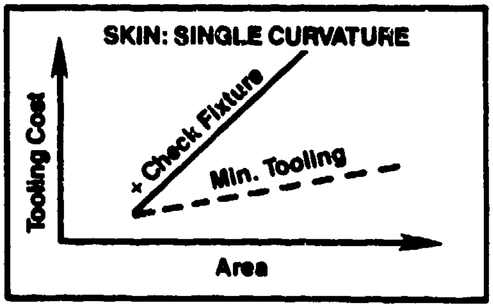


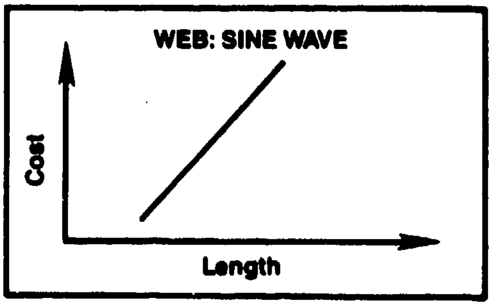


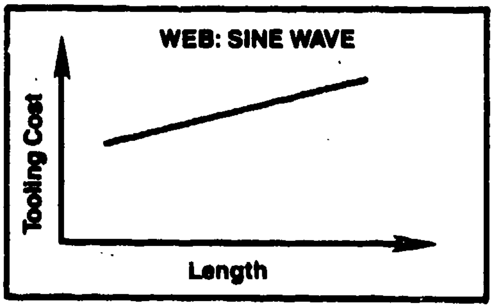












CONCEPTUAL DESIGN (CD)

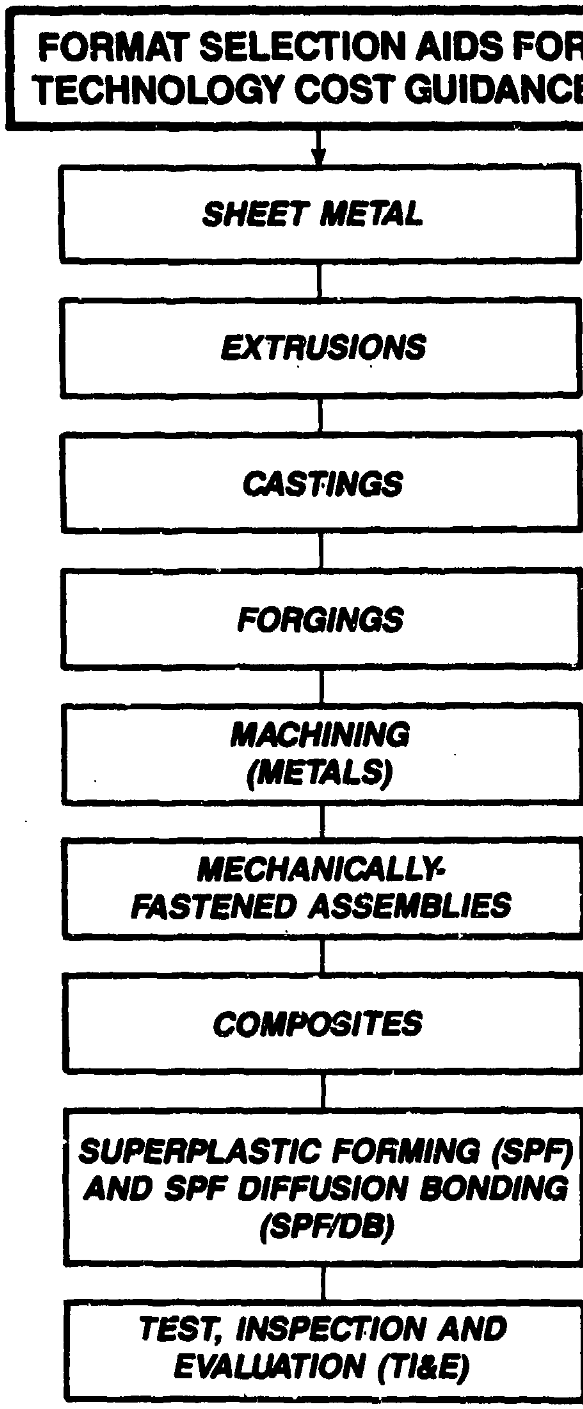
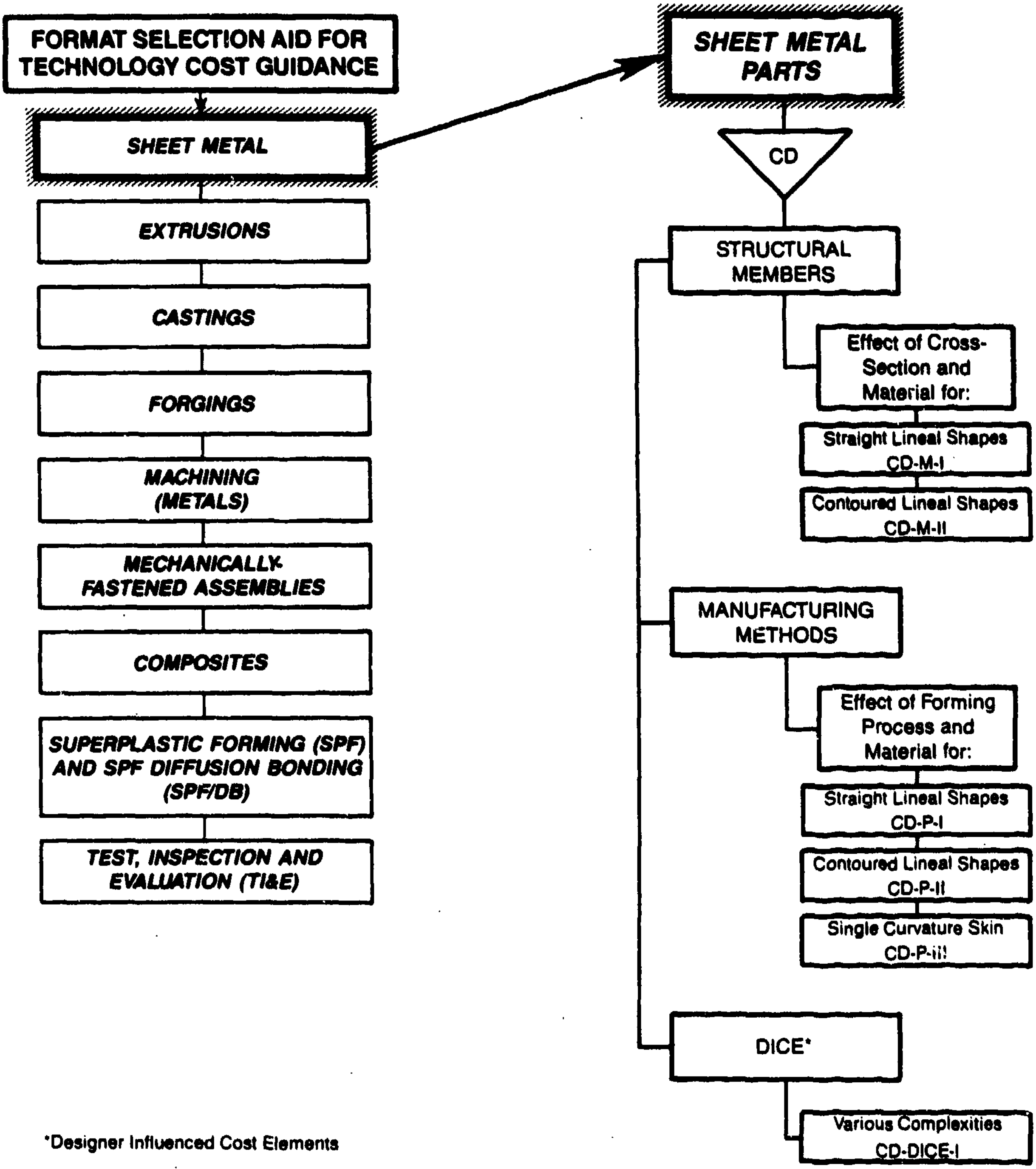


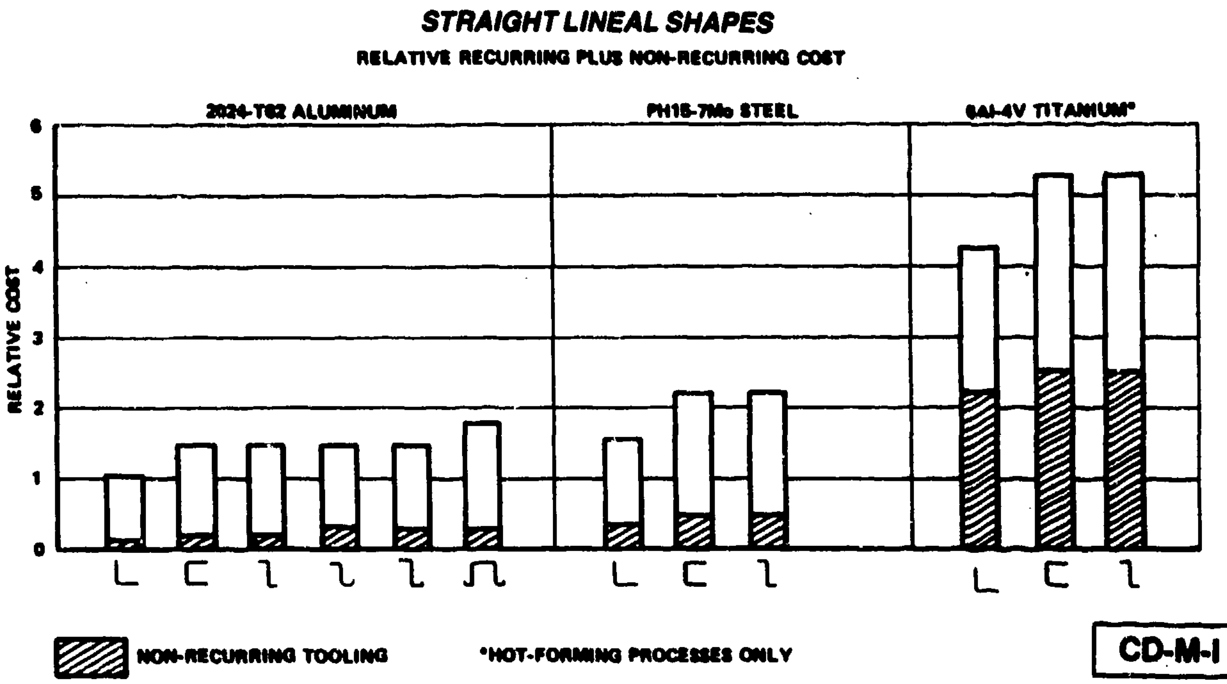
FIGURE 2.3-10 SELECTION AID FOR TECHNOLOGY COST GUIDANCE

CONCEPTUAL DESIGN (CD)



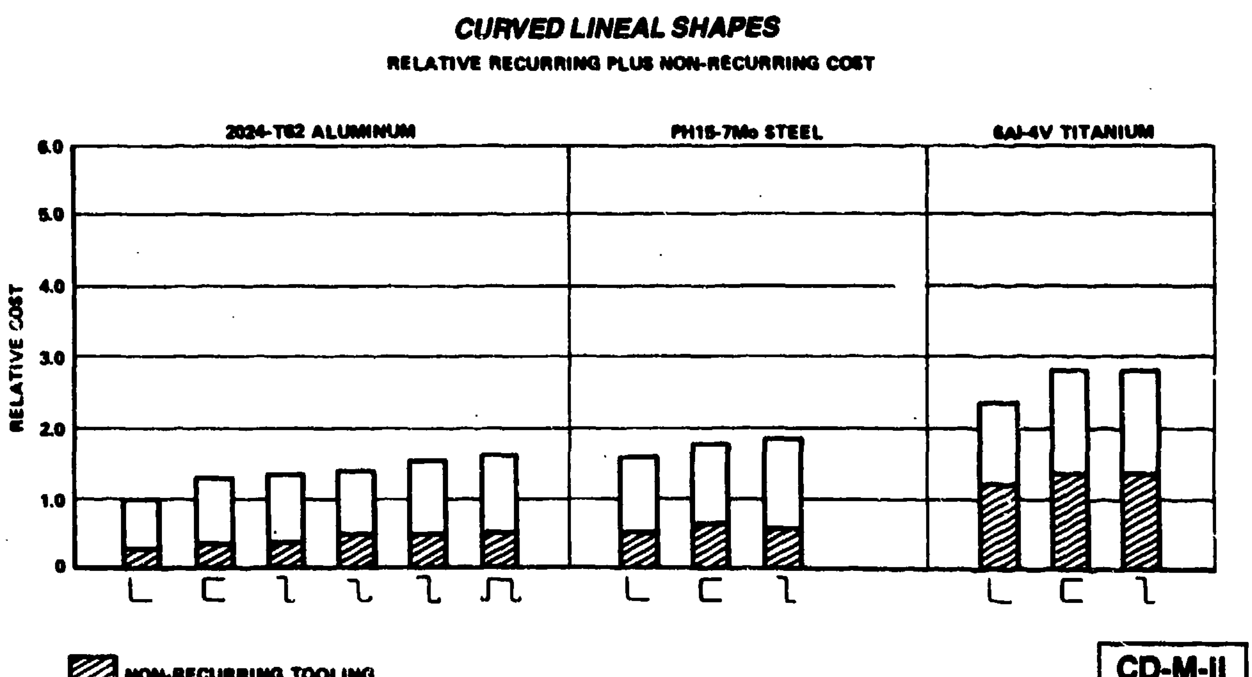
*Designer Influenced Cost Elements

EFFECT OF CROSS-SECTION AND MATERIAL ON PART FORMING COST



CD-M-I

EFFECT OF CROSS-SECTION AND MATERIAL ON PART FORMING COST

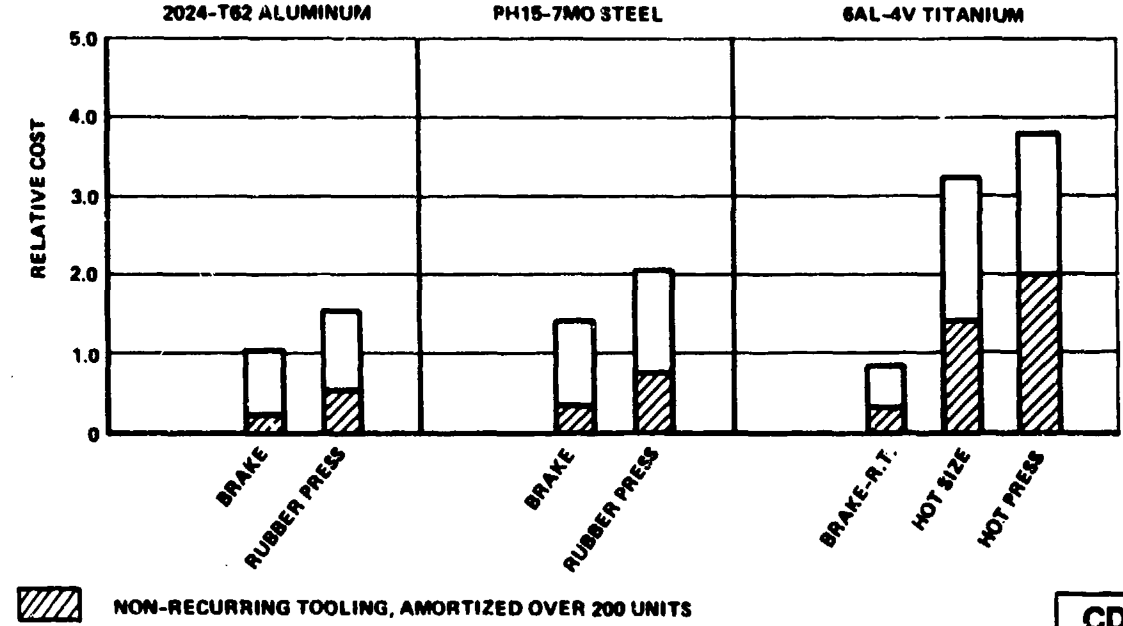


CD-M-II

EFFECT OF FORMING PROCESS AND MATERIAL ON PART FORMING COST

STRAIGHT LINEAL SHAPES

RECURRING PLUS NON-RECURRING COSTS



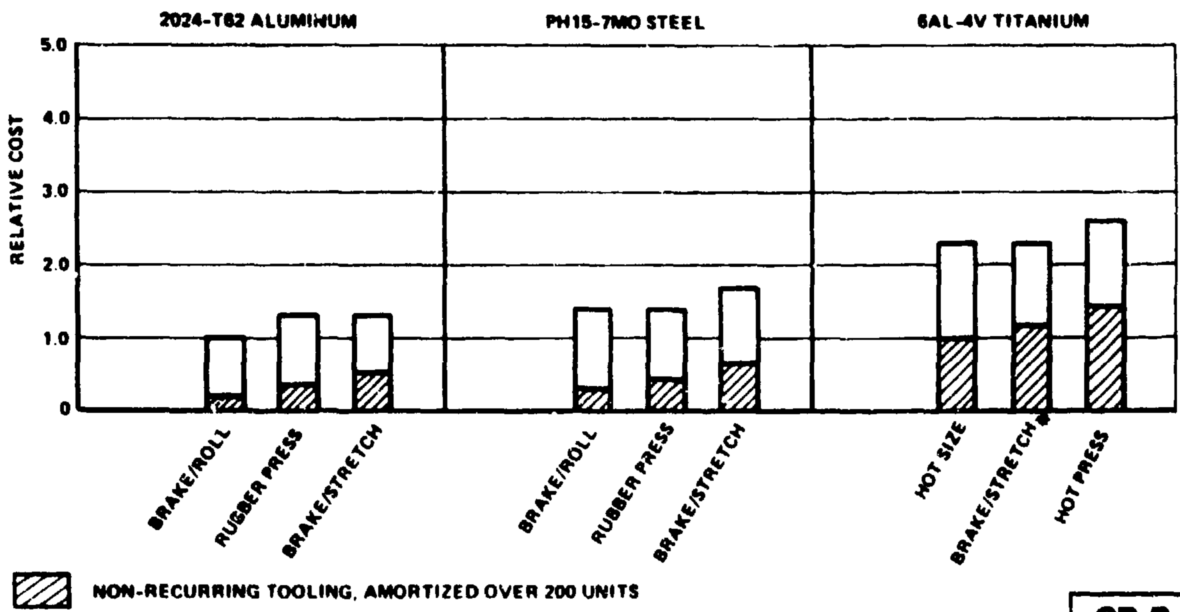
R.T.-ROOM TEMPERATURE

CD-P-I

EFFECT OF FORMING PROCESS AND MATERIAL ON PART FORMING COST

CURVED LINEAL SHAPES

RECURRING PLUS NON-RECURRING COSTS



* HOT STRETCH

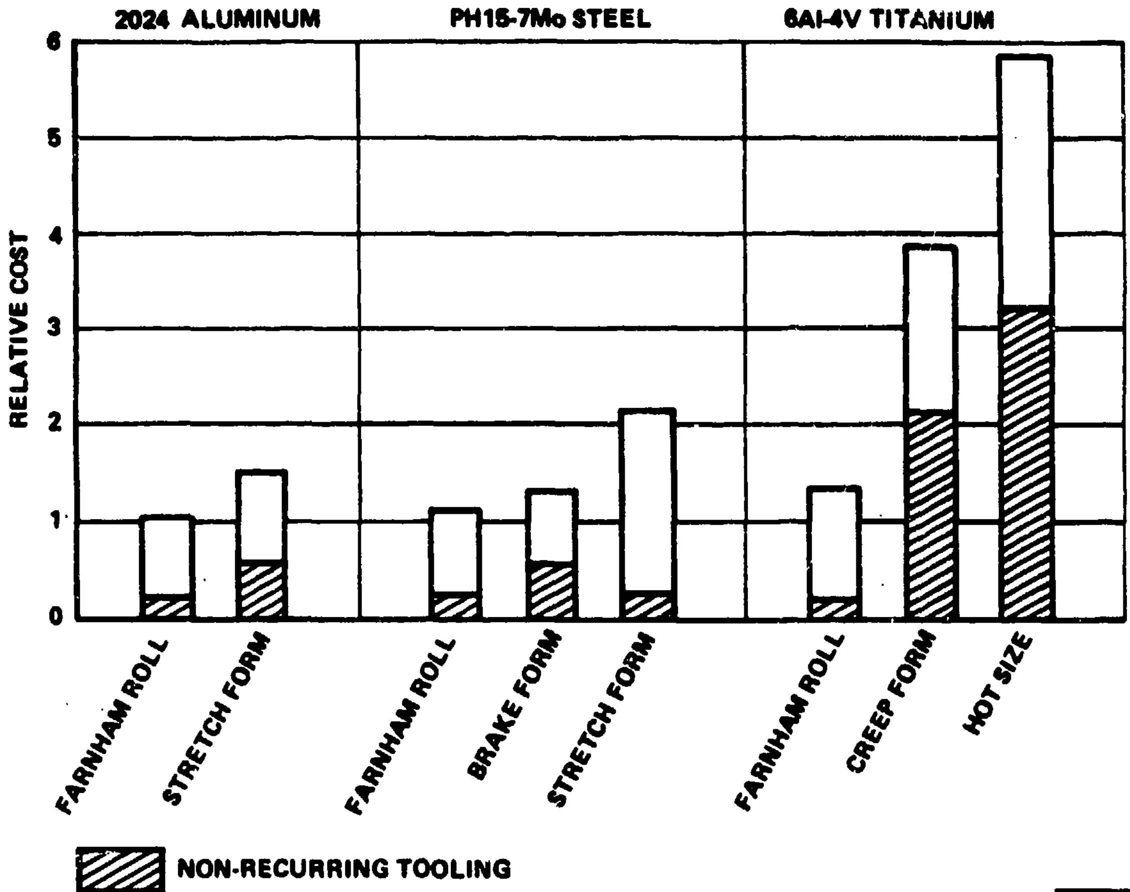
SEE GROUND RULES FOR LIMITATIONS AND CONDITIONS

CD-P-II

EFFECT OF FORMING PROCESS AND MATERIAL ON PART FORMING COST

SINGLE CURVATURE SKIN

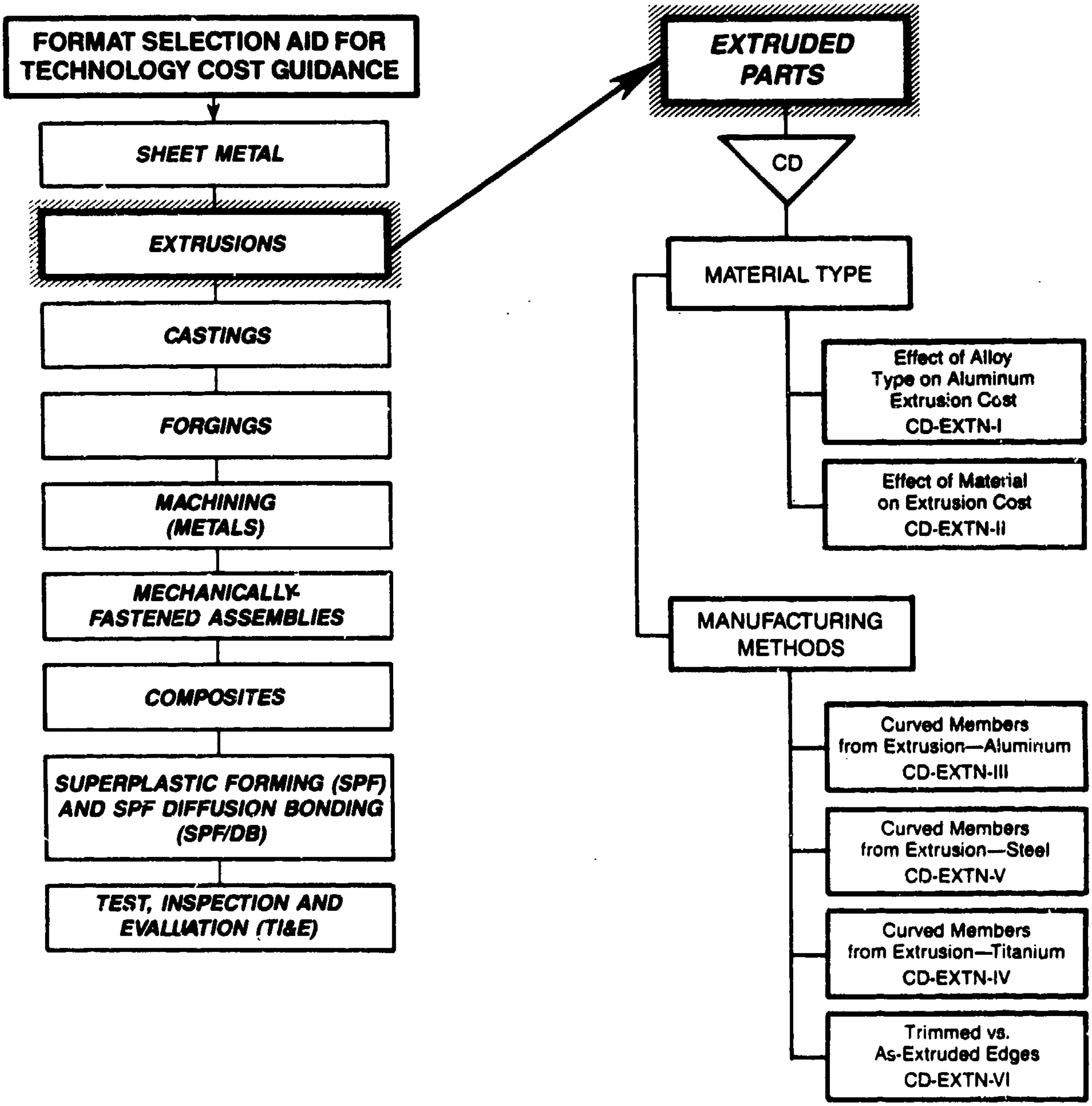
. RECURRING PLUS NON-RECURRING COSTS, INCLUDING TRIM



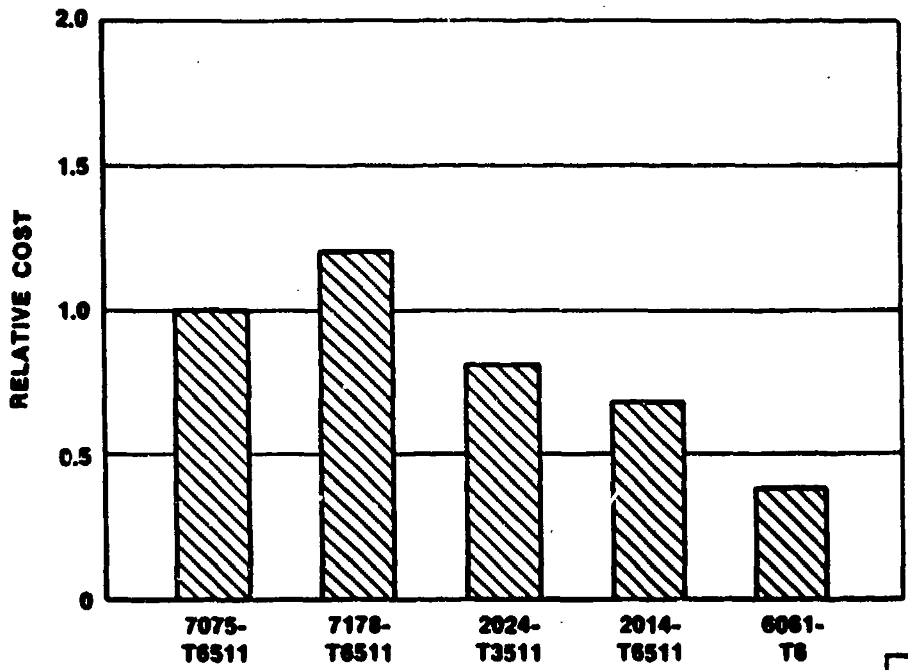
R.T. ∿ ROOM TEMPERATURE

CD-P-III

CONCEPTUAL DESIGN (CD)

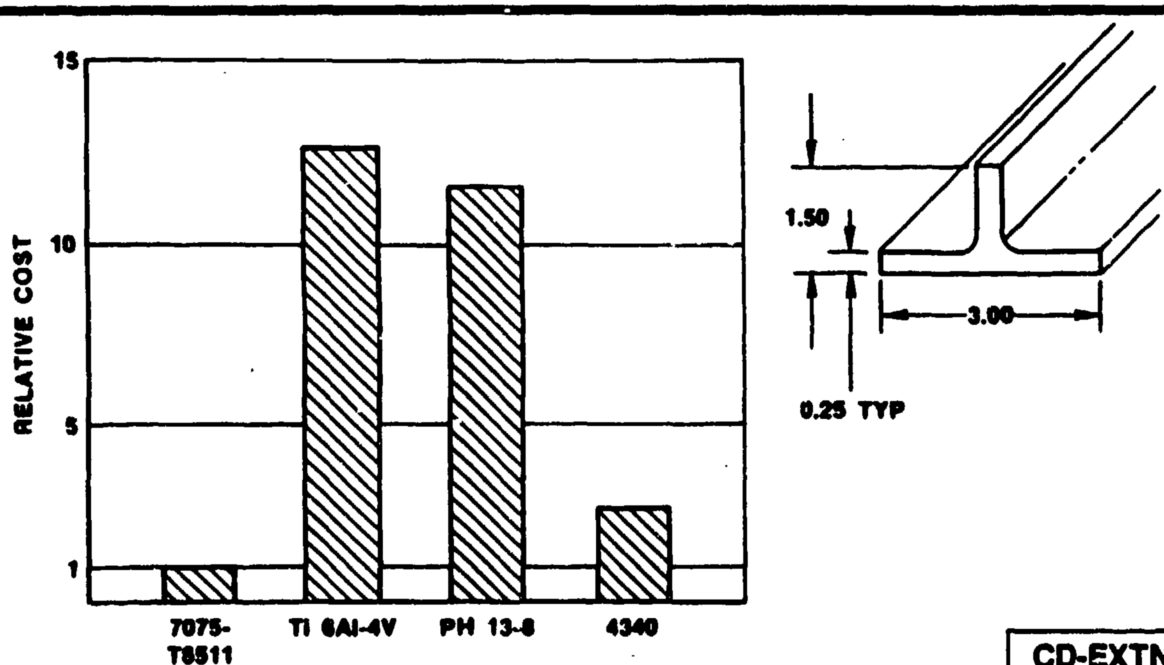


EFFECT OF MATERIAL ON COST OF ALUMINUM EXTRUSIONS



CD-EXTN-I

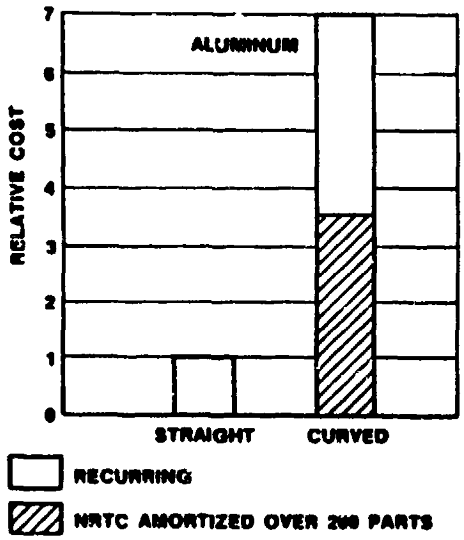
EFFECT OF MATERIAL ON THE COST/FOOT OF AN EXTRUSION



CD-EXTN-II

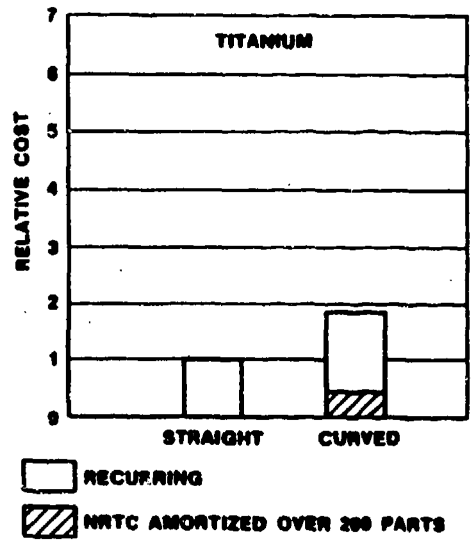
FABRICATION COST OF CURVED PARTS MADE FROM EXTRUSIONS

COMPARISON BASED ON A 8' LONG TEE EXTRUSION



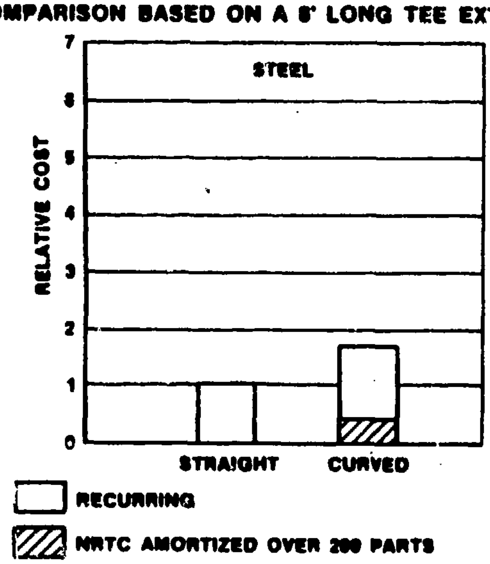
CD-EXTN-III

COMPARISON BASED ON A 8' LONG TEE EXTRUSION



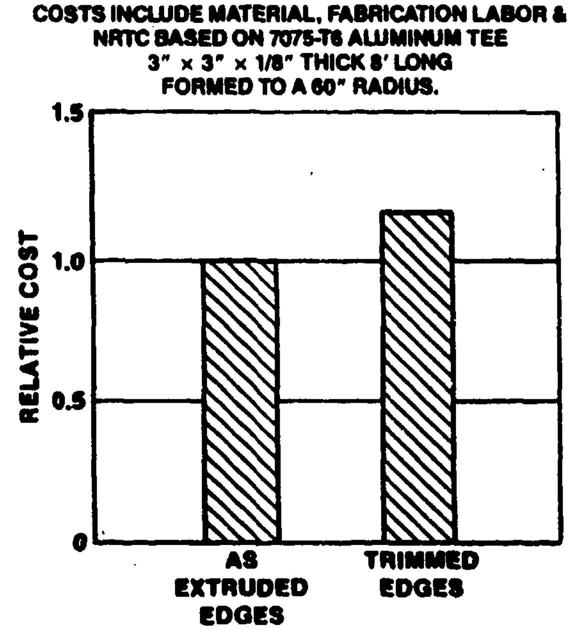
CD-EXTN-IV

COMPARISON BASED ON A 8' LONG TEE EXTRUSION



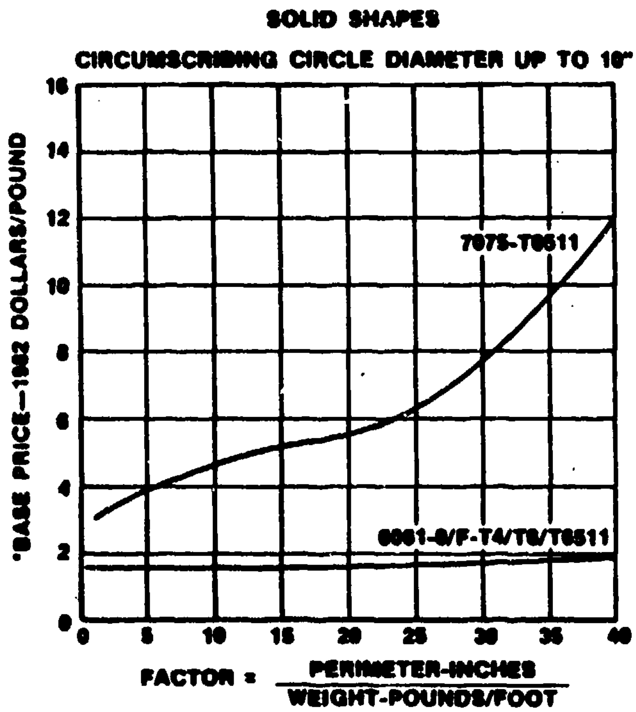
CD-EXTN-V

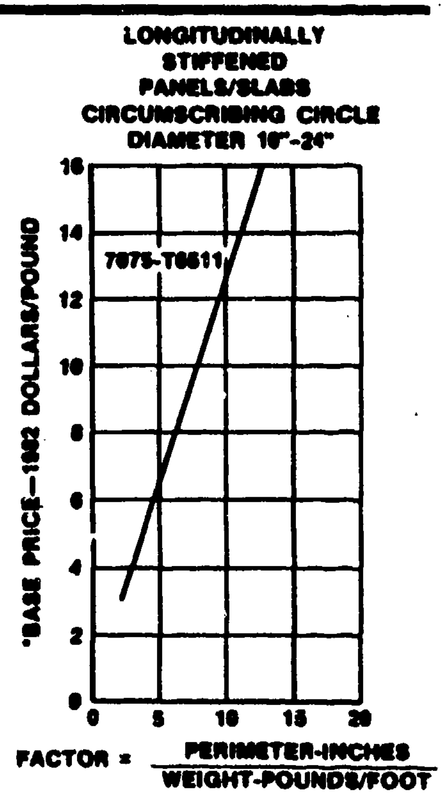
COST IMPACT OF TRIMMED EDGES COMPARED TO AS EXTRUDED EDGES



CD-EXTN-VI

MATERIAL COST—ALUMINUM

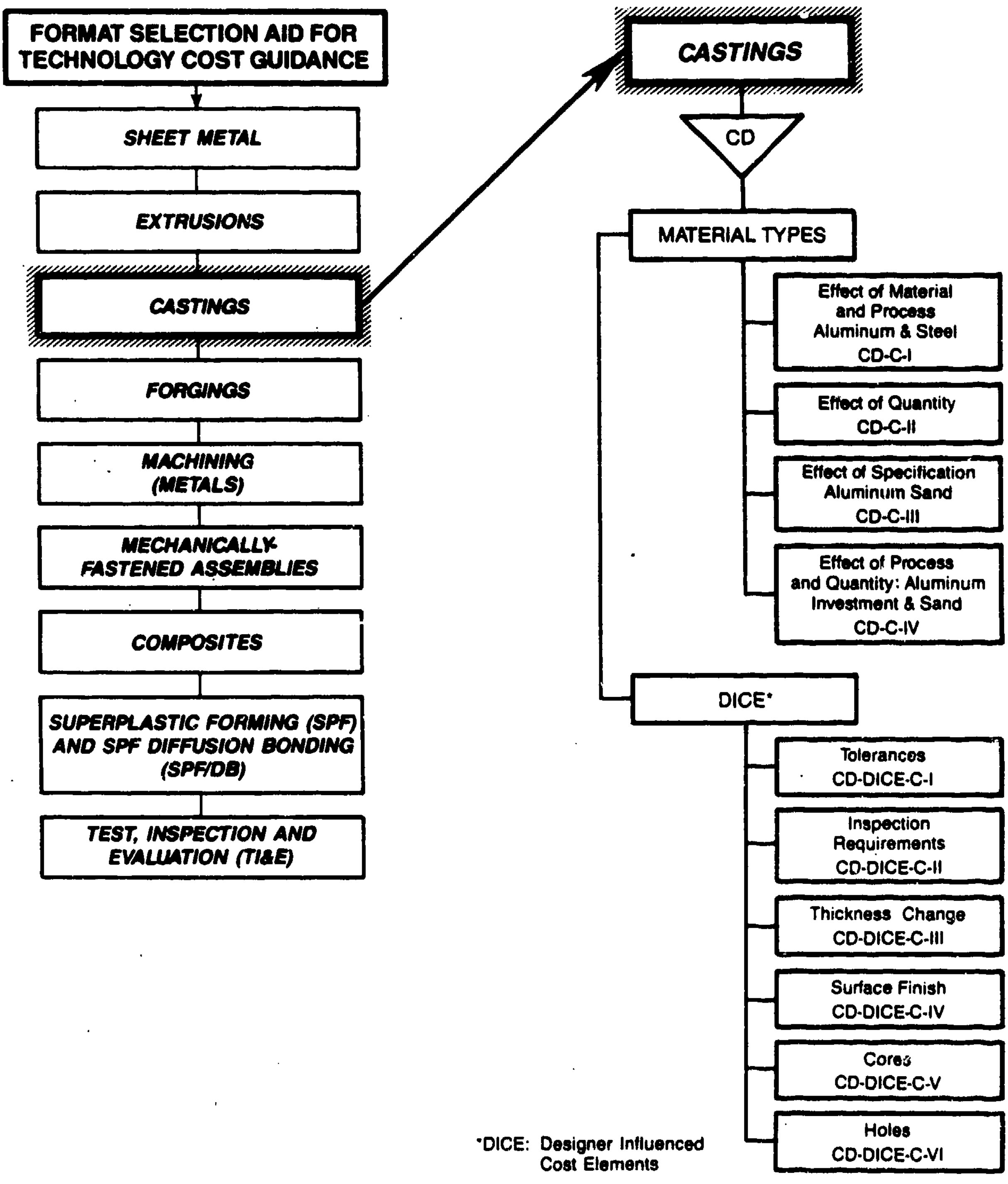




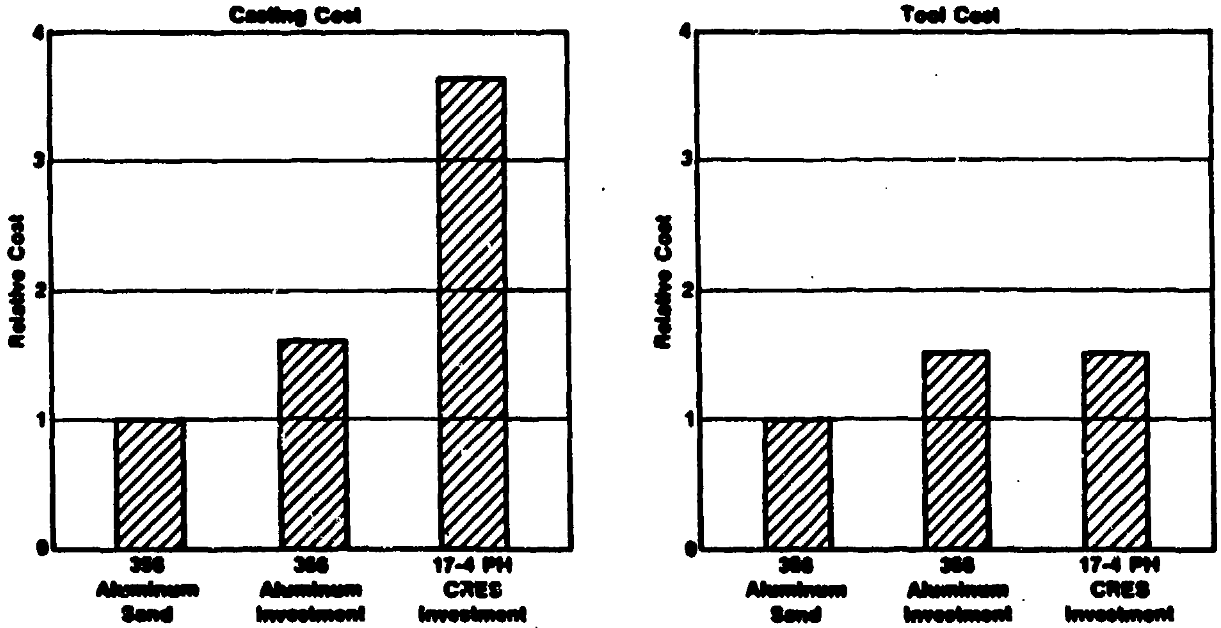
*INCLUDES TEST, INSPECTION AND EVALUATION (TI&E) COST FOR THE AS-EXTRUDED MATERIAL.

CD-EXTN-VII

CONCEPTUAL DESIGN (CD)

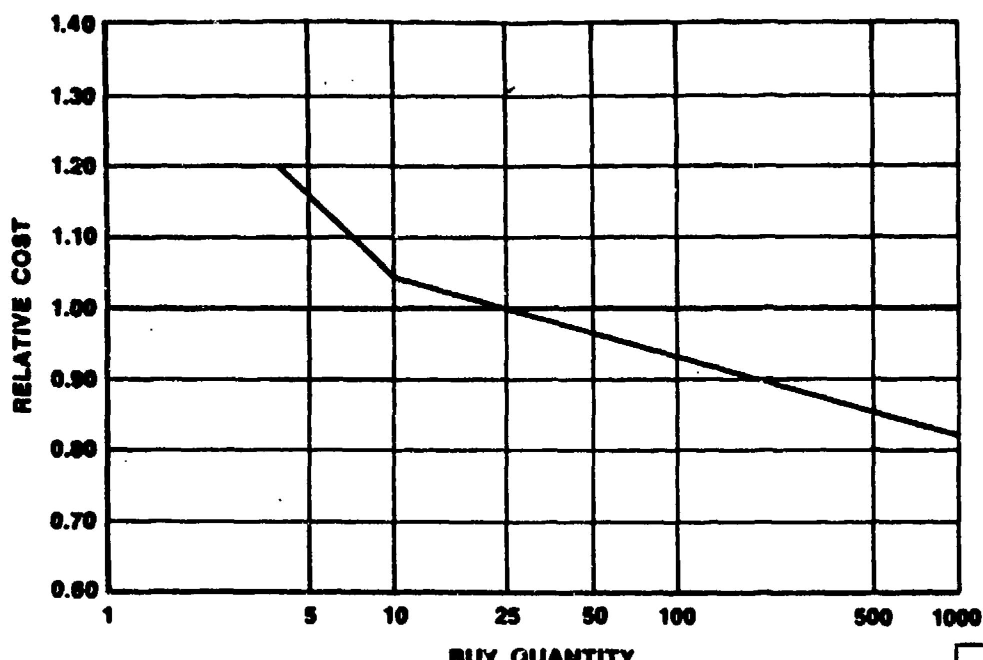


COST IMPACT OF CASTING MATERIAL & FOUNDRY PROCESS



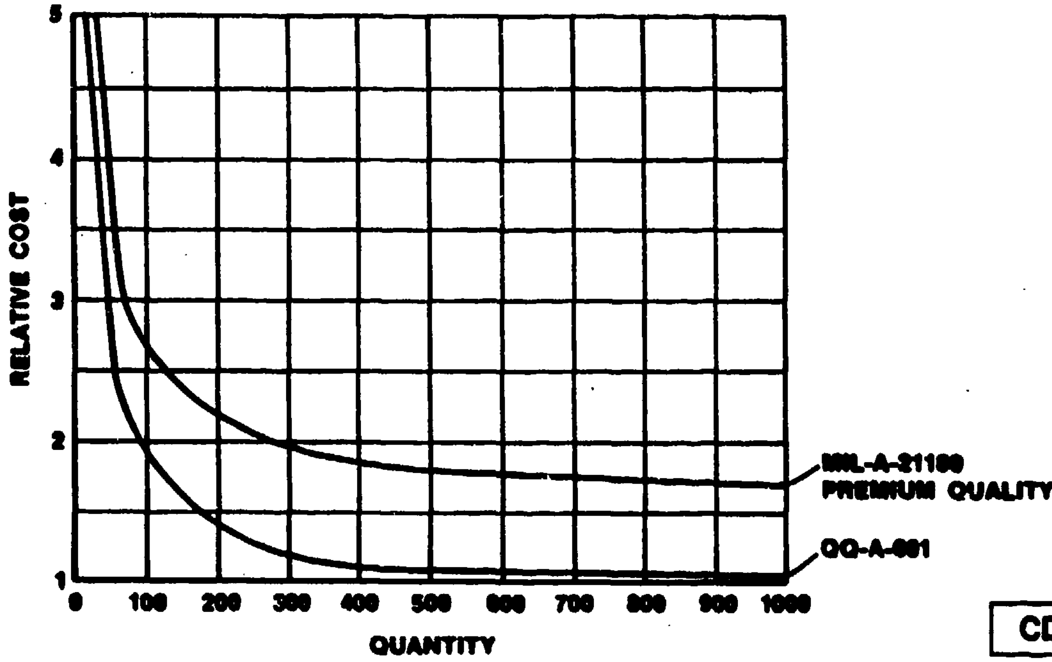
CD-C-I

EFFECT OF BUY QUANTITY ON CASTING COST ALL MATERIALS AND CASTING PROCESSES



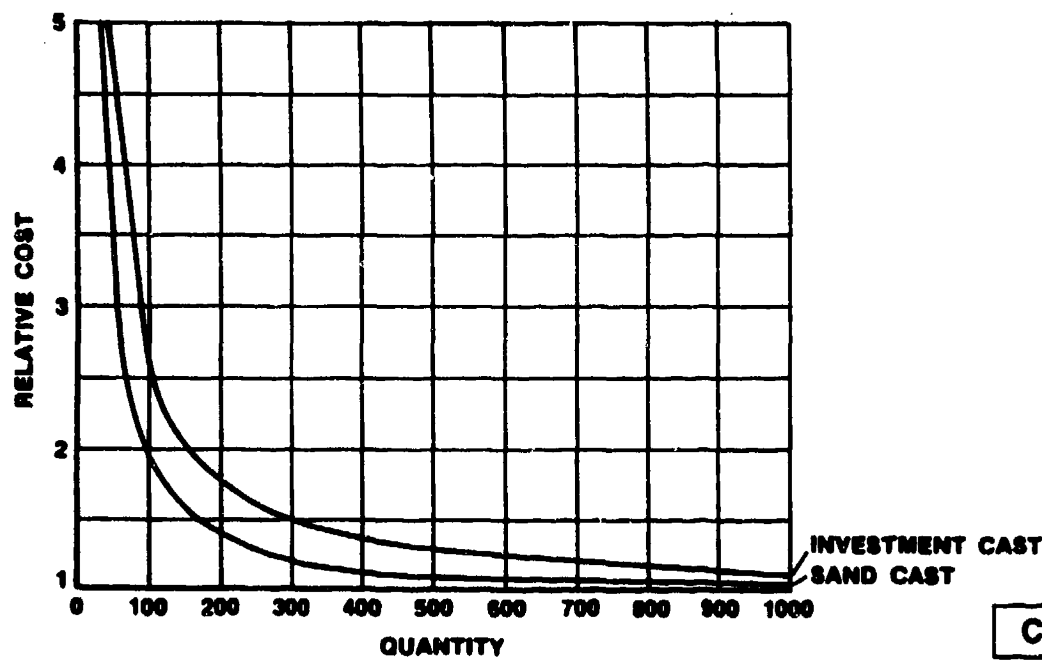
CD-C-II

EFFECT OF "SPECIFICATION SELECTION" ON COST OF 356/A356 ALUMINUM SAND CASTINGS

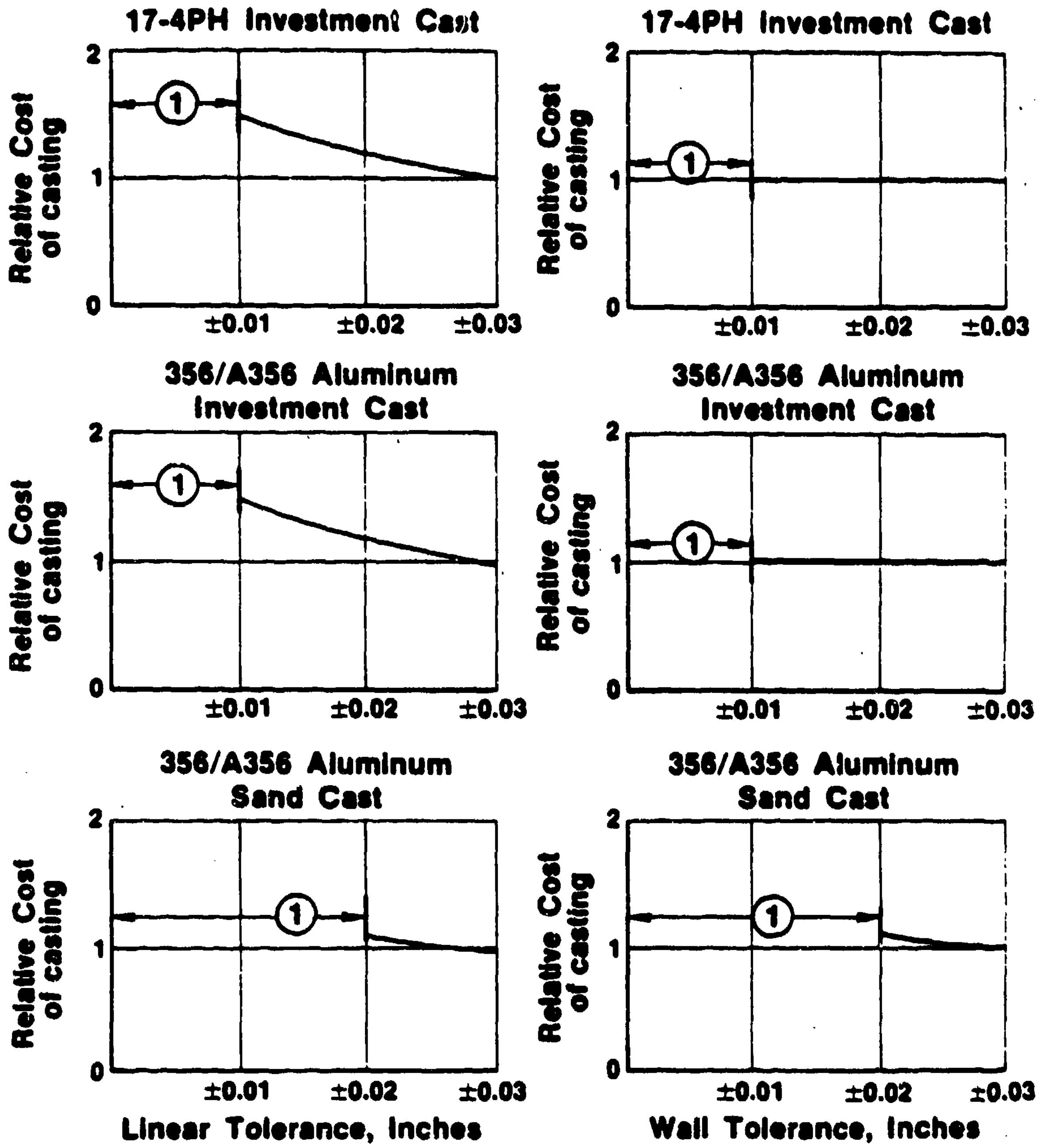


CD-C-III

EFFECT OF "FOUNDRY PROCESS" ON COST OF 356/A356 ALUMINUM CASTINGS



CD-C-IV



① Impractical
② Based on a 7-Inch Linear Dimension

CD-DICE-C-I

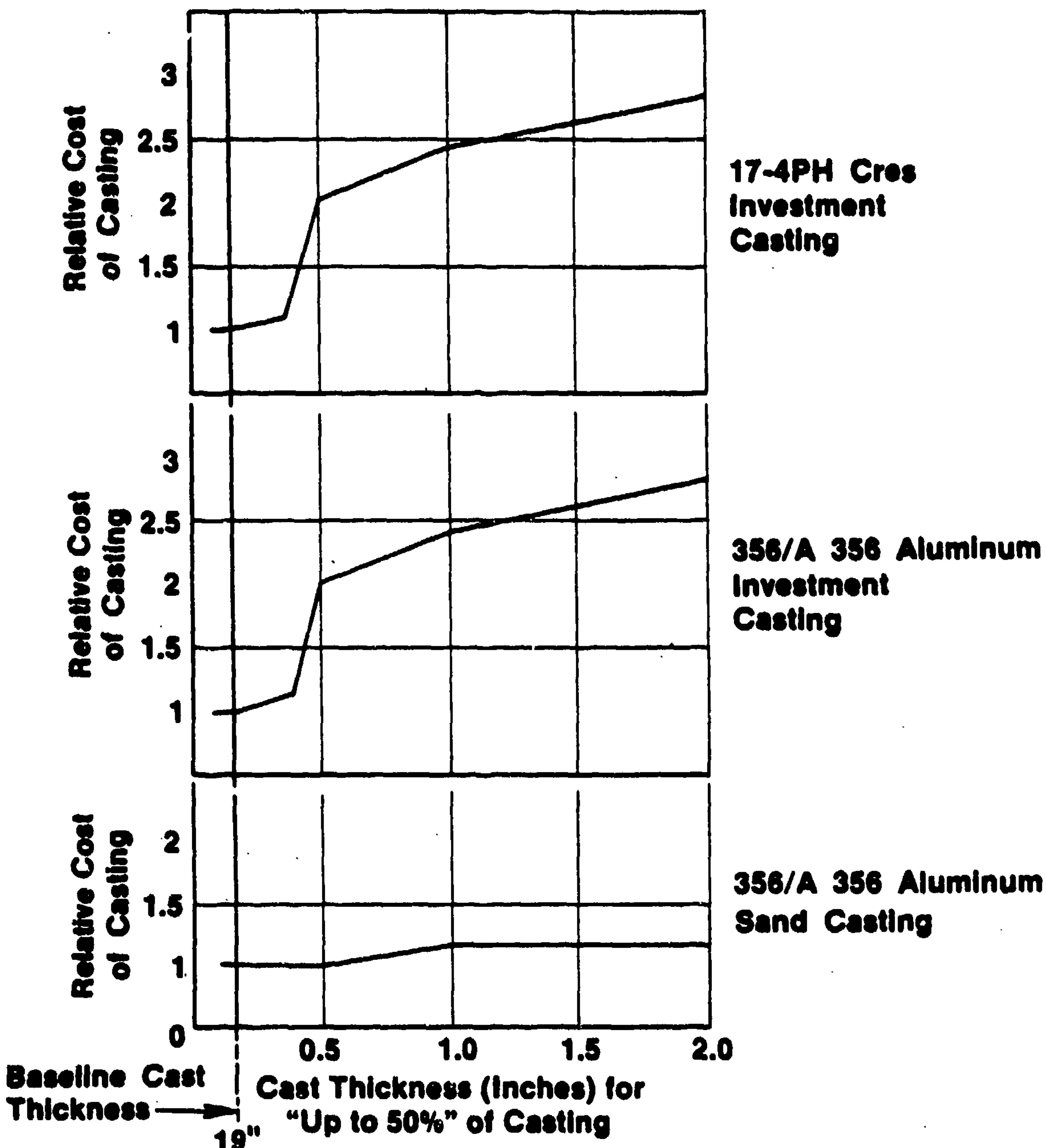
X-RAY GRADE REQUIREMENT

CASTING MATERIAL & PROCESS	X—RAY GRADE	COST EFFECT
356/A356 ALUMINUM SAND CAST	D OR C D OR C WITH 10% B D OR C WITH 50% B B	BASE +15% +25% +50%
356/A356 ALUMINUM INVESTMENT CAST	D OR C D OR C WITH 10% B D OR C WITH 50% B B	BASE +10% +20% +50%
17-4PH CRES INVESTMENT CAST	D OR C D OR C WITH 10% B D OR C WITH 50% B B	BASE +20% +30% +60%

NOTE: X-Ray Grade A is an Impractical Requirement for General or Local Areas of Casting.

CD-DICE-C-II

COST IMPACT OF CHANGE IN CAST THICKNESS



CD-DICE-C-III

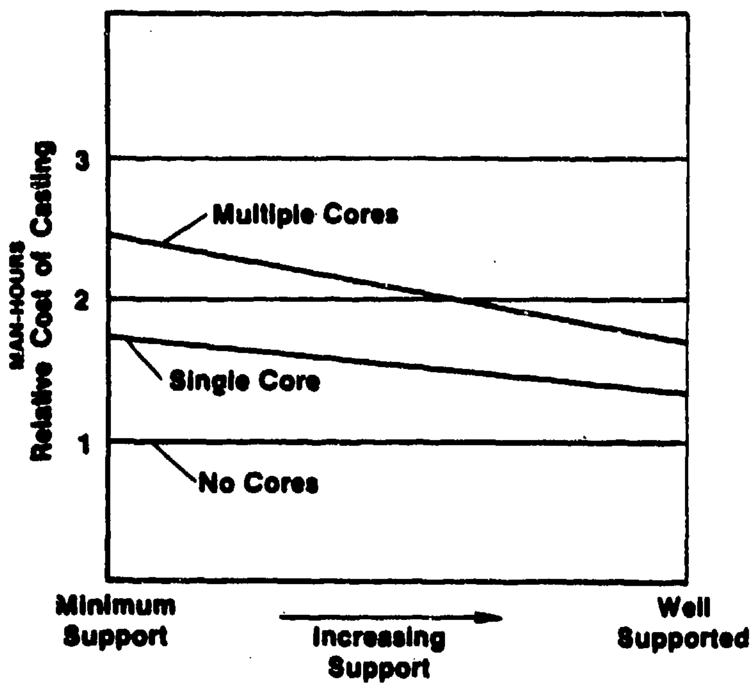
CAST SURFACE FINISH

Casting Surface		Cost Effort			
Cast Surface Finish Designation	Equivalent Machine Finish - Micro Inches	356/A356 Aluminum Sand Casting		356/A356 Aluminum & 17-4 Cres Investment Casting	
		% of Surface		% of Surface	
		10%	50%	10%	50%
C-25	250	Base	Base	Base	Base
C-20	200	+10%	+20%	↕	↕
C-15	150	+10%	①	↕	↕
C-12	125	+10%	①	Base	Base
C-9	90	①	①	①	①
C-6	63	①	①	①	①

① Impractical

CD-DICE-C-IV

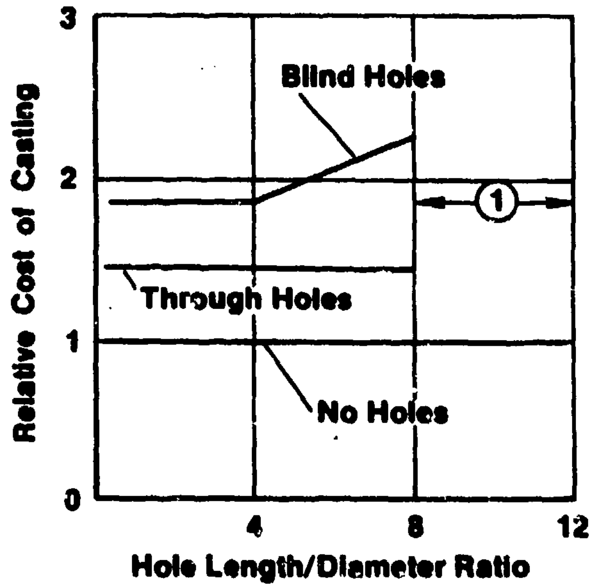
IMPACT OF CORES AND DEGREE OF CORE SUPPORT ON COST OF ALUMINUM SAND CASTINGS



CD-DICE-C-V

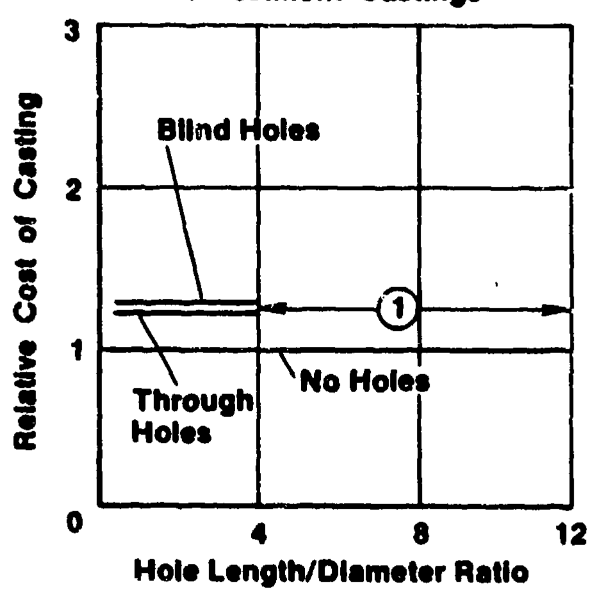
EFFECT OF THROUGH & BLIND HOLES ON THE COST OF CASTINGS

356/A356 Aluminum
Sand Castings



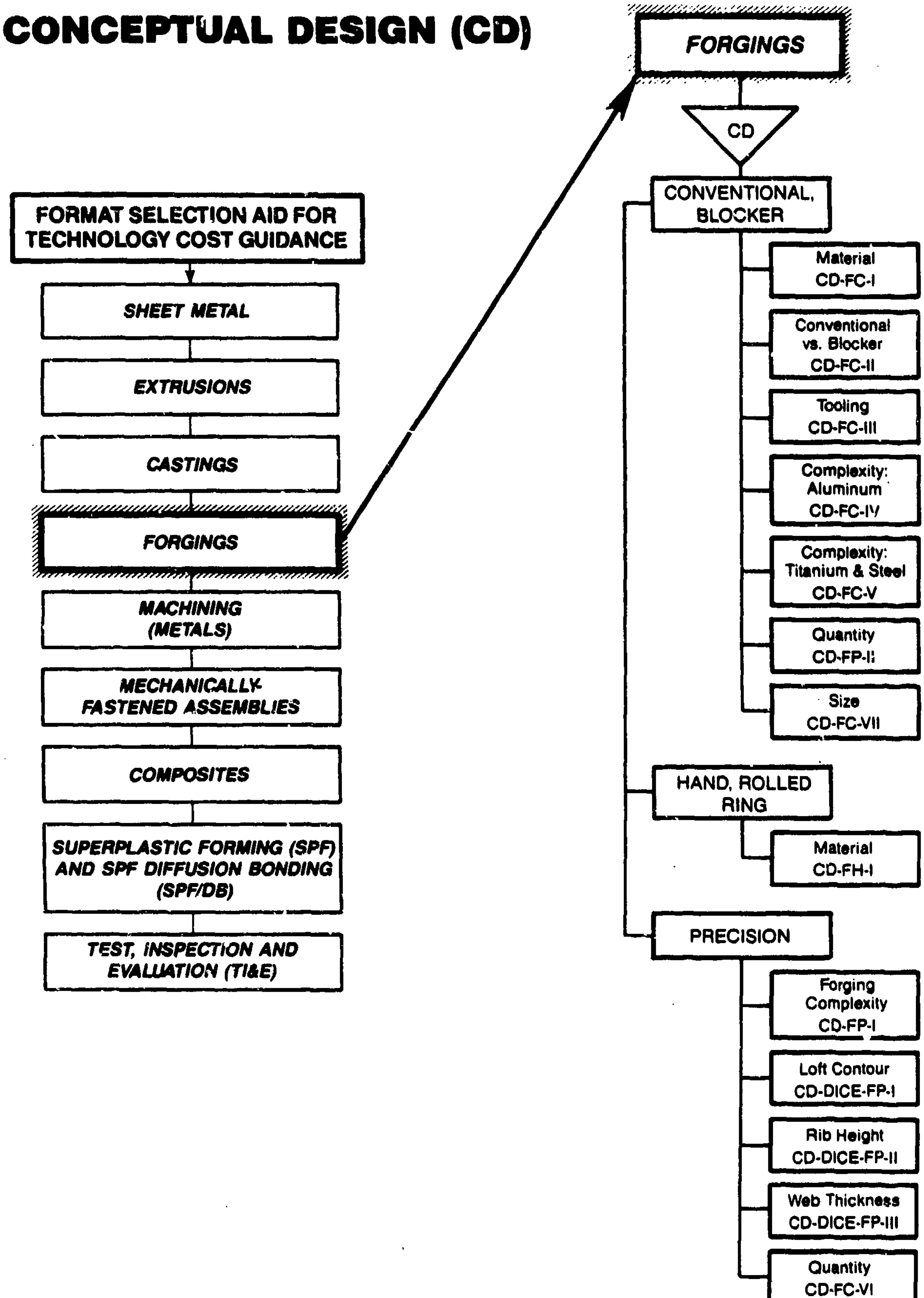
(1) Impractical

356/A356 Aluminum & 17-4 Cres
Investment Castings

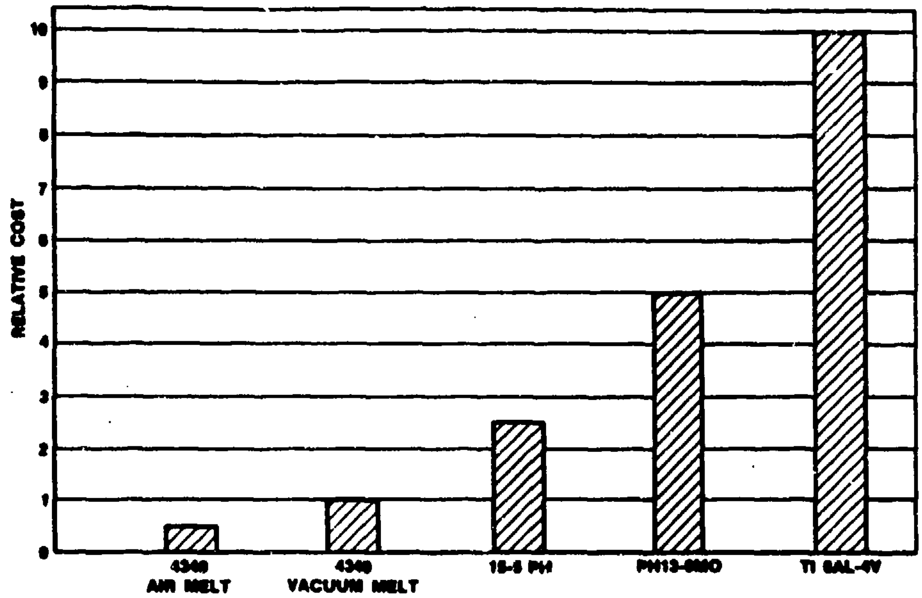


CD-DICE-C-VI

CONCEPTUAL DESIGN (CD)



IMPACT OF MATERIAL ON RECURRING COST OF TITANIUM AND STEEL CONVENTIONAL FORGINGS



CD-FC-I

COST OF CONVENTIONAL VS. BLOCKER FORGINGS

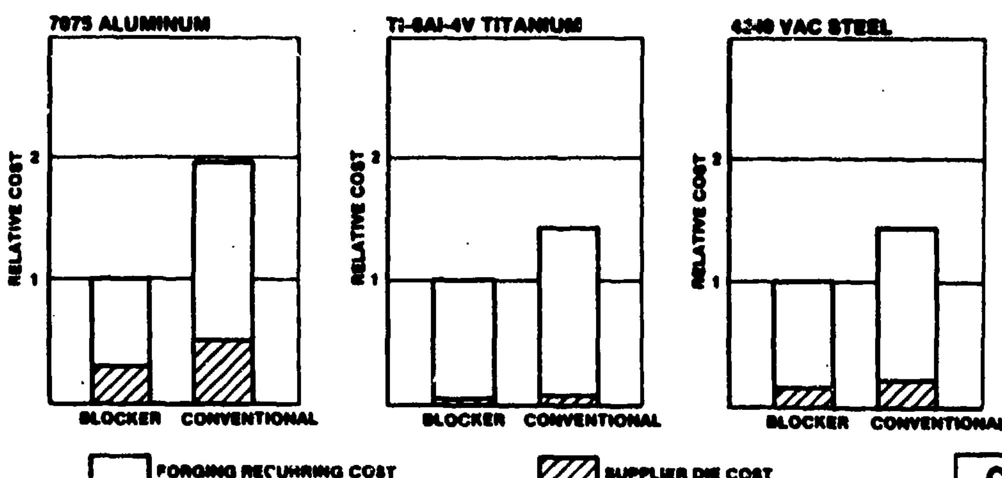
PREMISES

FINISHED PART — VOLUME — 160 CU IN.; PLAN AREA — 170 SQ. IN.; L-36", W-6", H-3"

DESIGN QUANTITY — 200 PARTS; BUY QUANTITY — 50 PARTS

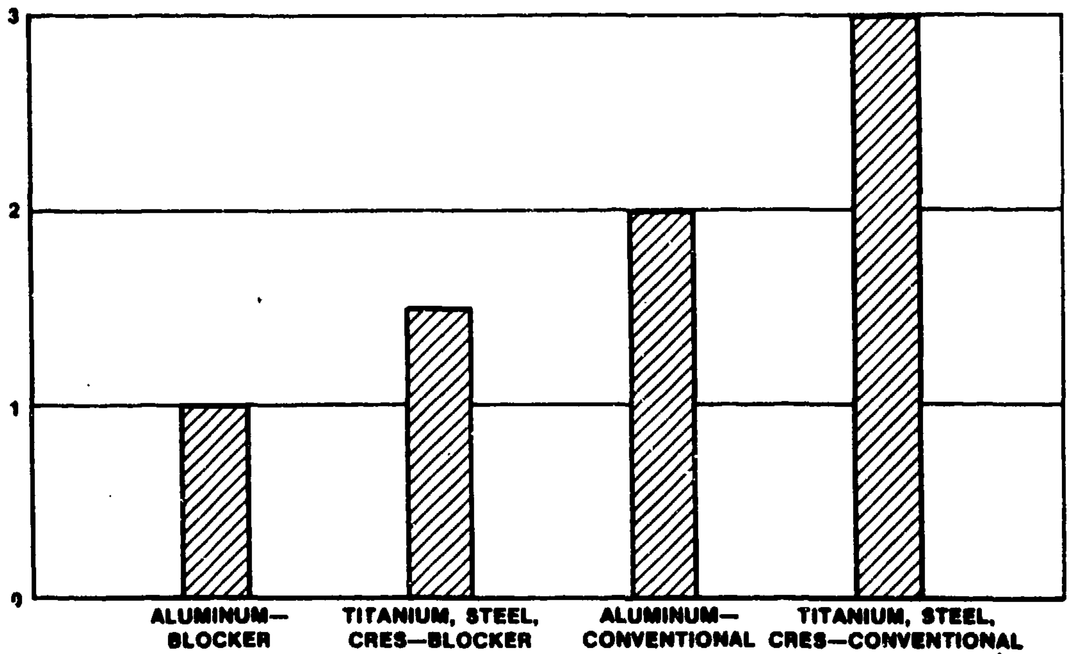
MACHINING OF FORGING TO FINISHED PART NOT INCLUDED

MATERIAL	FINISHED WEIGHT	AS-FORGED CONVENTIONAL	AS-FORGED BLOCKER
7075 ALUMINUM	10 LB.	30 LB.	50 LB.
TI-6AI-4V	16 LB.	80 LB.	112 LB.
4340 VAC STEEL	28 LB.	140 LB.	198 LB.



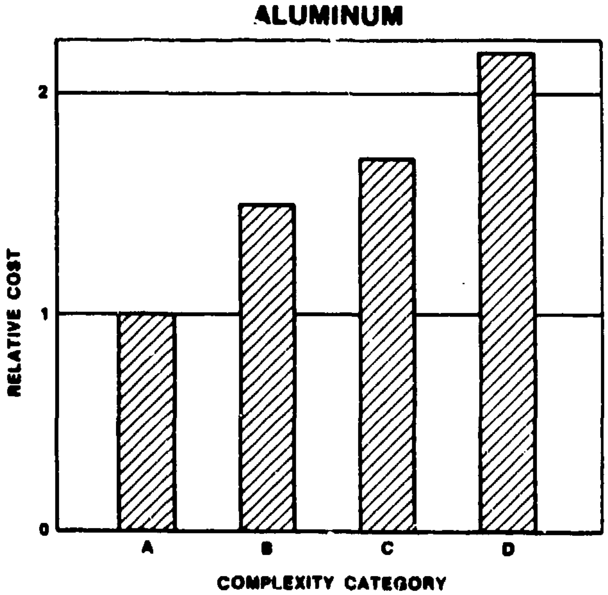
CD-FC-II

IMPACT OF SUPPLIER TOOLING COST

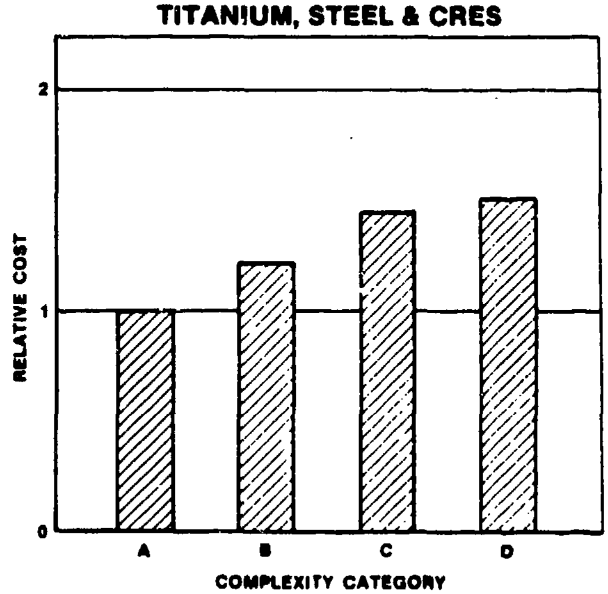


CD-FC-III

IMPACT OF COMPLEXITY ON RECURRING COST OF CONVENTIONAL FORGINGS

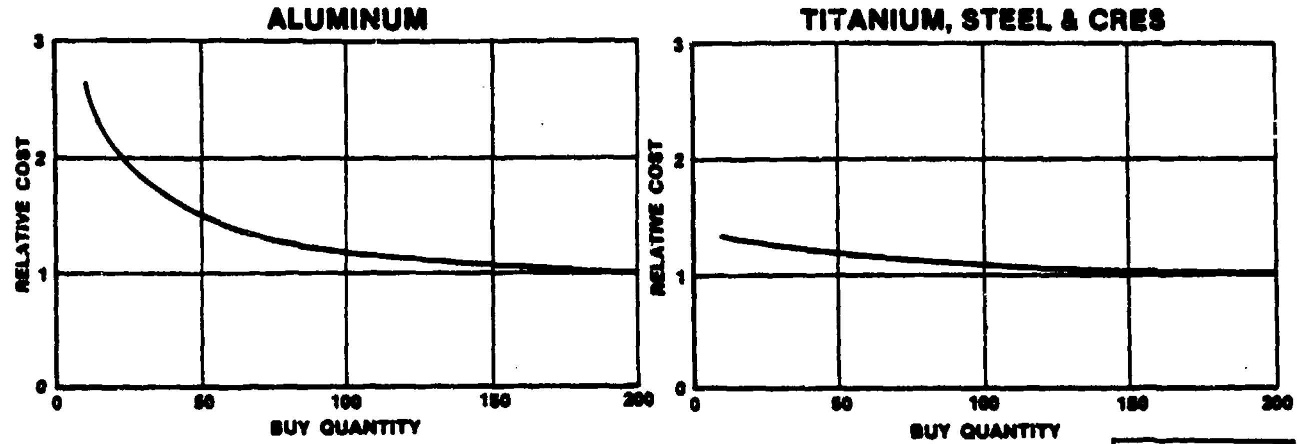


CD-FC-IV



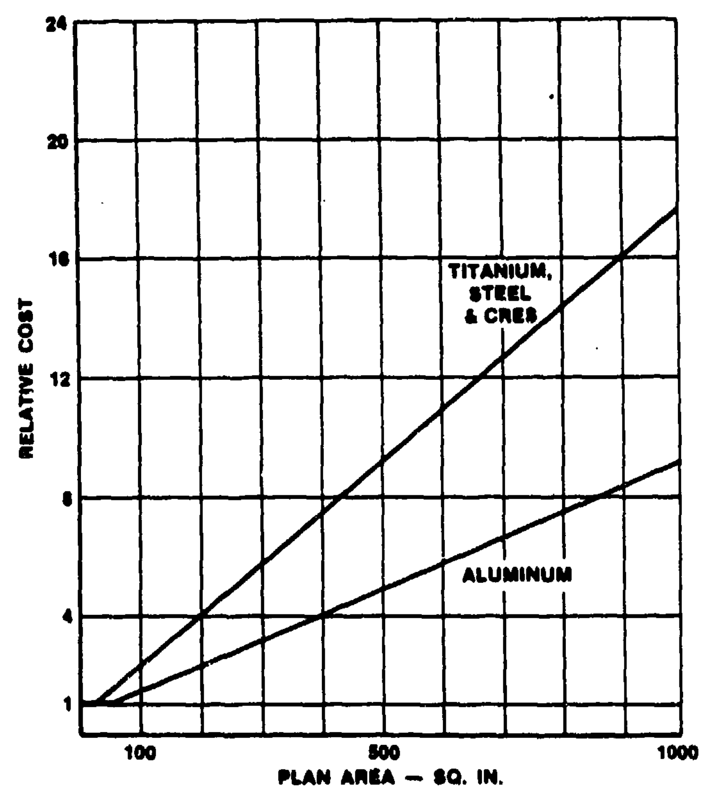
CD-FC-V

IMPACT OF QUANTITY ON RECURRING COST OF CONVENTIONAL FORGINGS



CD-FC-VI

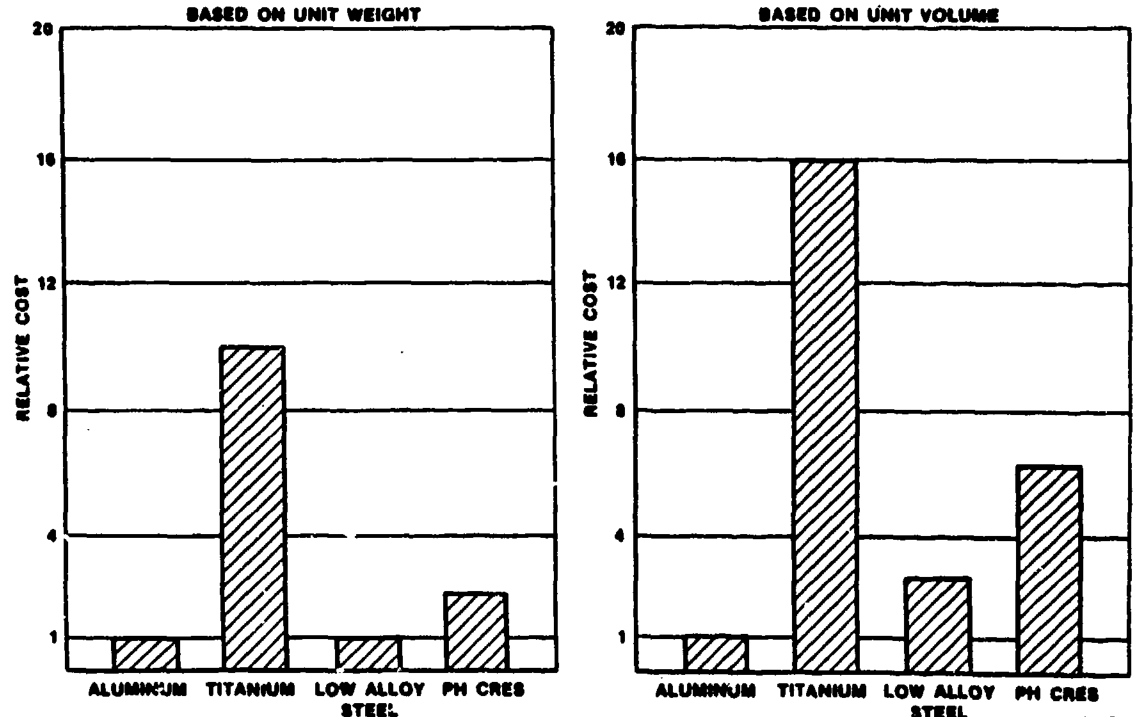
IMPACT OF FORGING SIZE (PLAN AREA) ON THE SETUP COST/PART FOR CONVENTIONAL FORGINGS



NOTE: BASED ON BUY QUANTITY OF 25

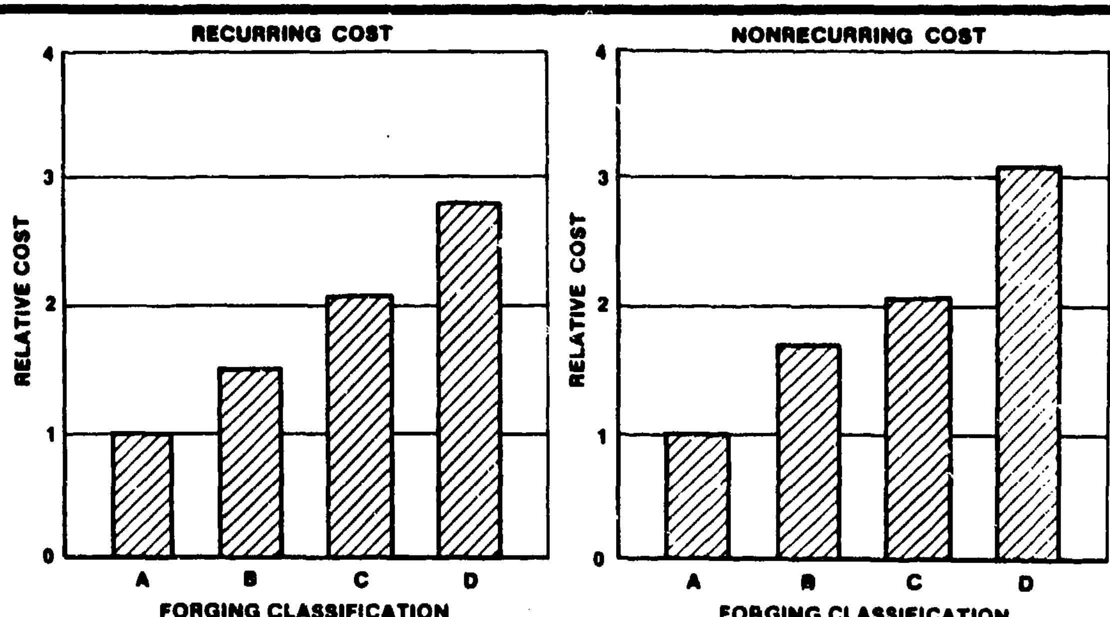
CD-FC-VII

HAND AND ROLLED RING FORGING
EFFECT OF MATERIAL ON COST/POUND OR COST/CUBIC INCH



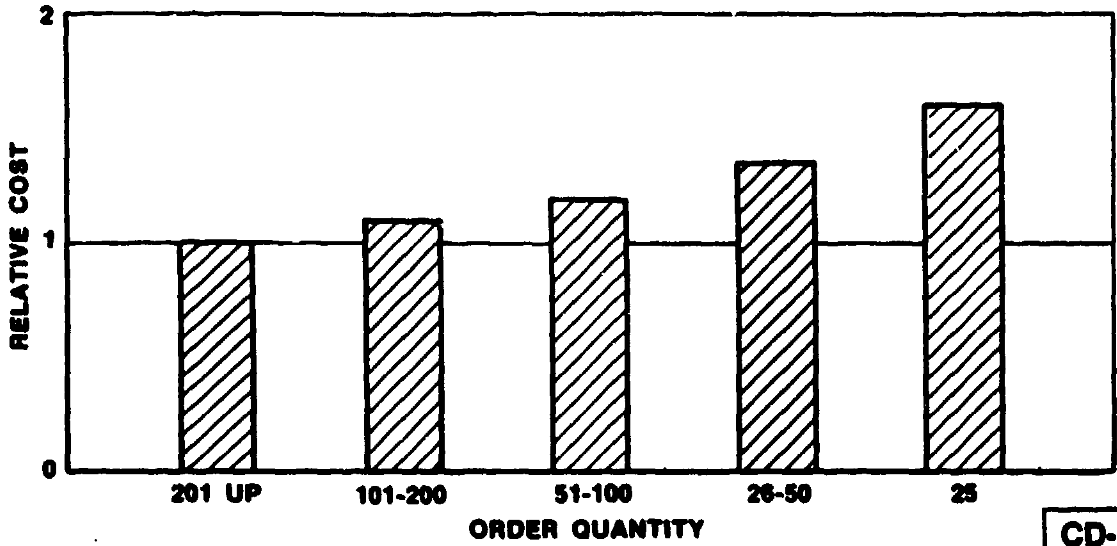
CD-FH-I

ALUMINUM PRECISION FORGING
EFFECT OF FORGING COMPLEXITY ON RECURRING AND NONRECURRING COSTS



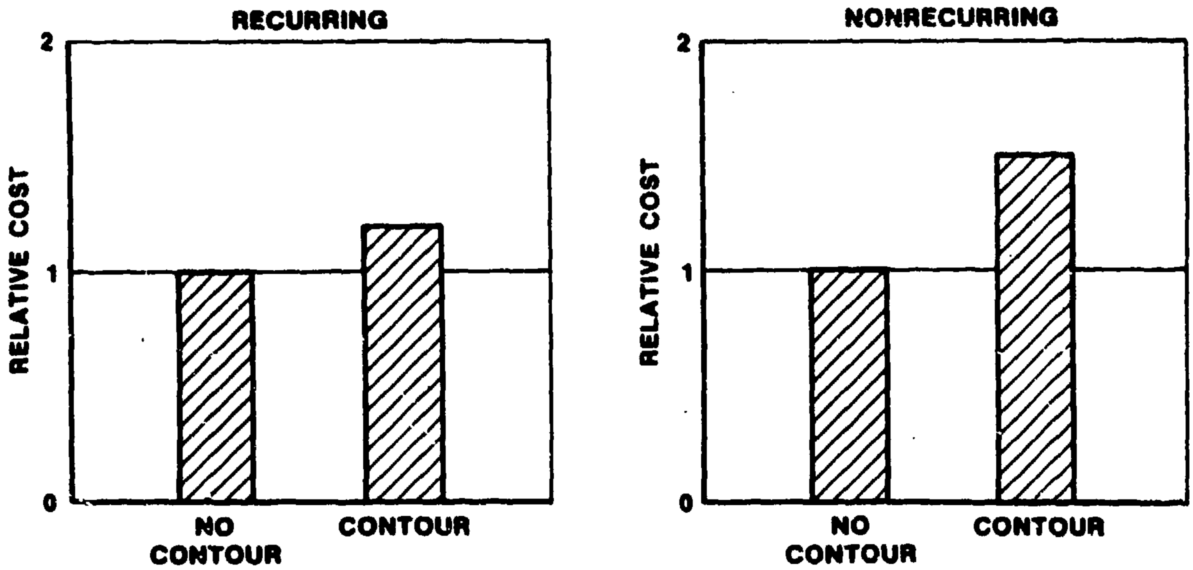
CD-FP-I

ALUMINUM PRECISION FORGING
EFFECT OF ORDER QUANTITY ON RECURRING COST



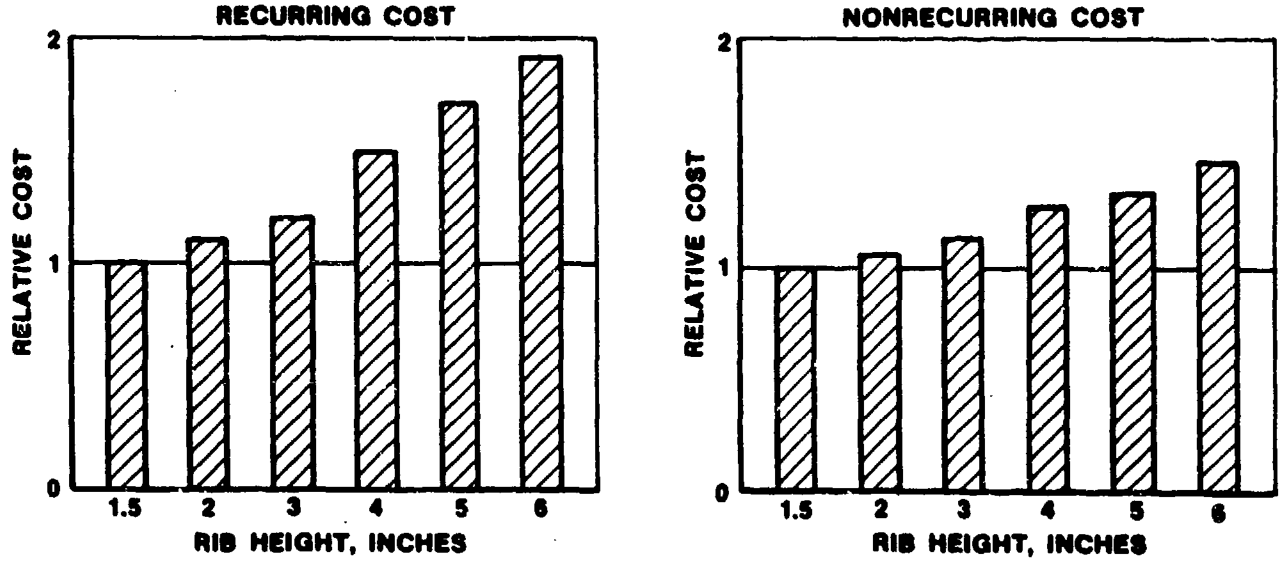
CD-FP-II

ALUMINUM PRECISION FORGINGS
EFFECT OF LOFT CONTOUR ON RECURRING AND NONRECURRING COST



CD-DICE-FP-I

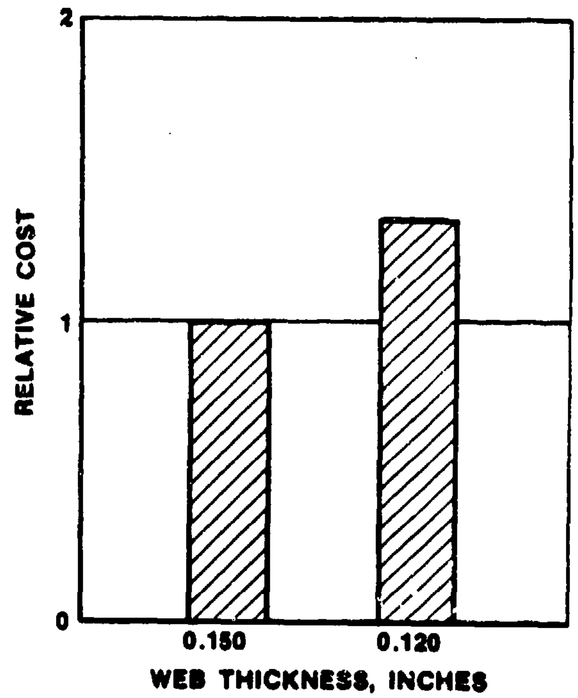
ALUMINUM PRECISION FORGINGS
EFFECT OF RIB HEIGHT ON RECURRING AND NONRECURRING COST



NOTE: BASED ON A 100 SQ. IN. CLASSIFICATION "D" FORGING

CD-DICE-FP-II

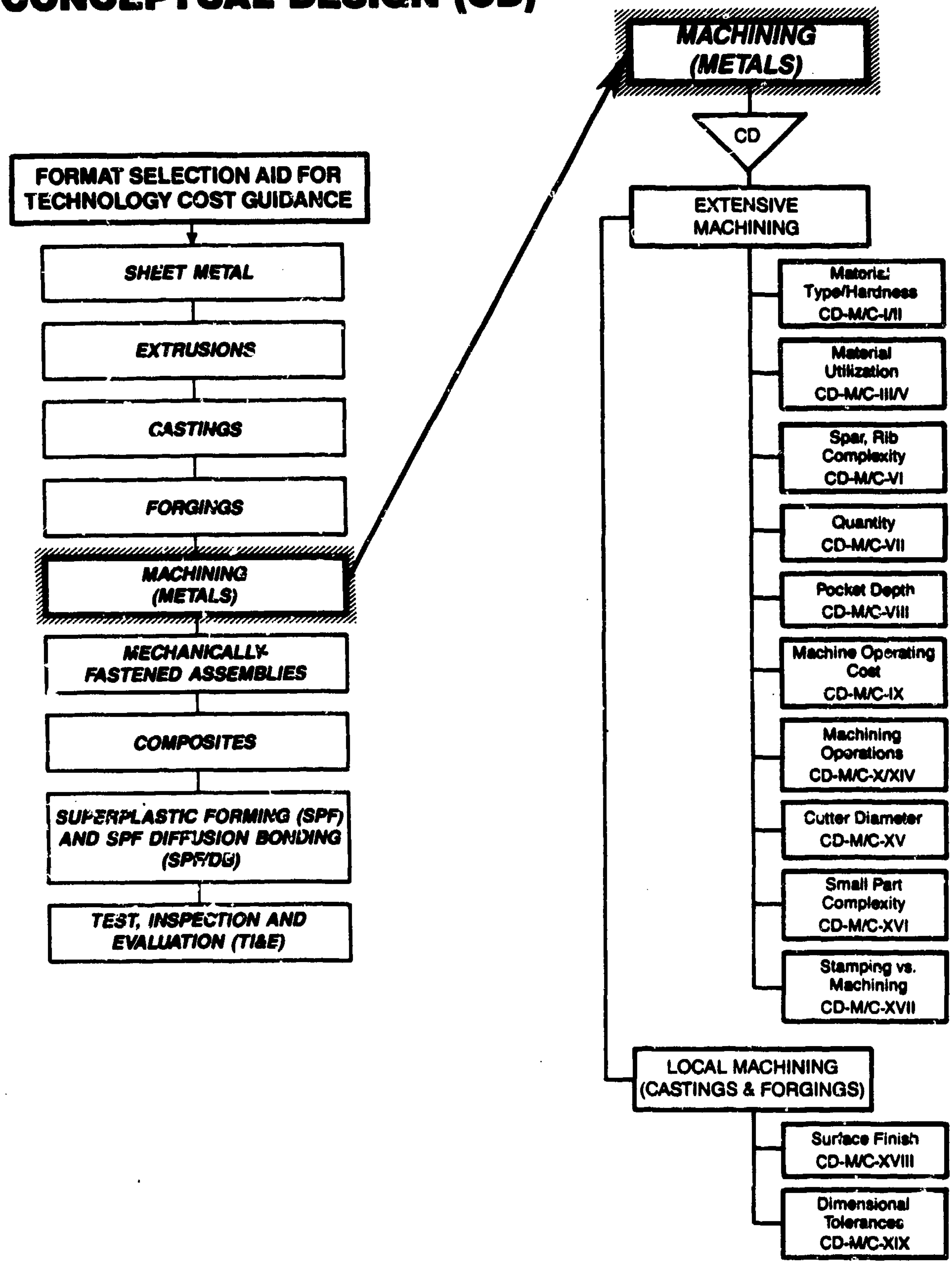
ALUMINUM PRECISION FORGING
EFFECT OF FORGED WEB THICKNESS ON RECURRING COST



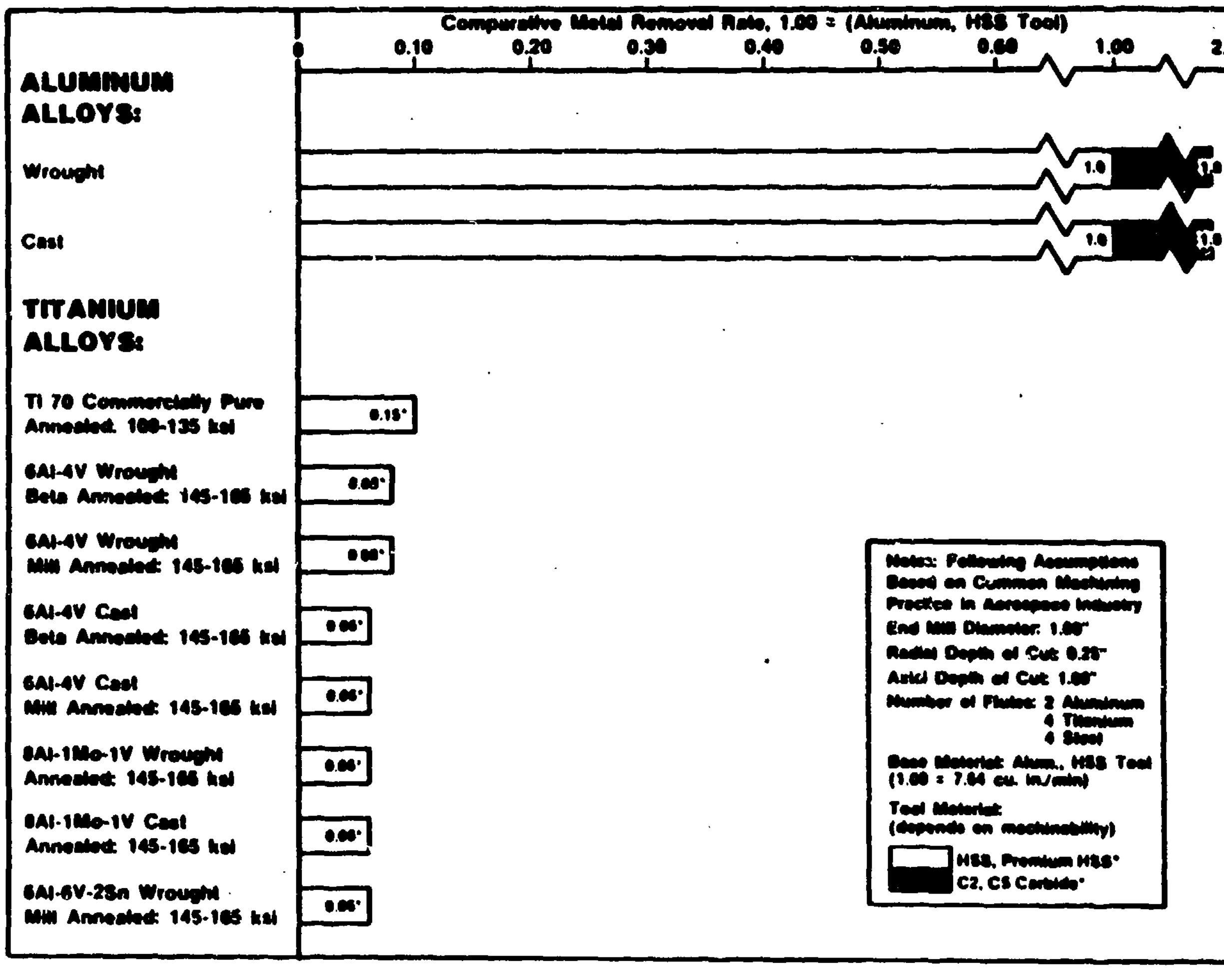
NOTE: BASED ON A 100 SQ. IN. FORGING

CD-DICE-FP-III

CONCEPTUAL DESIGN (CD)

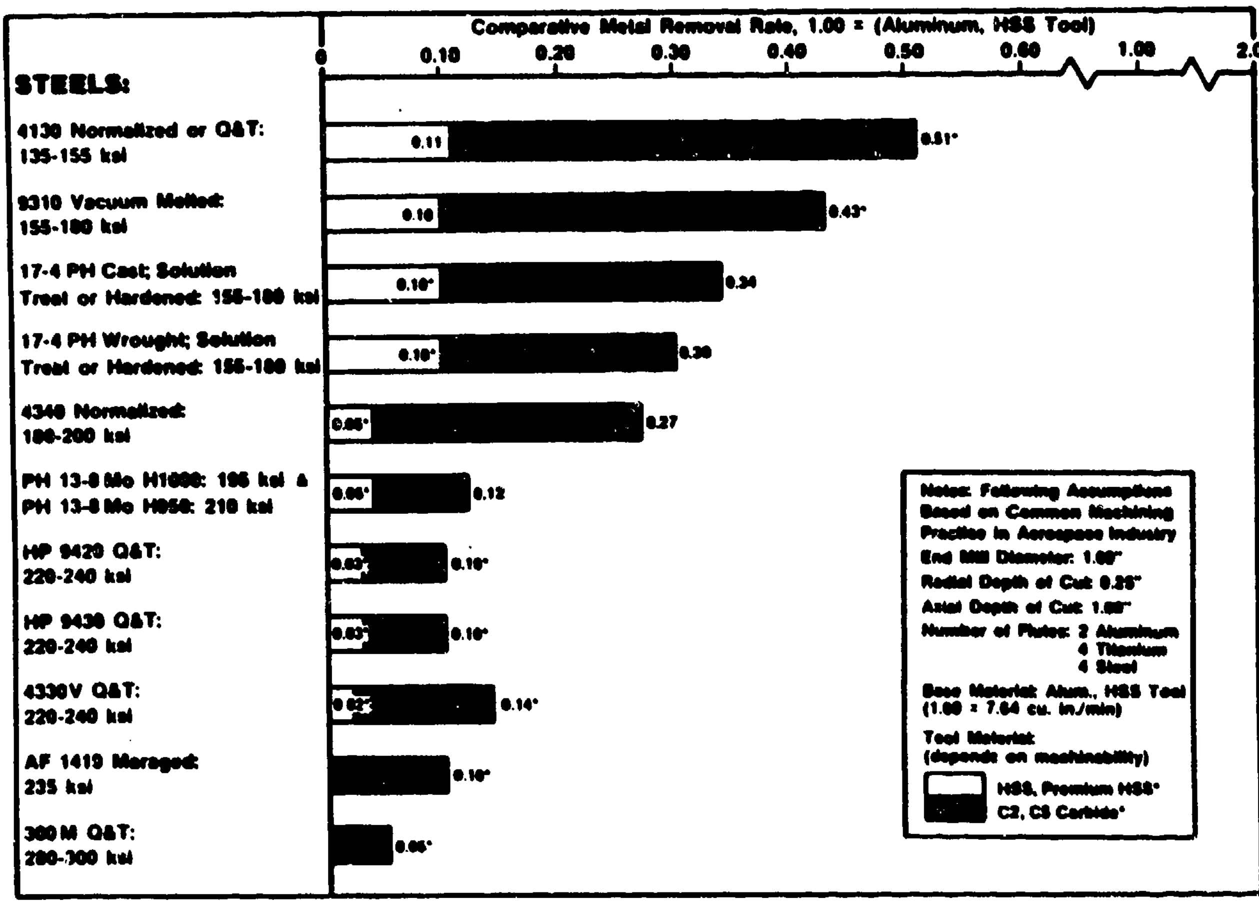


COMPARATIVE METAL REMOVAL RATES
ALUMINUM AND TITANIUM ALLOYS
(Peripheral End Milling)



CD-M/C-I

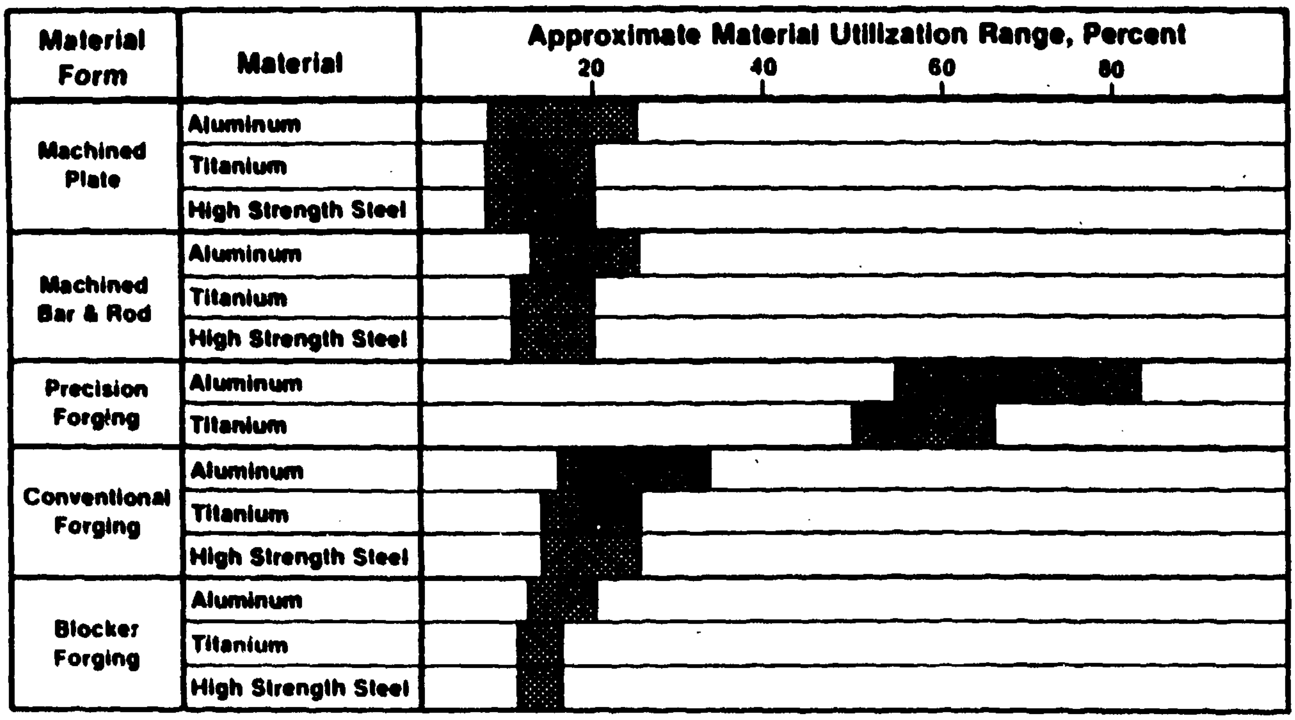
COMPARATIVE METAL REMOVAL RATES
STEELS
(Peripheral End Milling)



CD-M/C-II

EXAMPLES OF MATERIAL UTILIZATION FOR VARIOUS FORMS: PLATE, BAR, ROD, AND FORGINGS

(Excludes Drilling Holes, etc.)



CD-M/C-III

METAL REMOVAL RATIOS FOR TITANIUM BARS AND RODS GENERALLY APPLICABLE TO: ALUMINUM AND STEEL

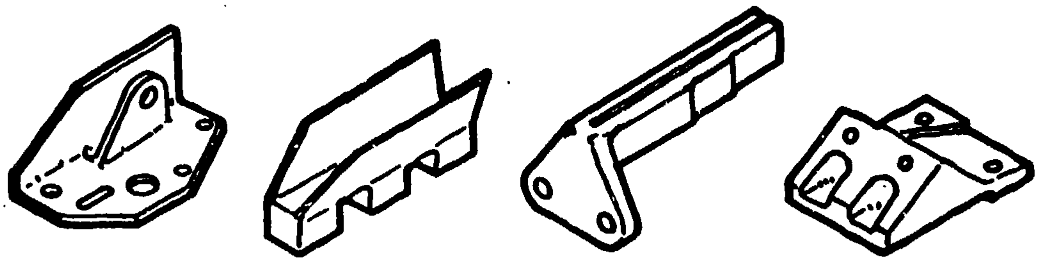
Principal Structural Applications:

Shafts, Tracks, Latches and Small Parts Where Material Grain Flow Does Not Justify Forged Part.

Metal Removal Operations:

Milling, Boring, Sawing, Drilling

Typical Machined Parts Made From Bar



Bar Stock	56 oz.	46 oz.	88 oz.	15 oz.
Finished Part	5 oz.	5 oz.	11 oz.	4 oz.
Metal Removal Ratio	11.2:1	9.2:1	8.0:1	3.7:1

Average Metal Removal Ratio with Allowance for Parts not so Severely Machined — 6.9:1

Courtesy of Lockheed Aircraft Systems Company, California Division

CD-M/C-IV

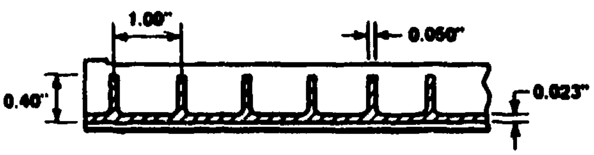
METAL REMOVAL RATIOS FOR TITANIUM PLATE GENERALLY APPLICABLE TO: ALUMINUM AND STEEL

Principal Structural Applications:

Secondary Wing Structure, Leading and Trailing Edge Integrally-Stiffened Skins

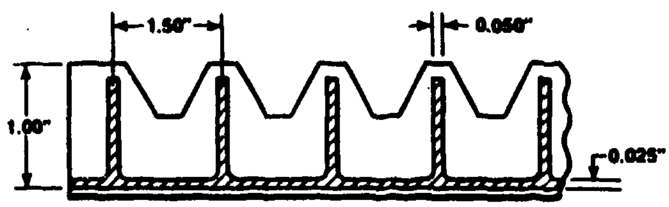
Metal Removal Operations: Milling, Boring, Sawing

Possible Alternative Configurations:



Typical Cross Section Machined from Flat Plate

Metal Removal Ratio - 12:1



Typical Cross Section Machined from Rolled Section

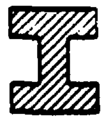
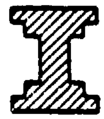
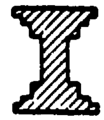
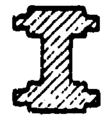
Metal Removal Ratio - 15:1

Average Metal Removal Ratio with Allowance for Scallop, Machine Grip and Trim - 14.5:1

Courtesy of Lockheed Aircraft Systems Company, California Division

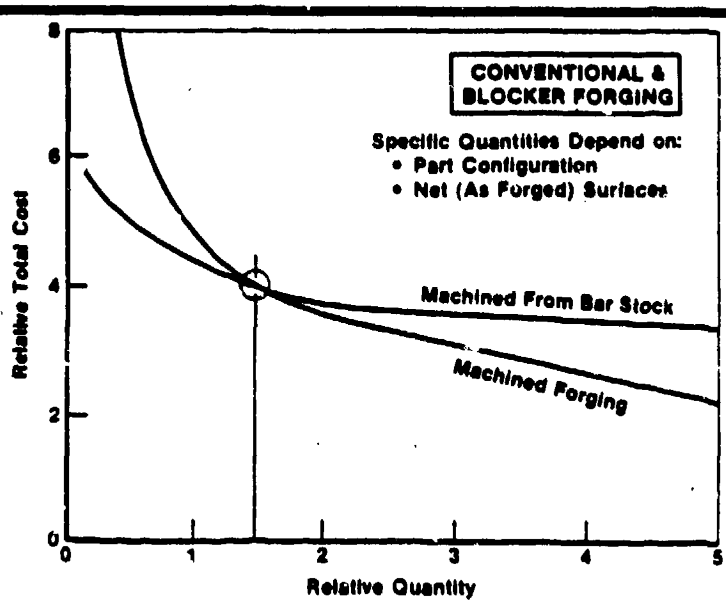
CD-M/C-V

EFFECT OF FLANGE/ATTACHMENT CONFIGURATION FOR SPARS AND RIBS

Raw Material Form	Material	Relative Machining Time			
					
Aluminum	Bar Stock	1	1.1	1.3	1.5
	Extrusion	0.4	0.6	0.8	0.9
	Close Tolerance Forging	0.5	0.6	0.8	0.9
Titanium	Bar Stock	9.5	9.5	12.5	13.0
	Extrusion	4.0	5.5	8.0	9.0
	Close Tolerance Forging	4.0	5.5	8.0	9.0
4340 Steel (Normalized)	Bar Stock	7.0	7.5	9.5	10.5
	Extrusion	3.0	4.5	6.0	6.5
	Close Tolerance Forging	3.0	4.5	6.0	6.5

CD-M/C-VI

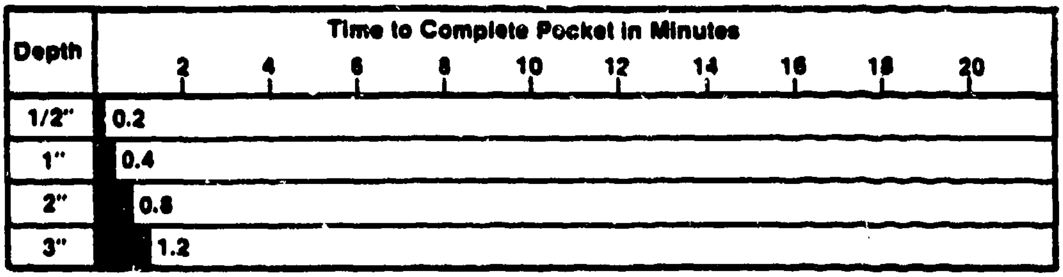
RELATIVE TOTAL COST OF PARTS MACHINED FROM FORGINGS AND BAR STOCK



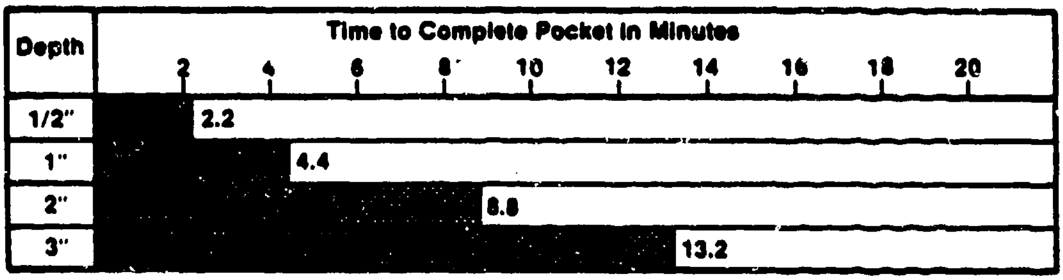
CD-M/C-VII

EFFECT OF METAL REMOVED ON MACHINING TIME
DEEP POCKET VS. SHALLOW (RIGID) POCKET

ALUMINUM

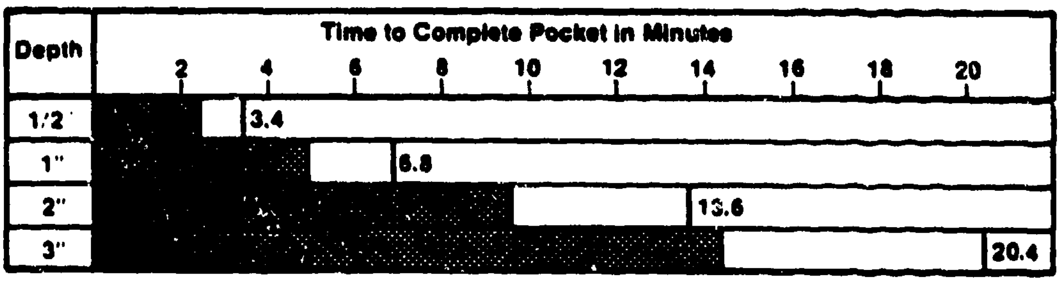


TITANIUM



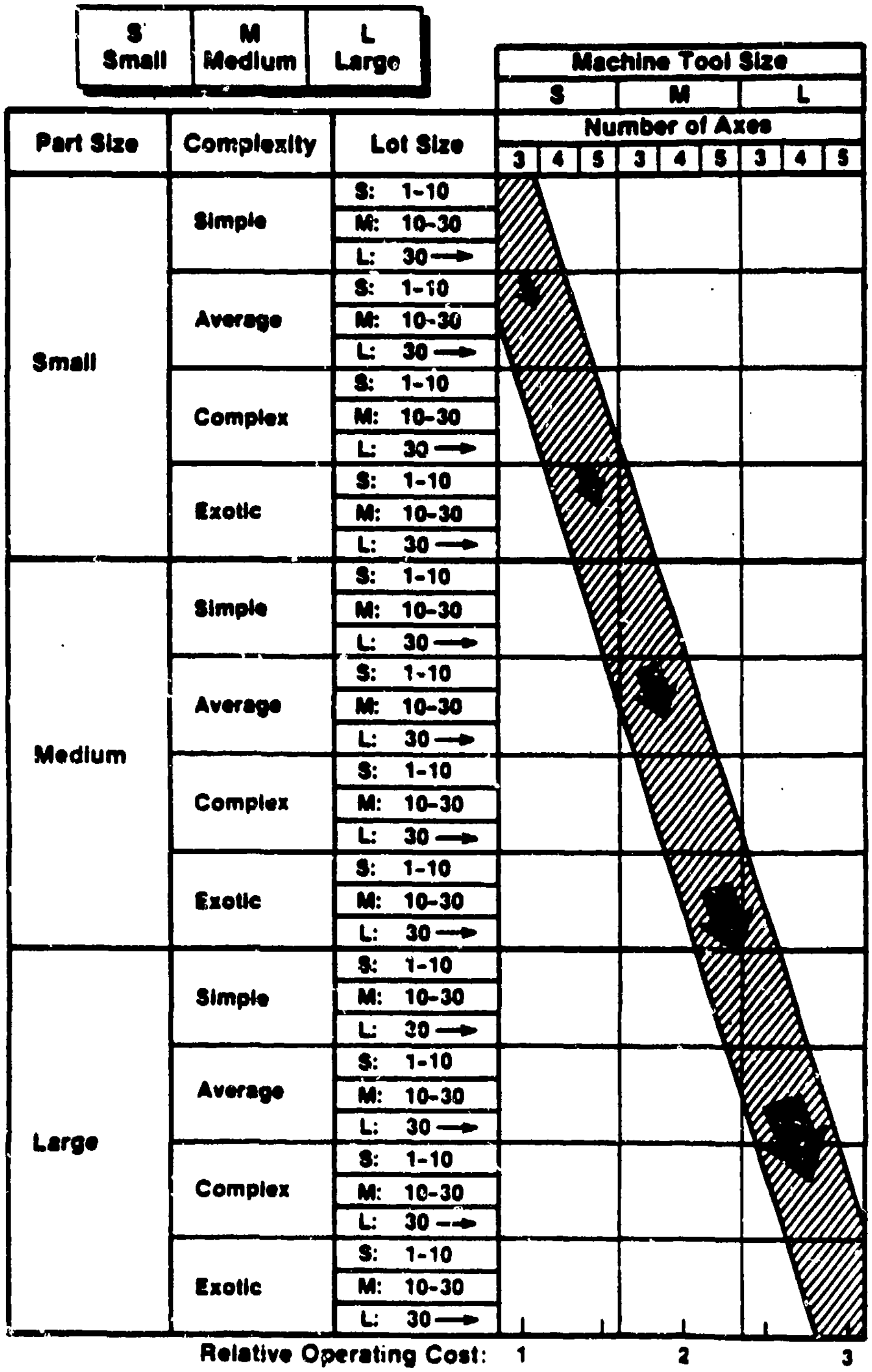
HIGH STRENGTH STEELS

4340 Steel (Normalized)
Average of Aerospace Steels



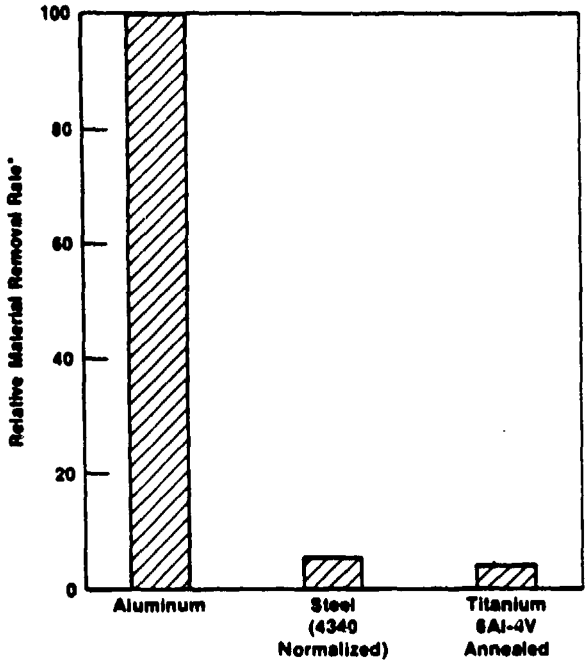
CD-M/C-VIII

INFLUENCE OF: PART SIZE, PART COMPLEXITY, AND LOT SIZE ON MACHINE TOOL SELECTION AND OPERATING COST



CD-M/C-IX

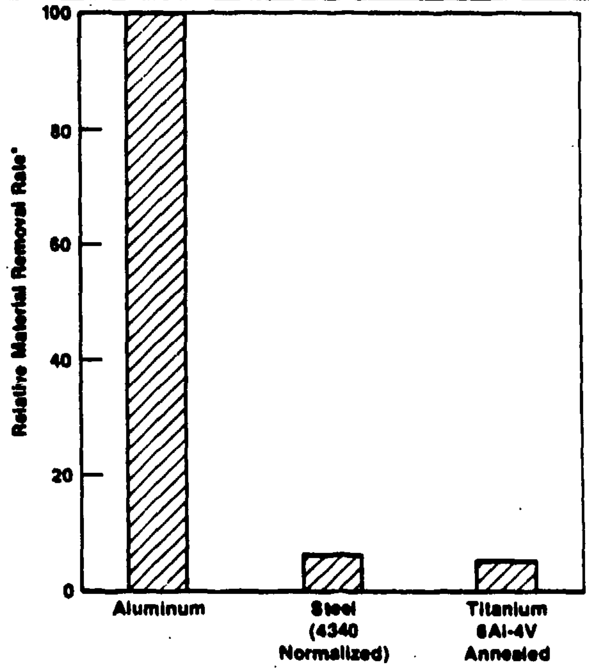
RELATIVE TIME TO MACHINE FOR TURNING



*Volumetric Cutting Rate; Exclusive of Setup and Handling

CD-M/C-X

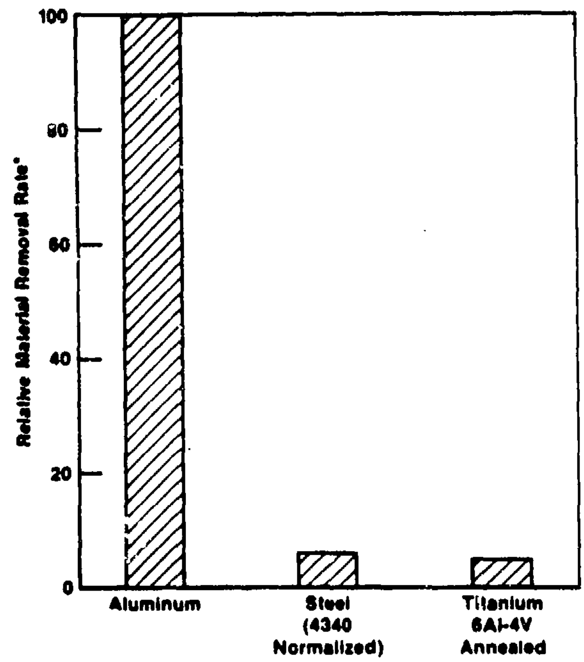
RELATIVE TIME TO MACHINE FOR END-MILLING



*Volumetric Cutting Rate; Exclusive of Setup and Handling

CD-M/C-XI

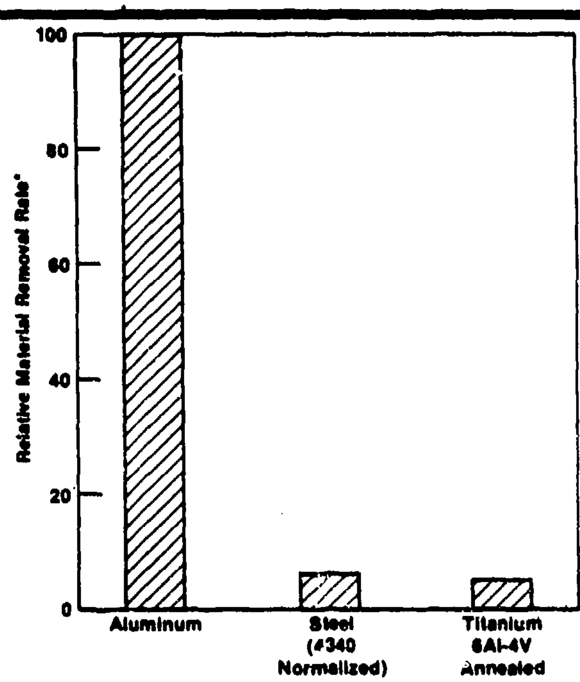
RELATIVE TIME TO MACHINE FOR DRILLING



*Volumetric Cutting Rate; Exclusive of Setup and Handling

CD-M/C-XII

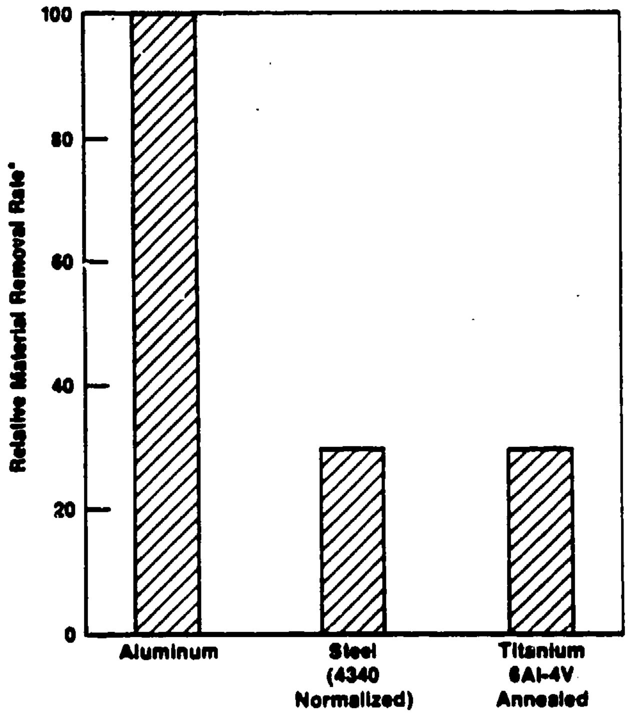
RELATIVE TIME TO MACHINE FOR REAMING



*Volumetric Cutting Rate; Exclusive of Setup and Handling

CD-M/C-XIII

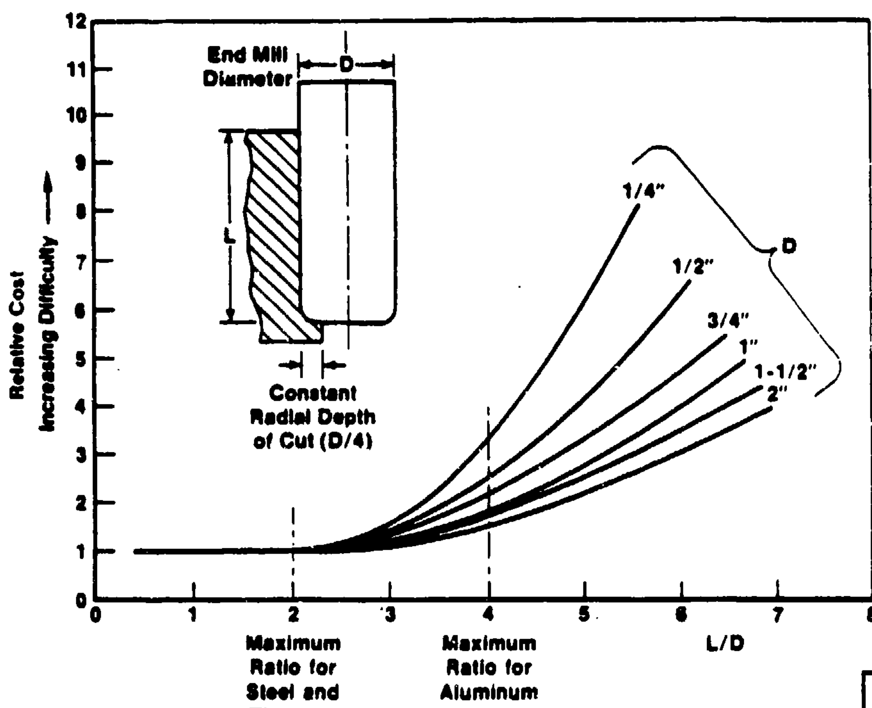
RELATIVE TIME TO MACHINE FOR TAPPING



*Volumetric Cutting Rate; Exclusive of Setup and Handling

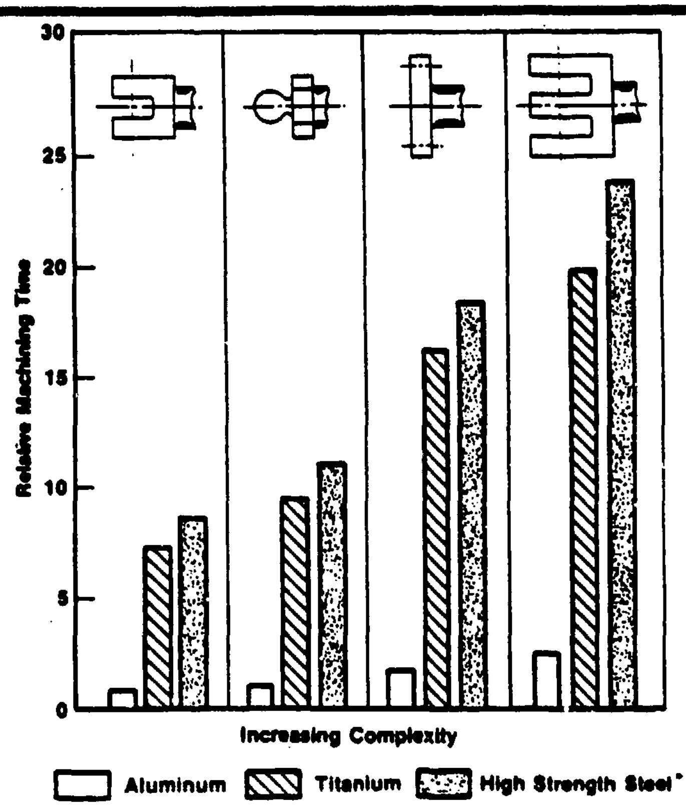
CD-M/C-XIV

EFFECT OF CUTTER DIAMETER ON MACHINABILITY FACTOR



CD-M/C-XV

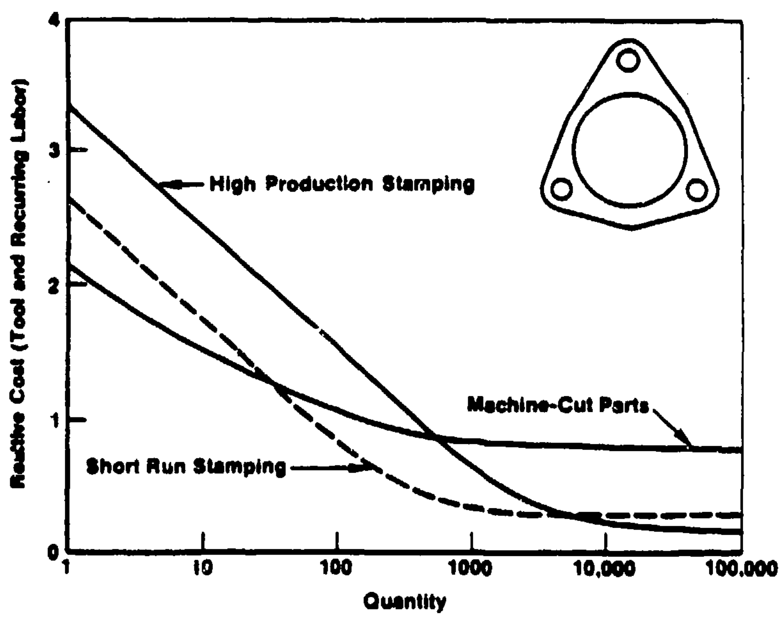
RELATIVE COST OF INCREASING PART COMPLEXITY



*After Heat-Treatment (Prior to Heat-Treatment Will be Less Than Titanium)

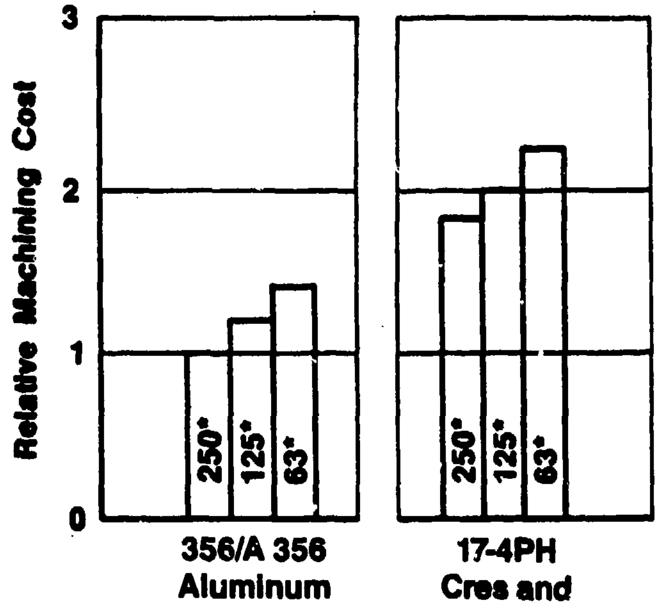
CD-M/C-XVI

RELATIVE COST OF STAMPING VS. MACHINING FOR A SPECIFIC TYPE OF SHEET METAL PART



CD-M/C-XVII

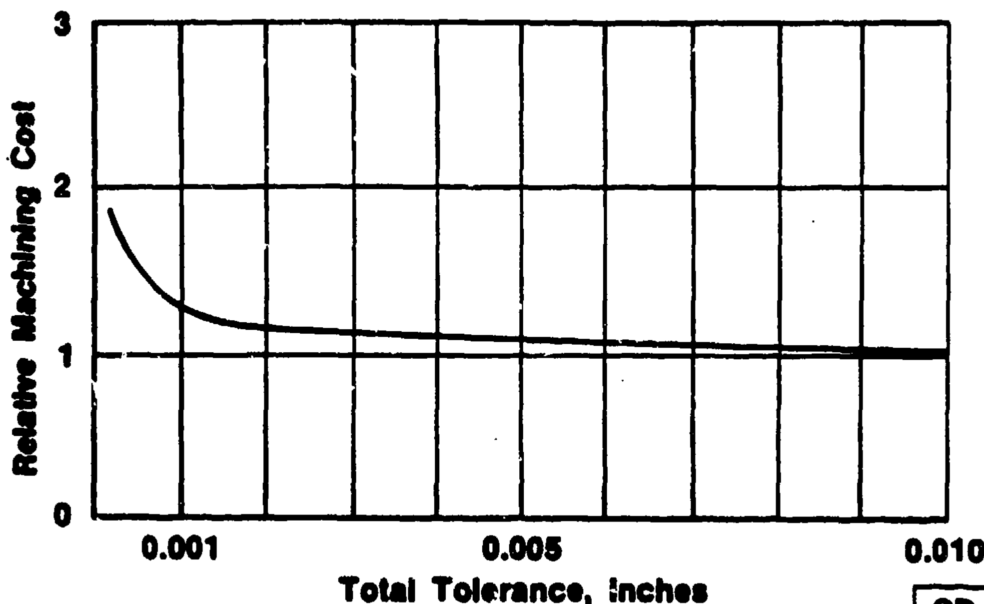
MACHINING OF CASTINGS AND FORGINGS
SURFACE FINISH



* Surface finish shown in micro-inches.

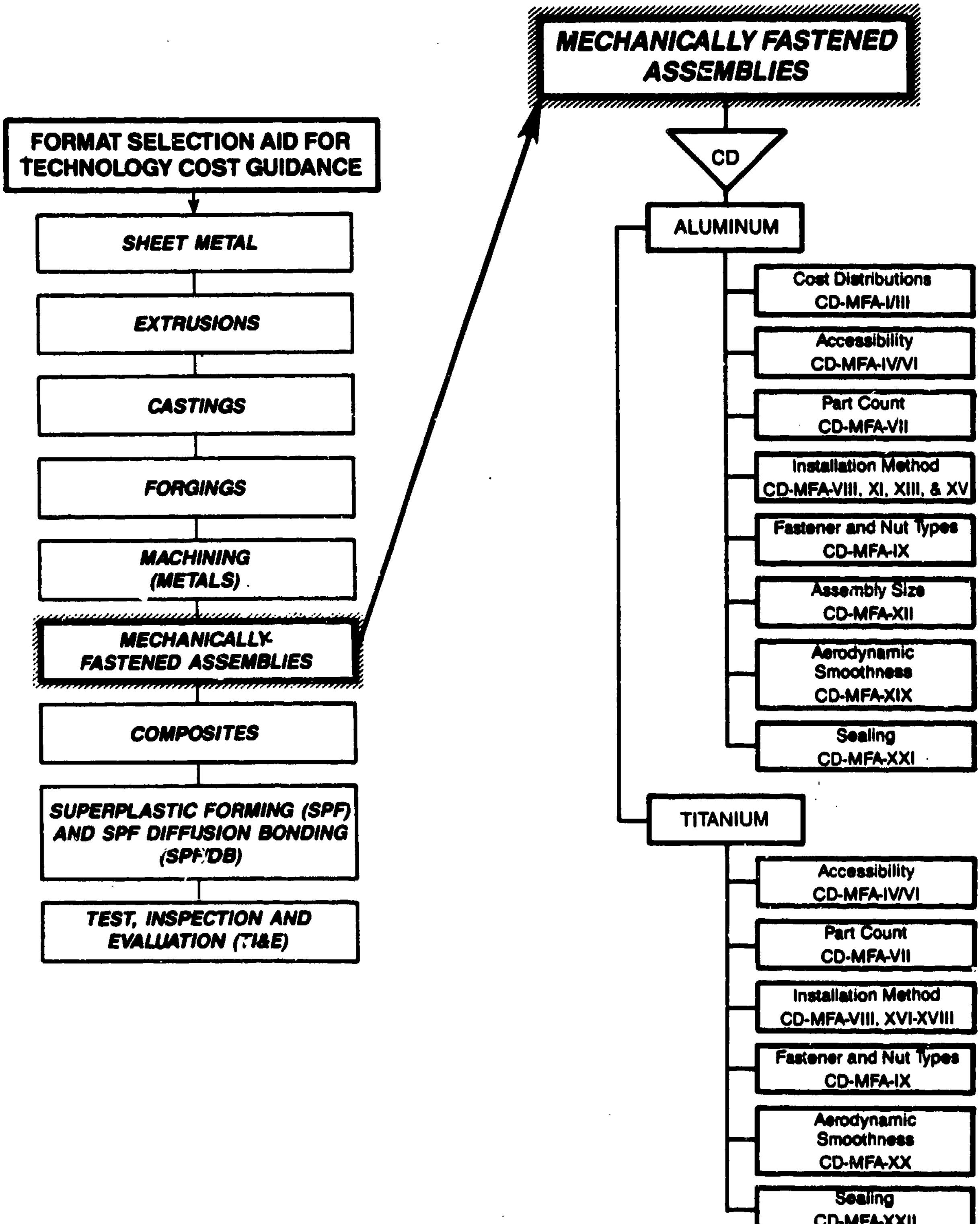
CD-M/C-XVIII

MACHINING OF CASTINGS AND FORGINGS
DIMENSIONAL TOLERANCES

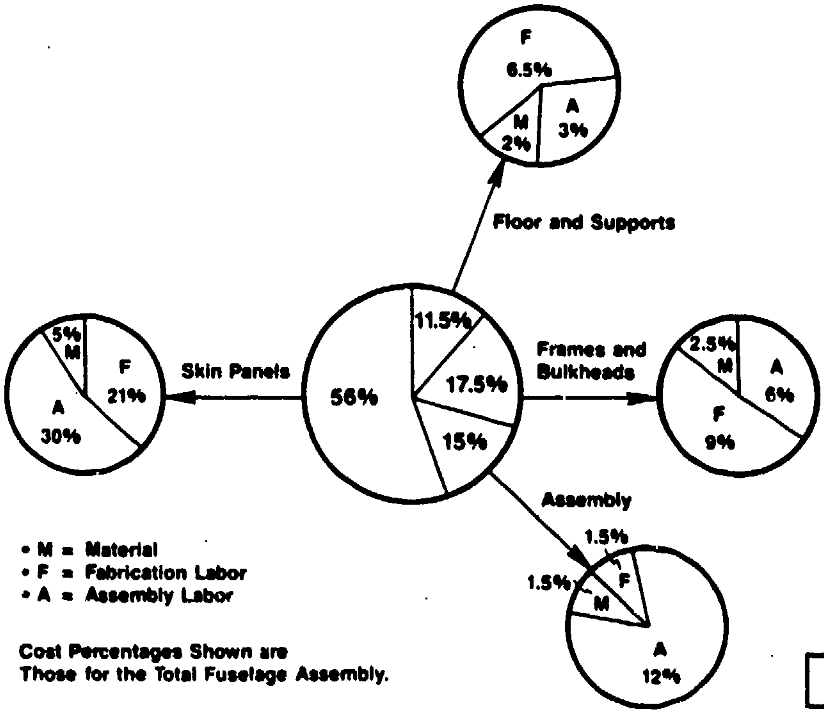


CD-M/C-XIX

CONCEPTUAL DESIGN (CD)



COST DISTRIBUTION FOR ALUMINUM FUSELAGE STRUCTURE OF MEDIUM TO LARGE COMMERCIAL/MILITARY TRANSPORT

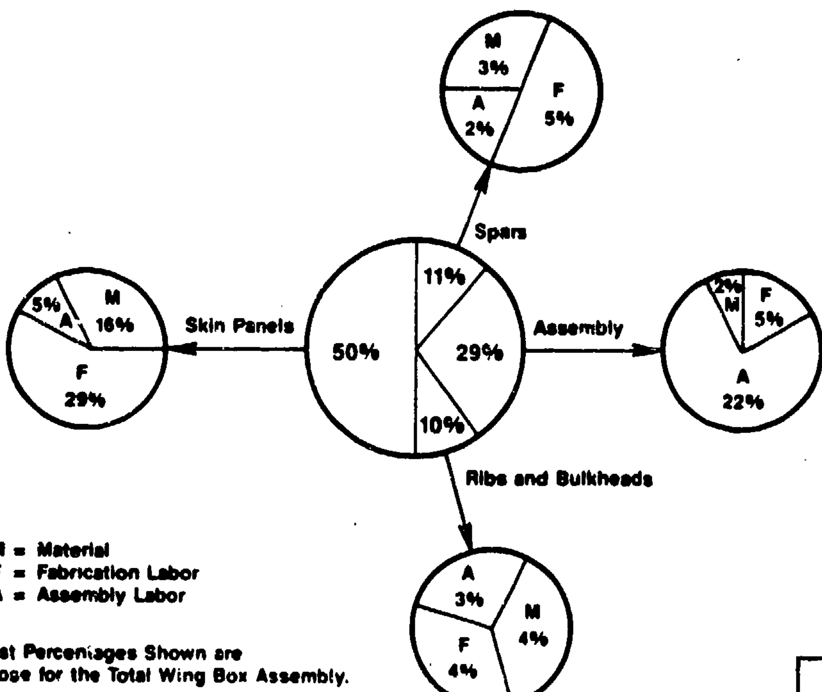


• M = Material
• F = Fabrication Labor
• A = Assembly Labor

Cost Percentages Shown are Those for the Total Fuselage Assembly.

CD-MFA-I

COST DISTRIBUTION FOR ALUMINUM WING-BOX STRUCTURE OF MEDIUM TO LARGE COMMERCIAL/MILITARY TRANSPORT

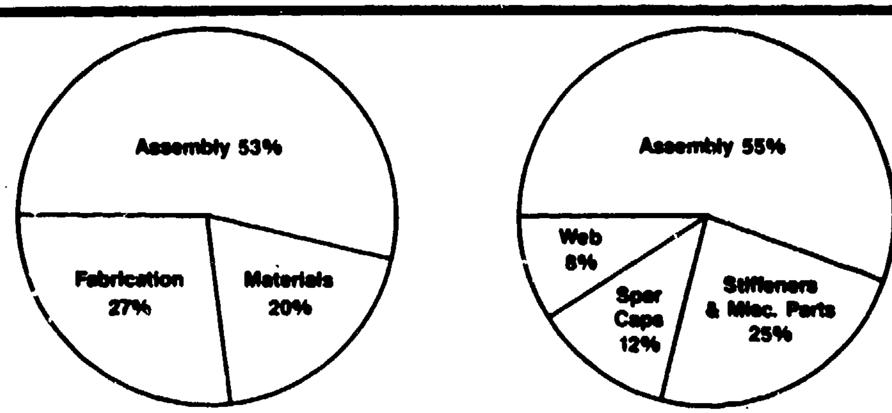


• M = Material
• F = Fabrication Labor
• A = Assembly Labor

Cost Percentages Shown are Those for the Total Wing Box Assembly.

CD-MFA-II

COST BREAKDOWN FOR A TYPICAL ALUMINUM SPAR



By Cost Element | **By Component**

(Fabrication: Materials and Labor)

CD-MFA-III

ACCESSIBILITY FACTORS FOR MANUAL ASSEMBLY OF ALUMINUM AND TITANIUM STRUCTURES

BENCH SUBASSEMBLY

Factor: 1.0

- No Assembly Tooling Required
- Pilot Holes in All Detail Parts
- Performed by One Operator
- Average Finger Dexterity Required
- Standard Tools Used
- Simple Subassembly
- Only Light Portable Hand Tooling Required
- Consistent Rivet Pattern
- All Rivets of Same Diameter
- No Close Tolerance Holes
- No Trimming Required
- No Tool Interference

1.5

- Simple Assembly Fixture Required
- Subassembly Handled by One Operator
- Above Average Finger Dexterity Required
- Standard Riveting Tools Used
- Light Weight
- May Require Some Lay-Out of Hole Spacing
- Varied Rivet Spacing
- Multiple Rivet Diameters and Lengths Required
- Restricted Access

2.5

- Complex Assembly Fixture Required
- Requires Lifting and Rotation of Fixture to Provide Accessibility to Assemble
- Requires Excellent Finger Dexterity
- Special Riveting Tools Needed
- Varied Rivet Sizes and Spacing
- Some Lay-Out of Hole Pattern Required
- Close Tolerance Holes
- Fit-Up and Trimming Required
- Some Shimming Required
- Requires Second Operator
- Skilled Special Operator Required
- May Require Handling Device
- Critical Assembly Sequence Necessary

CD-MFA-IV

- The above accessibility factors are not applicable to automatic fastening.

ACCESSIBILITY FACTORS FOR MANUAL ASSEMBLY OF ALUMINUM AND TITANIUM STRUCTURES (Continued)

MAJOR ASSEMBLY

Factor: 1.5	*3.0*	*4.0*
• Simple Assembly Fixture Required • All Parts are Jig Located • Average Finger Dexterity Required • Some Heavy Portable Tooling Required • Few Close Tolerance Holes • Flat or Slightly Contoured Surfaces • No Hand-Fitting or Trimming at Assembly • Good Worker Position • No Tooling Interference	• Requires Rotary Type Fixture to Provide Accessibility • Most Parts are Jig Located • Impaired Communication Between Workers • Above Average Finger Dexterity Required • Heavy Portable Tooling Requiring Hoist • Limited Number of Parts to Locate • Fuel Sealing in Confined Areas • Sharp Contours • Use of Standard Tools Impaired • Uncomfortable Worker Position • In-Process Inspection Required • May Require Work Above Floor Level • May Require Operator Working on Step-Stand	• Need for Complex Assembly Tooling • Large Number of Parts to Locate • Requires Partial Disassembly of Heavy Fixture Components to Unload Fixture • Poor Communication Between Workers • Requires Excellent Finger Dexterity • Special Riveting Tools Needed • Fuel Sealing Requirements • Some Trimming and Fit-Up Required • Shimming Required • Different Sized Fasteners Required • Distorted Worker Position • In-Process Inspection Required • Removable Staging Required • Sharp Contoured Surfaces • Protective Clothing Required

• The above accessibility factors are not applicable to automatic fastening.

CD-MFA-V

ACCESSIBILITY FACTORS FOR MANUAL ASSEMBLY OF ALUMINUM AND TITANIUM STRUCTURES (Continued)

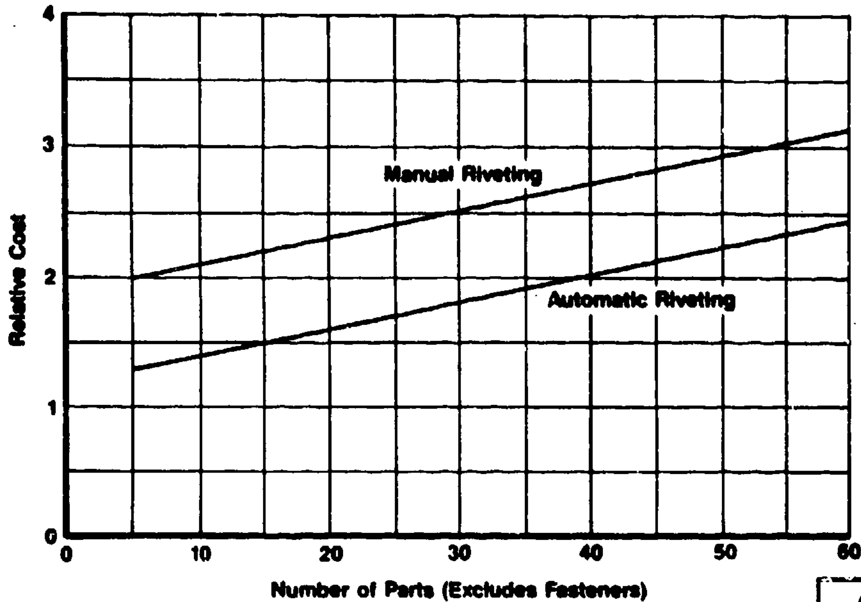
FINAL ASSEMBLY

Factor: 2.5	4.5	6.0
• No Removable Jig Components	• Some Removable Jig Components	• Numerous Jig Components to be Located and Removed to Permit Accessibility
• Average Finger Dexterity Required	• Above Average Finger Dexterity Required	• Use of Slings/Hoists Required to Position Subassemblies
• Hydraulic Fittings are Mechanical Only	• Limited Number of Hydraulic Tubing Installations	• In-Place Brazing of Tubing Required
• No Wire Terminations Required	• Limited Number of Wire Terminations	• Termination of Wiring Required
• Good Communication Between Workers	• Impaired Communication Between Workers	• Poor Communication Between Workers
• Good Visibility	• Fair Visibility	• Operator Working Blind or with Mirrors
• Standard Man-Hour Goal Achieved in Less Than 50 Assemblies	• Some Close Tolerance Holes	• Close Tolerance Holes
• Few Two-Piece Fasteners	• Some In-Process Inspection Required	• Two-Piece Fasteners Required
• No Hand-Trimming at Assembly	• Limited Hand Trimming at Assembly	• Some Hand-Trimming at Assembly
• Work at Floor Level	• May Require Work Above Floor Level or Overhead Cramped Area—Requires Small Operator	• Fuel Sealing Requirements
• Comfortable Working Position	• Uncomfortable Worker Position	• Requires Critical Loading Sequence of Parts/Subassemblies to Provide Accessibility
• May Require Working in Dark Areas with Drop-Lights	• Staging Required	• Highly Skilled Technicians Required
• No Tool Interference	• Working in Prone Position Required	• Continued In-Process Inspection Required
	• Tool/Jig Interference	• Removable Staging Required
		• Working in Small Confined Area with Lack of Good Ventilation
		• Special Riveting Tools Required
		• Distorted Worker Position

• The above accessibility factors are not applicable to automatic fastening.

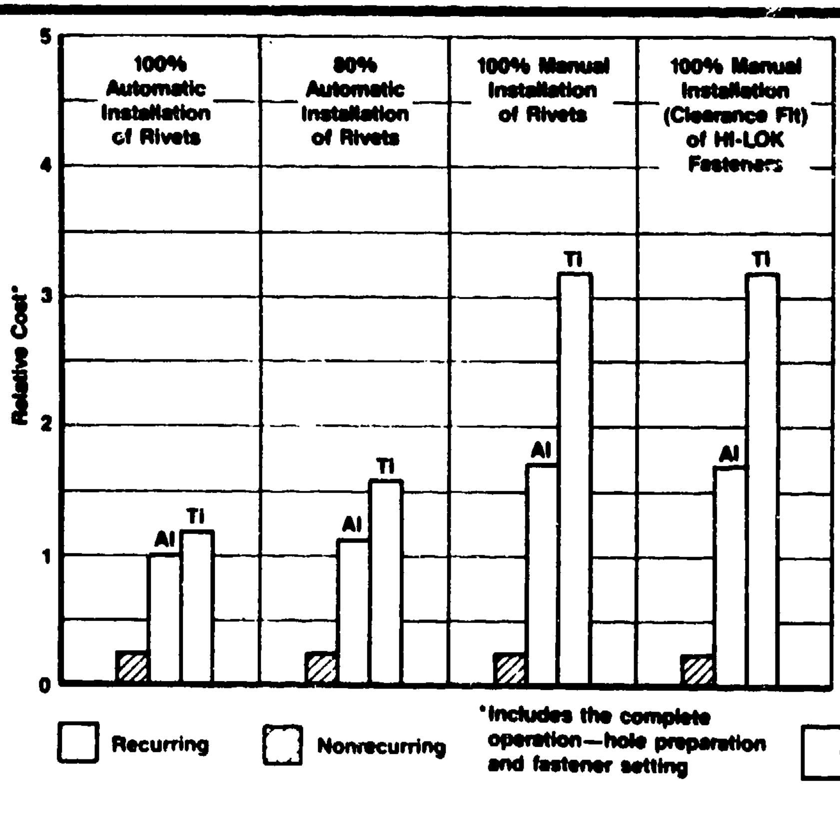
CD-MFA-VI

MECHANICALLY FASTENED ASSEMBLIES
EFFECT OF PART COUNT AND FASTENING METHOD



CD-MFA-VII

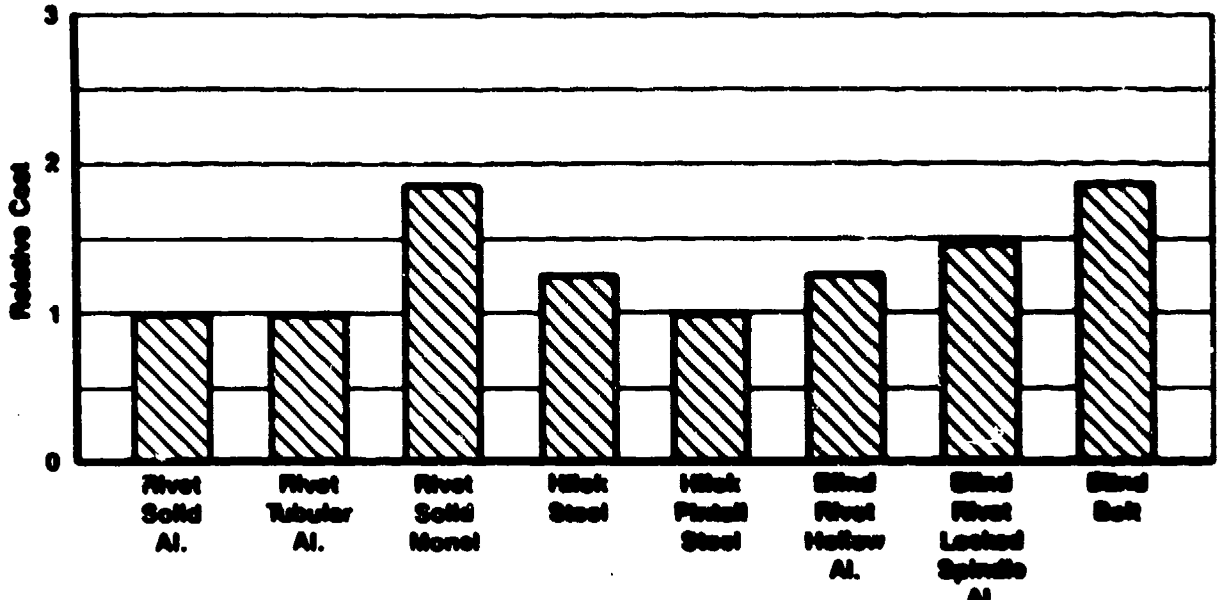
COST IMPACT OF INSTALLATION METHOD FOR ALUMINUM AND TITANIUM MECHANICALLY FASTENED ASSEMBLIES



*Includes the complete operation—hole preparation and fastener setting

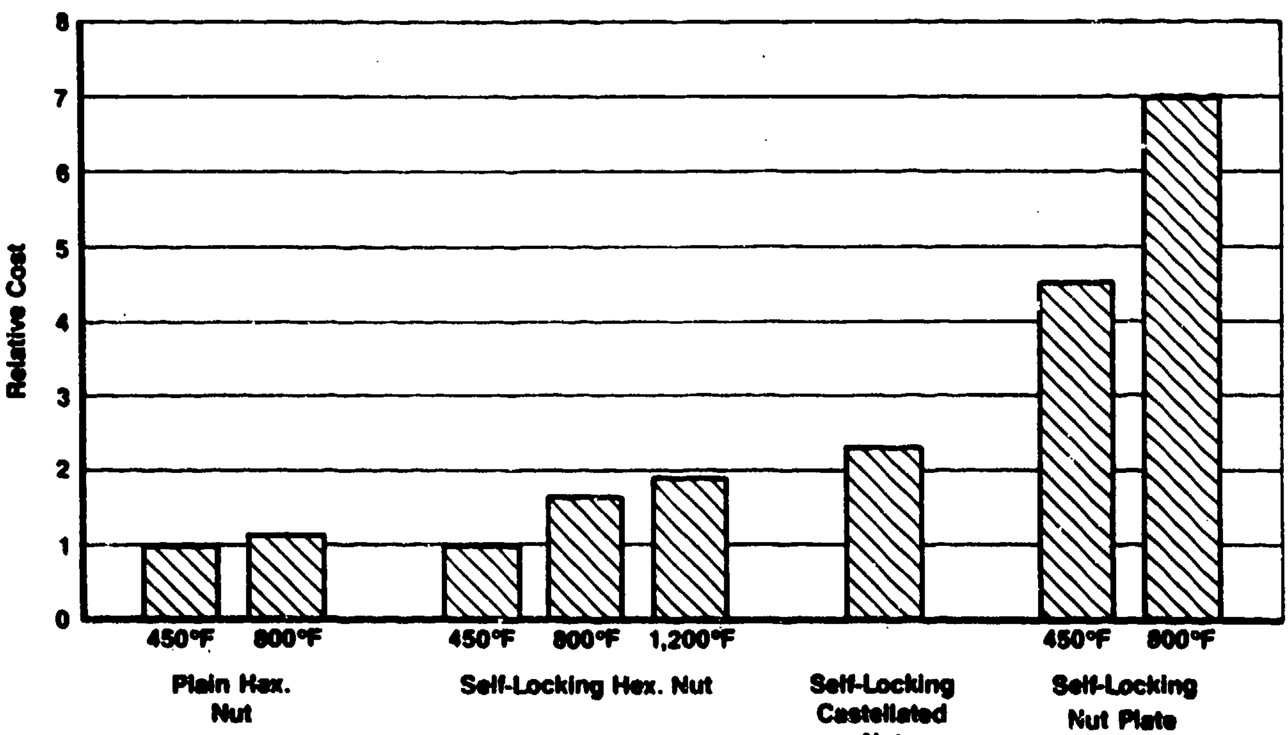
CD-MFA-VIII

IMPACT OF FASTENER TYPE ON TOTAL INSTALLED COST
MANUAL INSTALLATION



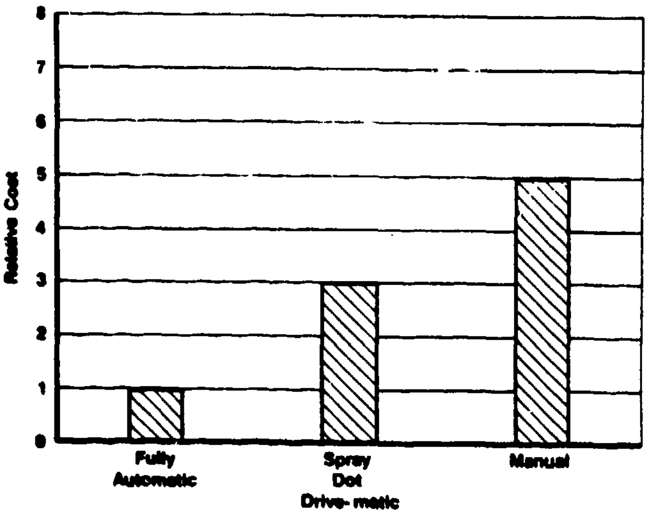
CD-MFA-IX

IMPACT OF NUT TYPE ON INSTALLED COST
MANUAL INSTALLATION



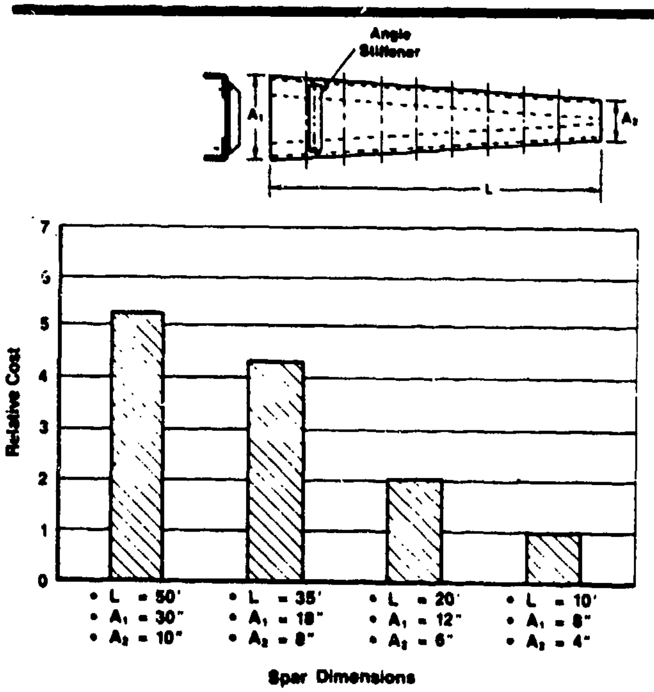
CD-MFA-X

IMPACT OF INSTALLATION METHOD ON TOTAL INSTALLED COST OF *ALUMINUM* SOLID RIVETS (MS 20426 & MS 20470)



CD-MFA-XI

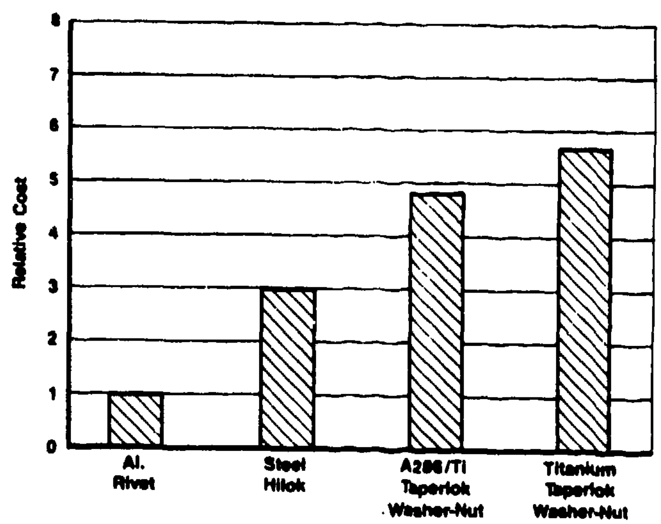
IMPACT OF SIZE ON RECURRING COST OF TYPICAL METALLIC SPARS



*Based on aluminum alloys stiffened by angle stiffeners

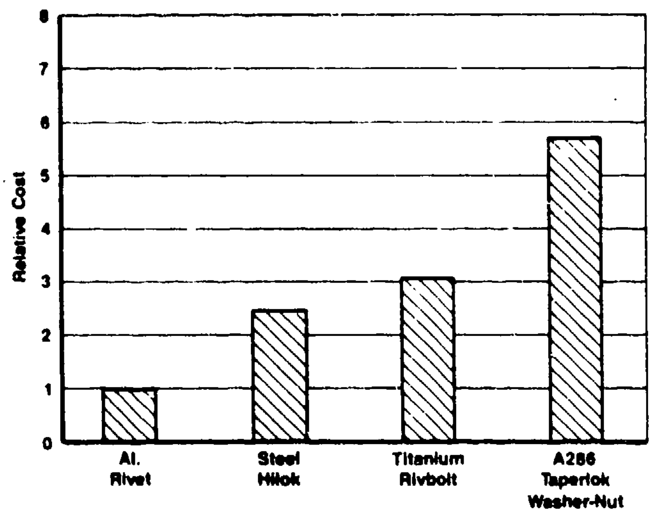
CD-MFA-XII

IMPACT OF FASTENER MATERIALS AND TYPE ON THE INSTALLED FASTENER COST FOR *ALUMINUM* ASSEMBLY USING GEMCOR METHOD



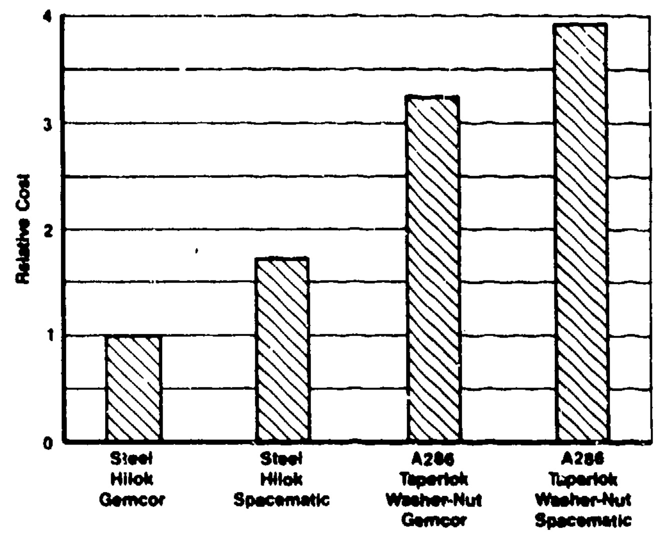
CD-MFA-XIII

IMPACT OF FASTENER MATERIAL AND TYPE ON THE INSTALLED FASTENER COST FOR *ALUMINUM* ASSEMBLY USING SPACEMATIC TEMPLATES



CD-MFA-XIV

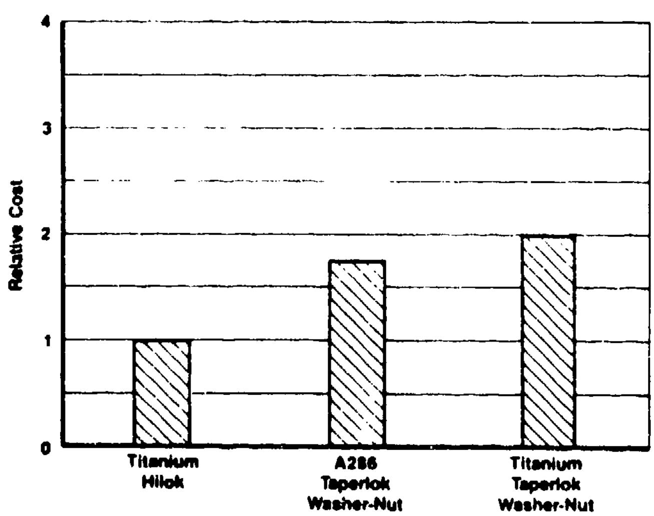
IMPACT OF INSTALLATION METHOD ON INSTALLED FASTENER COST IN *ALUMINUM* ASSEMBLY SPACEMATIC VS. GEMCOR



CD-MFA-XV

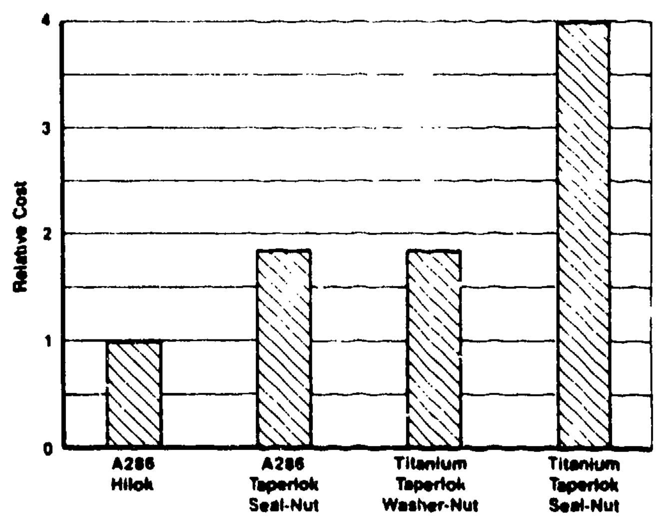
COMPARISON OF INSTALLED FASTENER COST IN *TITANIUM* ASSEMBLY

GEMCOR METHOD TAPERLOK VS. HILOK



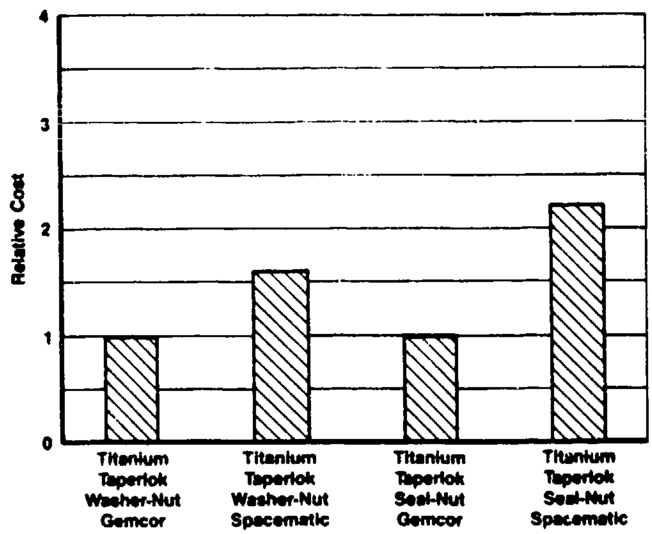
CD-MFA-XVI

SPACEMATIC METHOD TAPERLOK VS. HILOK



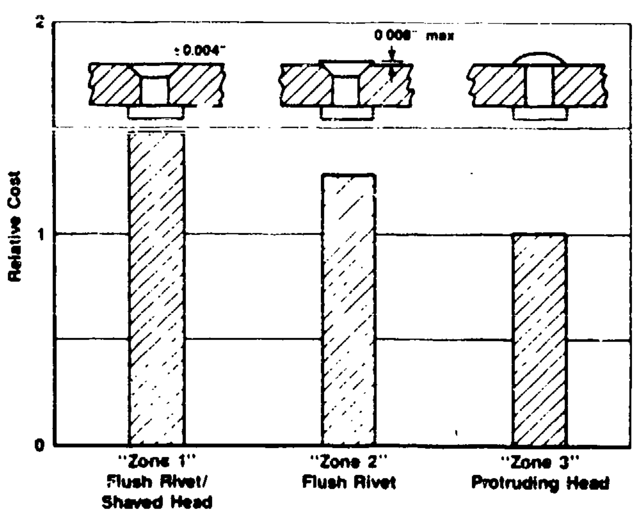
CD-MFA-XVII

IMPACT OF INSTALLATION METHOD ON INSTALLED FASTENER COST IN *TITANIUM* ASSEMBLY SPACEMATIC VS. GEMCOR



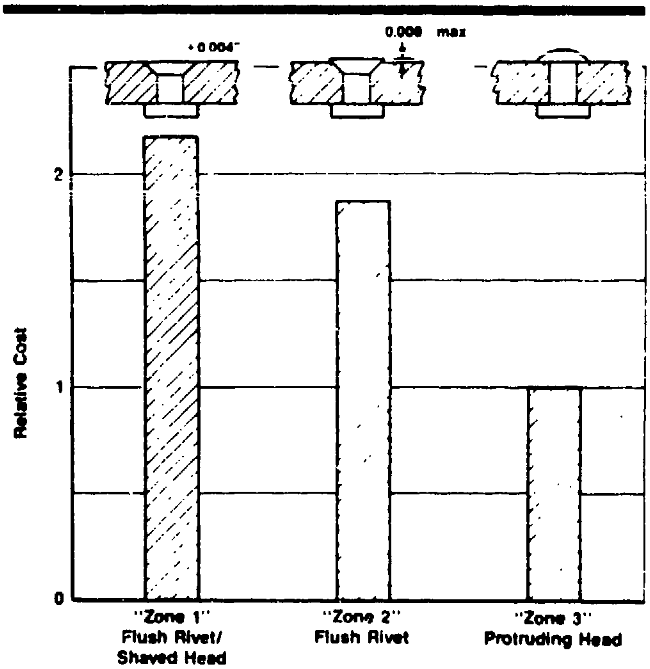
CD-MFA-XVIII

RELATIVE COST OF INSTALLING AERODYNAMICALLY CRITICAL *ALUMINUM* FASTENERS



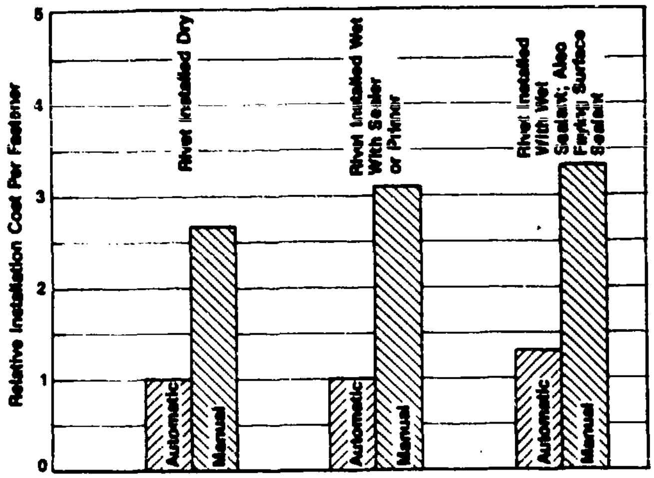
CD-MFA-XIX

RELATIVE COST OF INSTALLING AERODYNAMICALLY CRITICAL *TITANIUM* FASTENERS



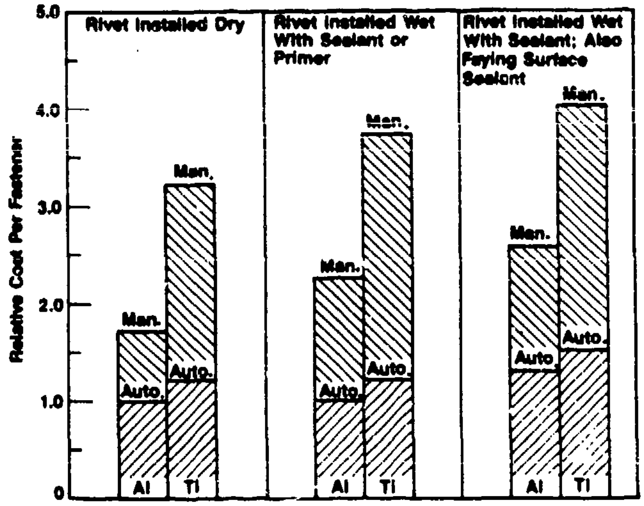
CD-MFA-XX

EFFECT OF SEALING ON FASTENER INSTALLATION COST *TITANIUM* ASSEMBLIES



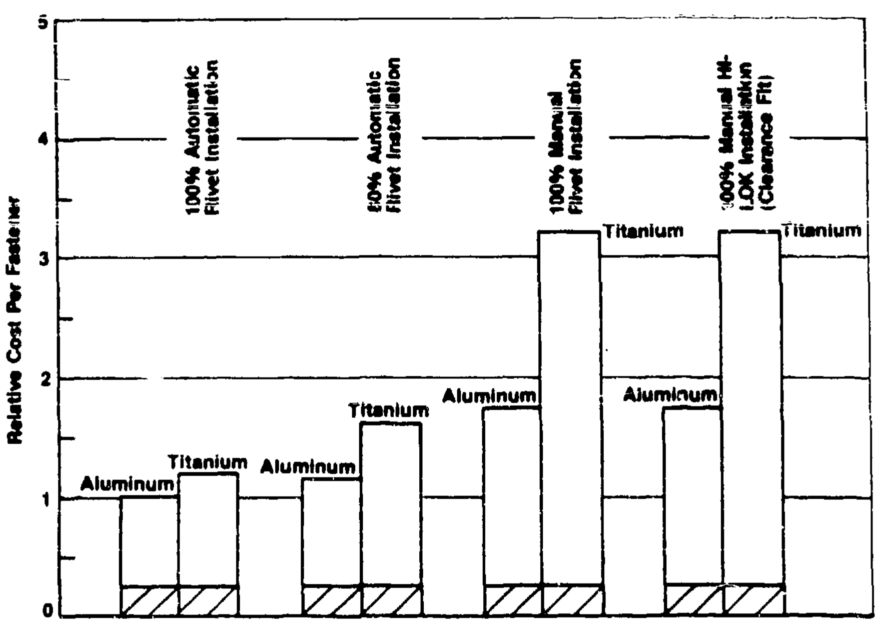
CD-MFA-XXIV

EFFECT OF SEALING ON FASTENER INSTALLATIN COST *ALUMINUM* AND *TITANIUM* ASSEMBLIES

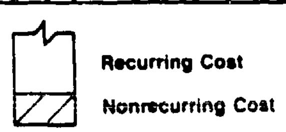


CD-MFA-XXV

COST IMPACT OF INSTALLATION* METHOD, ASSEMBLY MATERIAL AND FASTENER TYPE

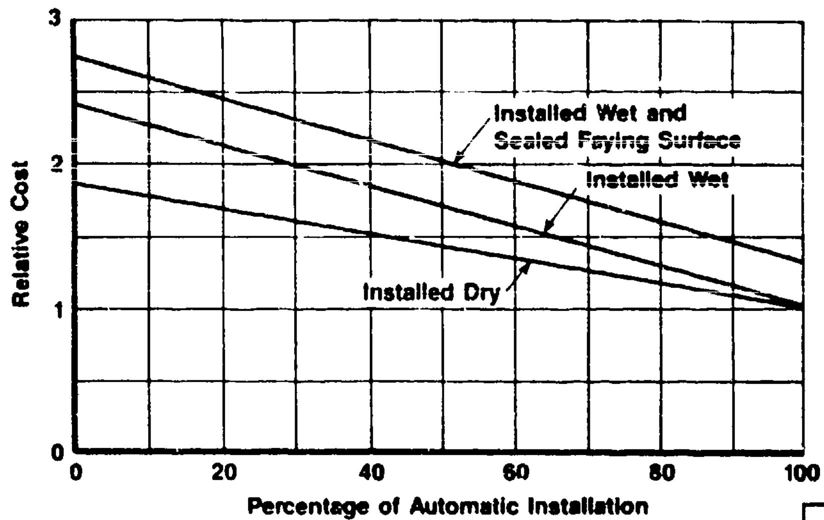


*Installation includes the complete operation-hole preparation and fastener setting



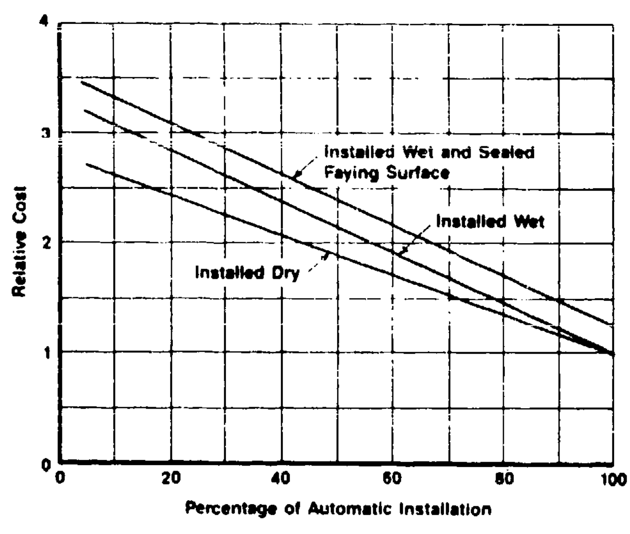
CD-MFA-XXVI

COST IMPACT OF SEALING FOR *ALUMINUM* ASSEMBLIES



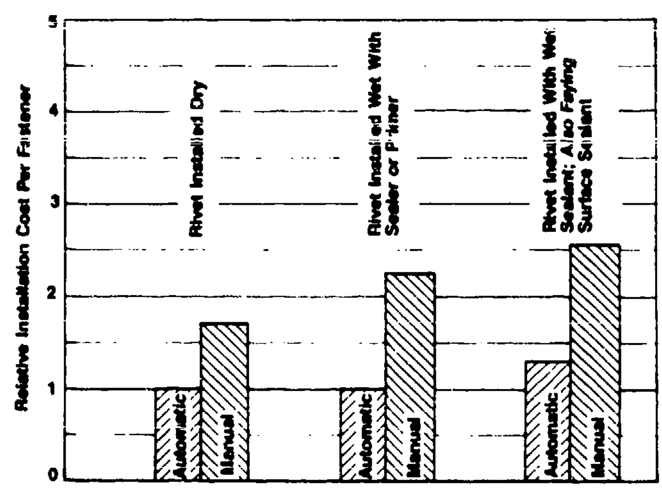
CD-MFA-XXI

COST IMPACT OF SEALING FOR *TITANIUM* ASSEMBLIES



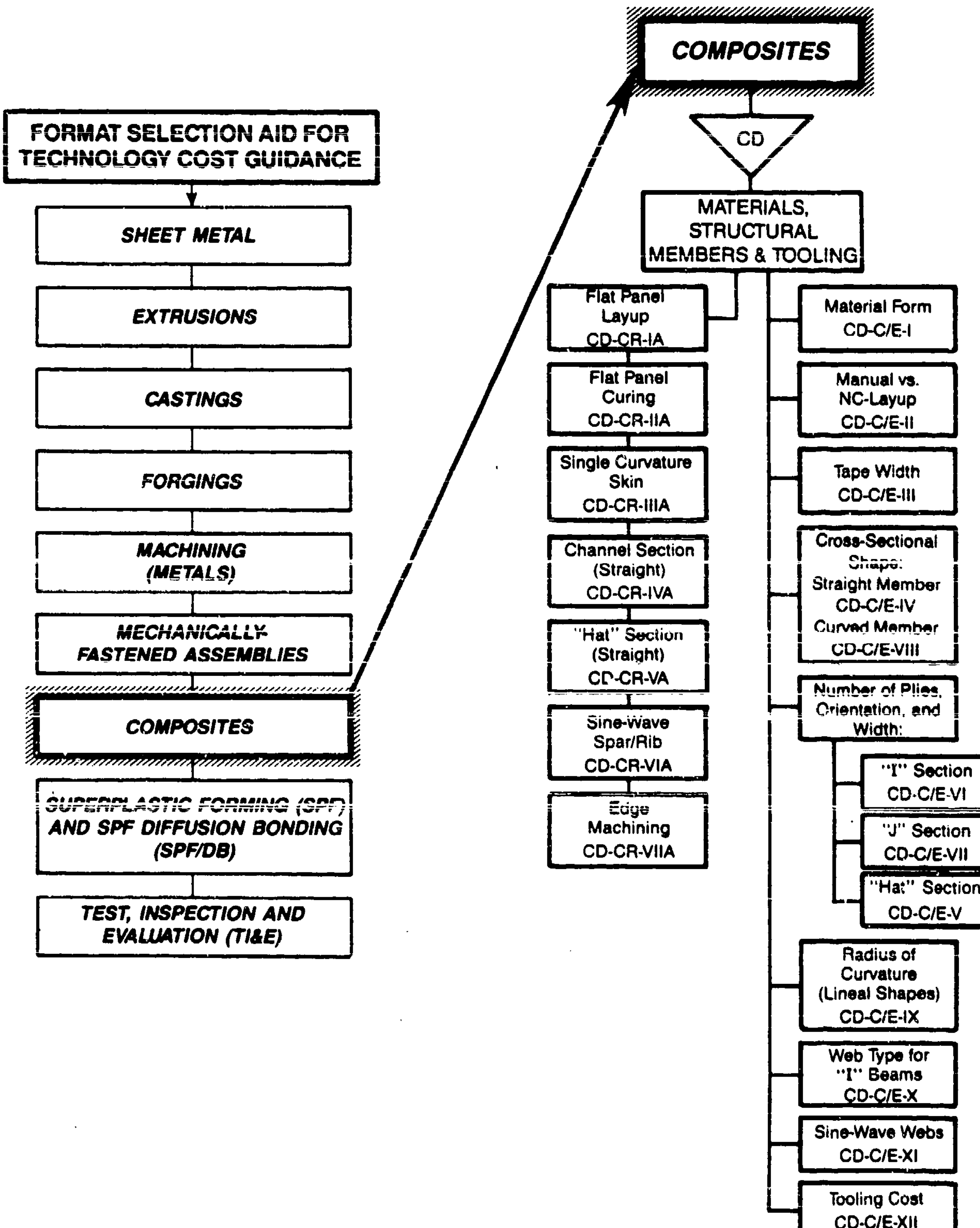
CD-MFA-XXII

EFFECT OF SEALING ON FASTENER INSTALLATION COST *ALUMINUM* ASSEMBLIES



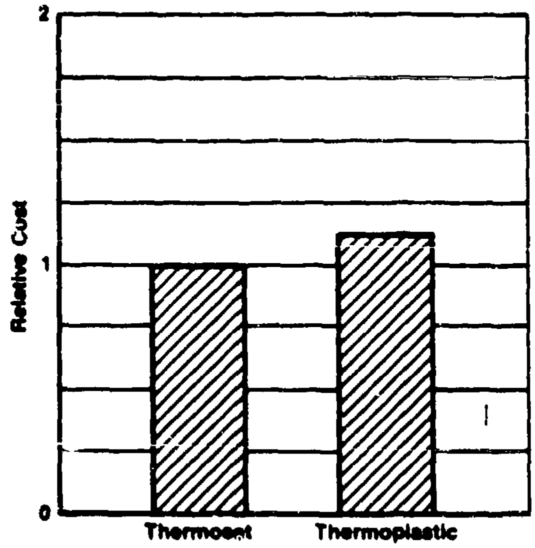
CD-MFA-XXIII

CONCEPTUAL DESIGN (CD)



THERMOPLASTIC VS. THERMOSETTING MATRIX

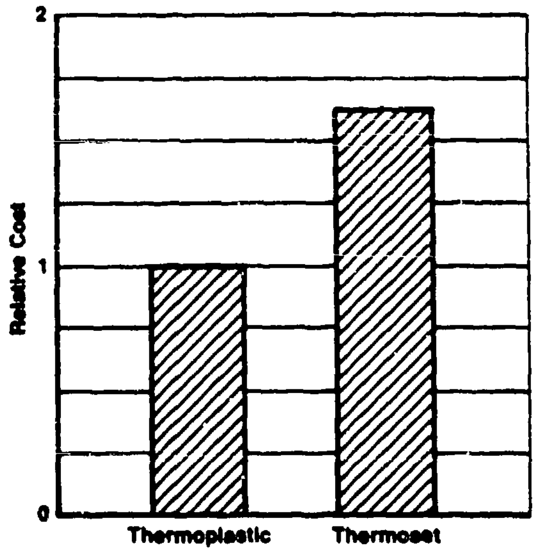
LAYUP OPERATION* OF FLAT PANELS



*Comparison limited to layup operation only.

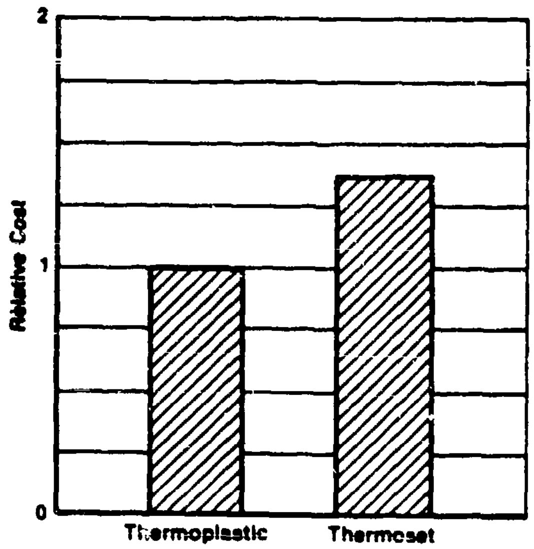
CD-CR-IA

COMPLETE MANUFACTURING PROCESS FOR COMPOSITE FLAT PANELS



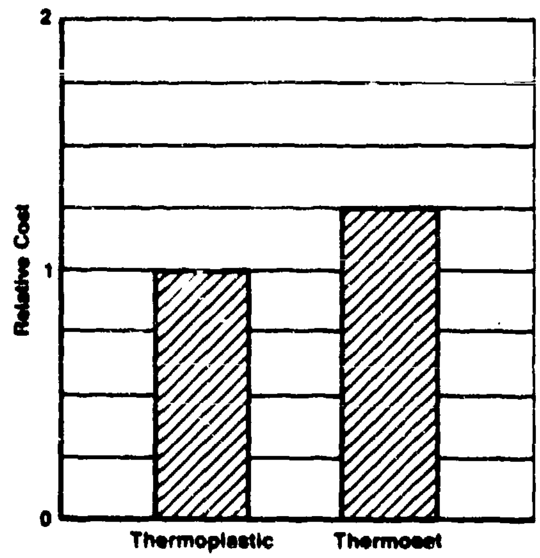
CD-CR-IIA

COMPOSITE SINGLE CURVATURE SKIN (TYPICAL OF LARGE FUSELAGE PANEL)



CD-CR-IIIA

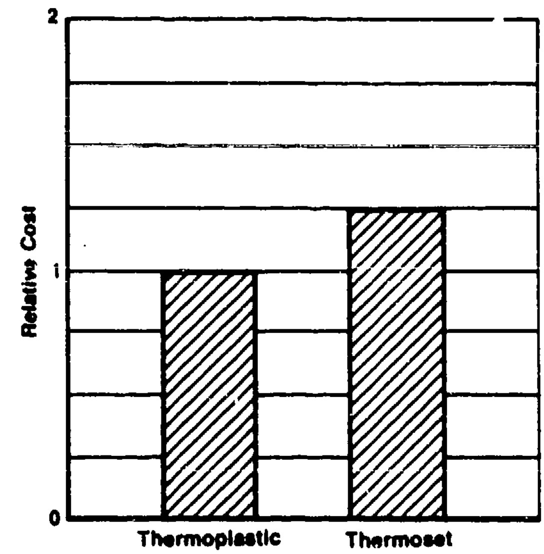
COMPOSITE STRAIGHT CHANNEL SECTION



CD-CR-IVA

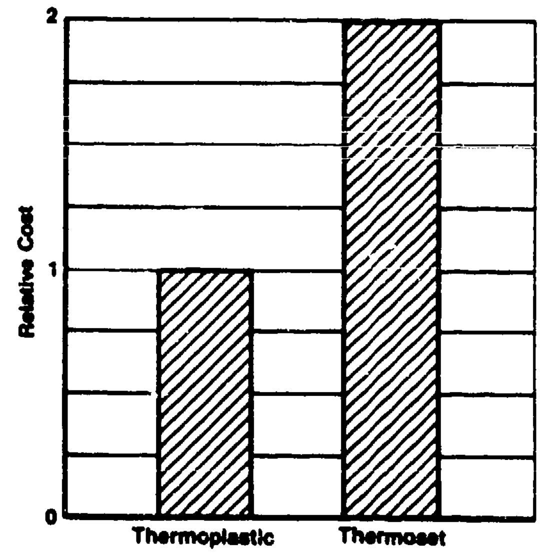
THERMOPLASTIC VS. THERMOSETTING MATRIX

COMPOSITE STRAIGHT HAT SECTION



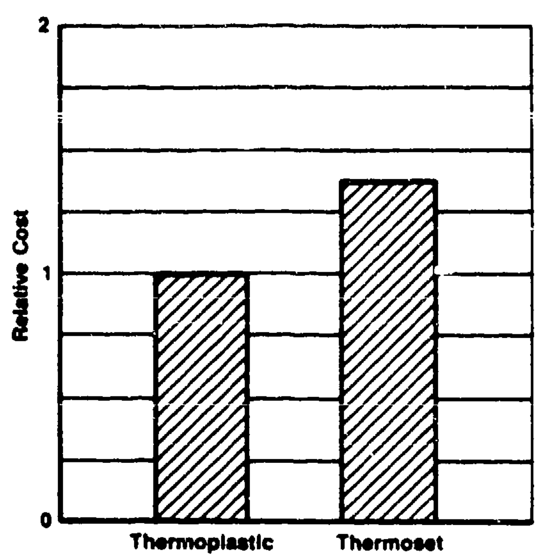
CD-CR-VA

COMPOSITE SINE-WAVE SPAR OR RIB WITH TWO FLANGES



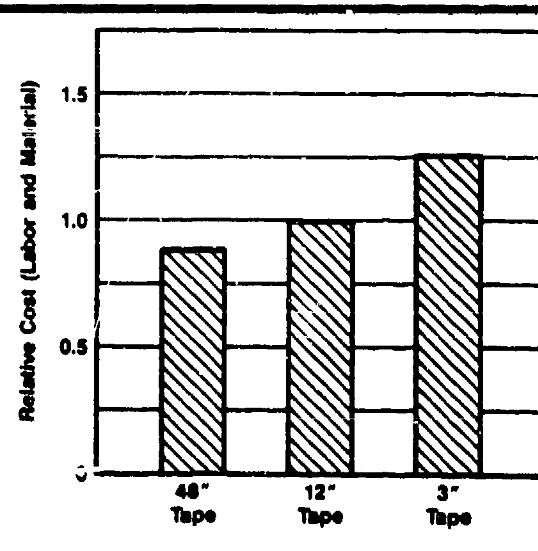
CD-CR-VIA

EDGE MACHINING OF COMPOSITE PANEL



CD-CR-VIIA

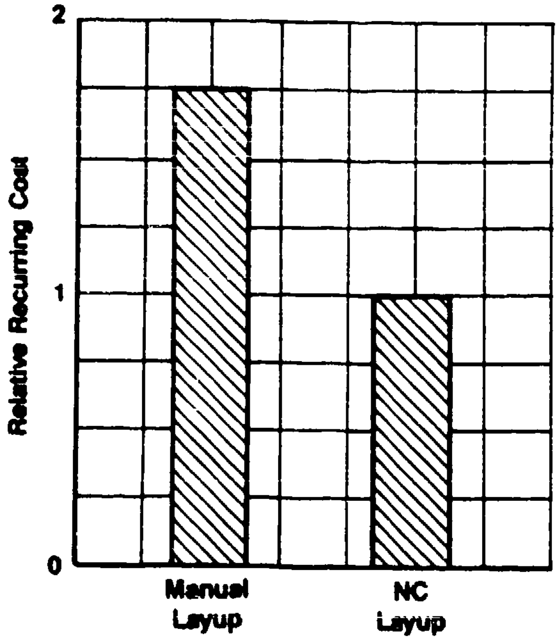
INFLUENCE OF MATERIAL FORM ON LAYUP COST THERMOSETTING MATRIX



CD-C/E-I

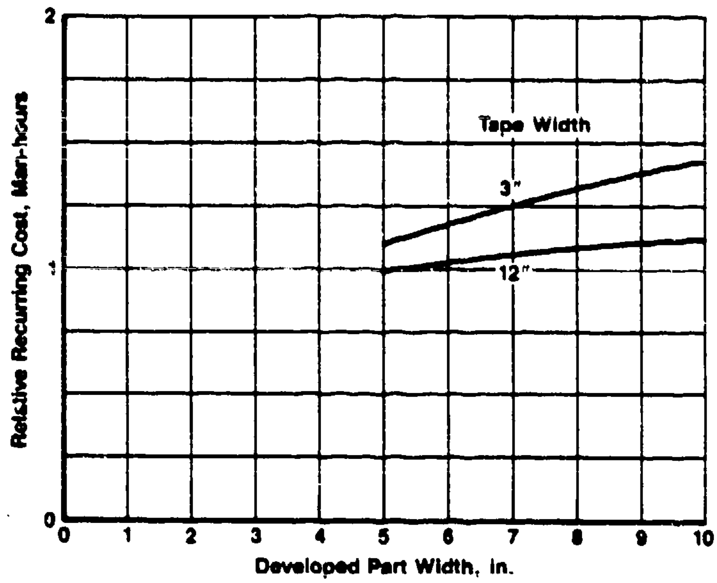
THERMOSETTING MATRIX

COMPARISON OF MANUAL VS. NC-LAYUP; COMPOSITE SINGLE CURVATURE PANEL



CD-C/E-ii

INFLUENCE OF TAPE WIDTH ON RECURRING COST OF LINEAL SHAPES

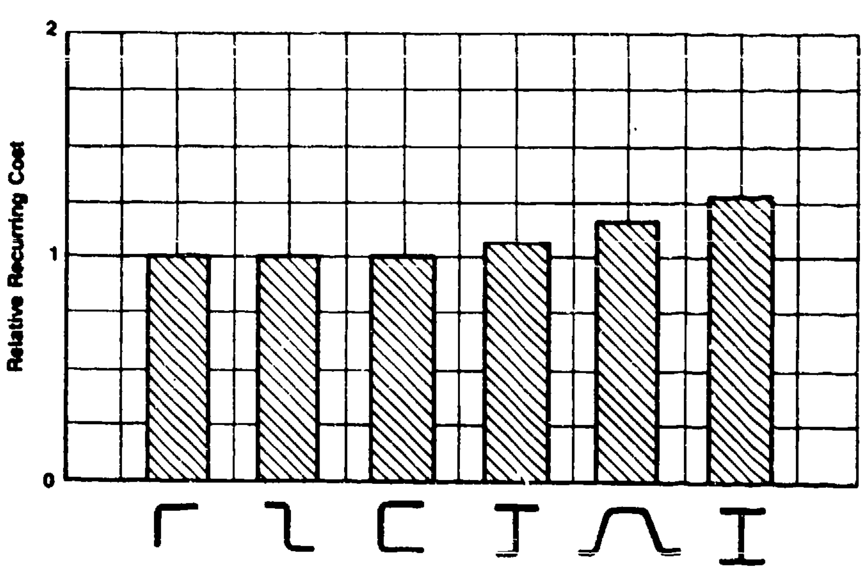


Notes:

- Part Length = 48"
- No Strip Plies

CD-C/E-III

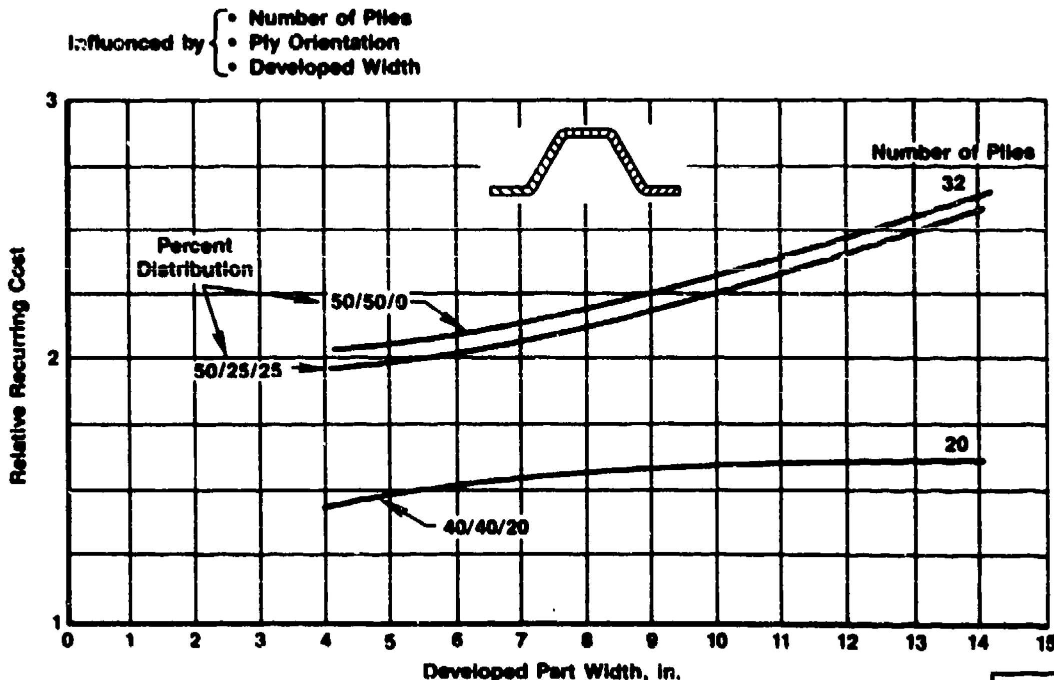
INFLUENCE OF CROSS-SECTION OF COMPOSITE *STRAIGHT* LINEAL STRUCTURAL MEMBERS; RECURRING COST



CD-C/E-IV

THERMOSETTING MATRIX

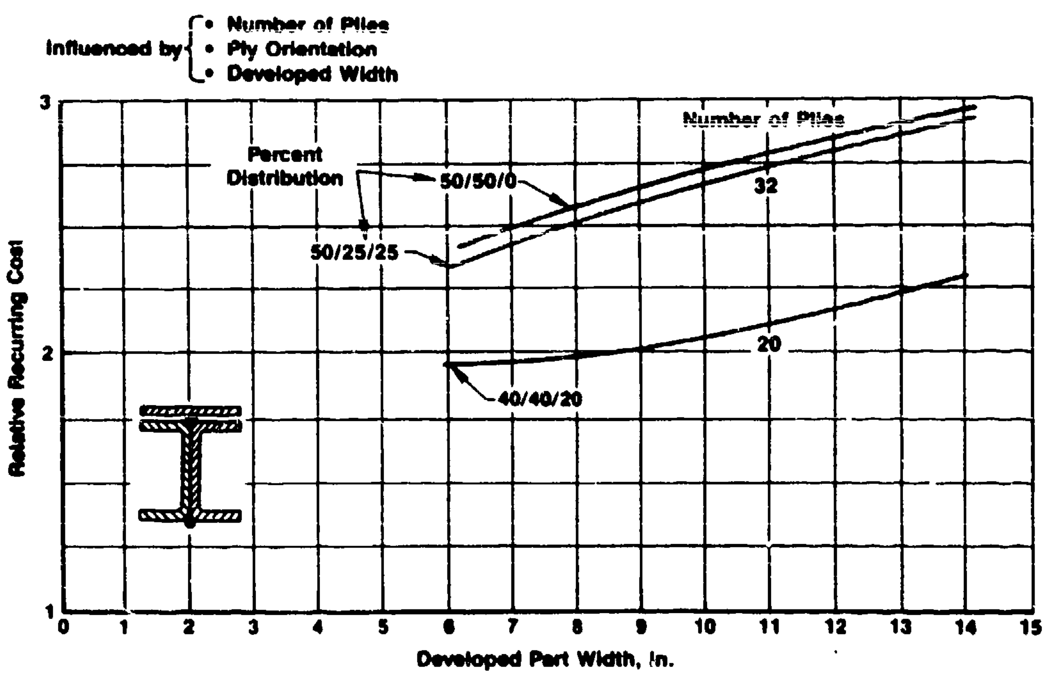
LINEAL HAT SECTION; RECURRING COST



*Ply Orientation Code: 0°/±45°/90°

CD-C/E-V

LINEAL "I" SECTION; RECURRING COST

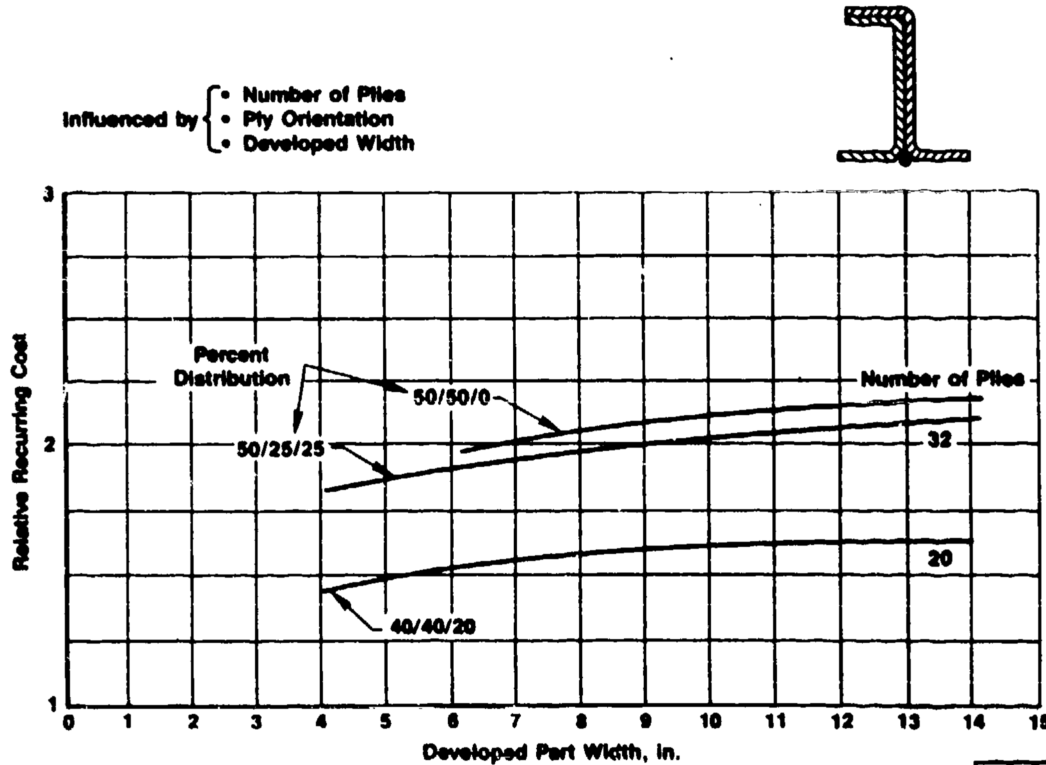


*Ply Orientation Code: 0°/±45°/90°

CD-C/E-VI

THERMOSETTING MATRIX
LINEAL "J" SECTION; RECURRING COST

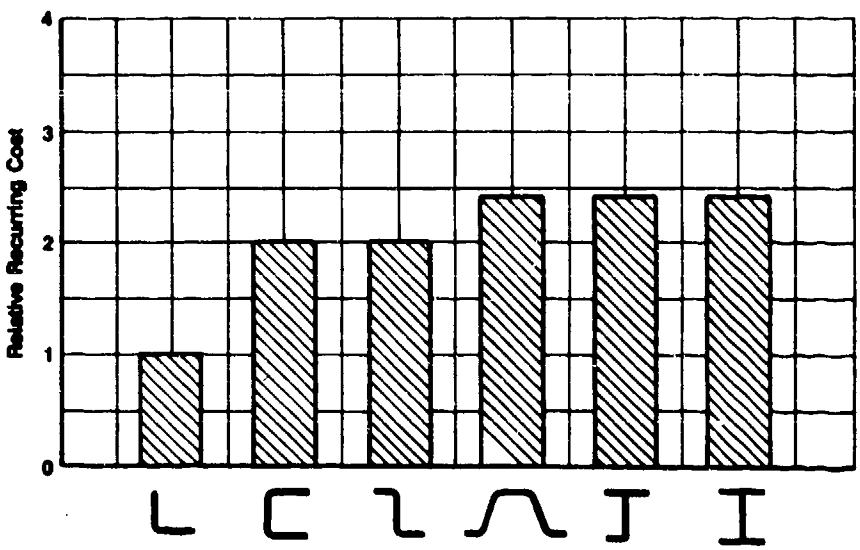
Influenced by {
- Number of Plies
- Ply Orientation
- Developed Width



CD-C/E-VII

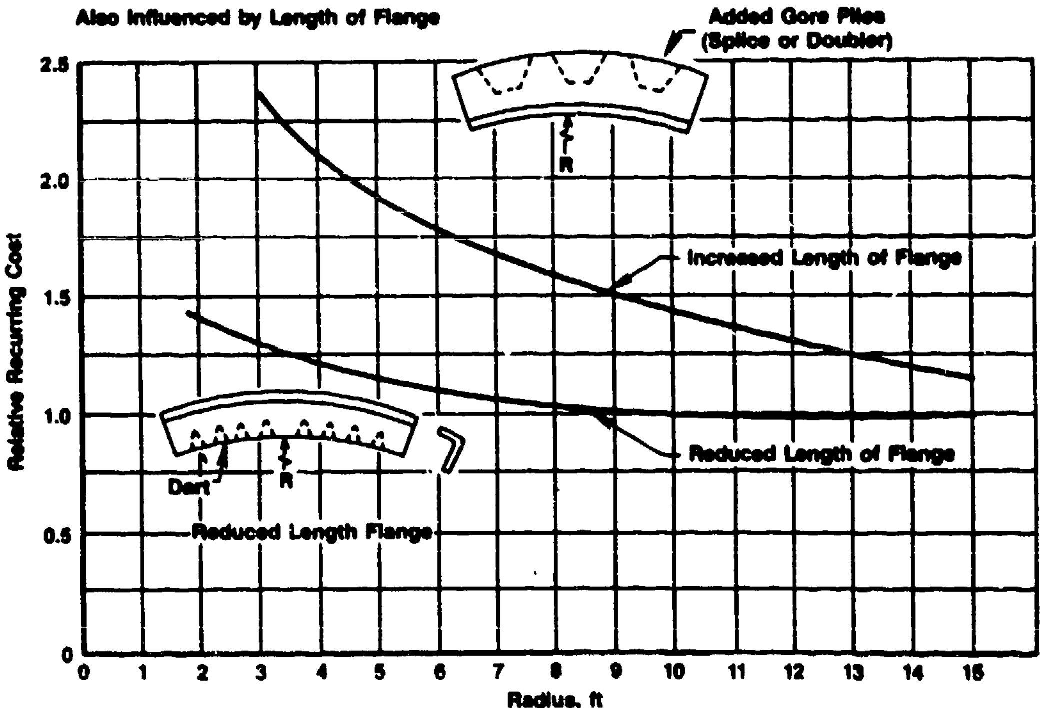
*Ply Orientation Code: 0°/ ±45°/90°

INFLUENCE OF CROSS-SECTION OF COMPOSITE *CURVED* LINEAL STRUCTURAL MEMBERS; RECURRING COST



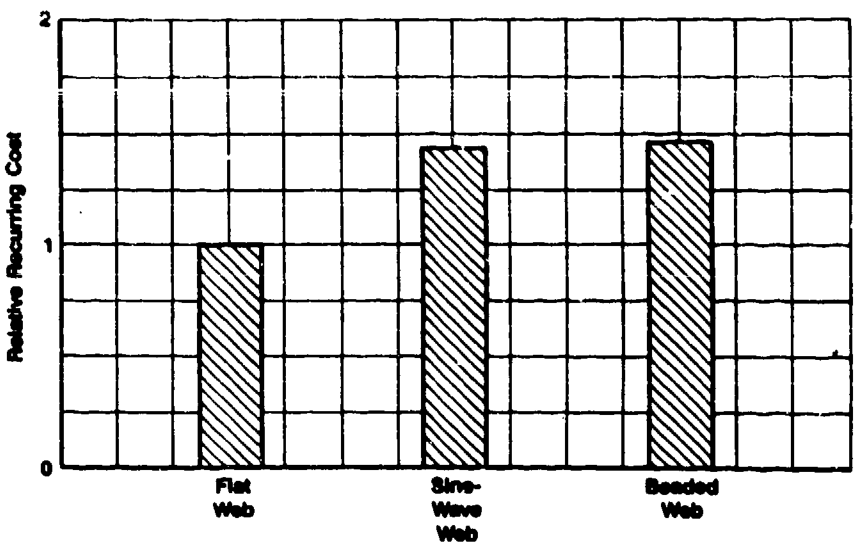
CD-C/E-VIII

THERMOSETTING MATRIX
INFLUENCE OF RADIUS OF CURVATURE OF LINEAL SHAPES; RECURRING COST



CD-C/E-IX

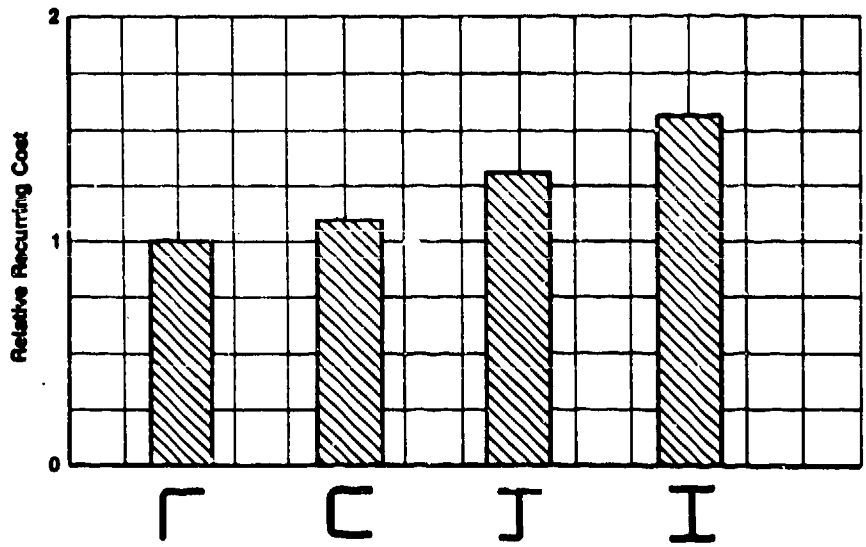
INFLUENCE OF WEB TYPES IN "I" BEAMS; RECURRING COST



CD-C/E-X

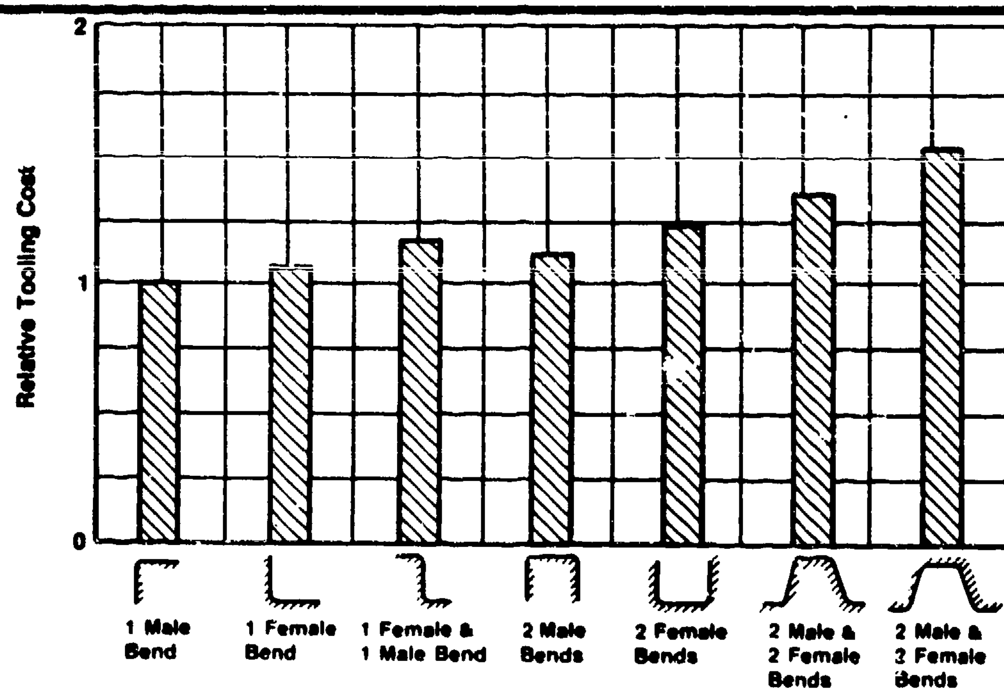
THERMOSETTING MATRIX

INFLUENCE OF SECTION OF COMPOSITE MEMBERS WITH SINE-WAVE WEBS; RECURRING COST



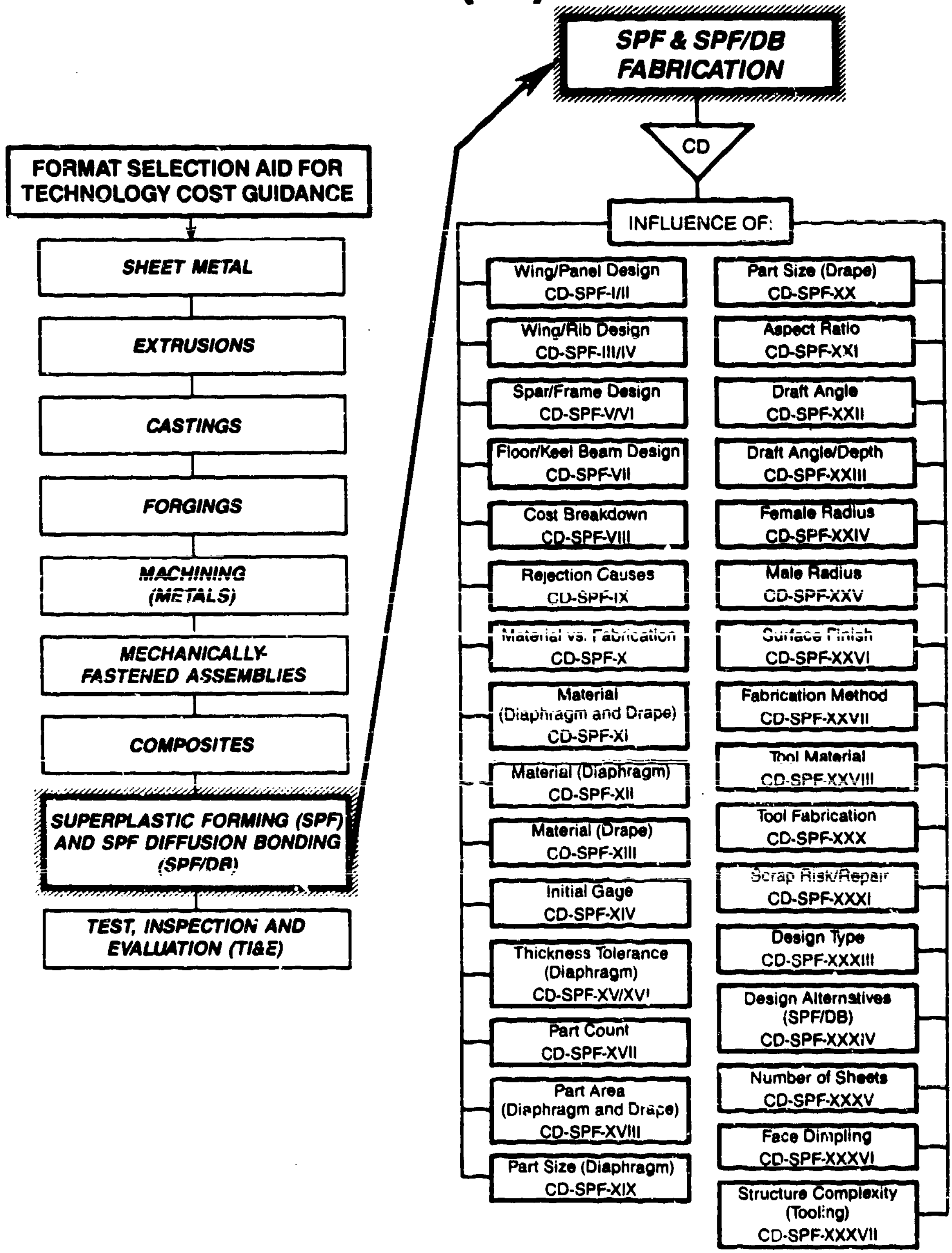
CD-C/E-XI

INFLUENCE OF { • NUMBER OF BENDS • SHAPE • TOOL TYPE } ON TOOLING COST OF COMPOSITE LINEAL SHAPES

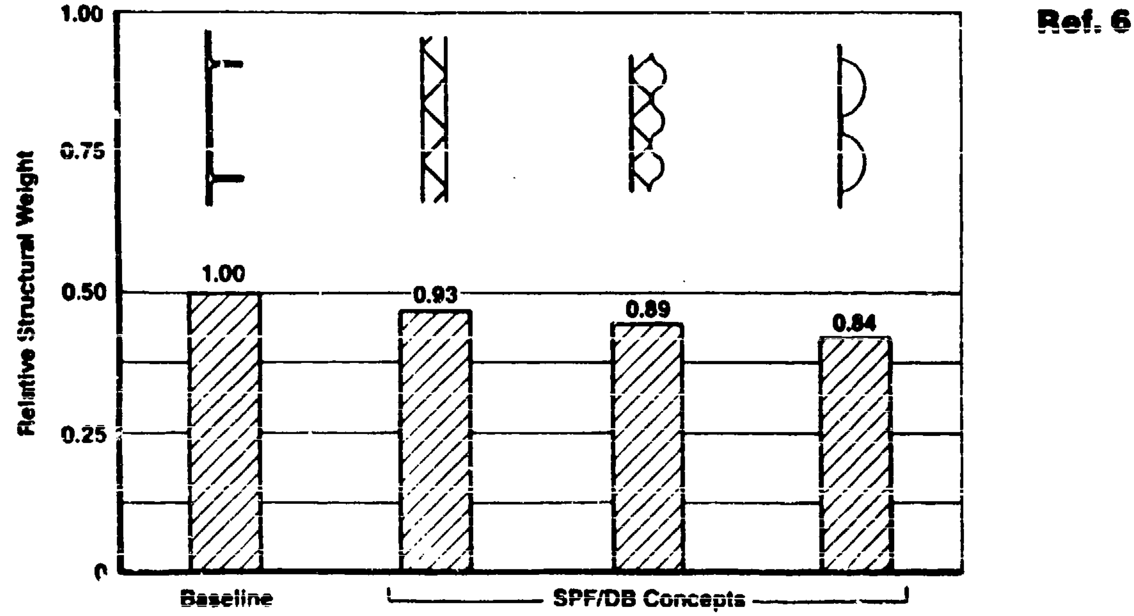


CD-C/E-XII

CONCEPTUAL DESIGN (CD)

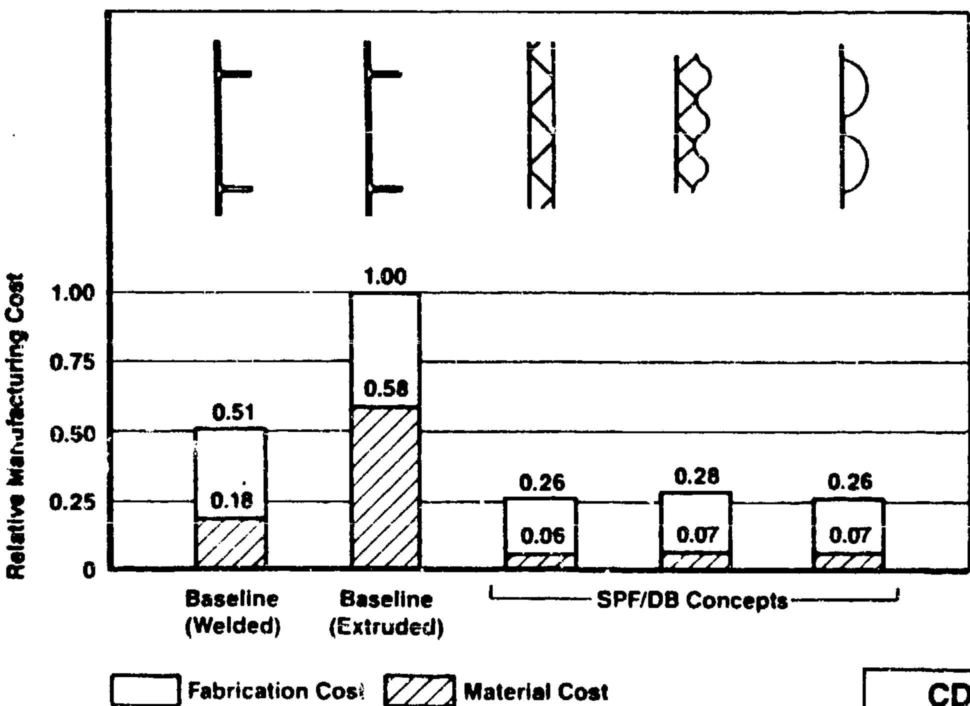


STRUCTURAL WEIGHT COMPARISON FOR VARIOUS WING PANEL CONFIGURATIONS



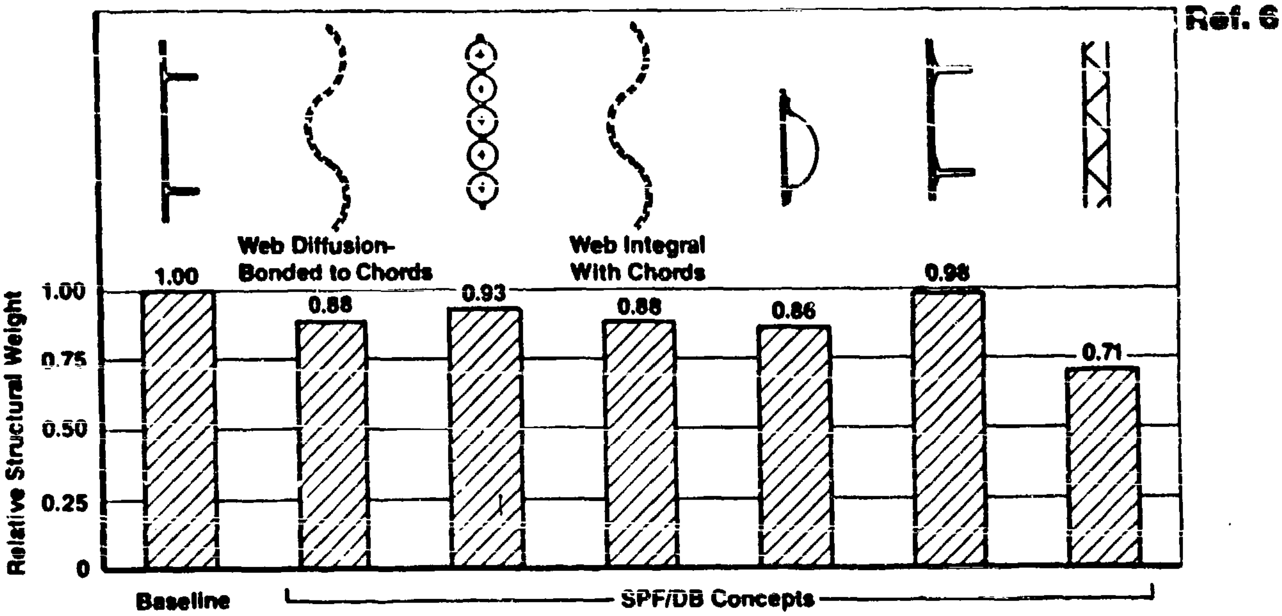
CD-SPF-I

TOTAL MANUFACTURING COST COMPARISON FOR VARIOUS WING PANEL CONFIGURATIONS (500-Airplane Program)



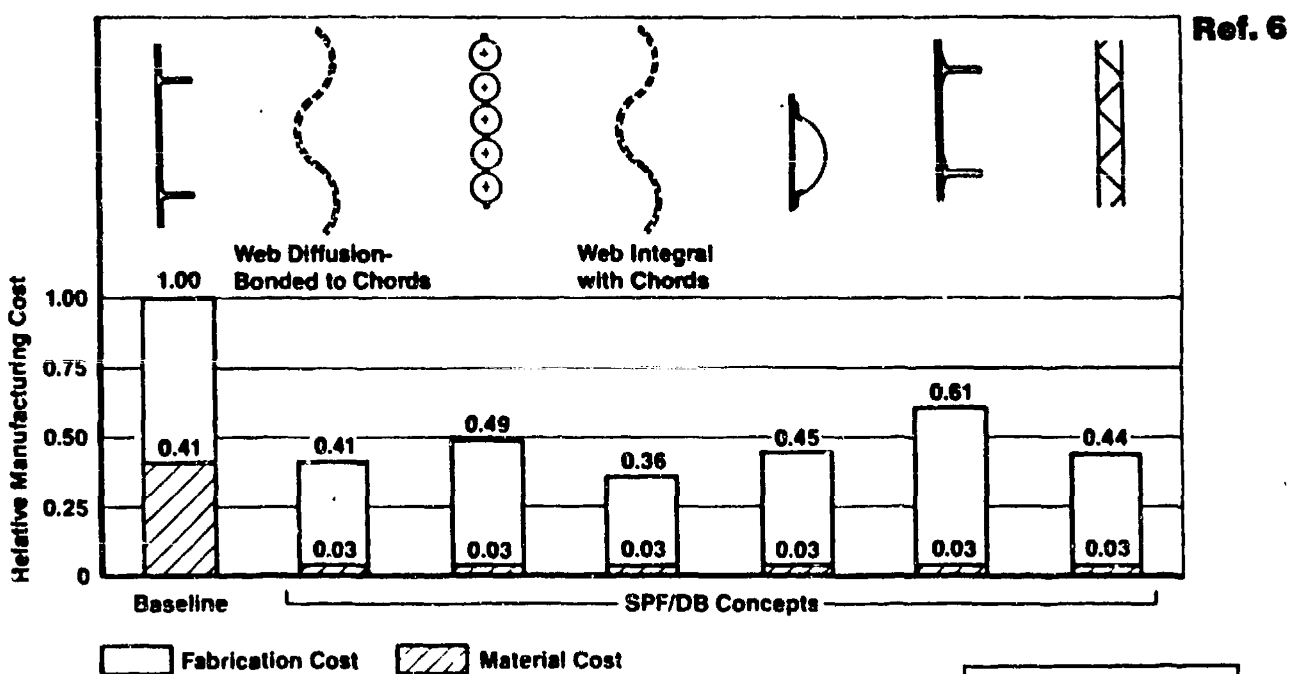
CD-SPF-II

STRUCTURAL WEIGHT COMPARISON FOR VARIOUS WING/RIB CONFIGURATIONS



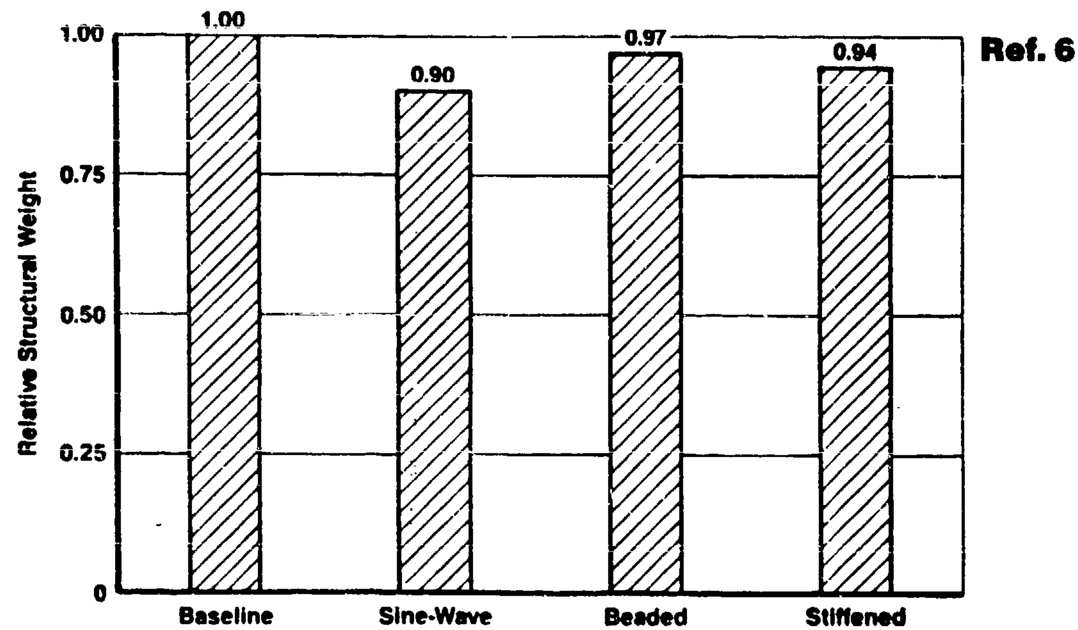
CD-SPF-III

TOTAL MANUFACTURING COST COMPARISON FOR VARIOUS WING/RIB CONFIGURATIONS (500-Airplane Program)



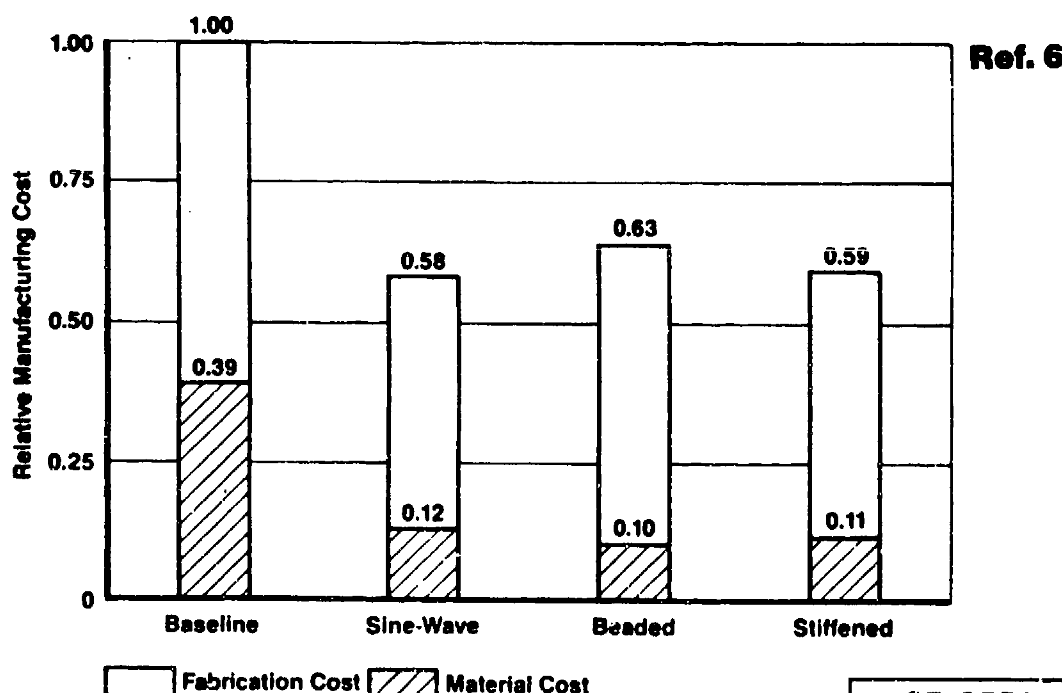
CD-SPF-IV

STRUCTURAL WEIGHT COMPARISON FOR VARIOUS SPAR/FRAME CONFIGURATIONS



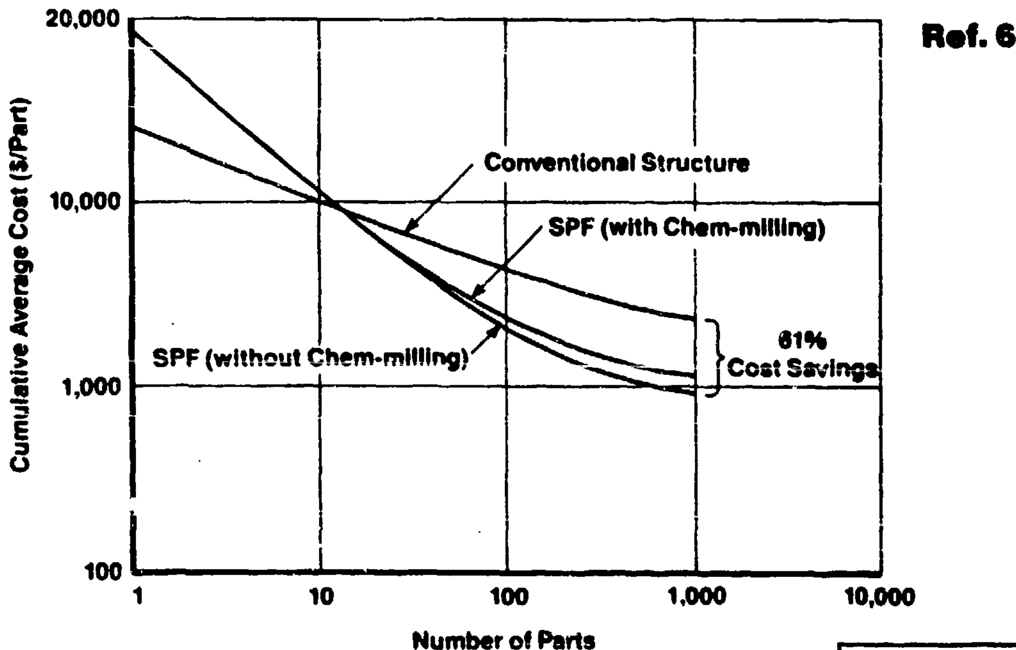
CD-SPF-V

TOTAL MANUFACTURING COST COMPARISON FOR VARIOUS SPAR/FRAME CONFIGURATIONS (500-Airplane Program)



CD-SPF-VI

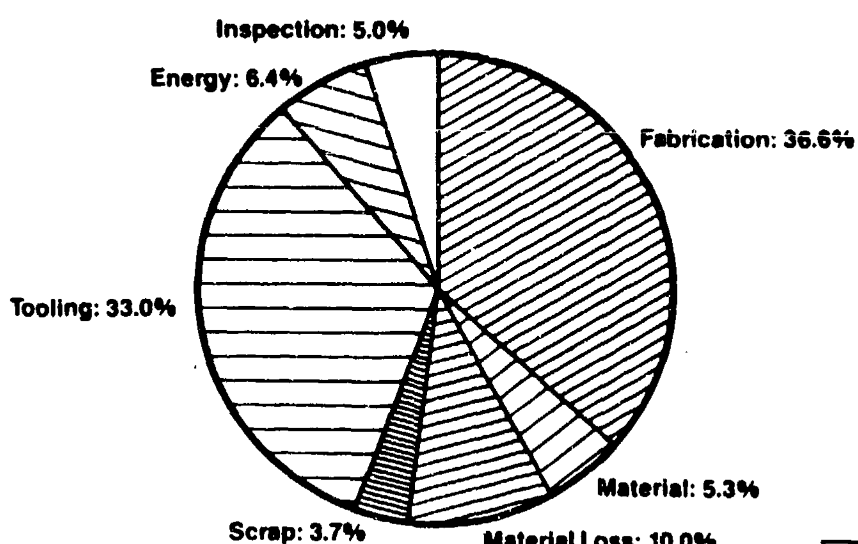
COST SAVINGS WHEN DESIGNING A HELICOPTER (AH-64A) FLOOR/KEEL BEAM



CD-SPF-VII

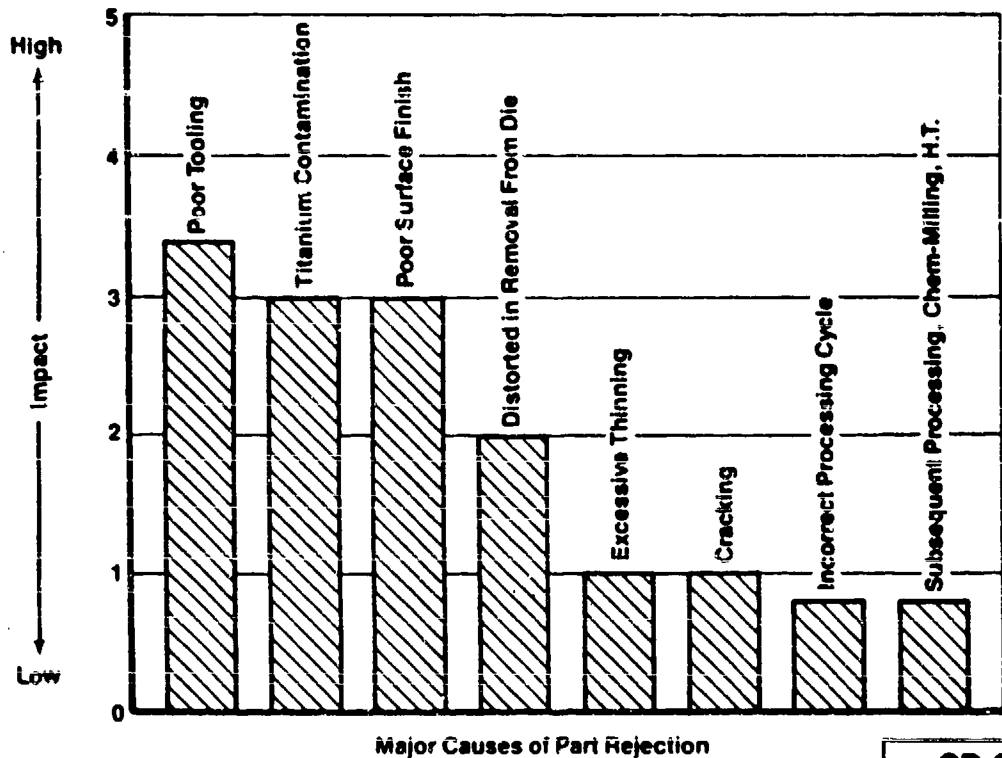
DISTRIBUTION OF COST FOR TITANIUM DEFLECTOR MANUFACTURED BY SPF

200 Cumulative Unit Average Cost per Part



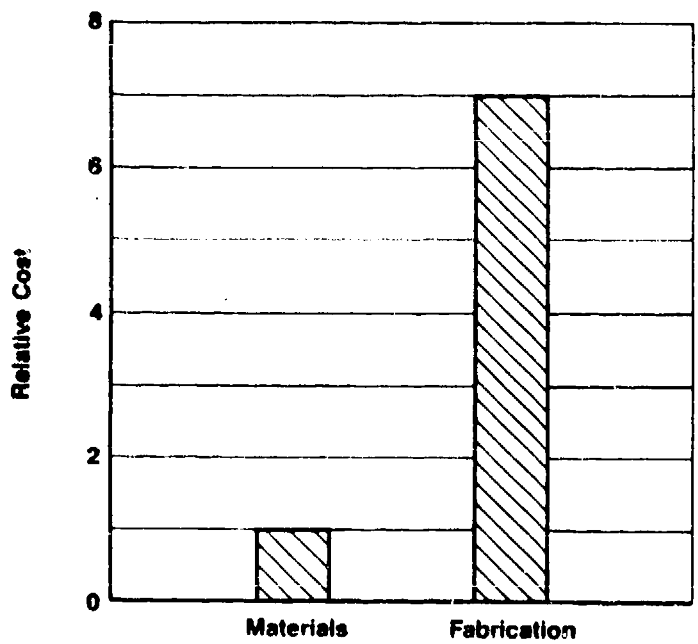
CD-SPF-VIII

MAJOR CAUSES OF PART REJECTION



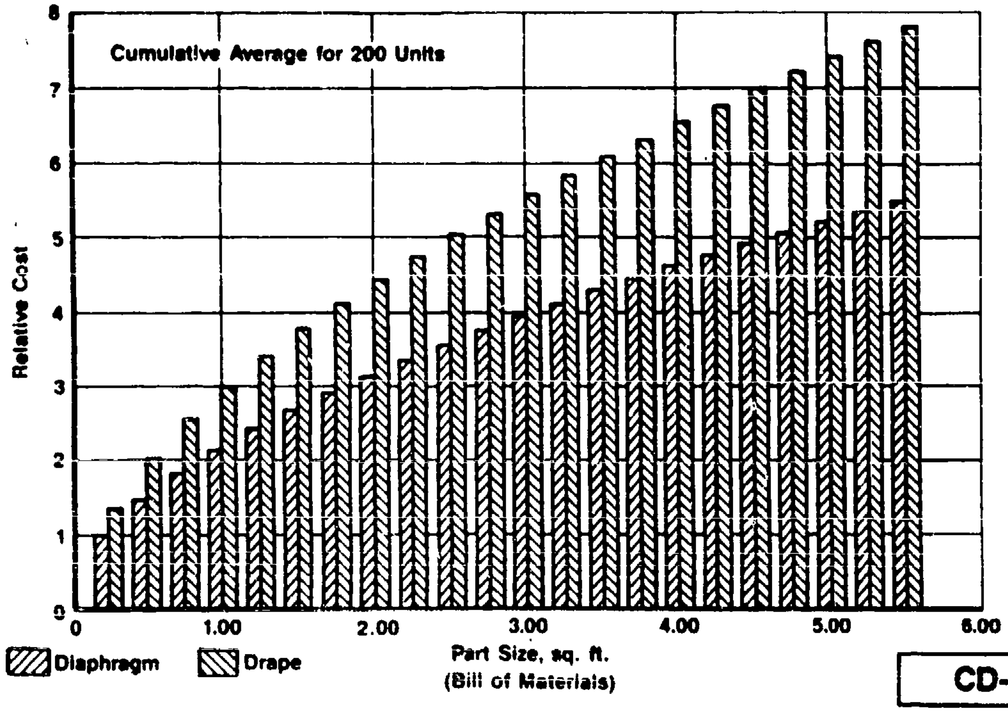
CD-SPF-IX

MATERIAL VERSUS FABRICATION COST FOR SPF PARTS



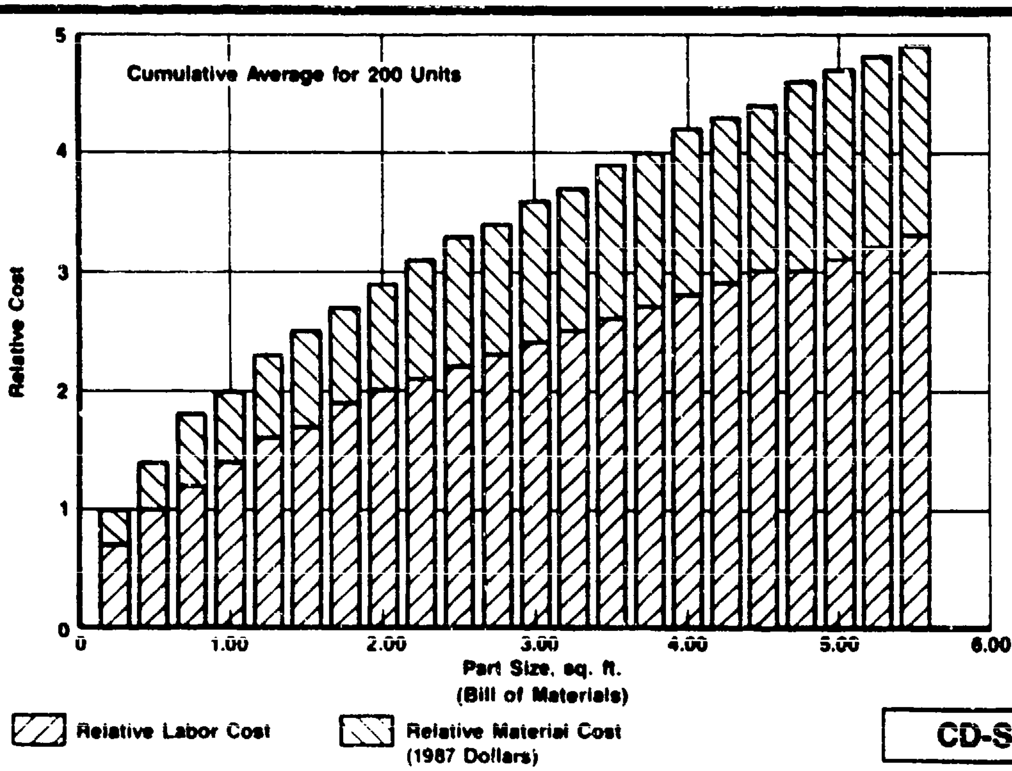
CD-SPF-X

INFLUENCE OF MATERIAL COST FOR SPF (DIAPHRAGM AND DRAPE)



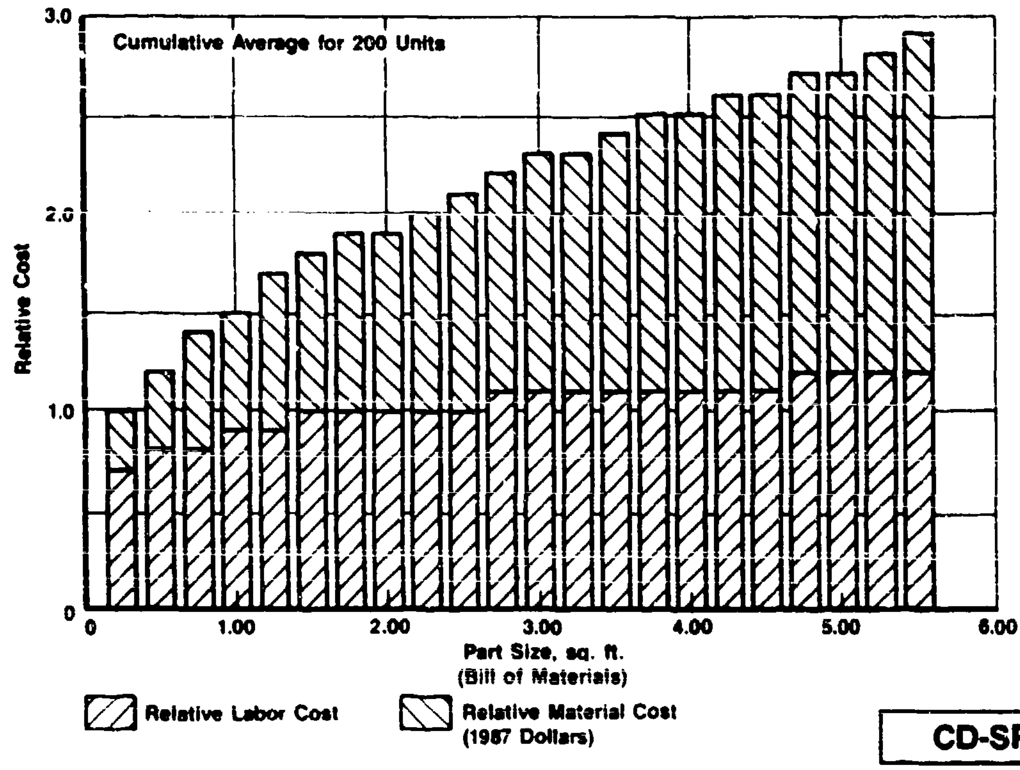
CD-SPF-XI

RELATIVE COST FOR MANUFACTURING AND MATERIAL FOR SPF (DIAPHRAGM)



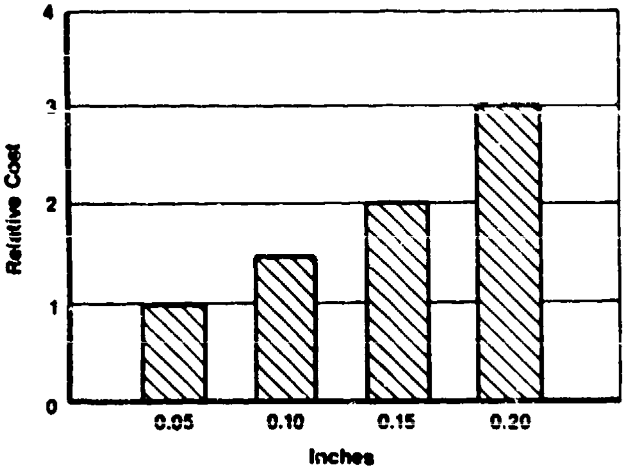
CD-SPF-XII

RELATIVE COST FOR MANUFACTURING AND MATERIAL FOR SPF (DRAPE)



CD-SPF-XIII

IMPACT OF INITIAL OR STARTING GAGE FOR SPF

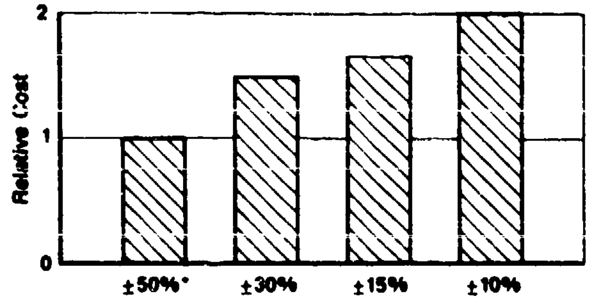


COST ELEMENTS:

- Requires higher pressure or longer time as thickness increases

CD-SPF-XIV

IMPACT OF SPF PART THICKNESS DESIGN TOLERANCE (DIAPHRAGM SPF)



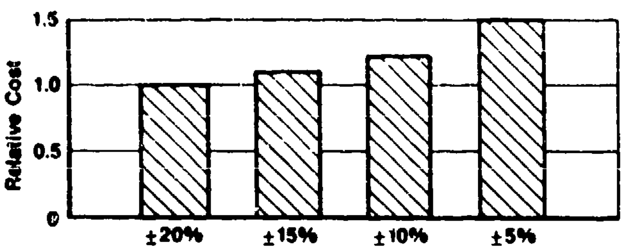
* Desired as "Minimum Gage" With No Maximum

COST ELEMENTS:

- Tighter gage tolerance requires selective chem-milling
- Influenced by aspect ratio
- Increased starting gage required with tighter tolerances

CD-SPF-XV

IMPACT OF SPF SHEET THICKNESS DESIGN TOLERANCE (DRAPE SPF)

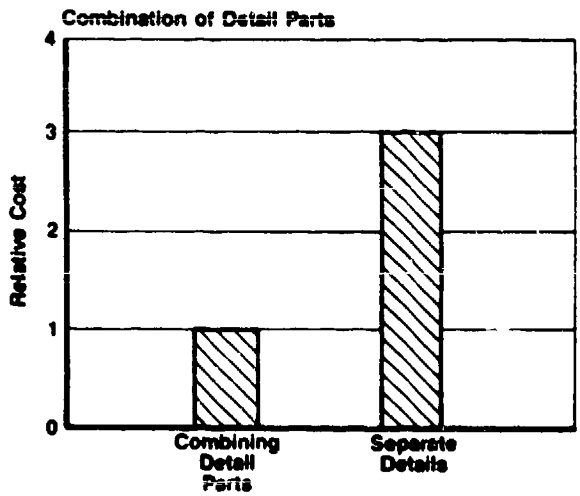


COST ELEMENT:

- Tolerances tighter than normal mill gage variations require: half tolerance sheet purchase and selective chem-milling

CD-SPF-XVI

INFLUENCE OF PART COUNT ON SPF COST

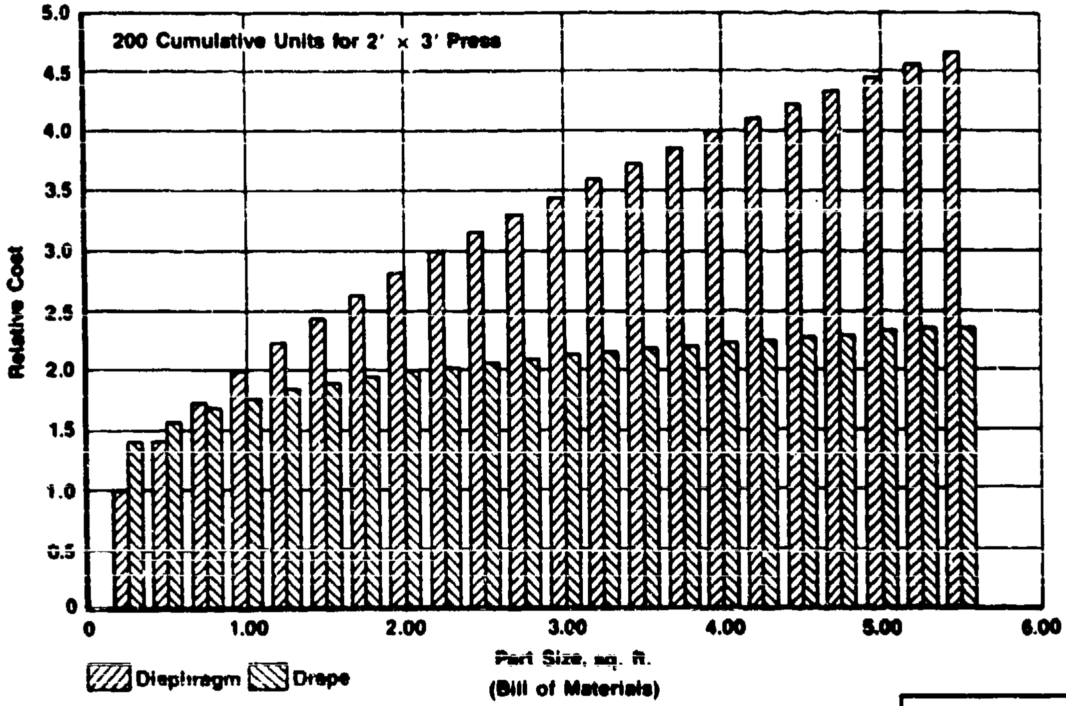


COST ELEMENTS:

- Each part number reduced by combining parts, saves cost of: design; drawing; release; planning; tool design; tool release; tool planning; tool order; checking; material plan; purchase order or tool build; production plan; crib records; inspection; inventory; etc.
- At least a 30% recurring cost savings potential with each part combination and 70% savings on non-recurring tool cost

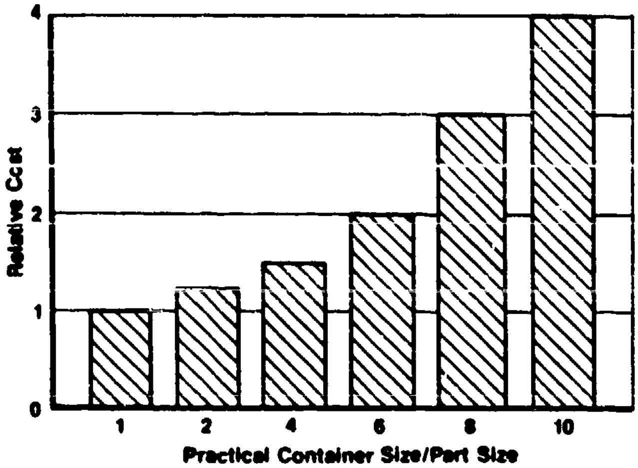
CD-SPF-XVII

INFLUENCE OF PART AREA FOR SPF (DIAPHRAGM AND DRAPE)



CD-SPF-XVIII

IMPACT OF PART SIZE ON SPF COST (DIAPHRAGM SPF)

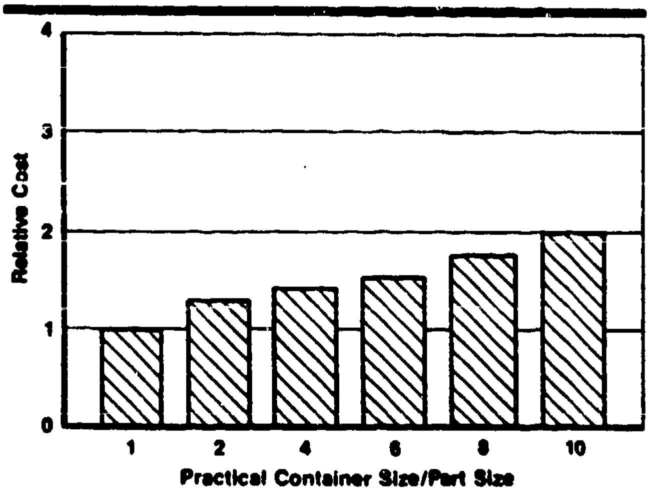


COST ELEMENTS:

- Depends upon tool nesting for least thinning variation
- Cost increase due to material utilization
- Affords opportunity for combining several parts into one
- Smaller the part reduces material utilization
- Smaller parts complicate tool nesting

CD-SPF-XIX

IMPACT OF PART SIZE ON SPF COST (DRAPE SPF)

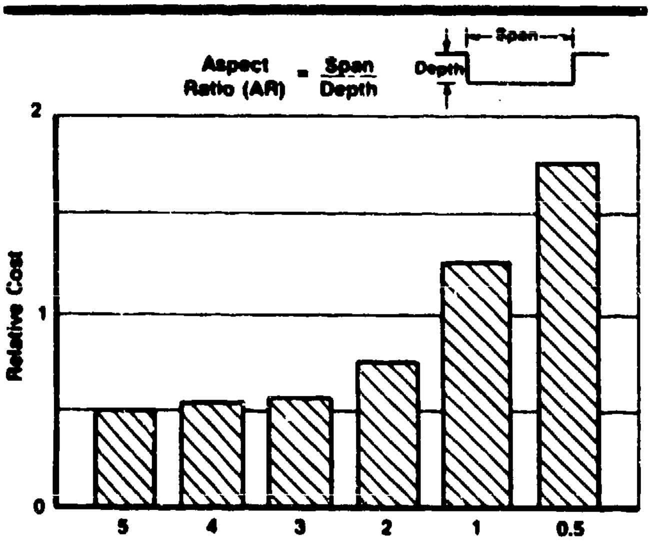


COST ELEMENTS:

- No effect on thinning
- Depends on tool nesting and part blank size
- Increased set-up time
- More tools in nest, longer SPF loading operation
- Small parts should be examined for combining with adjacent details

CD-SPF-XX

IMPACT OF ASPECT RATIO ON SPF COST (DIAPHRAGM OR DRAPE)

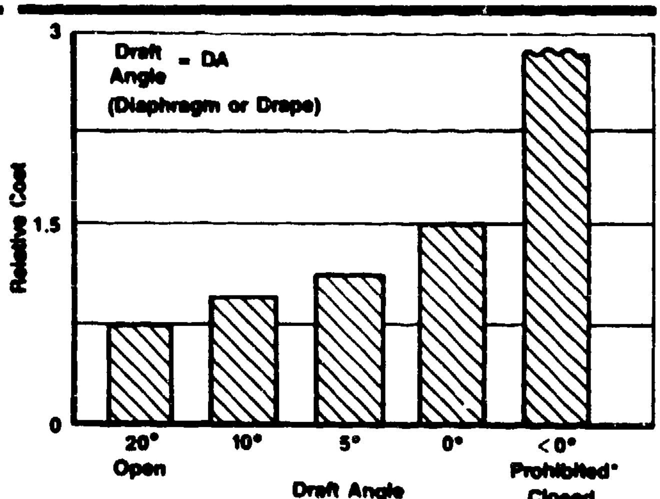


COST ELEMENTS:

- Narrow spans require increased pressure and time to reach depth
- Smaller AR causes larger female radii
- Very small AR may not be possible because of facility limitations
- Thinning variations become more severe at smaller AR
- Dependent upon draft angle

CD-SPF-XXI

IMPACT OF DRAFT ANGLE ON SPF COST (DIAPHRAGM OR DRAPE)



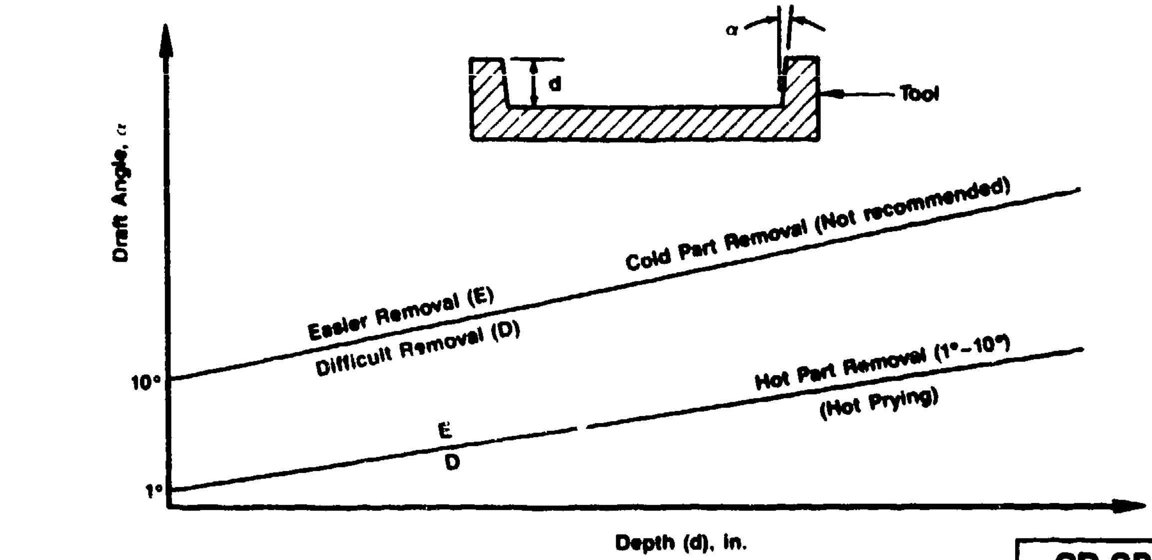
COST ELEMENTS:

- Part removal from tool not possible with closed angles; prohibited*
- 90° side walls (or 0° draft angle) cause: difficult part removal; requirement for steel tooling; increased tool maintenance
- Dependent upon aspect ratio

* Only possible with costly split tooling or breakaway tools

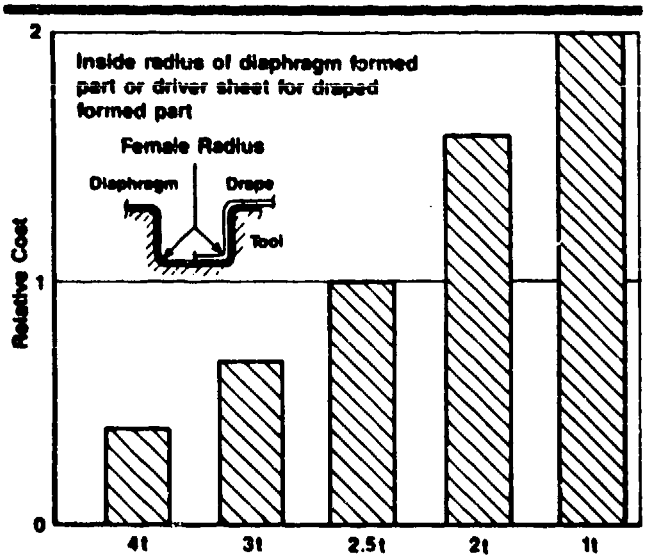
CD-SPF-XXII

SPF DESIGN FOR PART REMOVAL (DRAFT ANGLE VERSUS DEPTH)



CD-SPF-XXIII

IMPACT OF FEMALE RADIUS ON SPF COST

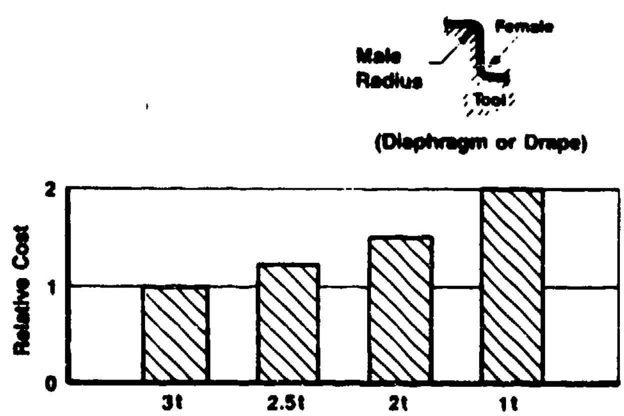


COST ELEMENTS:

- Sharp radii require higher SPF pressure and/or longer cycle
- Radii dependent on aspect ratio
- Minor tooling effect
- Designer should consult SPF specialists for radii < 2t

CD-SPF-XXIV

IMPACT OF MALE RADIUS ON SPF COST

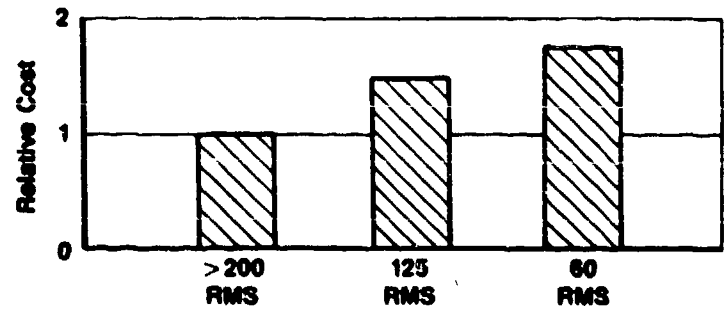


COST ELEMENTS:

- Sharper radii requires steel tooling
- Large radii allows ceramic tools
- Cost can increase also due to additional chemmilling and thicker material
- Sharp radii requires more frequent tool maintenance (particularly with ceramic tools)
- Sharp radii experience more thinning adjacent to radii

CD-SPF-XXV

IMPACT OF SURFACE FINISH CALLOUT ON SPF COST

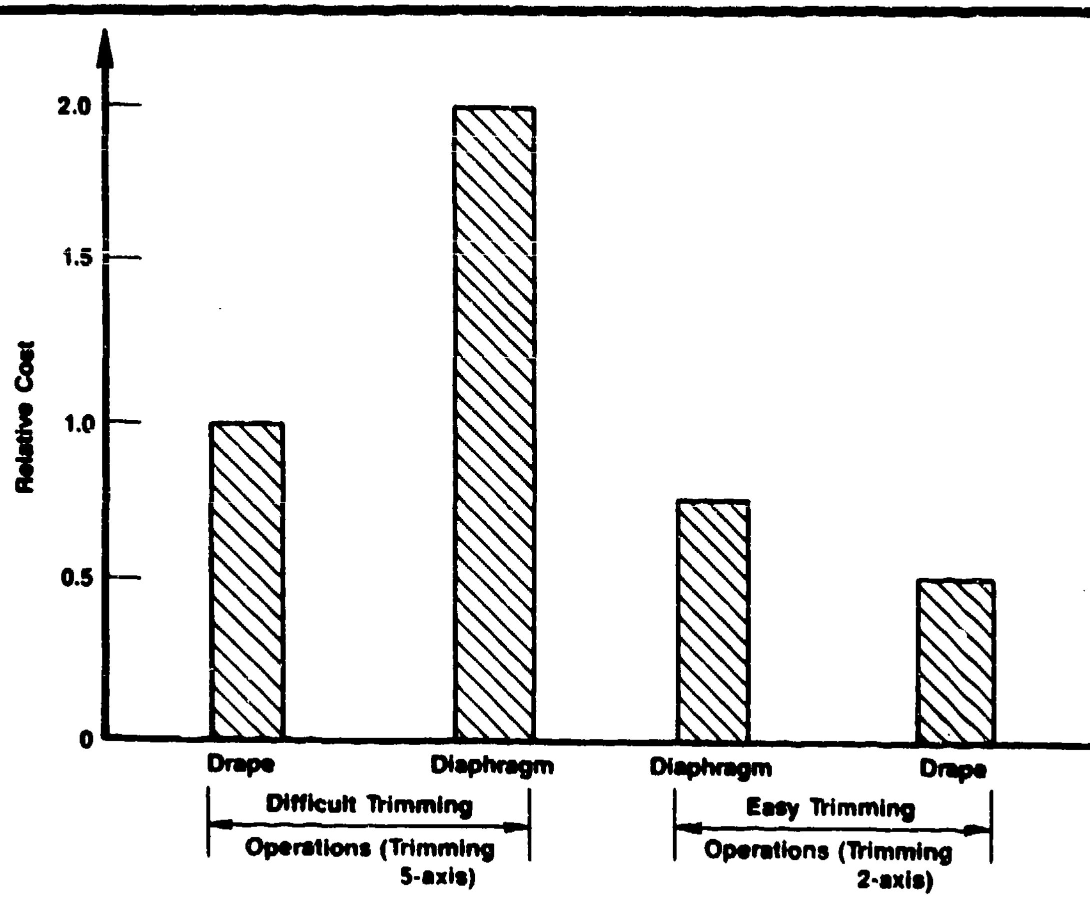


COST ELEMENTS:

- 125 RMS requires frequent tool maintenance
- 60 RMS requires part polishing plus tool maintenance

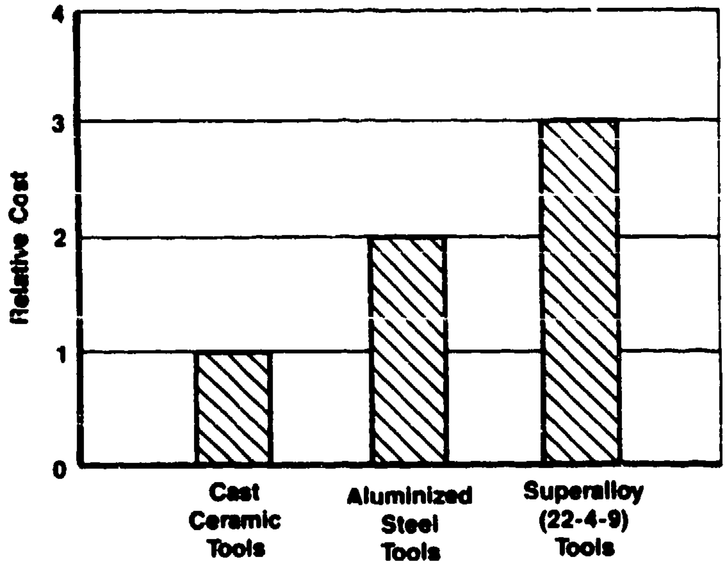
CD-SPF-XXVI

DIAPHRAGM VERSUS DRAPE FABRICATION FOR SPF PARTS



CD-SPF-XXVII

IMPACT OF SPF TOOL MATERIALS

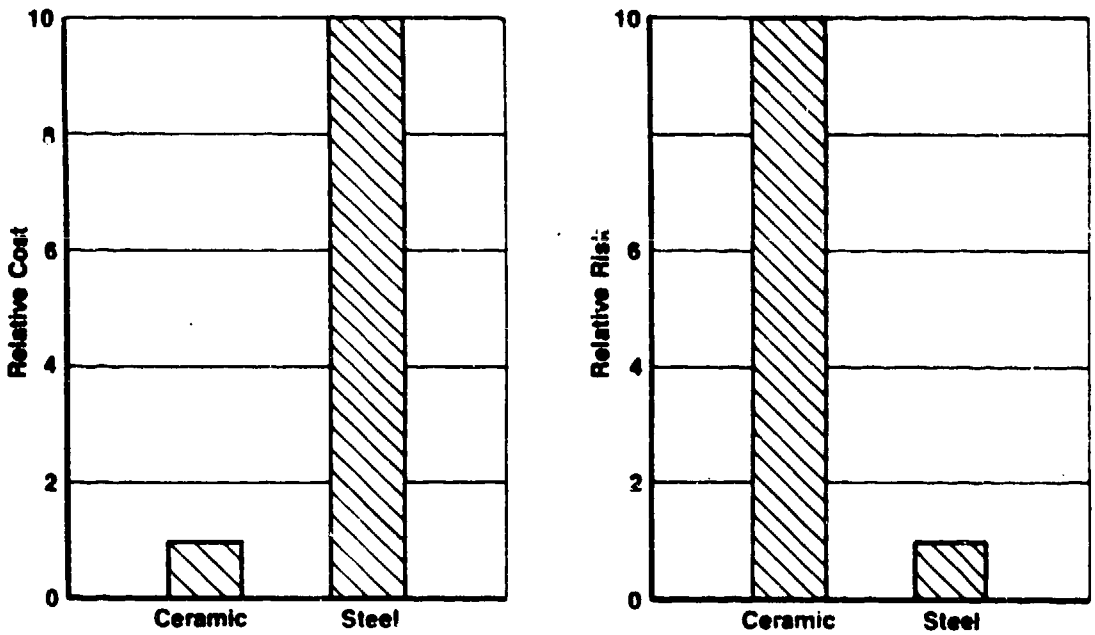


COST ELEMENTS:

- Ceramic requires model of part
- Steel tools are easily machined, but must be coated
- Superalloy tools difficult to machine (no coating required)

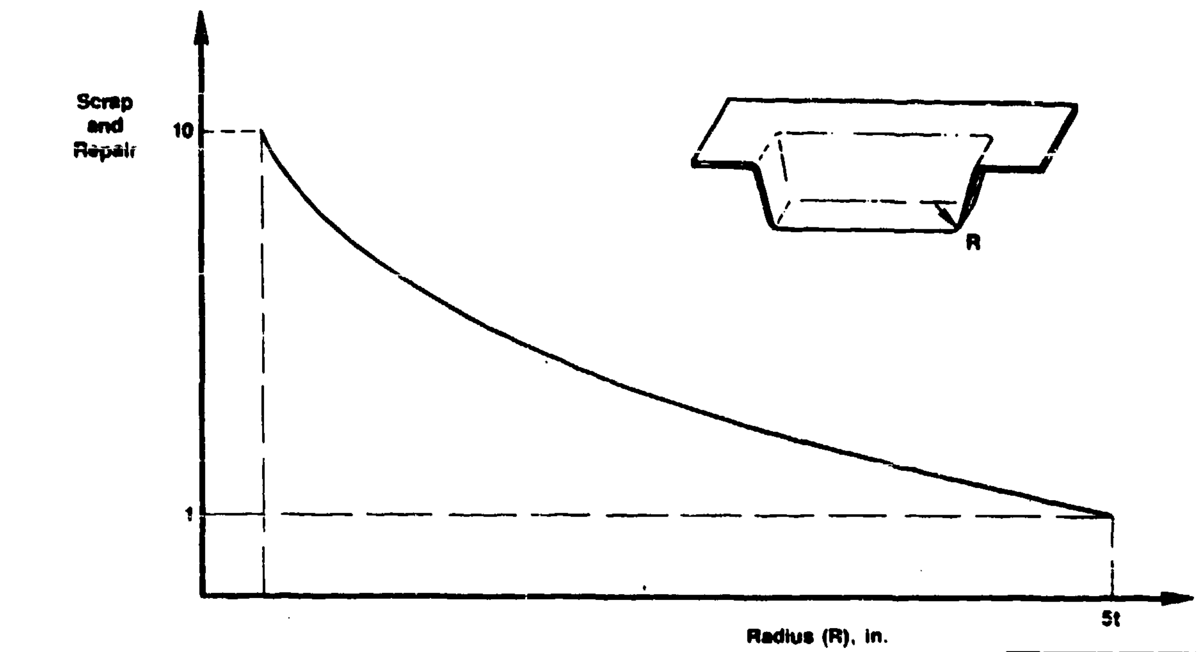
CD-SPF-XXVIII

TOOL FABRICATION COST VERSUS OPERATIONAL RISK FOR SPF PARTS



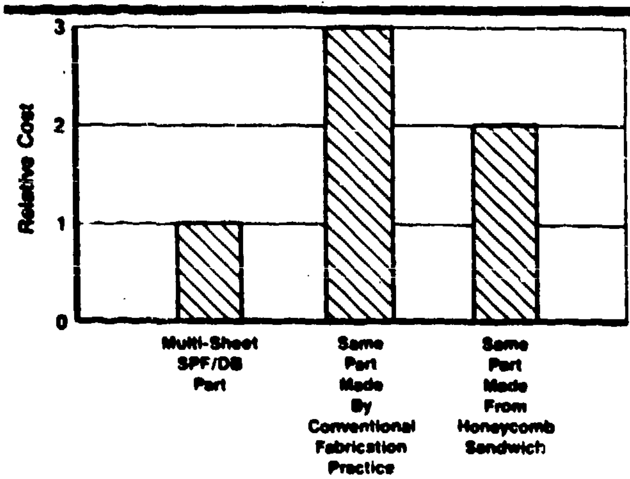
CD-SPF-XXIX

APPROXIMATION OF TREND IN SCRAP RISK AND REPAIR COSTS VERSUS RADIUS FOR SPF PARTS



CD-SPF-XXX

SPF/DB BENEFITS RELATIVE TO CONVENTIONAL FABRICATION AND SANDWICH CONSTRUCTION

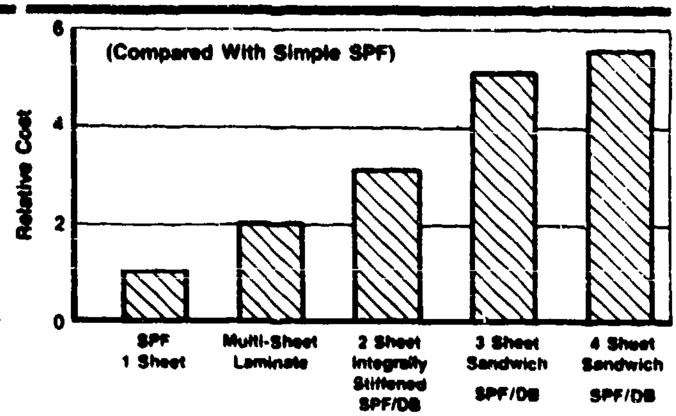


COST ELEMENTS:

- SPF/DB eliminates numerous conventional detail parts
- Eliminates assembly time and fasteners
- Usually lower weight structures with higher integrity
- Eliminates residual stresses caused by conventional assembly
- Eliminates cost of honeycomb core manufacture & assembly time

CD-SPF-XXXI

IMPACT OF SPF/DB ASSEMBLY TYPE ON COST

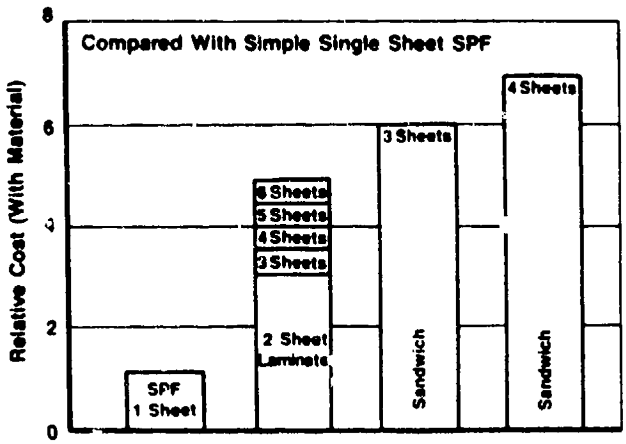


COST ELEMENTS:

- 3 and 4 sheet structures requires complex assembly
  - —Silk screen stop-off
  - —Resistance weld pattern
  - —Resistance weld edge sealing
  - —TIG weld fittings (between each layer)
  - —Complex plumbing
- The more assembly operations the greater the risk for
  - —Leaks
  - —Contamination
  - —Misalignment
- Laminated SPF/DB does not require added pressure tubes or seals

CD-SPF-XXXII

INFLUENCE OF NUMBER OF SHEETS ON SPF COST

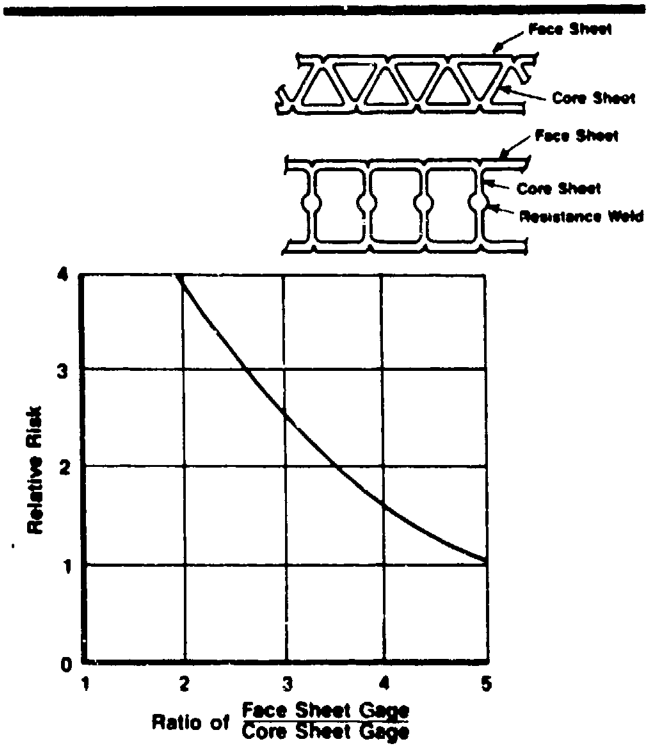


COST ELEMENTS:

- 2 sheet (e.g., doubler or flange addition to SPF sheet) required to be SPF/DB in ultra-clean system
- 2, 3 & 4 sheets by either silk screen stop-off or resistance weld methods (sandwich)
- 2 sheet method may be extended to multiple sheets by lamination (no sandwich)
  - –Used for reinforcing areas subject to extreme thinning
  - –Accomplished in ultra-clean environment

CD-SPF-XXXIII

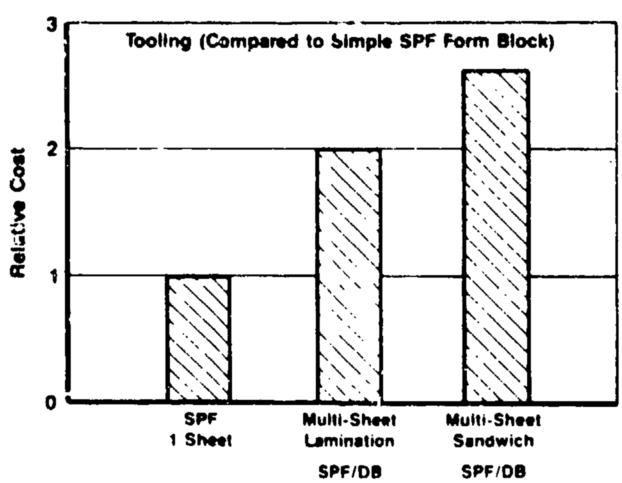
RELATIVE RISK OF FACE DIMPLING OR GROOVING (IMPACTING COST) DURING SPF/DB OPERATION



- Risk of dimpling or grooving decreases with increase in face to core thickness ratio

CD-SPF-XXXIV

IMPACT OF SPF/DB COMPLEXITY ON TOOLING COST

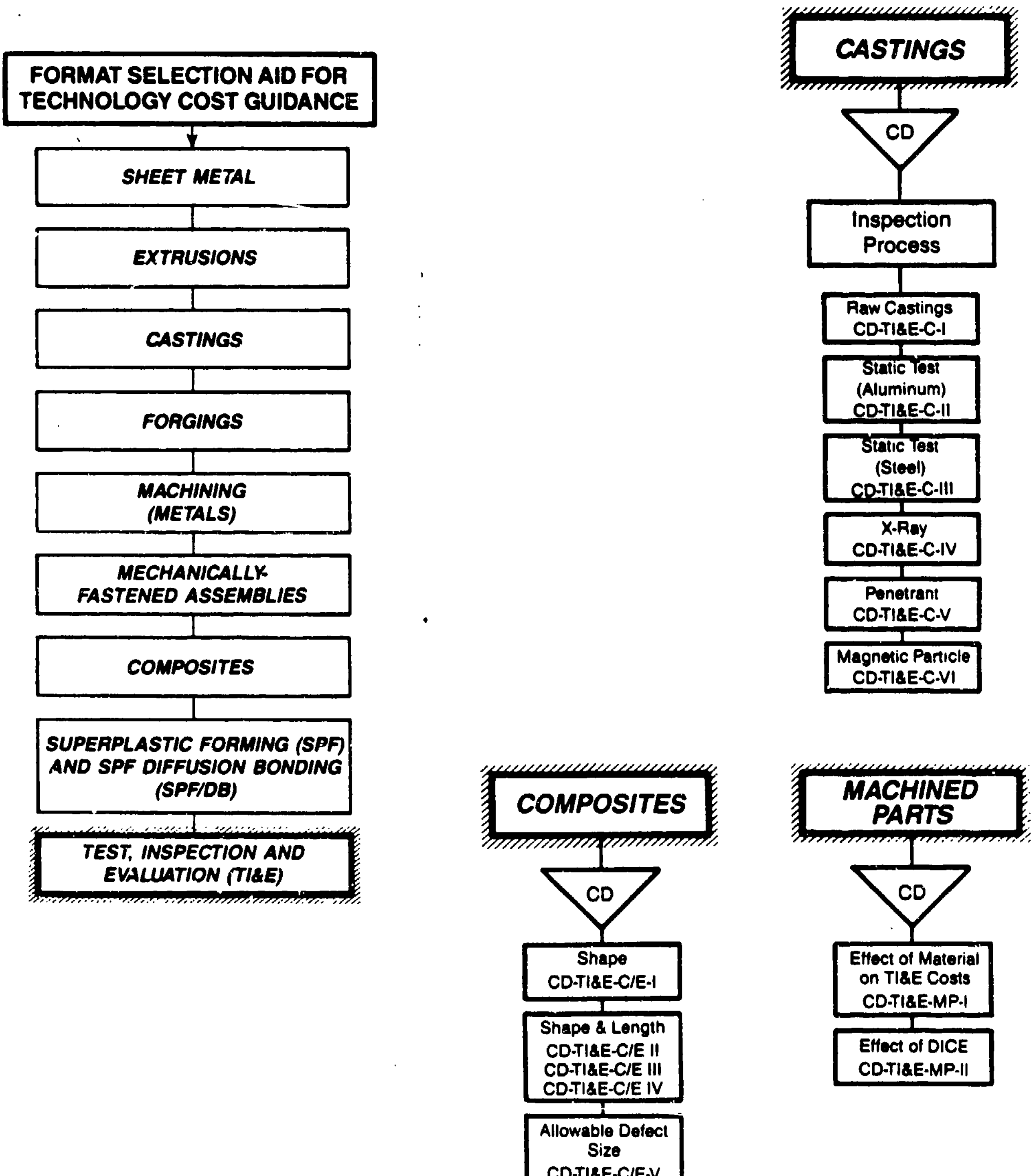


COST ELEMENTS:

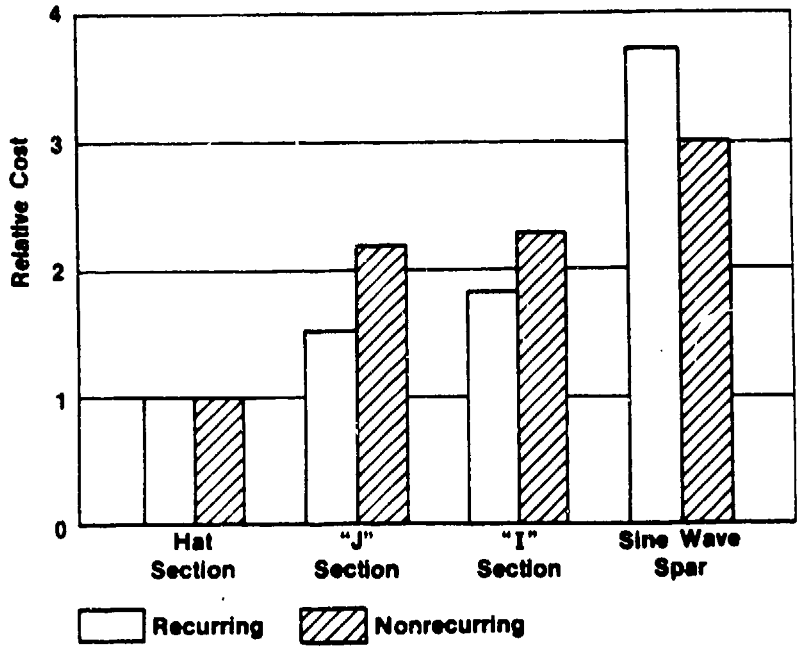
- Laminating tools (graphite, refractory metals, etc.) designed for vacuum furnace operation
- Multi-sheet sandwich designed with provisions for numerous tubes and seals for SPF/DB pressure management

CD-SPF-XXXV

CONCEPTUAL DESIGN (CD)
TEST, INSPECTION & EVALUATION

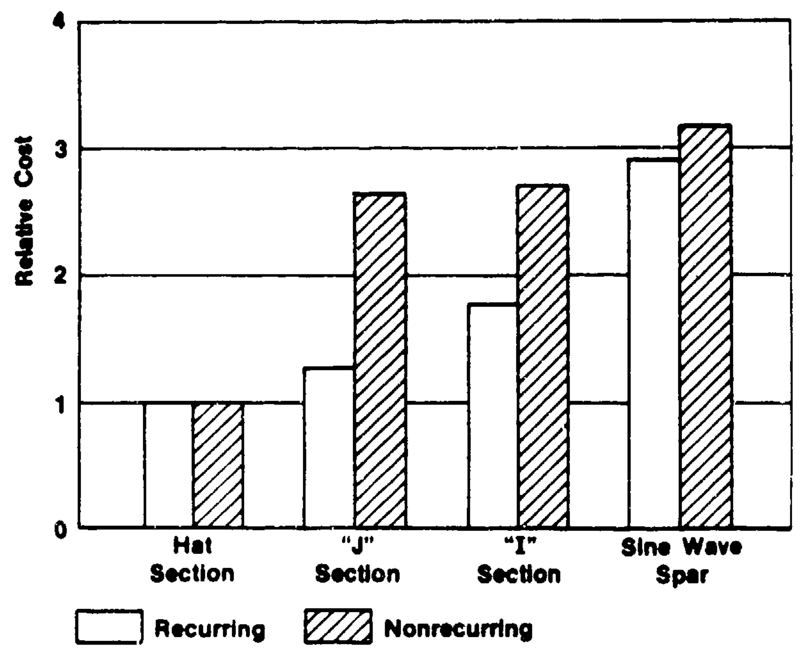


TEST, INSPECTION AND EVALUATION (TI&E) OF COMPOSITES EFFECT OF SHAPE ON RECURRING AND NONRECURRING TI&E COST



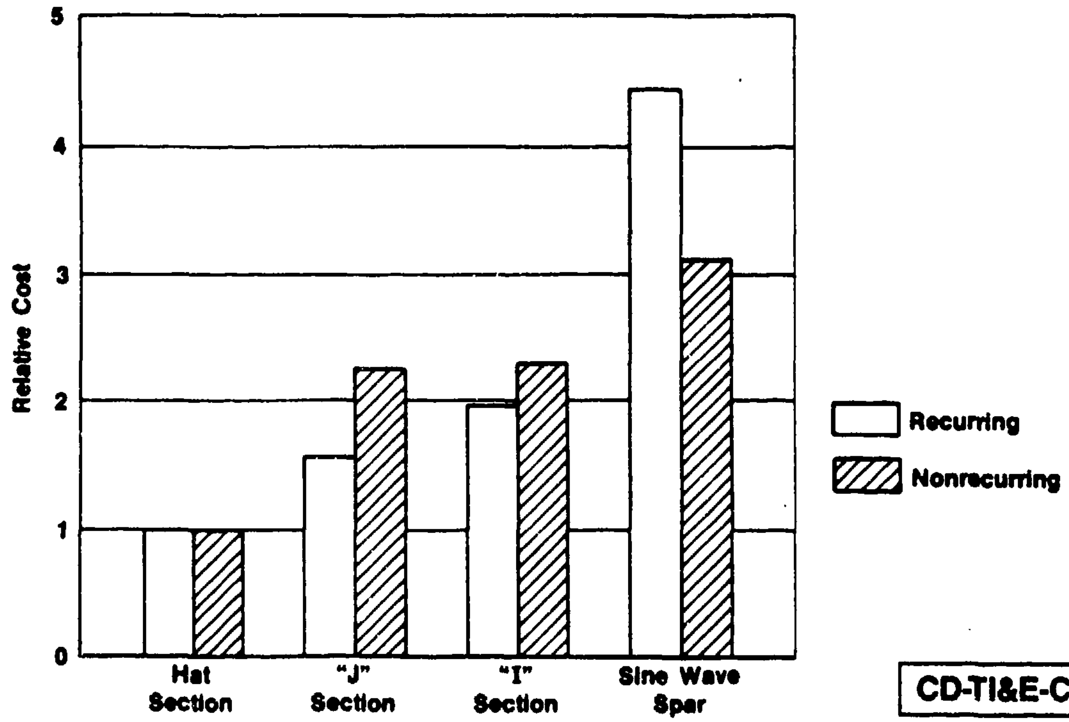
CD-TI&E-C/E-I

TEST, INSPECTION AND EVALUATION (TI&E) OF COMPOSITES EFFECT OF SHAPE ON RECURRING AND NONRECURRING TI&E COST 2-FOOT SECTION



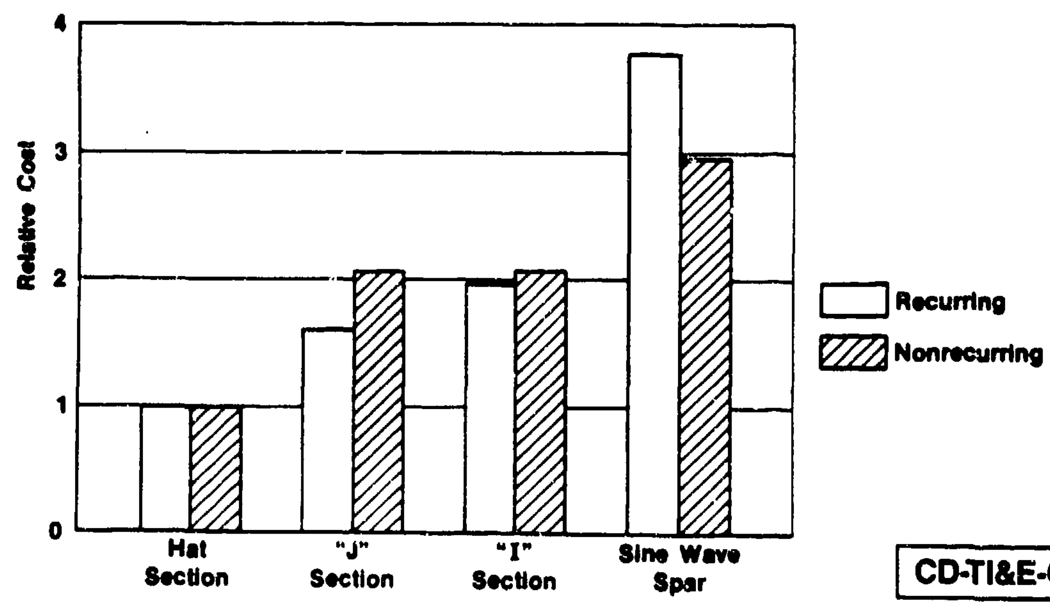
CD-TI&E-C/E-II

TEST, INSPECTION AND EVALUATION (TI&E) OF COMPOSITES
EFFECT OF SHAPE ON RECURRING AND NONRECURRING TI&E COST
8-FOOT SECTION



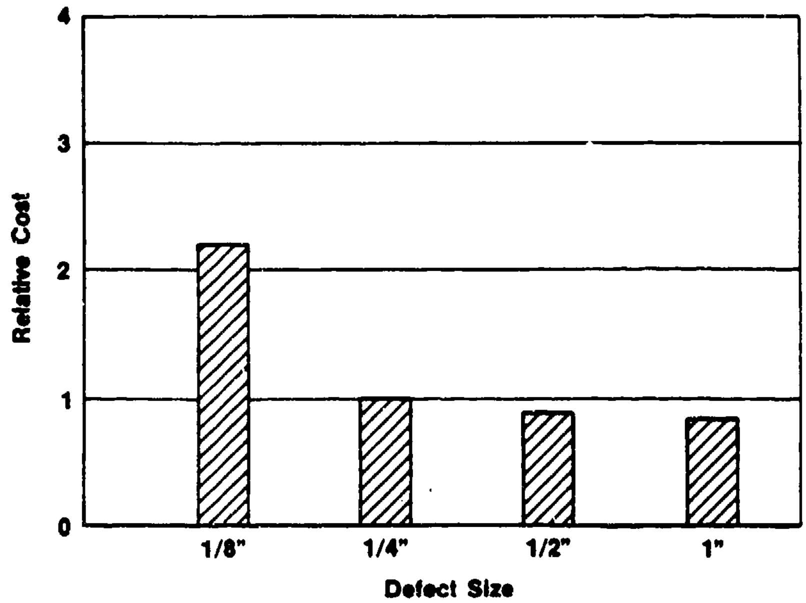
CD-TI&E-C/E-III

TEST, INSPECTION AND EVALUATION (TI&E) OF COMPOSITES
EFFECT OF SHAPE ON RECURRING AND NONRECURRING TI&E COST
12-FOOT SECTION



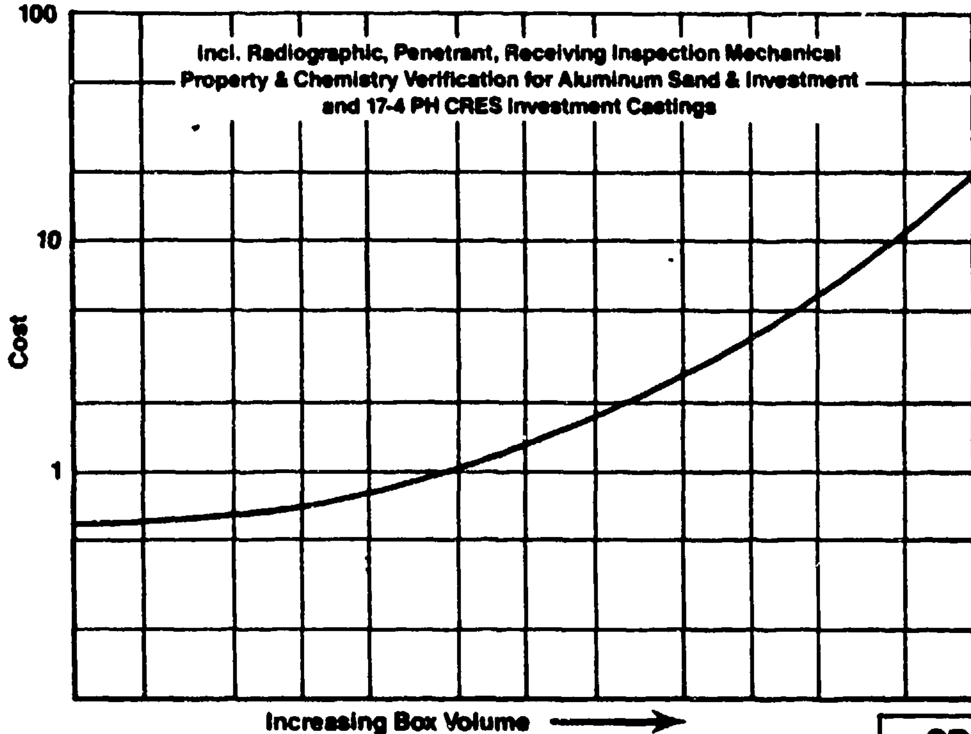
CD-TI&E-C/E-IV

TEST, INSPECTION AND EVALUATION (TI&E) OF COMPOSITES
EFFECT OF MAXIMUM ALLOWABLE DEFECT SIZE ON TI&E COST



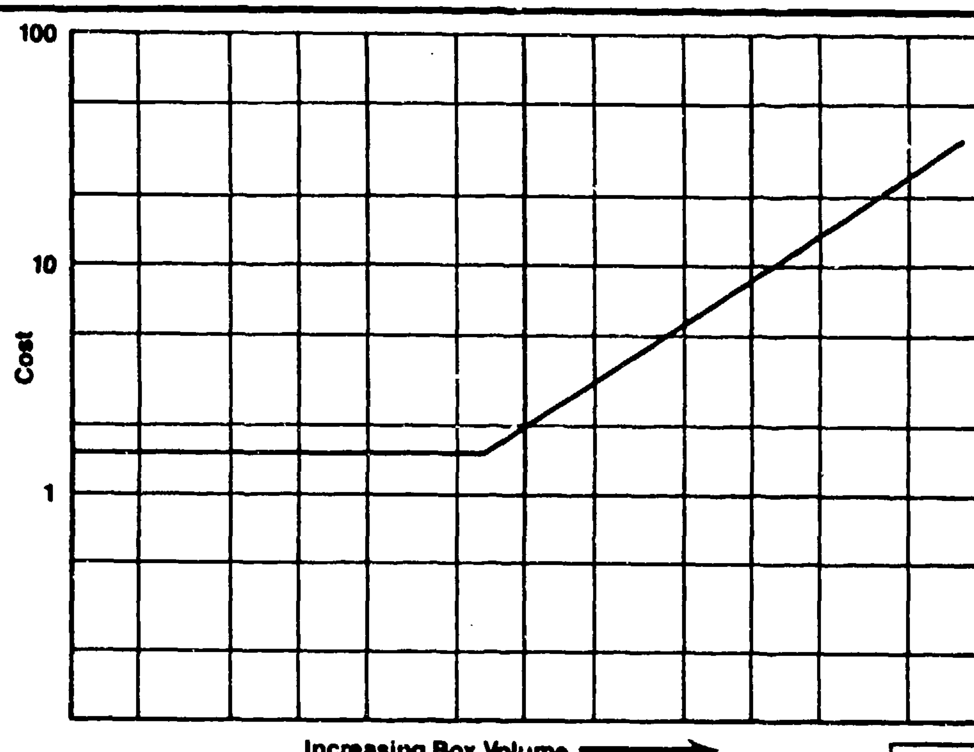
CD-TI&E-C/E-V

CASTINGS



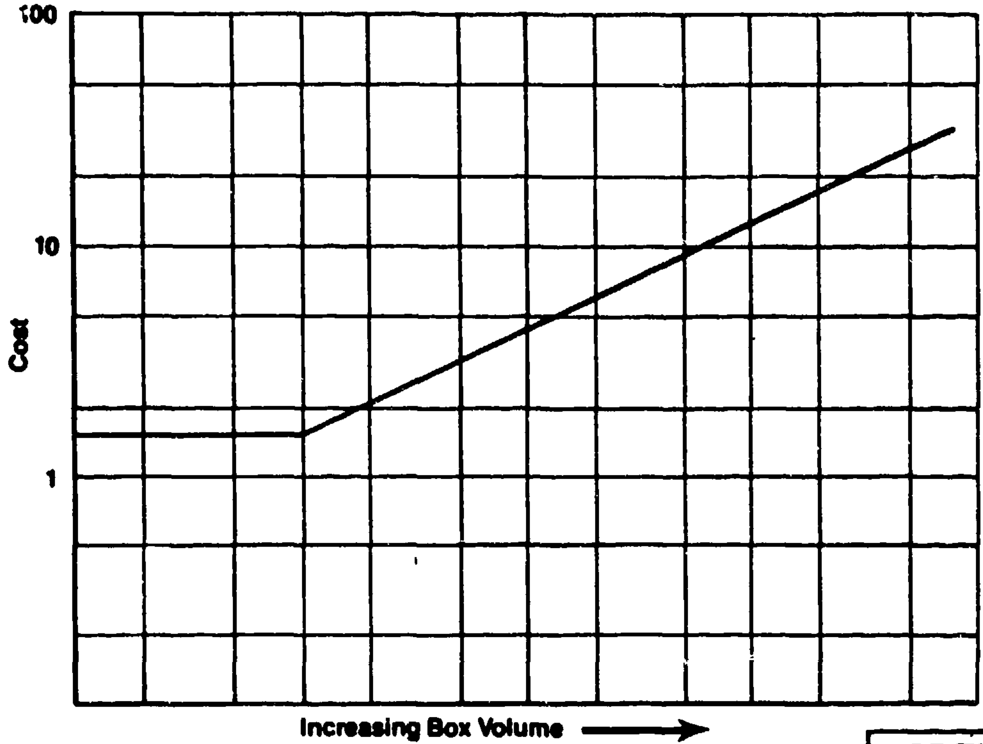
CD-TI&E-C-I

ALUMINUM CASTINGS
STATIC TEST COST



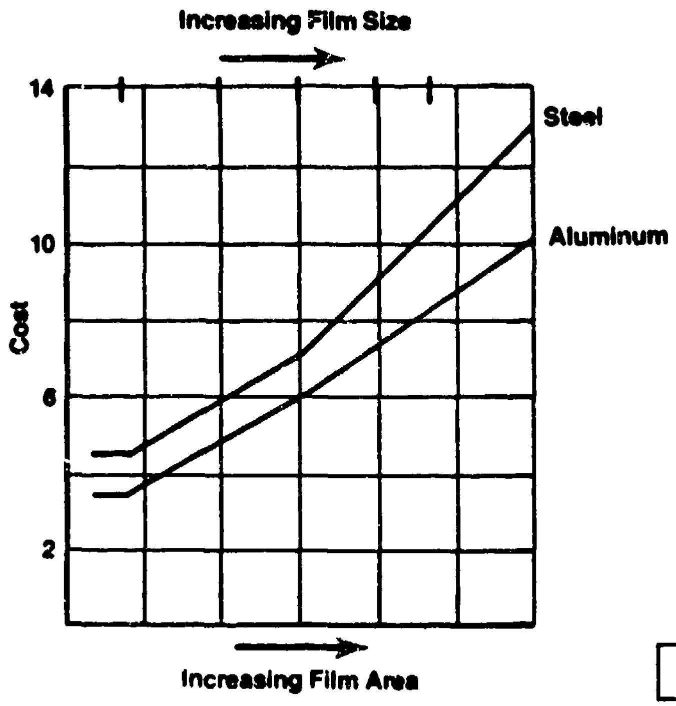
CD-TI&E-C-II

STEEL CASTINGS
STATIC TEST COST



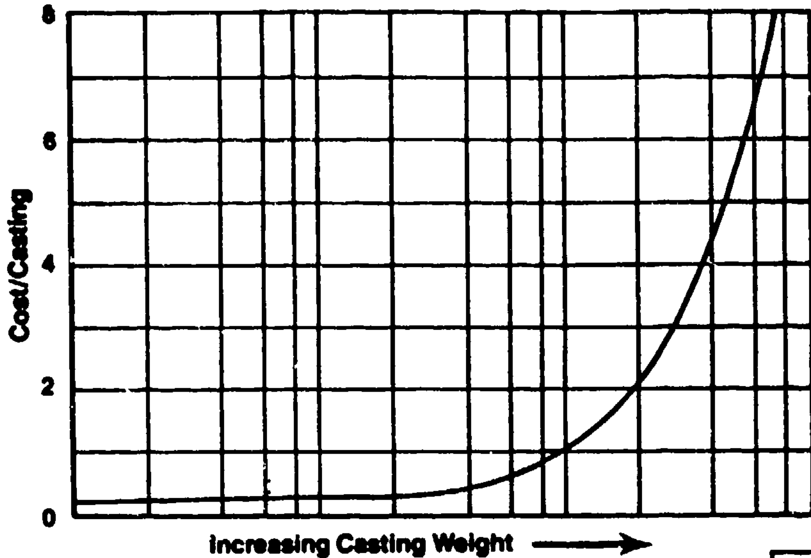
CD-TI&E-C-III

CASTINGS
X-RAY



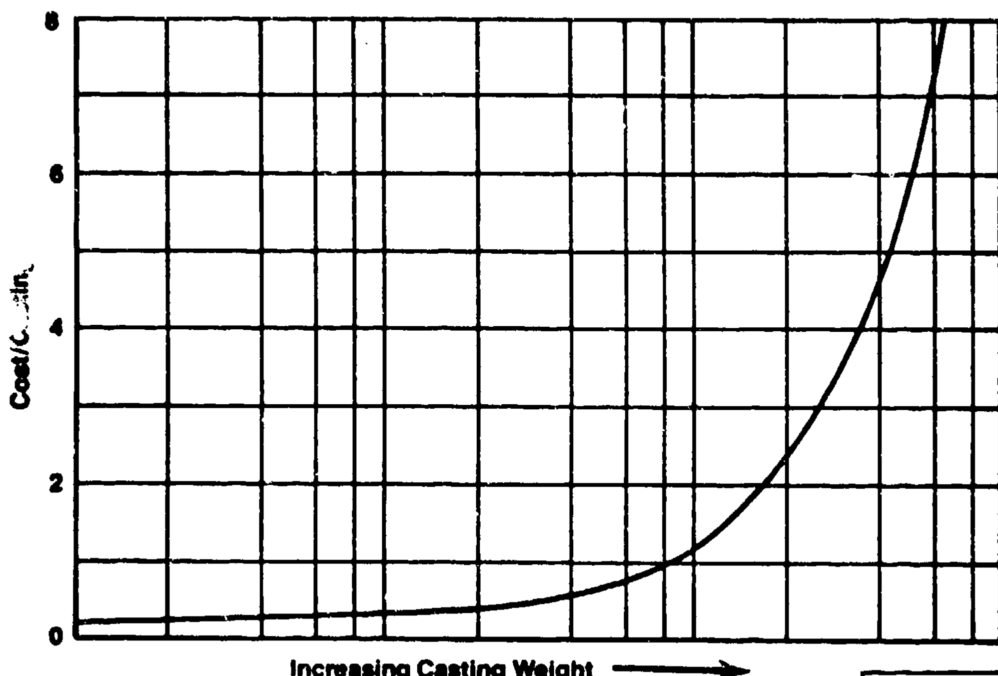
CD-TI&E-C-IV

CASTINGS
PENETRANT INSPECTION
(COMMERCIAL LABORATORY)



CD-TI&E-C-V

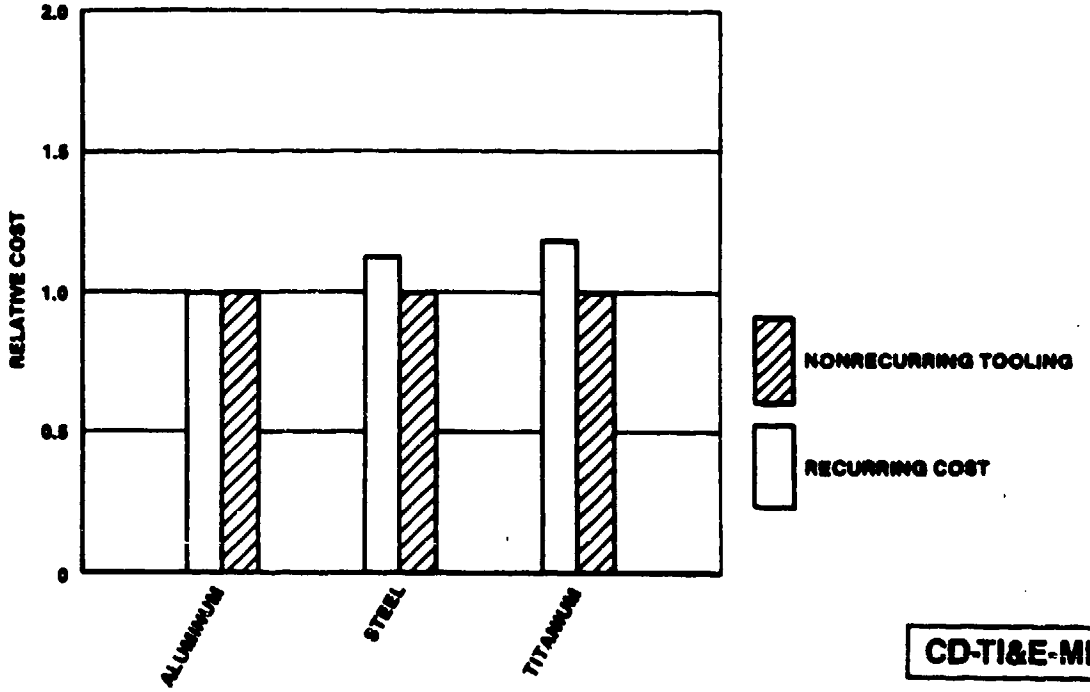
CASTINGS
MAGNETIC PARTICLE INSPECTION
(COMMERICAL LABORATORY)



CD-TI&E-C-VI

TEST, INSPECTION AND EVALUATION (TI&E) FOR MACHINED PARTS COST DRIVER EFFECTS

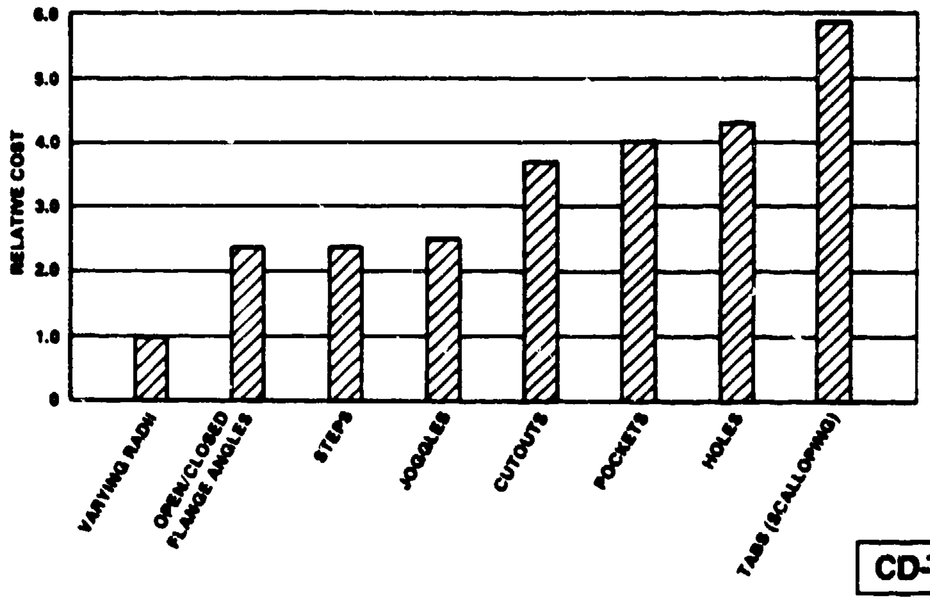
EFFECT OF MATERIAL ON TI&E COSTS



CD-TI&E-MP-I

TEST, INSPECTION AND EVALUATION (TI&E) FOR MACHINED PARTS COST DRIVER EFFECTS

EFFECT OF DICE



CD-TI&E-MP-II

2.6 SOFTWARE IMPLEMENTATION

2.6.1 Summary

This section describes the activities in developing computer-based software for assisting designers of sheet metal, mechanically fastened, assemblies. The methodology considered is for reducing assembly labor costs by indicating labor-intensive panel designs. This methodology already exists in hard copy, Reference 1. In the following, a brief introduction to the methodology is given and the current status of the software is reported. The constituent software modules are not included here.

2.6.2 Objective

The objective of this task is to examine the potential of a computer-based design aid by constructing a working prototype.

The methodology chosen for implementation was reported in Reference 1 for the design of sheet metal assemblies, in particular, aerospace panels. The goal of the method is to assist designers to rapidly reduce the cost of their assemblies by minimizing the labor required. The users of this method typically refer to a collection of graphs and charts and also make simple hand calculations in order to compare the assembly labor content of different stiffened panel designs.

It is possible that a satisfactory implementation of this designer's aid will lay the groundwork for expert system applications to design-to-cost studies.

2.6.3 Criteria for Development

The success of the software implementation is dependent upon several criteria:

- Direct comparison with manual methods. The speed of execution of a computer-based method should reduce the required designer's labor per candidate solution examined. Designer labor is considered directly proportional to designer man-hours and does not include: paper filing time, searching for initial data, and rate of fatigue. Designer labor does include: retrieving and selecting formats, reading formats, documentation of results, graph interpolations, and calculations.

- Additional benefits. Other criteria should be considered when comparing the computer method to manual methods. These criteria include:

  (1) Reduced designer fatigue enhancing innovation

  (2) Increased uniformity of documentation

  (3) On-line help

  (4) Reduced risk of calculation errors

  (5) More consistent agreement of results during independent tests.

2.6.4 Description of Methodology

A detailed description of the design of sheet metal assemblies methodology is provided in Reference 1. Nevertheless, a brief description of the methodology is also required here before continuing.

a). Origin

The design of sheet metal assemblies methodology was developed in Reference 1. It was desired to reduce labor costs during the assembly of stiffened sheet metal panels. It was concluded that significant cost reductions could be indirectly made by aerospace designers provided with appropriate information which was determined to be:

- Cost Driver Effect formats - graphs showing the effect of a designer's choice of stiffened panel design and installation methods on the man-hours of assembly labor. The labor data was provided in normalized form.

- Cost Estimating Data formats - graphs showing the estimated labor resulting from a choice of stiffened panel design and installation method. Cost estimating data provides a rapid estimation of the total labor content of each panel.

b). Initial Requirements

In order to use this design methodology, the following design/manufacturing factors must be available for each candidate design at the beginning of the assembly design evaluation session:

(1) Learning curve

(2) Primary material: aluminum or titanium

(3) Perimeter of panel

(4) Number of parts, excluding fasteners

(5) Number of fasteners

(6) Installation requirements (sealing details):

(a) dry
(b) primer or sealant on fastener
(c) primer or sealant on fastener and faying surface

(7) Hilok fasteners: used or not used

(8) Production volume

(9) Installation method - manual, automatic, or combination of these.

c). Phase I: Cost Driver Examination

Using the preceding 9 design/production factors, the designer of an assembly is first expected to examine the current values of the cost drivers associated with the candidate design. The choice of particular formats depends upon the primary material. The cost driver formats to be examined are:

For aluminum panels: $D_{CDE1}, D_{CDE2}, D_{CDE3}, D_{CDE4}, D_{CDE7}, D_{CDE8}$

For titanium panels: $D_{CDE}, D_{CDE2}, D_{CDE5}, D_{CDE6}, D_{CDE7}, D_{CDE8}$

The designer is expected to study the current value of cost drivers pertaining to the candidate design and to consider alternative designs that reduce the current cost driver value. Thus, a major assumption is implied:

Assumption 1: It is necessary that a designer studies the current cost drivers pertaining to the candidate concept within the context of a cost driver format.

This assumption is important in that it implies that a computerized system should also provide the equivalent of a cost driver format. Thus, a computerized system must either draw graphics on the screen or an effective equivalent of a cost driver format must be proposed.

An additional note for future activities concerns expert system applications of this method. For an expert system to be implemented using cost driver values, a large set of logical rules must be developed of the form:

<u>if</u> [COST DRIVER COMBINATION #1] exists, <u>then</u> propose [IMPROVEMENT <u>#1</u>] to the designer.

<u>if</u> [COST DRIVER COMBINATION #2] exists, <u>then</u> propose [IMPROVEMENT <u>#2</u>] to the designer.

d). Phase II. Cost Estimation

Using manual methods, cost drivers are looked up and estimated by a designer visually by looking at a cost driver format. Using computer methods, it is more efficient for the computer to make cost driver estimates using mathematical formulae; hence, estimating formulae were derived from the graphical data.

It may appear that excessive attention to logical and arithmetic formulation of the methodology is made in this report, since many of the concepts may be easy to understand verbally and by example. The reader is reminded that the current software implementation can draw its data only from arithmetic and logical explanations; hence, the logic-mathematical rules in this report are essential for proper software operation. Simple expert system implementations will also require these rules.

After the cost drivers are examined, a cost estimate can be rapidly made of the man-hours required to assemble the panel. CED formats exist for this purpose. Cost estimation is performed differently depending upon the panel material. First, cost estimation for aluminum assemblies will be examined. Then, cost estimation for titanium assemblies will be described.

The cost estimate considers both recurring and nonrecurring costs. Recurring costs are man-hour labor requirements that include all hands-on factory labor. Recurring costs <u>do include</u>: initial preparation for jig loading, drilling, fastener installation, and storage for the next assembly phase. Recurring costs <u>do not include</u>: tool maintenance, planning, and quality control. <u>For an aluminum panel</u>, the recurring cost C_{rA} is given by

$$C_{rA} = LC_{CED1} \quad (1)$$

where L is the learning curve factor. L reflects the skill of the assembly laborers in learning to perform the panel assembly efficiently and depends upon both the quantity of units to be assembled and the skill level of the assembly operator.

Nonrecurring costs are man-hour labor requirements for tool fabrication. Nonrecurring costs do not include tool design and tool planning costs. Typically, tools need to be replaced after a certain number of units are assembled; thus, nonrecurring costs are incurred every P units, where P is the tool life in units assembled. An aluminum panel's nonrecurring cost $C_{\tau A}$ is given by

$$C_{\tau A} = \left[\text{int} \left(\frac{N}{P} \right) + 1 \right] \frac{C_{CED3}}{N} \quad (2)$$

Where N is the number of units to be produced, P is the tooling life in units assembled per tooling, and the function int() takes the integer part of the ratio N/P. Typically, P is set to 200 units assembled per tooling.

Figure 2.6-1 is an illustration of nonrecurring cost of an aluminum assembly when C_{CED3} is 400 man-hours and P is 200 units/tooling.

Thus, for an aluminum panel, the total man-hour content, C_T, is

$$C_T = C_{rA} + C_{\tau A} \quad (3)$$

or

$$C_T = LC_{CED1} + \left[\text{int} \left(\frac{N}{P} \right) + 1 \right] \frac{C_{CED3}}{N} \quad (4)$$

Similarly, for a titanium panel, the recurring cost, C_{rT}, is given by

$$C_{rT} = LC_{CED2} \quad (5)$$

The nonrecurring cost, C_T, for a titanium panel is given by

$$C_{\tau T} = \left[\text{int} \left(\frac{N}{P} \right) + 1 \right] \frac{C_{CED3}}{N} \quad (6)$$

Thus, for a titanium panel, the total man-hour content, C_T, is

$$C_T = C_{rT} + C_{\tau T} \quad (7)$$

or

$$C_T = LC_{CED2} + \left[\text{int} \left(\frac{N}{P} \right) + 1 \right] \frac{C_{CED3}}{N} \quad (8)$$

2.6.5 Selection of Software Tools

Several types of software programming tools were considered. DBASE III+ was finally decided upon due to limited costs available for this

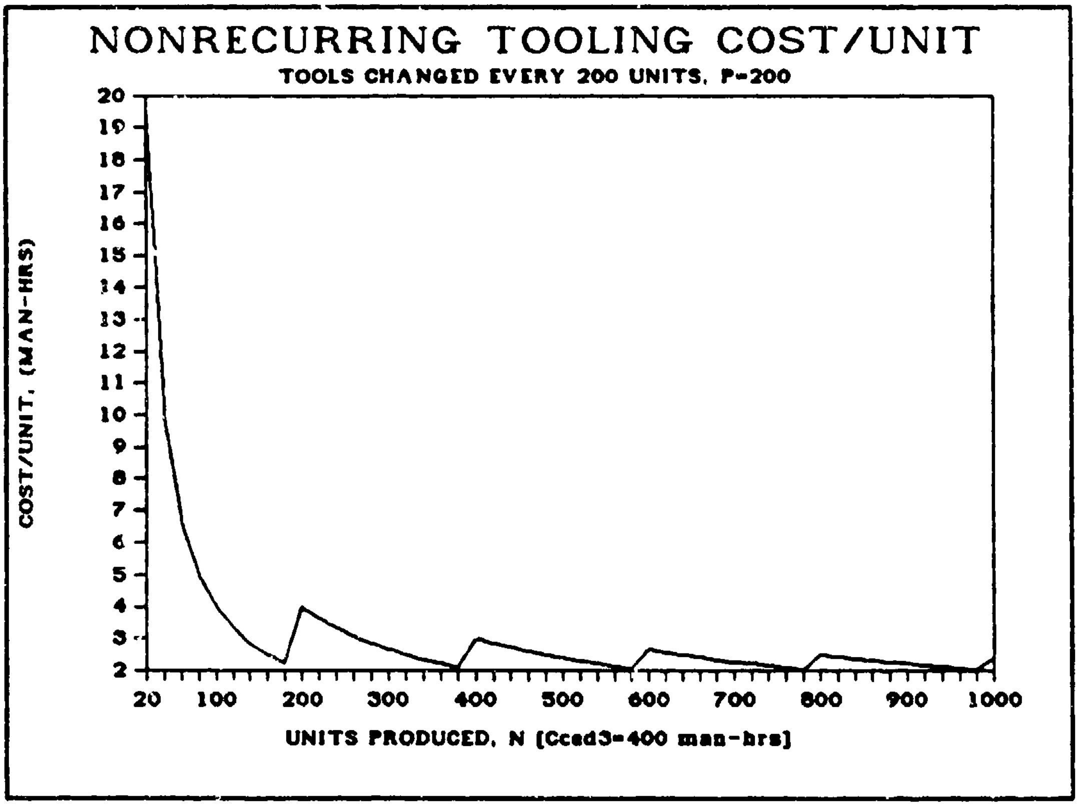


FIGURE 2.6-1 NONRECURRING TOOLING COSTS

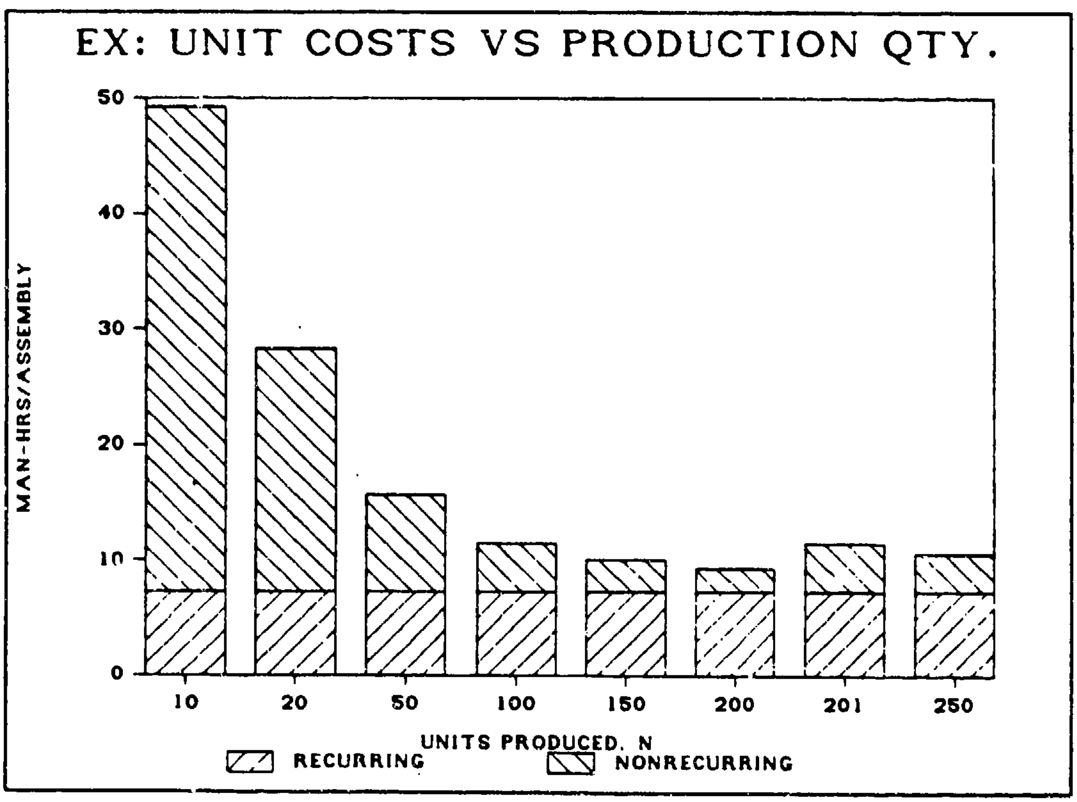


FIGURE 2.6-2 UNIT COSTS VERSUS PRODUCTION QUANTITY

task. The three major alternatives considered were C programming language, Prolog, and DBASE III+. The relative advantages and disadvantages are as follows:

C Programming Language - This programming language provides the most efficient code and no restrictions on distribution of finished software products. C also easily permits interactive graphics and scientific calculations. Nevertheless, development of a C database software implies that many basic database functions need to be prepared.

Prolog - This is a logic programming language directly allowing the future development of an expert system. Unfortunately, interfacing of prolog to a graphics interface is complex and resulting databases are not easily transported into conventional software packages.

DBASE III+ - This is the general purpose standard for constructing microcomputer business databases. All lower level database functions are supplied in the form of an interpreted language. Compiled and run time versions of DBASE III+ are readily available. Accessory software for DBASE III+ is available. The weaknesses of DBASE III+ is that it is not easily interfaced to graphics interfaces, does not support variable arrays, and does not support floating numbers with exponents. These weaknesses limit the ease with which DBASE III+ can perform scientific calculations and graphs.

Calculation of D_{CDE1}

If the material is aluminum and the installation method is manual, then

$$Y_1 = 1.75 + 0.25 \tag{9}$$

where 1.75 is the recurring labor and 0.25 is the nonrecurring labor.

If the material is titanium and the installation method is manual, then

$$Y_2 = 3.2 + 0.25 \tag{10}$$

where 3.2 is the recurring labor and 0.25 is the nonrecurring labor.

If the material is aluminum and the installation method is automatic, then

$$Y_3 = 1.0 + 0.25 \tag{11}$$

where 1.0 is the recurring labor and 0.25 is the nonrecurring labor.

If the material is titanium and the installation method is automatic, then

$$Y_4 = 1.2 + 0.25 \quad (12)$$

The value of D_{CDE1} for an aluminum material is then

$$D_{CDE1} = \frac{A}{100} Y_3 + \frac{(100 - A)}{100} Y_1 \quad (13)$$

where A is the percent automation used for the assembly.

Similarly, the value of D_{CDE1} for titanium material is

$$D_{CDE1} = \frac{A}{100} Y_4 + \frac{(100 - A)}{100} Y_2 \quad (14)$$

Calculation of D_{CDE2}

If the installation method is manual,

$$Y_1 = 0.020\, N_P + 1.90 \quad (15)$$

If the installation method is automatic

$$Y_2 = 0.020\, N_P + 1.19 \quad (16)$$

The value of D_{CDE2} for mixed automation is

$$D_{CDE2} = \frac{A}{100} Y_1 + \frac{(1 - A)}{100} Y_2 \quad (17)$$

Calculation of D_{CDE3}

If installation required is dry and the installation method is manual, then

$$Y_1 = 1.7 \quad (18)$$

If installation required is dry and the installation method is automatic, then

$$Y_2 = 1.0 \quad (19)$$

If installation required is wet and fay and the installation method is manual, then

$$Y_3 = 2.6 \quad (20)$$

If installation required is wet and fay and the installation method is automatic, then

$$Y_4 = 1.3 \tag{21}$$

If installation required is wet and the installation method is manual, then

$$Y_5 = 2.20 \tag{22}$$

If installation required is wet and the installation method is automatic, then

$$Y_6 = 1.0 \tag{23}$$

Thus, if installation required is dry,

$$C_{CED3} = \frac{A}{100} Y_2 + \frac{(100 - A)}{100} Y_1 \tag{24}$$

If installation required is wet and fay

$$C_{CED3} = \frac{A}{100} Y_4 + \frac{(100 - A)}{100} Y_3 \tag{25}$$

If installation required is wet,

$$C_{CED3} = \frac{A}{100} Y_6 + \frac{(100 - A)}{100} Y_5 \tag{26}$$

Calculation of D_{CDE4}

If installation required is dry, then

$$D_{CED4} = -0.009\,A + 1.85 \tag{27}$$

If installation required is wet, then

$$D_{CED4} = -0.014\,A + 2.4 \tag{28}$$

If installation required is wet and fay, then

$$D_{CED4} = -0.014\,A + 2.7 \tag{29}$$

Calculation of D_{CDE5}

If installation required is dry and the installation method is automatic, then

$$Y_1 = 1.0 \quad (30)$$

If installation required is dry and the installation method is manual, then

$$Y_2 = 2.7 \quad (31)$$

If installation required is wet and fay and the installation method is automatic, then

$$Y_3 = 1.3 \quad (32)$$

If installation required is wet and fay and the installation method is manual, then

$$Y_4 = 3.3 \quad (33)$$

If installation required is wet and the installation method is automatic, then

$$Y_5 = 1.0 \quad (34)$$

If installation required is wet and the installation method is manual, then

$$Y_6 = 3.1 \quad (35)$$

Thus, for dry installation required:

$$D_{CDE5} = \frac{A}{100} Y_1 + \frac{(100 - A)}{100} Y_2 \quad (36)$$

For wet and fay installation required:

$$D_{CDE5} = \frac{A}{100} Y_3 + \frac{(100 - A)}{100} Y_4 \quad (37)$$

For wet installation required:

$$D_{CDE} = \frac{A}{100} Y_5 + \frac{(100 - A)}{100} Y_6 \quad (38)$$

Calculation of D_{CDE6}

For dry installation required:

$$D_{CDE6} = -0.018\,A + 2.833 \tag{39}$$

For wet and fay installation required:

$$D_{CDE6} = -0.023\,A + 3.527 \tag{40}$$

For wet installation required:

$$D_{CDE6} = -0.023\,A + 3.33 \tag{41}$$

Calculation of D_{CDE7}

For this cost driver, the format shows an 80% automation value. This value is ignored and a more general interpolation for any degree of automation is used.

If the material is aluminum and the installation method is manual, then

$$Y_1 = 1.75 \tag{42}$$

If the material is aluminum and the installation method is automatic, then

$$Y_2 = 1.0 \tag{43}$$

If the material is titanium and the installation method is manual,

$$Y_3 = 3.2 \tag{44}$$

If the material is titanium and the installation method is automatic,

$$Y_4 = 2.0 \tag{45}$$

Thus, for aluminum,

$$D_{CDE7} = \frac{A}{100} Y_2 + \frac{(100 - A)}{100} Y_1 \tag{46}$$

and for titanium,

$$D_{CDE7} = \frac{A}{100} Y_4 + \frac{(100 - A)}{100} Y_3 \tag{47}$$

Calculation of D_{CDE8}

If dry installation is required, the installation method is manual, and the material is aluminum,

$$Y_1 = 1.75 \tag{48}$$

If dry installation is required, the installation method is manual, and the material is titanium,

$$Y_2 = 3.2 \tag{49}$$

If dry installation is required, the installation method is automatic, and the material is aluminum,

$$Y_3 = 1.0 \tag{50}$$

If dry installation is required, the installation method is automatic, and the material is titanium,

$$Y_4 = 1.2 \tag{51}$$

If wet and fay installation is required, the installation method is manual, and the material is aluminum,

$$Y_5 = 2.75 \tag{52}$$

If wet and fay installation is required, the installation method is manual, and the material is titanium,

$$Y_6 = 4.0 \tag{53}$$

If wet and fay installation is required, the installation method is automatic, and the material is aluminum,

$$Y_7 = 1.25 \tag{54}$$

If wet and fay installation is required, the installation method is automatic, and the material is titanium,

$$Y_8 = 1.5 \tag{55}$$

If wet installation is required, the installation method is manual, and the material is aluminum,

$$Y_9 = 2.25 \tag{56}$$

If wet installation is required, the installation method is manual, and the material is titanium,

$$Y_{10} = 3.75 \tag{57}$$

If wet installation is required, the installation method is automatic, and the material is aluminum,

$$Y_{11} = 1.0 \qquad (58)$$

If wet installation is required, the installation method is automatic, and the material is titanium,

$$Y_{12} = 1.2 \qquad (59)$$

For dry installation required and the material is aluminum,

$$D_{CDE8} = \frac{A}{100} Y_3 + \frac{(100 - A)}{100} Y_1 \qquad (60)$$

For dry installation required and the material is titanium,

$$D_{CDE8} = \frac{A}{100} Y_4 + \frac{(100 - A)}{100} Y_2 \qquad (61)$$

For wet and fay installation required and the material is aluminum,

$$D_{CDE8} = \frac{A}{100} Y_7 + \frac{(100 - A)}{100} Y_5 \qquad (62)$$

For wet and fay installation required and the material is titanium,

$$D_{CDE8} = \frac{A}{100} Y_8 + \frac{(100 - A)}{100} Y_6 \qquad (63)$$

For wet installation required and the material is aluminum,

$$D_{CDE8} = \frac{A}{100} Y_{11} + \frac{(100 - A)}{100} Y_9 \qquad (64)$$

For wet installation required and the material is titanium,

$$D_{CDE8} = \frac{A}{100} Y_{12} + \frac{(100 - A)}{100} Y_{10} \qquad (65)$$

It is evident that these explicit expressions for cost driver values are well suited for symbolic programming languages such as Prolog. The abundance of these types of rules in the methodology is the primary reason why Prolog was considered at the outset as one of the three software implementation languages.

e). Phase II: Cost Estimation

After cost drivers are examined, a cost estimate of the man-hours required to assemble the panel is rapidly made. Cost estimating data formats exist for this purpose. Cost estimation is performed differently depending upon the panel material. First, cost estimation for aluminum assemblies will be examined. Then, cost estimation for titanium assemblies will be described.

The cost estimate considers recurring costs and nonrecurring costs. Recurring costs are man-hour labor requirements that include all hands-on factory labor. Recurring costs do include: initial preparation for jig loading, drilling, fastener installation, and storage for the next assembly phase. Recurring costs do not include: tool maintenance, planning, and quality control. For an aluminum panel, the recurring cost, C_{rA}, is given by:

$$C_{rA} = LC_{CED1} \quad (66)$$

where L is the learning curve factor, reflecting the skill of the assembly workers in learning to perform the panel assembly efficiently and this depends upon both the quantity of units to be assembled and the skill level of the assembly operator.

Nonrecurring costs are man-hour labor requirements for tool fabrication. Nonrecurring costs do not include tool design and tool planning costs. Typically, tools need to be replaced after a certain number of units are assembled; thus, nonrecurring costs are incurred every P units, where P is the tool life in units assembled. An aluminum panel's nonrecurring cost, C_{tA}, is given by:

$$C_{tA} = \left[\text{int} \left(\frac{N-1}{P} \right) + 1 \right] \frac{C_{CED3}}{N} \quad (67)$$

where N is the number of units to be produced, P is the tooling life in units assembled per tooling, and the function int() takes the integer part of the ratio N/P. Typically, P is set to 200 units assembled per tooling.

Figure illustrates how the nonrecurring cost of an aluminum assembly varies with N when C_{CED3} is 400 man-hours and P is 200 units/tooling.

The variation of nonrecurring cost with production quantity N has several noteworthy features. The nonrecurring cost converges, i.e.

$$\underset{N \to \infty}{C_{tA}} = \frac{C_{CED3}}{P} \quad (68)$$

The maximum value of nonrecurring cost for any cycle is

$$\max C_{tA} = \frac{(i+1)\, C_{CED3}}{iP+1} \quad (69)$$

at

$N = iP + 1$ where $i = 0, 1, 2, \ldots$

The minimum value of nonrecurring cost for any cycle is:

$$\min C_{\tau A} = \frac{C_{CED3}}{P} \tag{70}$$

at

$N = (i + 1)P$ where $i = 0, 1, 2, \ldots$

These expressions for maxima and minima may be useful for cases when planning the production volume.

Considering both recurring and nonrecurring costs, for an aluminum panel, the total man-hour content, C_T, is:

$$C_T = C_{rA} + C_{\tau A} \tag{71}$$

or

$$C_T = LC_{CED1} + \left[\text{int} \left(\frac{N-1}{P} \right) + 1 \right] \frac{C_{CED3}}{N} \tag{72}$$

Figure 2.6-2 presents an example of the total unit cost of an aluminum assembly for varying production quantities.

The recurring cost, C_{rT}, for a titanium panel is given by:

$$C_{rT} = LC_{CED2} \tag{73}$$

The nonrecurring cost, $C_{\tau T}$, for a titanium panel is given by:

$$C_{\tau T} = \left[\text{int} \left(\frac{N-1}{P} \right) + 1 \right] \frac{C_{CED3}}{N} \tag{74}$$

Considering both recurring and nonrecurring costs for a titanium panel, the total man-hour content, C_T, is:

$$C_T = C_{rT} + C_{\tau T} \tag{75}$$

or

$$C_T = LC_{CED2} + \left[\text{int} \left(\frac{N-1}{P} \right) + 1 \right] \frac{C_{CED3}}{N} \tag{76}$$

f). Calculation of Cost Estimating Factors

Calculation of cost estimating factors C_{CED1}, C_{CED2}, and C_{CED3}, is performed in a manner similar to the calculation of cost driver functions.

Calculation of C_{CED1}

If dry installation is required and the installation method is manual:

$$Y_1 = 0.020\,N_F + 1.5 \text{ when } 1 \leq N_F < 700 \tag{77}$$

or

$$Y_1 = 0.018\,N_F + 2.7 \text{ when } 700 \leq N_F \leq 1100$$

If dry installation is required and the installation method is automatic:

$$Y_2 = 0.011\,N_F + 0.3 \text{ when } 1 \leq N_F < 700 \tag{78}$$

or

$$Y_2 = 0.0067\,N_F + 3.3 \text{ when } 700 \leq N_F \leq 1100$$

If wet installation is required and the installation method is manual:

$$Y_3 = 0.028\,N_F + 0.9 \text{ when } 1 \leq N_F < 700 \tag{79}$$

or

$$Y_3 = 0.025\,N_F + 3.0 \text{ when } 700 \leq N_F \leq 1100$$

If wet installation is required and the installation method is automatic:

$$Y_4 = 0.011\,N_F + 0.3 \text{ when } 1 \leq N_F < 700 \tag{80}$$

or

$$Y_4 = 0.0067\,N_F + 3.3 \text{ when } 700 \leq N_F \leq 1100$$

If wet and fay installation is required and the installation method is manual:

$$Y_5 = 0.032\,N_F + 1.1 \text{ when } 1 \leq N_F < 700 \tag{81}$$

or

$$Y_5 = 0.028\,N_F + 3.7 \text{ when } 700 \leq N_F \leq 1100$$

If wet and fay installation is required and the installation method is automatic:

$$Y_6 = 0.014\ N_F + 1.7 \text{ when } 1 \leq N_F < 700 \qquad (82)$$

or

$$Y_6 = 0.0083\ N_F + 5.7 \text{ when } 700 \leq N_F \leq 1100$$

Combining, for dry installation required:

$$\bar{C}_{CED1} = \frac{A}{100} Y_2 + \frac{(100 - A)}{100} Y_1 \qquad (83)$$

For wet installation required:

$$C_{CED1} = \frac{A}{100} Y_4 + \frac{(100 - A)}{100} Y_3 \qquad (84)$$

For wet and fay installation required:

$$C_{CED1} = \frac{A}{100} Y_6 + \frac{(100 - A)}{100} Y_5 \qquad (85)$$

Calculation of C_{CED2}

If dry installation is required and the installation method is manual:

$$Y_1 = 0.041\ N_F + 1.3 \text{ when } 1 \leq N_F < 700 \qquad (86)$$

or

$$Y_1 = 0.030\ N_F + 9.0 \text{ when } 700 \leq N_F \leq 1100$$

If dry installation is required and the installation method is automatic:

$$Y_2 = 0.014\ N_F + 0.2 \text{ when } 1 \leq N_F < 700 \qquad (87)$$

or

$$Y_2 = 0.0067\ N_F + 5.3 \text{ when } 700 \leq N_F \leq 1100$$

If wet installation is required and the installation method is manual:

$$Y_3 = 0.046\ N_F + 1.8 \text{ when } 1 \leq N_F < 700 \qquad (88)$$

or

$$Y_3 = 0.040\ N_F + 6.0 \text{ when } 700 \leq N_F \leq 1100$$

If wet installation is required and the installation method is automatic

$$Y_4 = 0.014\ N_F + 0.2 \text{ when } 1 \le N_F < 700 \qquad (89)$$

or

$$Y_4 = 0.0067\ N_F + 5.3 \text{ when } 700 \le N_F \le 1100$$

If wet and fay installation is required and the installation method is manual:

$$Y_5 = 0.050\ N_F + 2.5 \text{ when } 1 \le N_F < 700 \qquad (90)$$

or

$$Y_5 = 0.042\ N_F + 8.3 \text{ when } 700 \le N_F \le 1100$$

If wet and fay installation is required and the installation method is automatic:

$$Y_6 = 0.017\ N_F + 1.1 \text{ when } 1 \le N_F < 700 \qquad (91)$$

or

$$Y_6 = 0.010\ N_F + 6.0 \text{ when } 700 \le N_F \le 1100$$

Combining, for dry installation required:

$$C_{CED2} = \frac{A}{100} Y_2 + \frac{(100 - A)}{100} Y_1 \qquad (92)$$

For wet installation required:

$$C_{CED2} = \frac{A}{100} Y_4 + \frac{(100 - A)}{100} Y_3 \qquad (93)$$

For wet and fay installation required:

$$C_{CED2} = \frac{A}{100} Y_6 + \frac{(100 - A)}{100} Y_5 \qquad (94)$$

Calculation of C_{CED3}

If installation method is manual:

$$Y_1 = 16.67O + 183 \text{ when } 9 \le O < 16 \qquad (95)$$

or

$$Y_1 = 28.750 - 10 \text{ when } 16 \leq 0 < 24$$

If installation method is automatic:

$$Y_2 = 16.670 + 208 \text{ when } 9 \leq 0 < 16 \qquad (96)$$

or

$$Y_2 = 28.130 + 25 \text{ when } 16 \leq 0 < 24$$

combining,

$$C_{CED3} = \frac{A}{100} Y_2 + \frac{(100 - A)}{100} Y_1 \qquad (97)$$

2.7 CURRENT STATUS

Much of the software prototype is operational, with the exception of the graphics presentation of formats.

2.7.1 Implemented Features

At its current stage of development, the prototype contains the following features:

- Automated calculation of cost driver values
- Automated cost estimation of the man-hours required to assemble the candidate designs
- Removal or addition of new concepts to be evaluated
- A comparative presentation of different product candidates in the form of: cost estimating tables, cost driver tables, and specification tables
- Automated interpolation of cost driver and cost estimating functions for any percentage of assembly automation
- A three-level structure for working at: (I) the assembly level, (II) the design candidate summary level, or (III) the individual candidate level

- One-letter command entry and one-line command bar displays
- Addition or removal of a product candidate
- Interactive editing of a product candidate
- Automated default values for a new product candidate.

The prototype, at this stage, does not contain:

- Adequate presentation of formats
- Automated calculation of learning curve factors
- Sufficient technical software documentation
- An on-line help function.

2.7.2 Using the Software

Using the software is straightforward. A three-level command system exists:

I. Commands that affect different products

II. Commands that summarize all the candidates for a given product

III. Commands that affect a particular candidate.

Three levels were used in order to reduce the risk of using certain commands (especially delete commands) at improper times. Also, by using three levels, all available commands will fit into a command line found at the bottom of the screen. Commands are executed by pressing the first letter of the command displayed on the current command bar.

To start the software, start DBASE III+ by typing 'dbase'. When the dot prompt appears, type 'do dbasenoton/nmain' to begin program execution.

a). Level I: Several Assembly Types

Figure shows a typical level I screen. Note that product refers to assembly. In level I, the following commands are available:

(L)ist Products: Show all the current products available in the directory.

(D)el Product:	Delete a product and all of its constituent candidates.
(A)dd Product:	Add a new product (panel) to be analyzed.
(G)et Product:	Prepare one of the listed products for level II commands.
e(X)it:	Exit from program.

b). Level II: Candidates of One Product

Figures through show typical candidate comparison tables available using level II commands. In level II, the following commands are available:

(C)ost Comp.:	Comparison of cost estimating data for different candidates of the same product.
(D)river Comp.:	Comparison of cost-drivers for different candidates of the same product.
(S)pec. Comp.:	Comparison of panel specifications for the nine design/production factors used by the methodology.
(M)odify Candidates:	Look at and edit the information about individual candidates.
e(X)it:	Exit level II and return to level I commands.

c). Level III: One Candidate

Figure shows an example screen for a single product candidate. Available commands are:

(S)earch:	Search for a candidate by design alternative name or substring within name.
(E)dit:	Edit the candidate currently displayed on the screen.
(N)ext:	Display the next product candidate.
(P)rev:	Display the previous product candidate.
(D)el:	Delete the current candidate.

(A)dd: Add a new candidate.

(C)alculate: Calculate or recalculate all the cost estimating and cost driver functions.

(G)raph: Graph the formats with respect to the current candidate. Currently, this function is not operational.

e(X)it: Exit level III and return to level II.

2.7.3 Software Organization

The following modules are used during program execution:

Name	Ext	Size	Description
CDEI	PRG	470	Calculates cost driver 1
CDEII	PRG	241	Calculates cost driver 2
CDEIII	PRG	604	Calculates cost driver 3
CDEIV	PRG	298	Calculates cost driver 4
CDEV	PRG	601	Calculates cost driver 5
CDEVI	PRG	312	Calculates cost driver 6
CDEVII	PRG	452	Calculates cost driver 7
CDEVIII	PRG	1398	Calculates cost driver 8
CED1	PRG	734	Calculates cost estimate 1
CED2	PRG	804	Calculates cost estimate 2
CED3	PRG	344	Calculates cost estimate 3
NCALC	PRG	8775	Calls and executes all cost driver and cost estimate functions for a particular candidate
NGRAPH	PRG	667	Sample module using DBASE tools for C graphics functions
NMAIN	PRG	4207	Main module for software

NPMENU	PRG	5903	Level II command module
NMODELDB	DBF	1186	Model database structure
NPOLY	PRG	257	Example 6th-order polynomial curve extrapolation routine. Suffers from round-off problems inherent in DBASE scientific calculations
NSCREEN	PRG	2483	Candidate screen
NSELECT	PRG	922	Test module, superceded by NCALC
NVMENU	PRG	4888	Level III command module
PRODUCT	DBF	2306	Sample candidate
PRODUCT	FMT	2580	Candidate format file
PRODUCT	SCR	4262	Candidate screen file
PRODUCT	TXT	4077	Database structure text file

2.7.4 Difficulties Encountered

Several difficulties have been encountered during the project. They are related to some limitations of DBASE III+ and the commercial software accessories for DBASE III+.

a). Precision

In order for the computer to calculate a value for a cost estimating format or a cost driver format, some numerical representation of the function is required. Calculating values from bar charts entails only a simple weighted average. Calculating values from straight lines is also easy. Some formats contained curves that would have been simpler to approximate by fitting a simple polynomial to the curve.

It was discovered that fitting a polynomial to a curve in DBASE III+ is difficult because scientific number representation is not available. Thus, a number $x10^{-16}$ disappears. An additional problem is that variable arrays are not supported. This causes difficulty, since most numerical curve interpolation techniques use dimensioned variables.

After several approaches with polynomial models of curves, polynomial curve fitting was not pursued further. Instead, piecewise linear approximations were used and these approximations appear satisfactory.

Use of a DBASE III+ interface to C was attempted, but the interface is quite tedious to establish and the memory resident interface prevents other commercial packages from loading unless the computer is rebooted.

b). Graphics

It is desired to present formats graphically, preferably showing the values of the current candidate. A graphics library interface to DBASE III+ was attempted. The graphics interface switches the EGA screen into low-resolution CGA mode. Low-resolution CGA mode graphics is unacceptable for the detail required by the formats. In addition, the memory resident graphics interface prevented the loading of other software packages.

Currently, several alternative solutions are being considered. The first solution is to draw the formats by writing C-base graphics programs using HALO. The second solution is to hand-draw the formats using a mouse and an interactive graphics program called DR. HALO III. In either case, the images would be called DBASE III+ as a self-executive module.

2.7.5 Proposed Further Work

Several tasks are proposed for further efforts on computerization:

- A satisfactory presentation of formats
- Automatic calculation of learning curve factors
- An on-line help function.

2.7.6 Conclusion

The conclusion of this task is that, in spite of several technical problems, development of a computer-based design aid continues; a working prototype is feasible.

Further developments are required for a full-featured computer design aid. When the design aid has been developed, it still remains to determine the degree of success of the system over manual methods and the acceptance of such a system by both experienced and unseasoned designers.

2.7.7 Symbols and Definitions

Candidate Design	A candidate is a specific product design that meets all of the design requirements. There will be several possible candidates for one product or system.
Cost Driver Effect (CDE)	A normalized function indicating the effect of one or more design factors on the man-hours of labor required, in this example, for assembly. CDE functions are typically displayed in graphical form. They are not used for cost estimating; rather, they are used for designer guidance in all phases from conceptual to production design.
Cost Estimating Data (CED)	A function indicating the effect of one or more design factors on the man-hours of labor required for assembly. CED functions are typically displayed in graphical form and the data are used for design/manufacturing cost trade-off studies.
Fastener	In the scope of this MC/DG section on mechanically fastened assembly, the fasteners are either: (1) upset rivets, (2) pins, or (3) collars.
Format	A bar or line graph displaying either a CDE function or a CED function. Cost Estimating Data formats are coded: CED-MFA-1, CED-MFA-2, CED-MFA-3. Cost Driver Effect formats are coded: CDE-MFA-I, CDE-MFA-II, CDE-MFA-III, ..., CDE-MFA-VIII.
Installation Method	Installation methods may be manual or automatic riveting, or various combinations of the two.
Installation Requirements	Installation requirements may be: (1) installed dry, (2) installed wet, or (3) installed wet and fay surface sealed.
Labor Learning Curve	Reflects the skill of the assembly laborers in learning to perform the panel assembly efficiently. Typical values are 65%, 70%, ..., 95%.

Materials	Sheet materials may be either aluminum or titanium.
Perimeter	The outside perimeter of the panel measured in feet.
Product	In the context of this task, a product consists of the set of one or more design candidates which meet the design requirements of the panel to be produced.
Nonrecurring Costs	Nonrecurring costs are man-hour labor requirements for tool fabrication. Nonrecurring costs do not include tool design and tool planning costs. Typically, tools need to be replaced after a certain number of units are assembled; thus, nonrecurring costs are incurred every P units, where P is the tool life in units assembled.
Recurring Costs	Recurring costs are man-hour labor requirements that include all hands-on factory labor. Recurring costs do include: initial preparation for jig loading, drilling, fastener installation, and storage for the next assembly phase. Recurring costs do not include: tool maintenance, planning, and quality control.
A	Percent automation.
C_{CED1}	Recurring installation costs (in man-hours/assembly) for aluminum rivets obtained from format CED-MFA-1. It is a function of: (1) installation requirements, (2) installation method and (3) total number of fasteners in the assembly.
C_{CED2}	Recurring installation costs (in man-hours/assembly) for titanium rivets obtained from format CED-MFA-2. It is a function of: (1) installation requirements, (2) installation method and (3) total number of fasteners in the assembly.
C_{CED3}	Nonrecurring tooling cost (in man-hours) for aluminum and titanium assemblies; obtained from format CED-MFA-3. It is a function of: (1) perimeter of the assembly in feet and (2) the installation method.

C_{rA}	Recurring cost (in man-hours) for the assembly of an aluminum panel.
C_{rT}	Recurring cost (in man-hours) for the assembly of a titanium panel.
$C_{\bar{r}A}$	Nonrecurring cost (in man-hours) for the assembly of an aluminum panel.
$C_{\bar{r}T}$	Nonrecurring cost (in man-hours) for the assembly of a titanium panel.
C_T	Total cost (in man-hours) for the assembly of one panel. Includes both recurring and nonrecurring labor.
D_{CDE1}	Relative cost of installation (in normalized man-hours) obtained from format CDE-MFA-I. It is a function of: (1) material and (2) installation method.
D_{CDE2}	Relative cost (in normalized man-hours) obtained from format CDE-MFA-II. It is a function of: (1) the number of parts excluding fasteners and (2) installation method.
D_{CDE3}	Relative installation cost (in normalized man-hours) for aluminum assemblies obtained from format CDE-MFA-III. It is a function of: (1) installation method and (2) installation requirements.
D_{CDE4}	Relative installation cost (in normalized man-hours) for aluminum assemblies obtained from format CDE-MFA-IV. It is a function of: (1) installation requirements and (2) installation method.
D_{CDE5}	Relative installation cost (in normalized man-hours) for titanium assemblies obtained from format CDE-MFA-V. It is a function of: (1) installation method and (2) installation requirements.
D_{CDE6}	Relative installation cost/fastener (in normalized man-hours) for titanium assemblies obtained from format CDE-MFA-VI. It is a function of: (1) installation method and (2) installation requirements.

D_{CDE7}	Relative installation cost/fastener (in normalized man-hours) obtained from format CDE-MFA-VII. It is a function of: (1) material and (2) installation method.
D_{CDE8}	Relative cost/fastener (in normalized man-hours) for aluminum and titanium assemblies obtained from format CDE-MFA-VIII. It is a function of: (1) installation requirements, (2) material and (3) installation method.
L	Learning curve factor. Learning curve reflecting labor skill. The factor is provided in each manufacturing technology section of the "Manufacturing Cost/Design Guide" (MC/DG).
N	Production volume, the number of units to be assembled.
N_F	Number of fasteners.
N_P	Number of parts, excluding fasteners.
O	Outside perimeter of panel.
P	Life of tools in units assembled. For example, if P is 200, tools must be replaced after each batch of 200 units is assembled.

DESIGN OF ASSEMBLIES OF SHEET METAL PARTS

Prototype Database Package for

Design-to-Cost

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first of a series of Design-to-Cost Software

------------Press any key to begin------------

FIGURE 2.6-3 IDENTIFIER SCREEN

```
                    EXISTING PRCDUCT ANALYSES

Database Files     # Records     Last Update      Size
PRODUCT.DBF              4          5/5/89        2306
FOIL.DBF                 1          5/5/89        1466
FOIL2.DBF                1          5/5/89        1536
TRUCK.DBF                2          5/5/89        1746
PLANE.DBF                4          5/5/89        2306

   9360 bytes in     5 files.
9304064 bytes remaining on drive.





(L)ist Products (D)el Product (A)dd Product (G)et Product e(X)it
```

FIGURE 2.6-4 LEVEL I. PRODUCT LEVEL COMMANDS

COST COMPARISON SUMMARY FOR GENERIC 1of1

CANDIDATE	UNIT (m-hr)	TOTAL (m-hr)	RECUR. (m-hr)	NONREC. (m-hr)
wet seal aluminum	9.53	1906	5.11	2.12
dry seal aluminum	1.81	2	0.04	1.75
wet and fay sealing aluminum	1.82	2	0.05	1.75
Al panel 20% automation	18.25	182500	10.62	2.85

(C)ost comp. (D)river comp. (S)pec. comp.(M)odify candidates e(X)it

FIGURE 2.6-5 LEVEL II. COST COMPARISON SURVEY FOR PRODUCT 'GENERIC'

INSTALLATION/PART COUNT DRIVERS SUMMARY FOR GENERIC 1of3

CANDIDATE	I	II	VII
wet seal aluminum	2.00	1.98	1.75
dry seal aluminum	2.00	1.98	1.75
wet and fay sealing aluminum	2.00	1.98	1.75
Al panel 20% automation	1.85	1.84	1.60

KEY: I=relative INSTALLATION cost wrt. automation and material
II=relative ASSEMBLY cost wrt. automation and part count
VII=relative FASTENER cost wrt. automation and material

-- Press any key to continue --

FIGURE 2.6-6 LEVEL II. COST DRIVER SURVEY FOR PRODUCT 'GENERIC'

FASTENER TYPE DRIVERS SUMMARY FOR GENERIC 2of3

CANDIDATE	I	VII
wet seal aluminum	2.00	1.75
dry seal aluminum	2.00	1.75
wet and fay sealing aluminum	2.00	1.75
Al panel 20% automation	1.85	1.60

KEY: I=relative INSTALLATION cost wrt. automation and material
VII=relative FASTENER cost wrt. automation and material
-- Press any key to continue --

FIGURE 2.6-7 LEVEL II. COST DRIVER SURVEY FOR PRODUCT 'GENERIC'

SEALING DRIVERS SUMMARY FOR GENERIC 3of3

CANDIDATE	III/V	IV/VI	VIII
wet seal aluminum	2.60	2.70	2.75
dry seal aluminum	1.70	1.85	1.75
wet and fay sealing aluminum	2.60	2.70	2.75
Al panel 20% automation	1.96	2.12	2.00

KEY: III/V=relative INSTALLATION cost wrt. material, automation and technique
IV/VI=relative INSTALLATION cost wrt. automation and technique
VIII =relative FASTENER cost wrt. material,automation and technique

-- Press any key to continue --

FIGURE 2.6-8 LEVEL II. COST DRIVER SURVEY FOR PRODUCT 'GENERIC'

SPECIFICATION COMPARISON FOR GENERIC 1of3

CANDIDATE	MATERIAL	PERIM. (feet)	NO.PARTS	NO.FAST.
wet seal aluminum	Al	14.40	4	133
dry seal aluminum	Al	10.00	4	300
wet and fay sealing aluminum	Al	10.00	4	300
Al panel 20% automation	Al	20.00	4	400

-- Press any key to continue --

FIGURE 2.6-9 LEVEL II. SPECIFICATION SURVEY FOR PRODUCT 'GENERIC'

SPECIFICATION COMPARISON FOR GENERIC 2of3

CANDIDATE	HILOK	SEALING	AUTO.
wet seal aluminum	unused	wet rivet and faying	0%
dry seal aluminum	unused	dry rivetted	0%
wet and fay sealing aluminum	unused	wet rivet and faying	0%
Al panel 20% automation	used	wet rivetted	20%

-- Press any key to continue --

FIGURE 2.6-10 LEVEL II. SPECIFICATION SURVEY FOR PRODUCT 'GENERIC'

SPECIFICATION COMPARISON FOR GENERIC 3of3

CANDIDATE	VOLUME	% LEARNING CURVE
wet seal aluminum	200	80%
dry seal aluminum	1	80%
wet and fay sealing aluminum	1	80%
Al panel 20% automation	10000	80%

-- Press any key to continue --

FIGURE 2.6-11 LEVEL II. SPECIFICATION SURVEY FOR PRODUCT 'GENERIC'

```
                                                 Caps
DESIGN OF SHEET METAL        -Product Name---------------------------
     ASSEMBLIES              GENERIC
                             -Design Alternative---------------------
**** USER SPECIFIED ****     wet seal aluminum

- Labor Learning Curve --    ********* CALCULATED/RETREIVED DATA ********
   80 (65,70,75,...,95%)          drivers                 estimators
--- Primary Material ----      ------ CDE ------      ------ CED -------
      1  (1)Al (2)Ti          no.    X        Y     no.   X          Y
------ Perimeter --------      I    1.00     2.00   1   133.00      5.11
       14.4feet               II    4.00     1.98   2     0.00      0.00
--- Number of Parts -----     III   2.00     2.60   3    14.40    423.34
     4(excl. fasteners)       IV    0.00     2.70
-- Number of Fasteners --      V    0.00     0.00
      133 per unit            VI    0.00     0.00   -- Learning Factor --
--- Sealing*;-- HILOK ---     VII   1.00     1.75          1.45
      3          F (Y/N)     VIII   3.00     2.75
--- Production Volume ---     -- Est. Unit Labor -  -- Est. Total Labor --
        200 units                 9.53 man-hrs        1906.00 man-hrs
----- % Automation ------
     0 (0,20,80,100)

*/(1)Dry rivet, (2)Wet rivet, (3)Wet rivet and faying
(S)earch (E)dit (N)ext (F)rev (D)el (A)dd (C)alculate (G)raph e(X)it
```

FIGURE 2.6-12 LEVEL III. EXAMPLE CANDIDATE SCREEN

REFERENCES

Item	Description
1	Summary of Air Force/Industry Manufacturing Cost Reduction Study, Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. Technical Report No. AFML-TM-LT-73-1, January 1973.
2	Summary Report on the Low Cost Manufacturing/Design Seminar, Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. Technical Report No. AFML-TM-LT-74-3, December 15, 1973.
3	Aerospace Cost Savings - Implications for NASA and the Industry, National Materials Advisory Board, National Academy of Sciences, Report No. NMAB-328, 1975.
4	Noton, B. R., et al, "Manufacturing Cost/Design Guide," Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. Technical Report AFML-TR-76-227, December 1976.
5	Noton, B. R., Claydon, C. R., Larson, M., "ICAM Manufacturing Cost/Design Guide," Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. Technical Report AFWAL-TR-80-4115, September 1977-July 1979. a. Volume I: Demonstration Sections b. Volume II: Appendices to Demonstration Sections c. Volume III: Computerization
6	"Superplastic Forming of Aluminum Airframe Components," Rockwell International, North American Aircraft Operations. Briefing to U.S. Army Aviation Systems Command in Los Angeles, California, January 28, 1986.
7	Noton, B. R., et al, "Manufacturing Cost/Design Guide," Volume V - Machining, Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. Technical Report No. AFWAL-TR-83-4033, March 1985.
8	Noton, B. R., et al, "Manufacturing Cost/Design Guide for Aerospace Applications". Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. Technical Report No. AFWAL-TR-88-4049, May 1988.
9	Gallagher, J., and Brazier, G., Minutes of Design Integration Subcommittee, American Institute of Aeronautics and Astronautics, April 28, 1982.

APPENDIX A

USERS' NEEDS SURVEY FOR A COMPUTERIZED MANUFACTURING COST/DESIGN GUIDE

1.1 INTRODUCTION

At the outset of the initial "Manufacturing Cost/Design Guide" (MC/DG) program, a survey was conducted of the potential users in the design process. The original responses and objectives of the series of volumes are still timely and important. The results of the survey are therefore included in this report as an Appendix.

The questionnaire was sent to designers, with varying degrees of experience, at eight major aerospace companies. For some questions, the total number of responses exceeded 80.

The questions asked were in the following general categories:

1. General questions on the "Manufacturing Cost/Design Guide"

2. Data sources, retrieval and presentation

3. Experience and attitudes concerning computers.

1.2 OVERVIEW OF CONCLUSIONS FROM SURVEY

The following is an overview of the results of the survey. The detailed responses are included in Table A-1.

1.2.1 Background of Designers

- The majority of those designers surveyed work on fuselages and wings of military fighter and attack aircraft and have over ten years of design experience. The MC/DG is particularly useful for such subassemblies.

1.2.2 Design Activities

- The MC/DG should be used in all phases of design, i.e., from conceptual through detail design. Hence, the MC/DG for conceptual design has been developed and is included in the main section of this report.

- The most time-consuming functions of the designer are drafting and creative/conceptual activities. Hence, there is a need to address manufacturing cost at the outset of system development.

- The most frequently consulted cost data/information sources are graphs of standard parts and materials. Prior to the MC/DG development, no other data and formats existed to stimulate innovative design of unique structures which are designed to minimize manufacturing cost.

1.2.3 Formats or Design Charts

- The MC/DG and its formats or design charts should be easy and quick to use. The design-to-cost function must enable the creative momentum and designer enthusiasm to be maintained and should not exceed 10 percent of the total design time.
- Most of the designers interviewed felt that the MC/DG should be structured to guide the designer through the design-to-cost process and that it should be very beneficial to unseasoned engineers.
- The most preferred presentation modes for MC/DG information were x-y graphs with text, including utilization examples.
- A listing of Designer Influenced Cost Elements (DICE), Cost Driver Effects (CDE) and Cost Estimating Data (CED) in the MC/DG was judged to be useful. It is a building-block approach with DICE added to base parts.

1.2.4 Computerized MC/DG

- Most designers surveyed have used computerized job aids previously and found them generally helpful, but, at that time, they did not use them frequently (partially due to management constraints).
- Most designers surveyed felt that a computerized MC/DG would help most in performing trade-off studies and for design-to-cost. They need the tool particularly in the creative/conceptual design phase.
- The ability to store parts in the data base as members of a subassembly in the computer, and the ability to use simultaneously design and analysis programs, while utilizing the MC/DG were considered valuable.

1.2.5 Hard Copy of MC/DG

- The designers indicated that the MC/DG would be utilized almost equally in the conceptual, preliminary, and detail design phases.

- The hard copy of the MC/DG would be applied in all phases of design as an aid in the selection and evaluation of structural configurations and for performing trade-off studies on components. It would also be used as a reference manual in meetings (especially when justifying designs with management).

- The support groups stated that the MC/DG would be useful in each of the following areas:

  - Analysis of cost-competitive designs

  - Manufacturing engineering and producibility

  - Justification of investments in facilities.

- Designers felt that the hard copy of the MC/DG would be used extensively and, unless the response time was minimal, possibly more than a computerized guide. It should be mentioned that the average age of designers exceeds 57 years and the majority of these professionals have not been trained in the use of computers. However, this would rapidly be changed by management when evidence is observed that a computerized guide could speed up the design process and, hence, reduce the cost of design. The response time is extremely important. The need is evident to sell computer-aided design-to-cost to management and convince them to invest in appropriate computerized systems to ensure the local availability of the computer to the designer for minimizing manufacturing cost.

TABLE A-1. GENERAL QUESTIONS IN SURVEY ON MC/DG

Number of Responses for Each Question Indicated: (XX)

Question Number	Question	Response Categories	Total Number of Responses
1	With what aerospace systems are you involved?	Military Aircraft (24); Commercial Aircraft (12); Spacecraft (2)	38
		Large Aircraft (15); Medium Aircraft (12); Small Aircraft (15)	42
		Fighter (17); Bomber (6); Attack (12); Cargo (7); Helicopter (1); Missile (4); Other (4)	51
2	At what stage are you in the development cycle?	Research & Development (6) Conceptual Design, Preliminary Design (15) Design Sizing (17) Design Refinement, Design Verification (18) Production Go-Ahead (1) Detail Design (18) Product Manufacture, Product Verification (4) Product Support (5)	84
3	Primarily a designer of	Systems (5); Subassemblies (14); Parts (15); Other (3)	82
		Fuselages (20); Wings (20); Landing Gear (2); Power Plant (0); Other (3)	
4	Design Experience	0-5 Years (2); 5-10 Years (3); 10-20 Years (8); Over 20 Years (13)	26
9	Would a hard copy of the MC/DG be required for	Personal Use (15); Group Use (13); Department Use (0)	28

TABLE A-1. GENERAL QUESTIONS IN SURVEY ON MC/DG (Concluded)

Question Number	Question	Response Categories	Total Number of Responses
12	Should a listing of DICE[1] be included?	Yes (22); No (0); Maybe (4)	26
13	Should CDE[2] and CED[3] be displayed in the MC/DG?	Yes (23); No (0); Maybe (3)	26
15	Should the MC/DG be structured to <u>guide</u> the designer through the process?	Yes (24); No (0); Maybe (3)	27
16	How often would you use the MC/DG if it were available?	<u>Hard Copy</u>: Often (17); Sometimes (11); Never (1)	29
		<u>Computerized</u>: Often (3); Sometimes (19); Never (5)	27

(1) DICE refers to designer-influenced cost elements.

(2) CDE refers to cost-driver effects.

(3) CED refers to cost-estimating data.

TABLE A-2. DATA SOURCES, RETRIEVAL AND PRESENTATION

Percentage, Frequency or Relative Values, Responses or Averages Indicated: (XX)

Question Number	Question	Response Categories	Total Number of Responses
6	Which functions are most time consuming? (% of time)	Data Gathering (11); Data Browsing (6); Verification of Data Accuracy, Age, and Reliability (4); Statistical Analysis of Data (2); Interpreting Retrieved Data (4); Drafting (31); Cost Analysis/Trade-off or Design-to-Cost (8); Creative/ Conceptual (30); Other (7)	29
8	Which cost data/ information resources are used and how frequently? Note: Rating indicated - ( )	Rating system used: 1 - constantly; 2 - daily; 3 - 2 or 3 times a week; 4 - weekly; 5 - biweekly; 6 - monthly; 7 - rarely Vendor Catalogs (6); Handbooks, Manuals, Guides (3); Tables (4); Reference Books (5); Trade Publications (6); Research Journals, Papers (7); In-house Standard Parts and Shapes Lists (3); Cost Estimation Handbooks (6); Computerized System (6); Other (4)	26
10	Where are most of your sources stored, and in what form? Note: Distance indicated - (yds)	Your Office/Desk, Group, Department or Area: Average Distance (14 yds); Hard Copy (25); Microform (9); On-line Computer Terminal (9)	43
		Company Library: Average Distance (52 yds); Hard Copy (25); Microform (13); On-line Computer Terminal (1)	39

TABLE A-2. DATA SOURCES, RETRIEVAL AND PRESENTATION (Concluded)

Question Number	Question	Response Categories	Total Number of Responses
10 (Cont'd)	Where are most of your sources stored, and in what form? Note: Distance indicated - (yds)	Other In-house Research Facility: Average Distance (80 yds) Hard Copy (10) Microform (8) On-line Computer Terminal (4)	22
		Outside Sources: Average Distance (40 yds) Hard Copy (2) Microform (1) On-line Computer Terminal (0)	3
11	Prioritize cost data/information in order of frequent usage Note: frequency indicated - ( ) (1 most frequent to 7 least frequent)	**Display Mode** Statistical Tables (4) Formulas (4); Test (4); Index (5); Charts (3) Graphs (3); Other (6)	25
		Topic of Data Standard Parts List (2) Standard Shapes List (3) Standard Materials (2) Formability Data (4) Tolerance Data (4) Surface Treatment Data (5) Other (7)	24
14	What is your expected presentation mode for the hard copy MC/DG? Rate value of each (1 very valuable to 5 no value) Note: Value indicated - ( )	Tables (3); x-y Graphs (2); Bar Charts (3); Pie Charts (4) Text (Including Instructions) (3) Equations (Cost Trade-off, etc.) (3) Line Drawings (Parts Illustrations) (3)	26

TABLE A-3. EXPERIENCE/ATTITUDES CONCERNING COMPUTERS

Responses or Averages Indicated: (XX)

Question Number	Question	Response Categories	Total Number of Responses
1	Have your used computerized job aids?	Yes (20); No (6)	26
	How frequently?	Often (4); Sometimes (13); Rarely (4)	21
	When did you last use a computerized job aid?	During Last Week (6); Last Month (8); Years Ago (7)	21
	Have the aids been	Very Helpful? (14); Somewhat Helpful? (5); Of Not Much Use? (2)	21
2	What is your attitude towards using computerized job aids?	Eager to Use (13); Would Use Sometimes (12); Feel Uncomfortable Using (5) Because: Too Hard (4); Too Much Training (3); Not Reliable (0); Other (5)	30
3	How much time could you be authorized to spend learning a new computerized job aid?	Up to 1/2 day (3); 1/2 to 1 day (4); 2 to 7 days (11); More (0)	18
4	What equipment do you have available?	Computers: IBM (19); CDC (9); UNIVAC (0); DEC (3); Other (6)	37
		On-line Terminals: Teletype (5); Hazeltine (1); Texas Instruments (2); IBM (8); Other (8)	24
		Graphic Display Terminals: CRT (Video) (9); Calcomp (5); Tektronix (7); Other (11)	32

TABLE A-3. EXPERIENCE/ATTITUDES CONCERNING COMPUTERS (Concluded)

Question Number	Question	Response Categories	Total Number of Responses
5	What would you accept as an average wait for access to the computer?	(4.0) hours	18
6	Would the ability to store parts as subassemblies in a special file be	Very Valuable? (6); Valuable? (8); Somewhat Valuable? (9); Useless? (1)	24
7	Would the ability to use design and analysis programs with the MC/DG be	Very Valuable? (3); Valuable? (14); Somewhat Valuable? (6); Useless? (0)	23
8	Are programs maintained by a computer center or by you?	You (2); Computer Center (9); Both (8)	19

APPENDIX B

MECHANICALLY FASTENED ASSEMBLY SECTION OF THE MC/DG

4.2 Mechanically Fastened Assembly Section

This section contains format selection aids, identification of the types of parts analyzed for data to determine the manufacturing man-hour data, examples of how the data are utilized in airframe design and a set of mechanically fastened assembly formats. These formats include cost-driver effects (CDE), cost-estimating data (CED), and designer-influenced cost elements (DICE).

4.2.1 Format Selection Aids

Format selection aids are presented to provide the user with a building-block approach to determine manufacturing cost data for alternative designs or processes. The designer can review the format selection trees and identify those areas that have an impact on his design. The formats provide cost-driver effects (CDE) for qualitative guidance to lowest cost and cost-estimating data (CED) in man-hours for conducting trade-off studies.

FORMAT SELECTION AID

MECHANICALLY FASTENED ASSEMBLIES

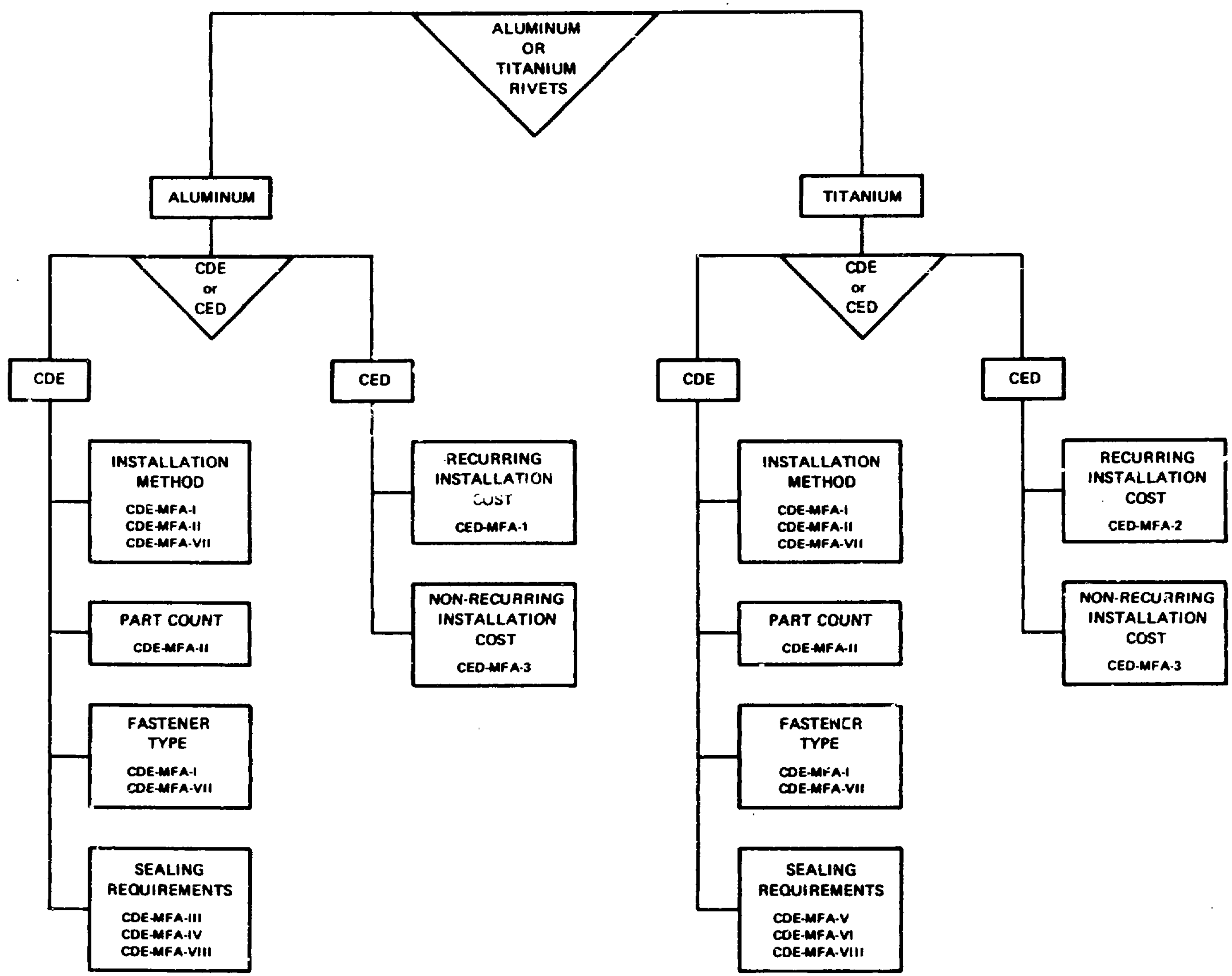


FIGURE 4.2-1

4.2.2 Example of Utilization

This example demonstrates to the designer how the mechanically fastened assembly data is utilized on a specific design problem. The example shows how to identify applicable formats, how to extract data from the formats, and provides a discussion on how the data are used to determine the part cost in man-hours or dollars. The MC/DG cost worksheet can be used to record the cost data for easy reference and to determine the total program cost. The MC/DG worksheet appears as Table 3-3.

4.2.2.1 Utilization Example of Aluminum First Level Assembly

Problem Statement

Determine manufacturing cost (man-hours) for an aluminum (2024) first level assembly shown in Figure 4.2-1. The order will be for 200 units.

Procedure

The following procedure is used to determine the manufacturing cost (man-hours) for the assembly.

1. Review the Format Selection Aid (Fig. 4.2-1) for Mechanically Fastened Assemblies.
2. Determine the formats to use. In this case, Formats CED-MFA-1 (Fig. 4.2-3) and CED-MFA-3 (Fig. 4.2-4) are required.
3. Study the formats to determine the parameters and conditions needed for use. To use CED-MFA-1, the number of fasteners, fastening method, and sealing requirements must be specified. The sketch indicates 133 fasteners with the faying surface sealed. For this example, manual and automatic riveting will be considered. To use CED-MFA-3, the part perimeter (ft) and fastening method is required. The perimeter in this case is 14.4 ft, and again, both automatic and manual riveting will be considered by the designer.
4. Determine the values for recurring cost and nonrecurring tooling cost (NRTC) from the formats:

   (a) Manual

   - From CED-MFA-1, read that the recurring cost = 5.0 man-hours per part
   - From CED-MFA-3, read that NRTC = 420 man-hours
     NRTC = 420 man-hours per 200 parts
     = 2.10 man-hours per part
   - The learning curve factor to convert unit cost at 200 to cumulative average cost for an 80 percent curve and a quantity of 200 is 1.45 (see (Table 4.2-1).

   Total cost = 1.45 (5.0) + 2.1 = 9.35 man-hours per part.

(b) Automatic

- From CED-MFA-1, read that recurring cost at unit 200 = 3.25 man-hours per part
- From CED-MFA-3, read that
  NRTC = 440 man-hours per 200 parts
  = 2.2 man-hours per part.

Total cost = 1.45 (3.25) + 2.2 = 6.91 man-hours per part.

5. No applicable DICE are indicated, and, therefore, the costs determined above are the final total costs for assembling the part.

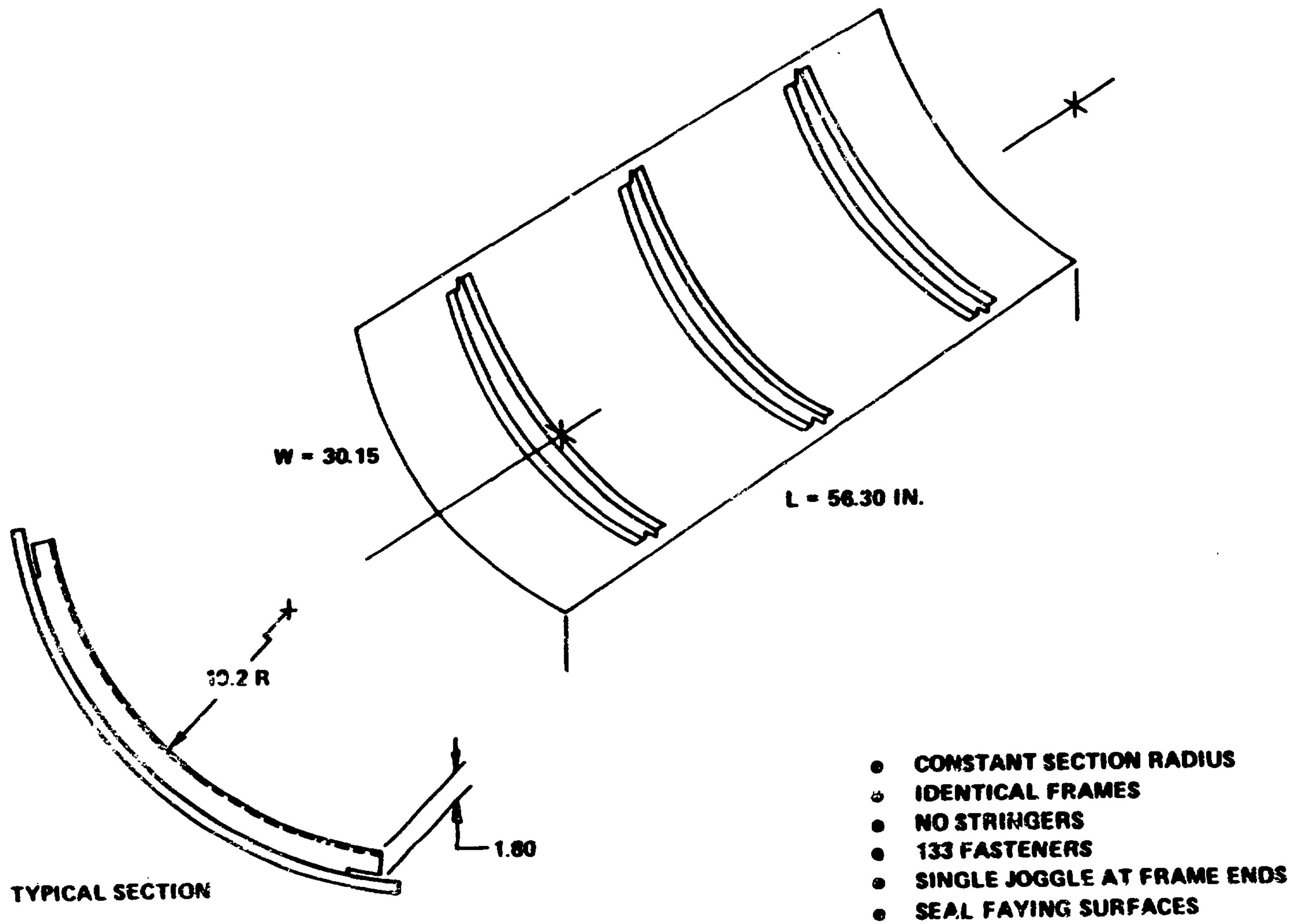
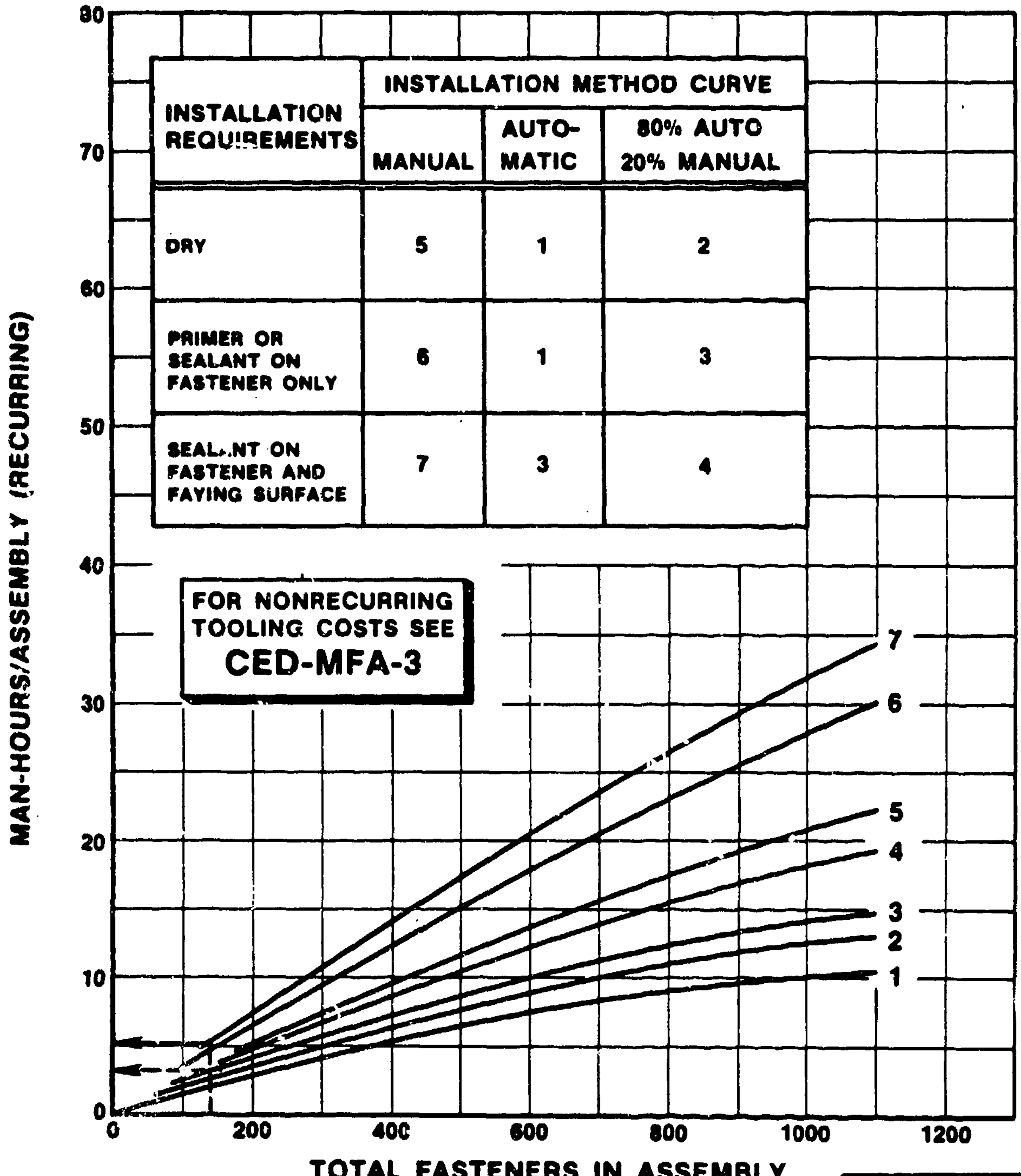


FIGURE 4.2-2. ALUMINUM (2024) FIRST LEVEL ASSEMBLY STATEMENT

INSTALLATION COSTS FOR ALUMINUM RIVETS



INSTALLATION REQUIREMENTS	INSTALLATION METHOD CURVE		
	MANUAL	AUTO-MATIC	80% AUTO 20% MANUAL
DRY	5	1	2
PRIMER OR SEALANT ON FASTENER ONLY	6	1	3
SEALANT ON FASTENER AND FAYING SURFACE	7	3	4

CED-MFA-1

FIGURE 4.2-3. FORMAT USED IN EXAMPLE

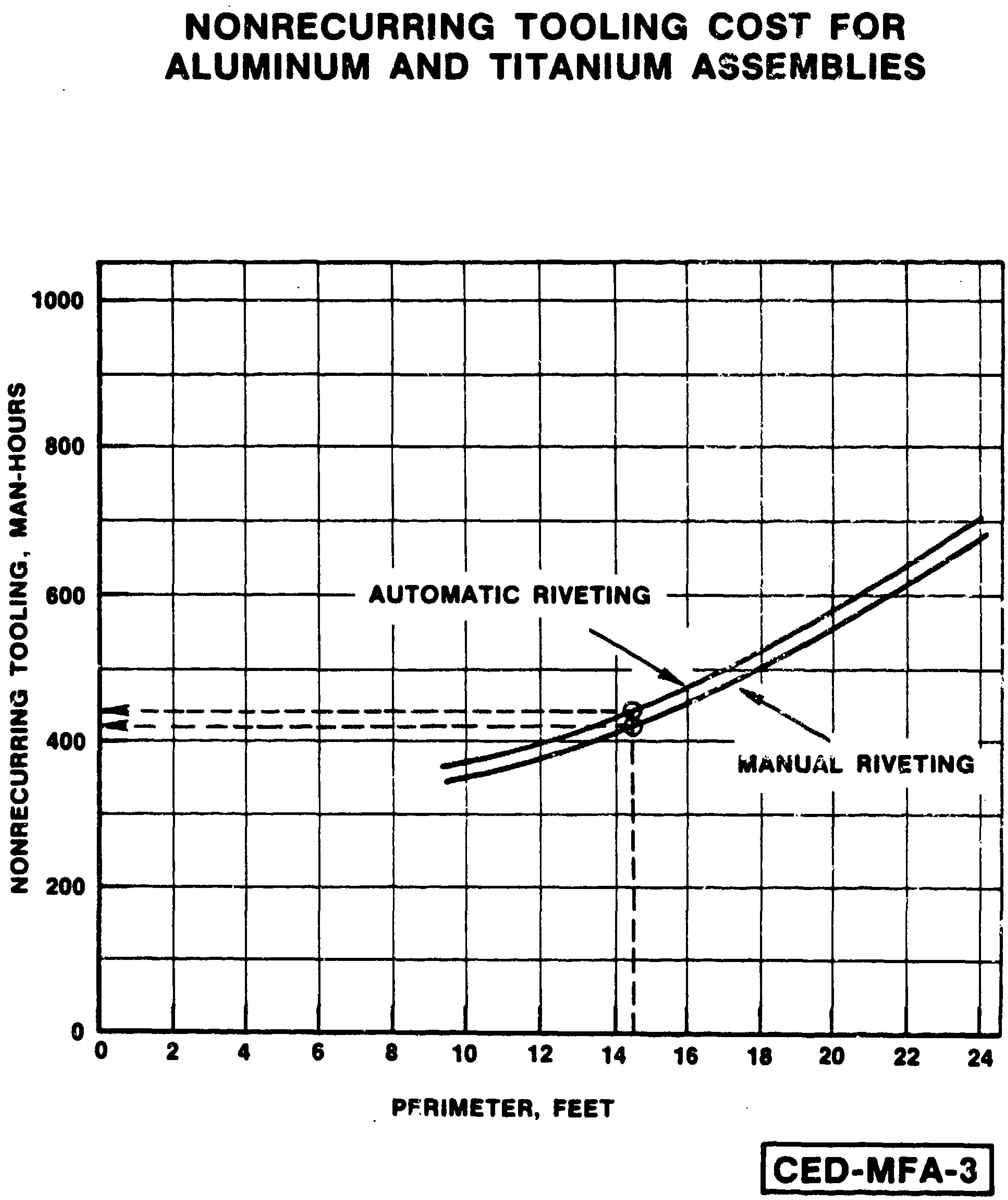


FIGURE 4.2-4. FORMAT USED IN EXAMPLE

TABLE 4.2-1

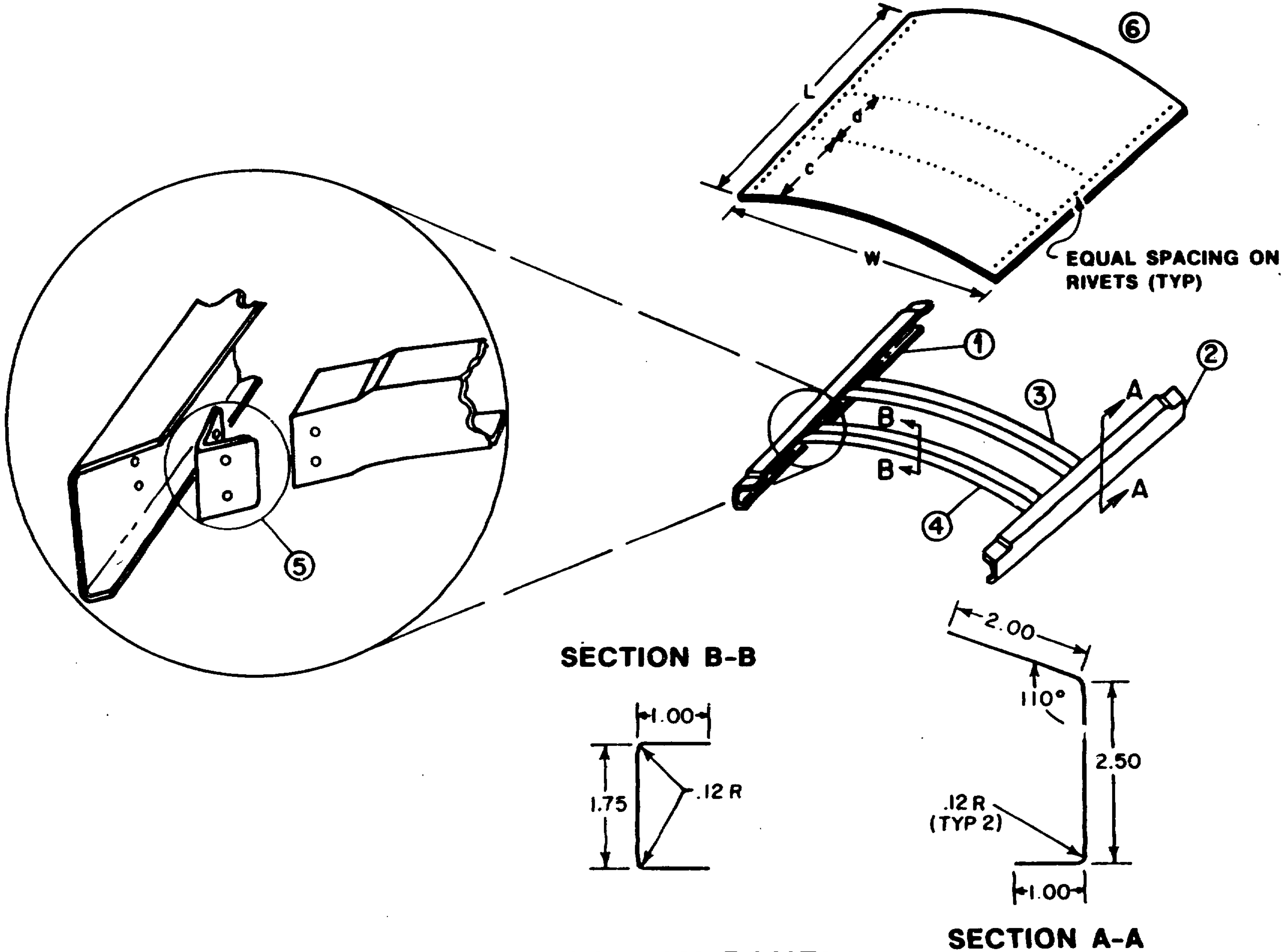
FACTORS TO CONVERT THE MC/DG 200TH UNIT COST TO THE CUMULATIVE AVERAGE COST FOR THE DESIGN QUANTITY AND LEARNING CURVE INVOLVED

DESIGN QUANTITY	LEARNING CURVE-%						
	95	90	85	80	75	70	65
1	1.48	2.25	3.48	5.50	9.00	15.00	27.00
10	1.33	1.79	2.47	3.48	5.04	7.53	11.67
25	1.25	1.59	2.05	2.71	3.68	5.13	7.43
50	1.19	1.44	1.79	2.22	2.65	3.76	5.14
100	1.13	1.30	1.52	1.80	2.18	2.73	3.51
200	1.08	1.17	1.30	1.45	1.66	1.95	2.36
350	1.04	1.08	1.14	1.22	1.33	1.48	1.70
500	1.01	1.02	1.05	1.09	1.15	1.24	1.38
750	0.98	0.96	0.96	0.96	0.97	1.01	1.09
1000	0.96	0.92	0.89	0.87	0.87	0.88	0.91

4.2.3 Airframe Assemblies

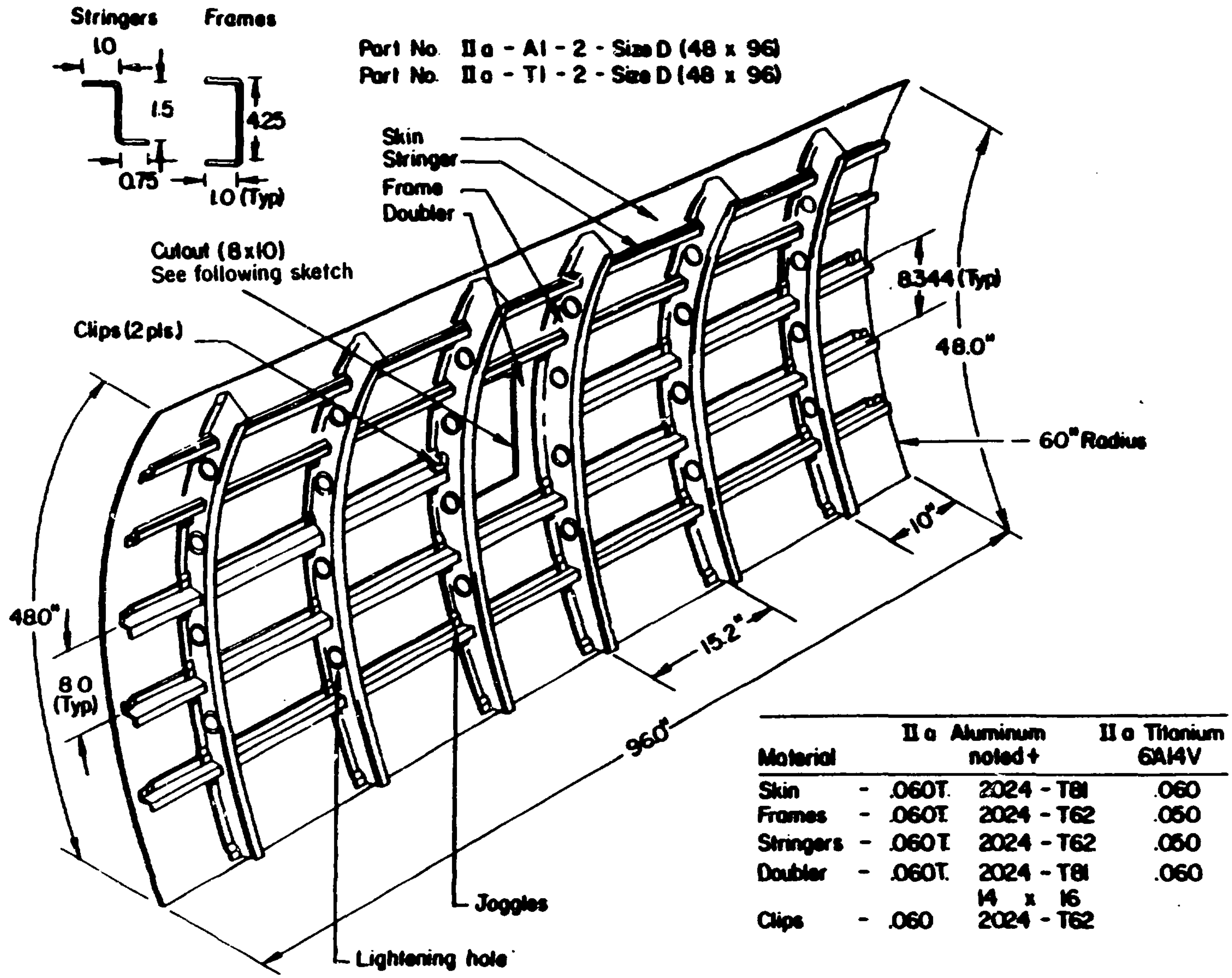
To determine the manufacturing man-hours for first level mechanically fastened assemblies, the assemblies shown in Figures 4.2-5 to 4.2-8 were analyzed. The assemblies were:

- Avionics Panel
- Fuselage Panel
- Fuselage Door.



AVIONICS BAY PANEL

FIGURE 4.2-5. ASSEMBLY ANALYZED TO DEVELOP DATA



Material		II a Aluminum noted +		II a Titanium 6Al4V
Skin	-	.060T.	2024 - T81	.060
Frames	-	.060T.	2024 - T62	.050
Stringers	-	.060T.	2024 - T62	.050
Doubler	-	.060T.	2024 - T81	.060
			14 x 16	
Clips	-	.060	2024 - T62	

MECHANICALLY FASTENED ASSEMBLY FUSELAGE PANEL

FIGURE 4.2-6. ASSEMBLY ANALYZED TO DEVELOP DATA

FUSELAGE CUT-OUT

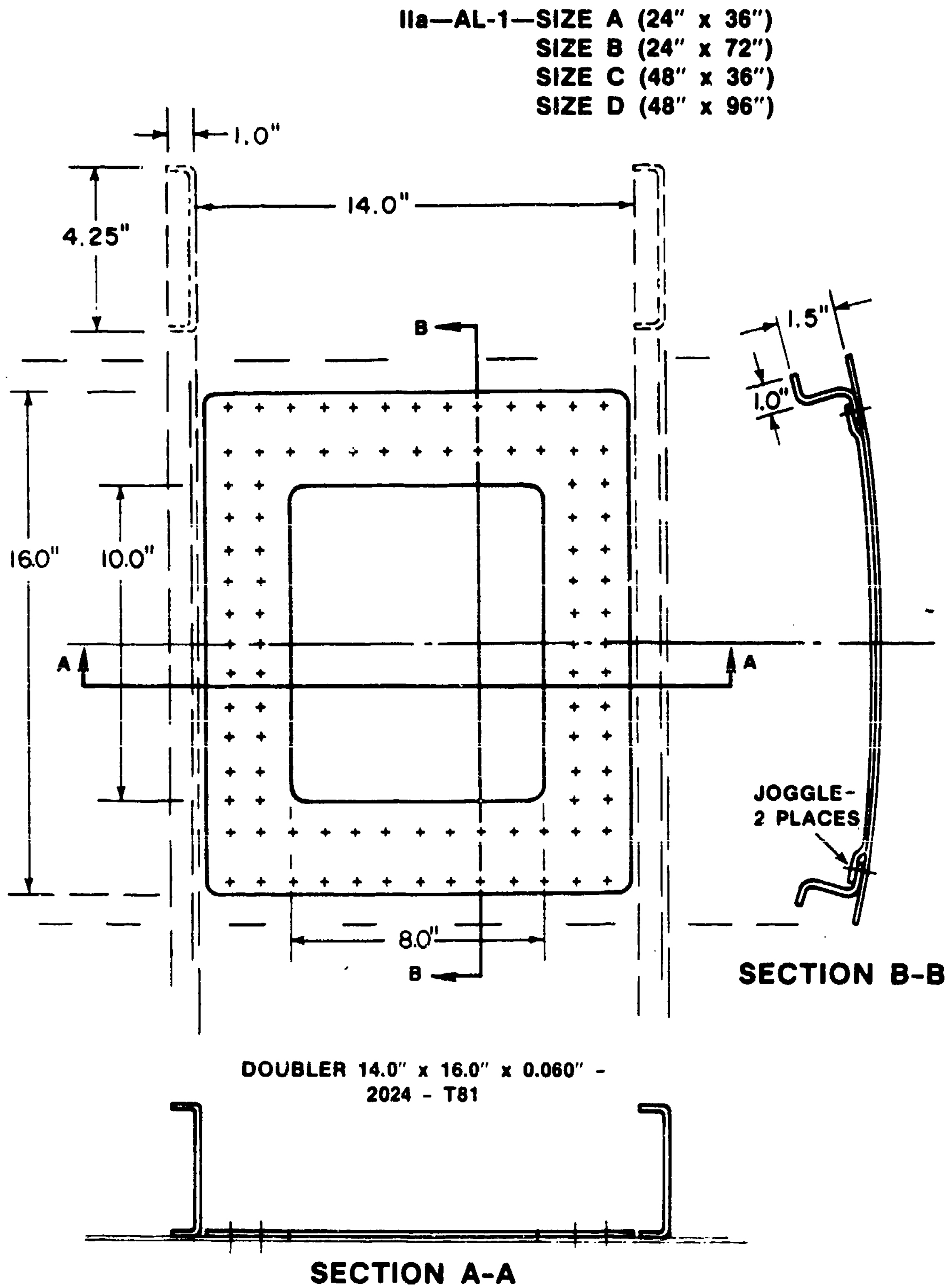


FIGURE 4.2-7. DETAILS OF WINDOW IN FIGURE 4.2-5

FUSELAGE DOOR ASSEMBLY

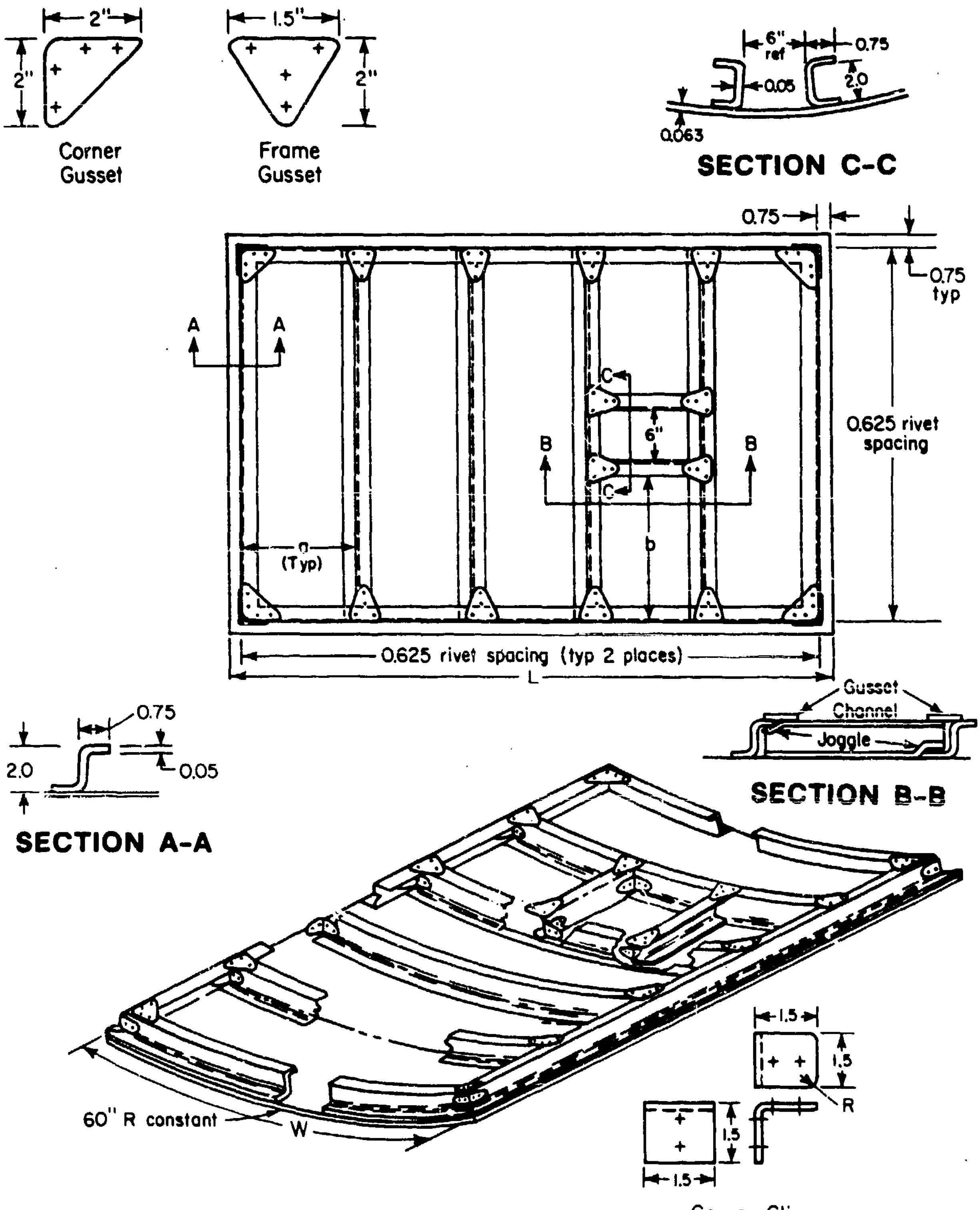


FIGURE 4.2-8 ASSEMBLY ANALYZED TO DEVELOP DATA

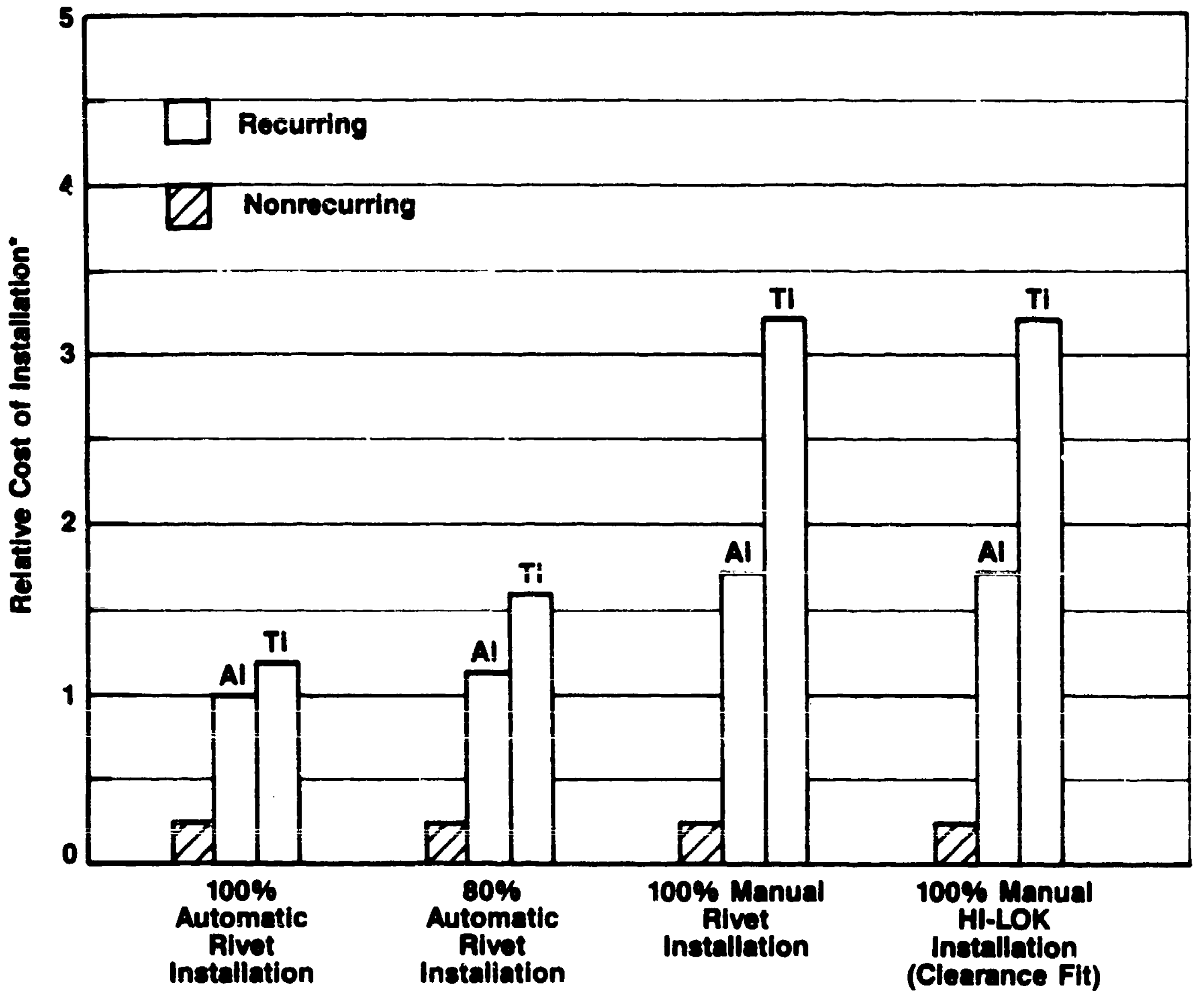
TABLE 4.2-2. DIMENSIONS AND MATERIALS OF ASSEMBLIES ANALYZED

Assembly Type	Material	Size Classification	Size, Inches
Avionics Bay Panel	Aluminum-1	A	24x36
		B	24x72
		C	48x36
		D	48x96
Fuselage Panel	Aluminum-2	A	24x36
		B	24x72
		C	48x36
		D	48x96
Fuselage Door	Aluminum-3	A	24x36
		B	24x72
		C	48x36
		D	48x96
Avionics Bay Panel	Titanium-1	A	24x36
		B	24x72
		C	48x36
		D	48x96
Fuselage Panel	Titanium-2	A	24x36
		B	24x72
		C	48x36
		D	48x96
Fuselage Door	Titanium-3	A	24x36
		B	24x72
		C	48x36
		D	48x96

4.2.4 Manufacturing Data for Airframe Assemblies

The following data for airframe assemblies are presented using cost-estimating data (CED) and cost-driver effect (CDE) formats for conducting trade-studies.

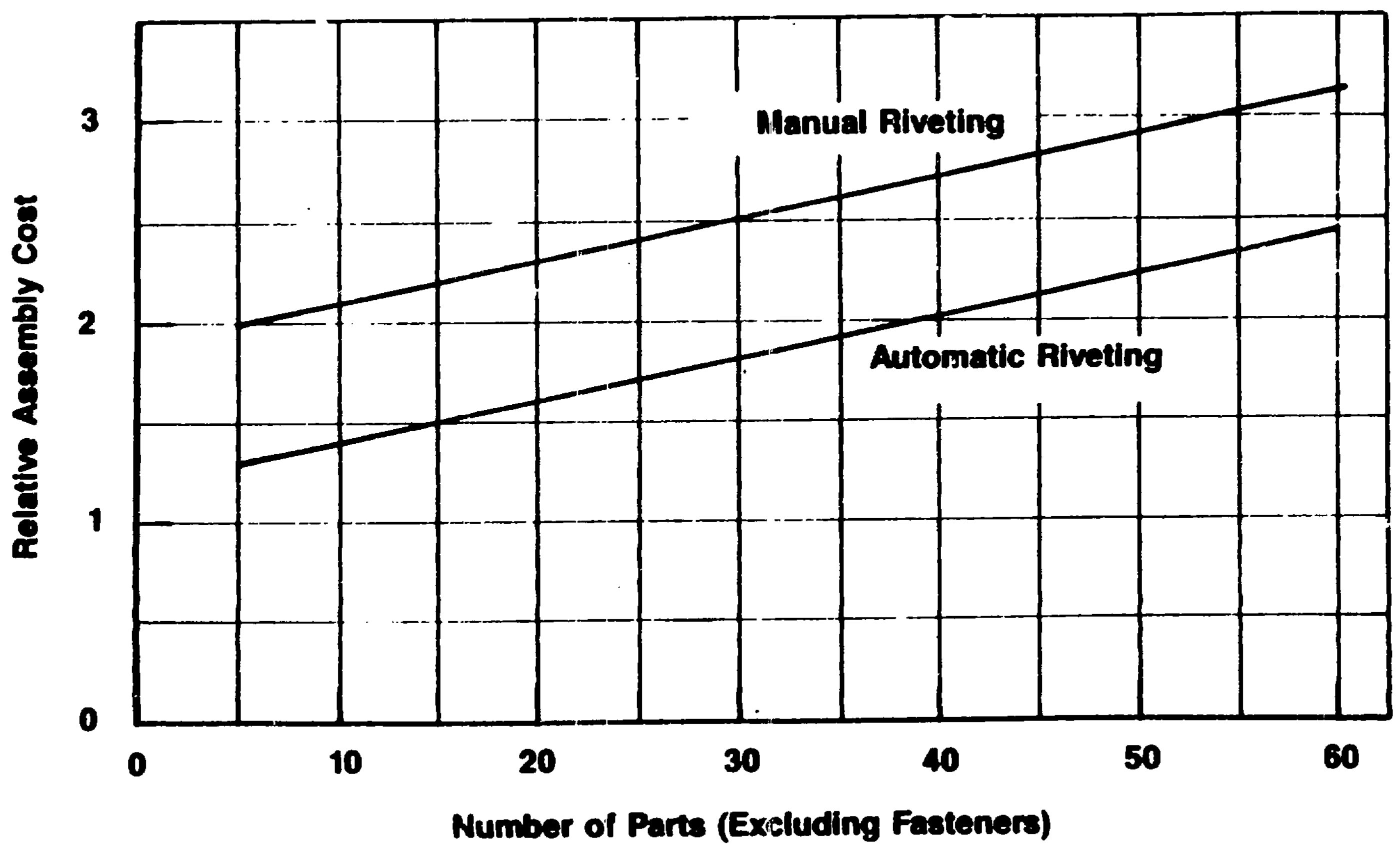
EFFECT OF INSTALLATION METHOD FOR ALUMINUM AND TITANIUM ASSEMBLES



*Includes the complete operation-hole preparation and fastener setting

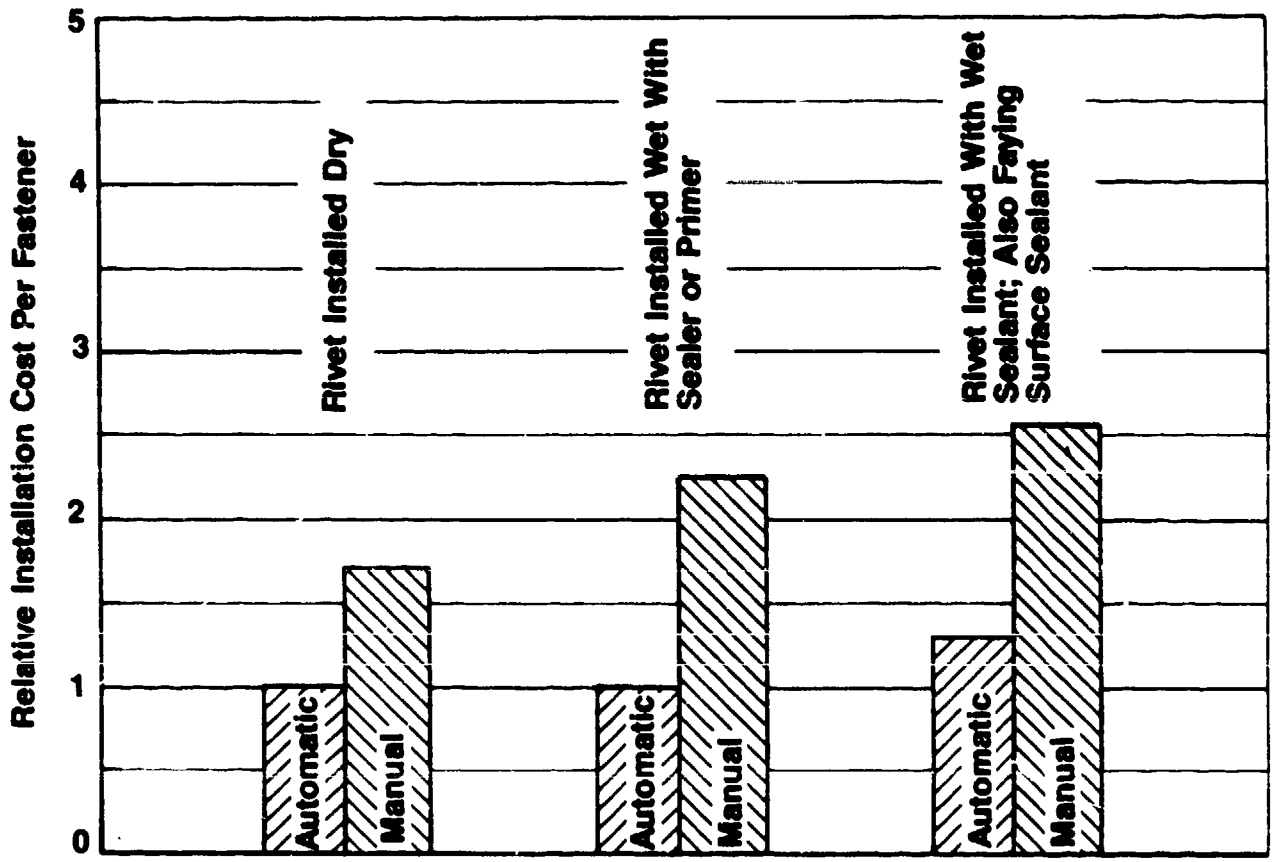
CDE-MFA-I

EFFECT OF PART COUNT AND FASTENING METHOD



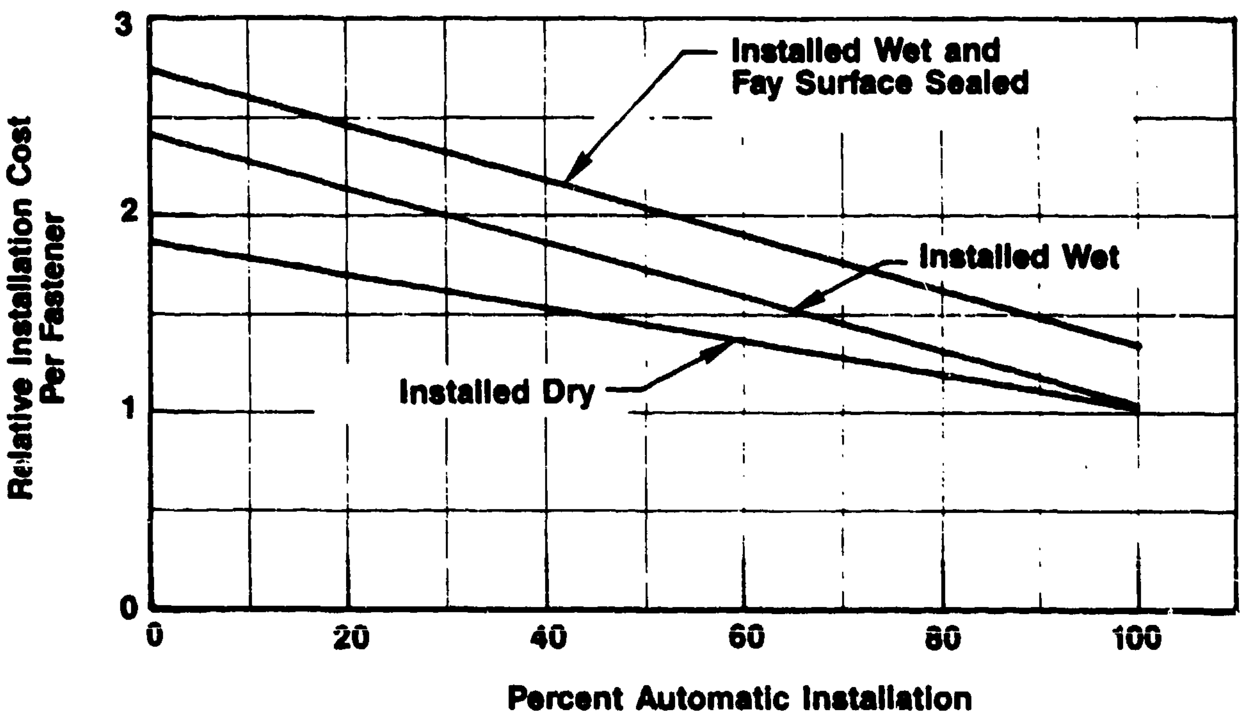
CDE-MFA-II

EFFECTS OF SEALING ON FASTENER INSTALLATION COST ALUMINUM ASSEMBLIES



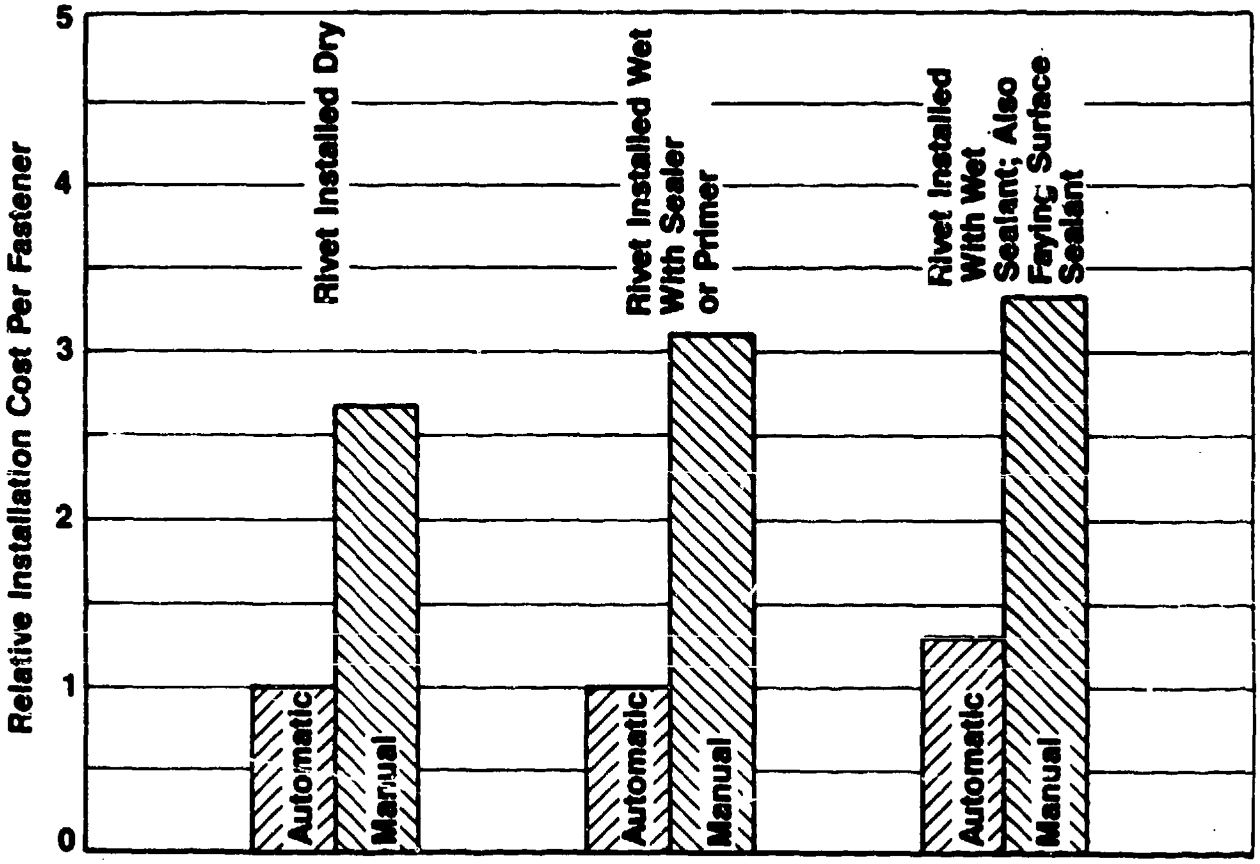
CED-MFA-III

EFFECT OF SEALING ON ASSEMBLY COST
ALUMINUM ASSEMBLIES



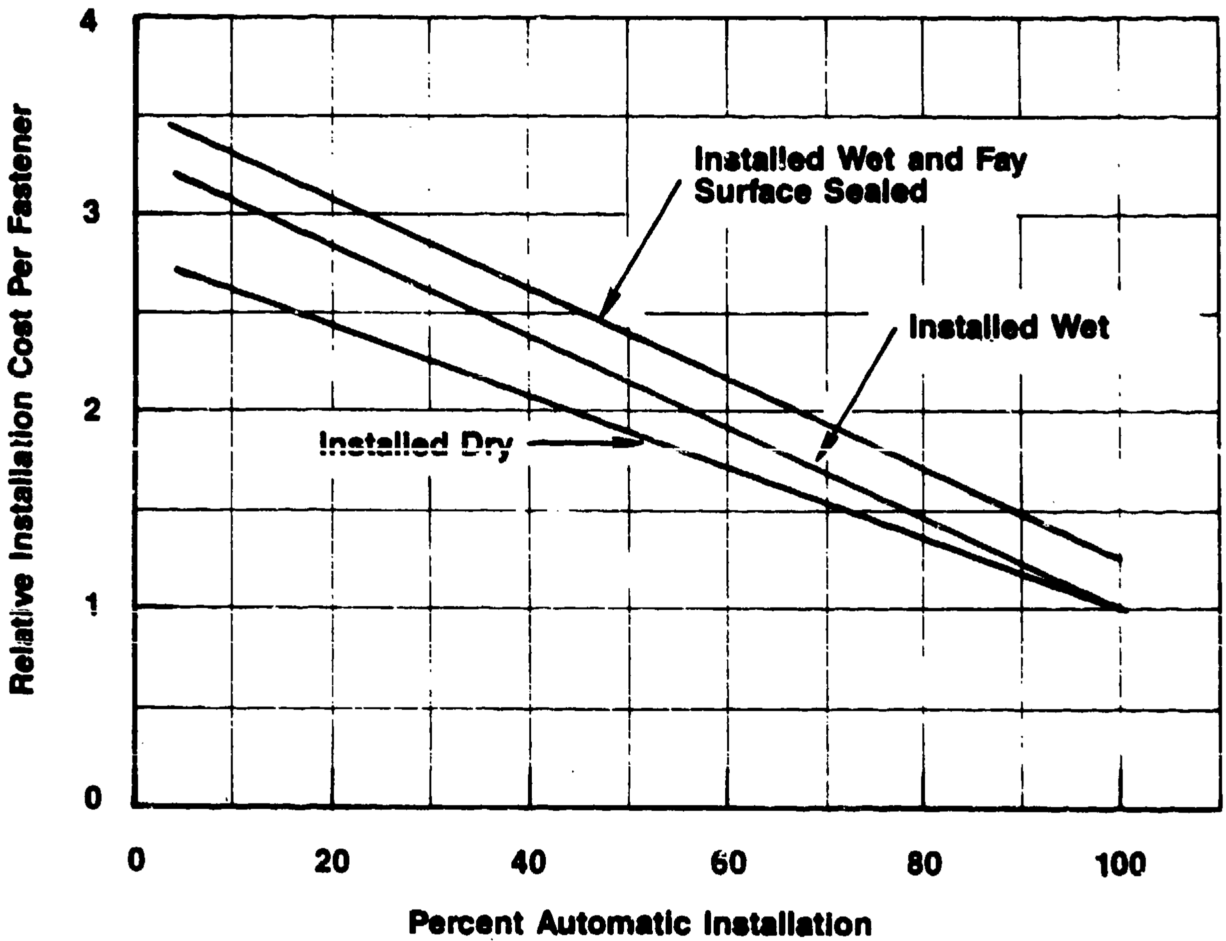
CDE-MFA-IV

EFFECT OF SEALING ON FASTENER INSTALLATION COST TITANIUM ASSEMBLIES



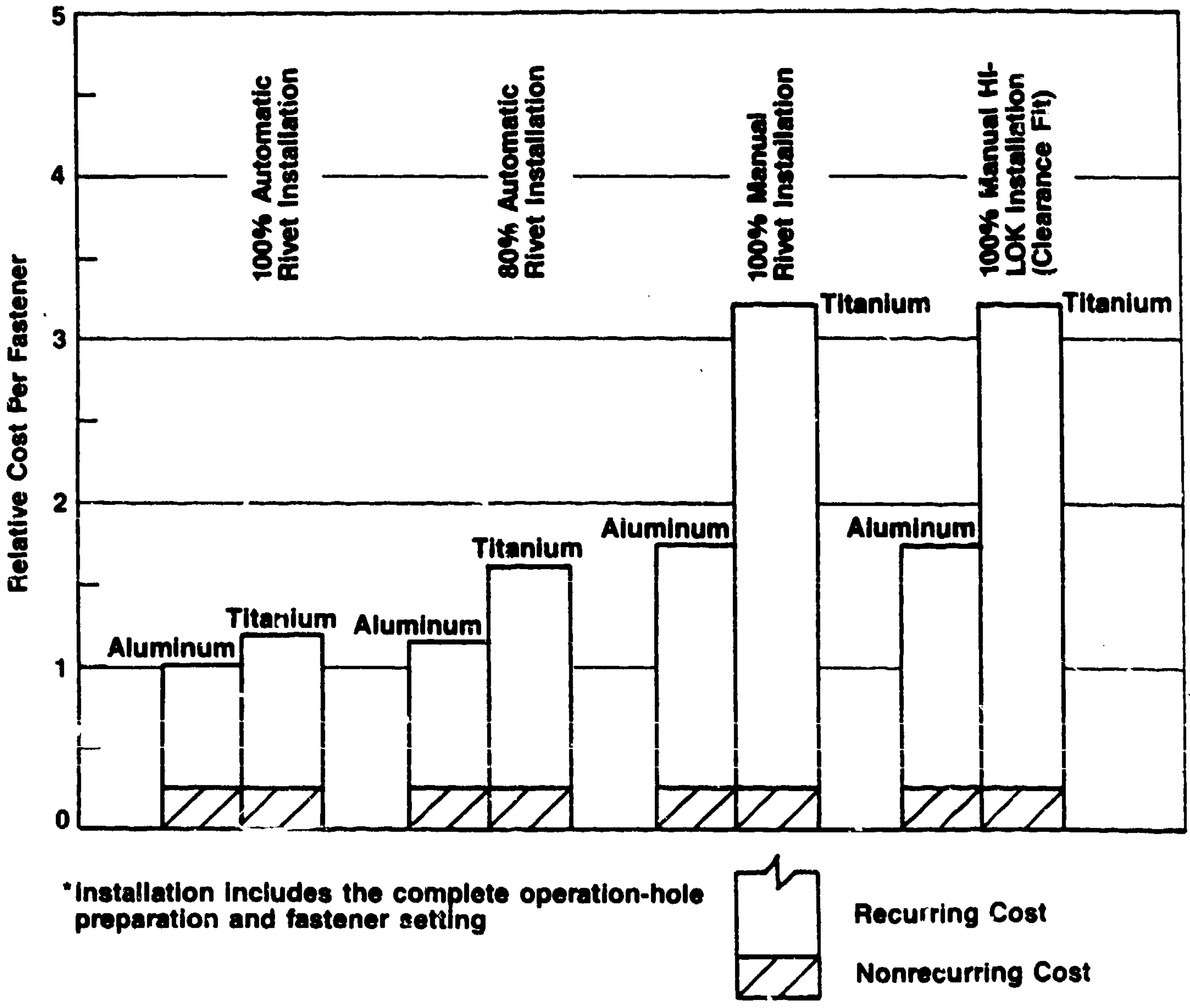
CDE-MFA-V

EFFECT OF SEALING ON ASSEMBLY COST
TITANIUM ASSEMBLIES



CDE-MFA-VI

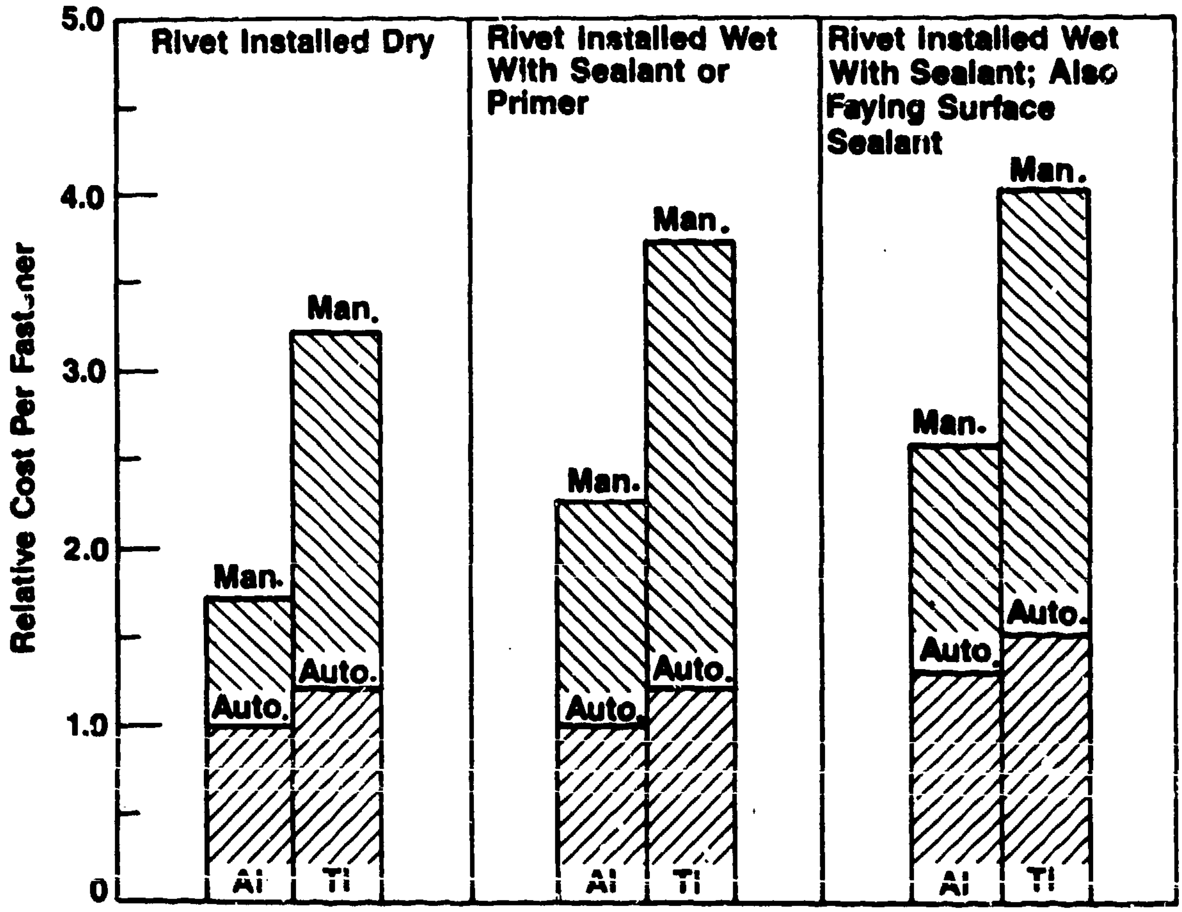
COST EFFECTS OF INSTALLATION* METHOD, ASSEMBLY MATERIAL AND FASTENER TYPE



*Installation includes the complete operation-hole preparation and fastener setting

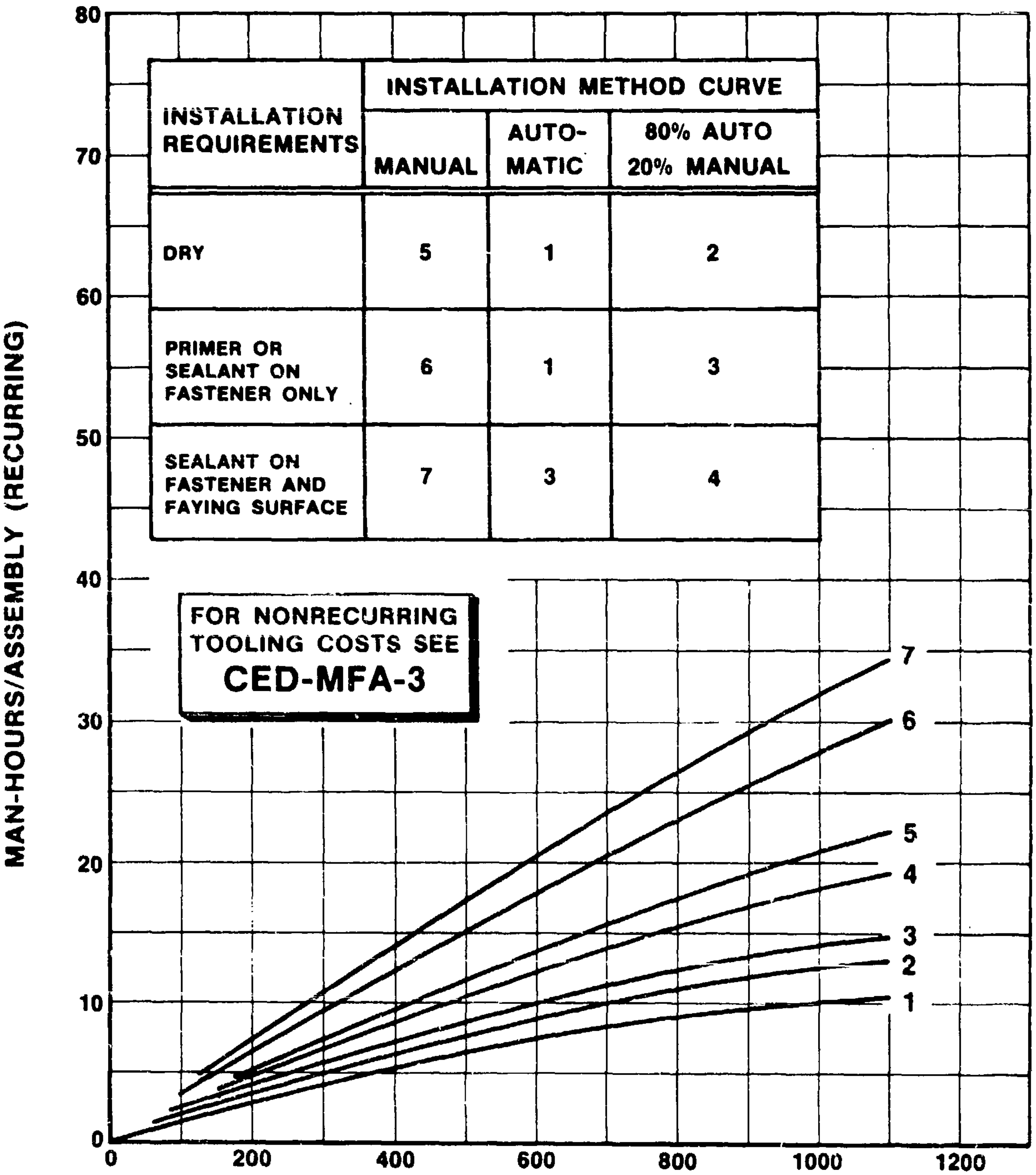
CDE-MFA-VII

EFFECT OF SEALING ON FASTENER INSTALLATION COST: ALUMINUM AND TITANIUM ASSEMBLIES



CDE-MFA-VIII

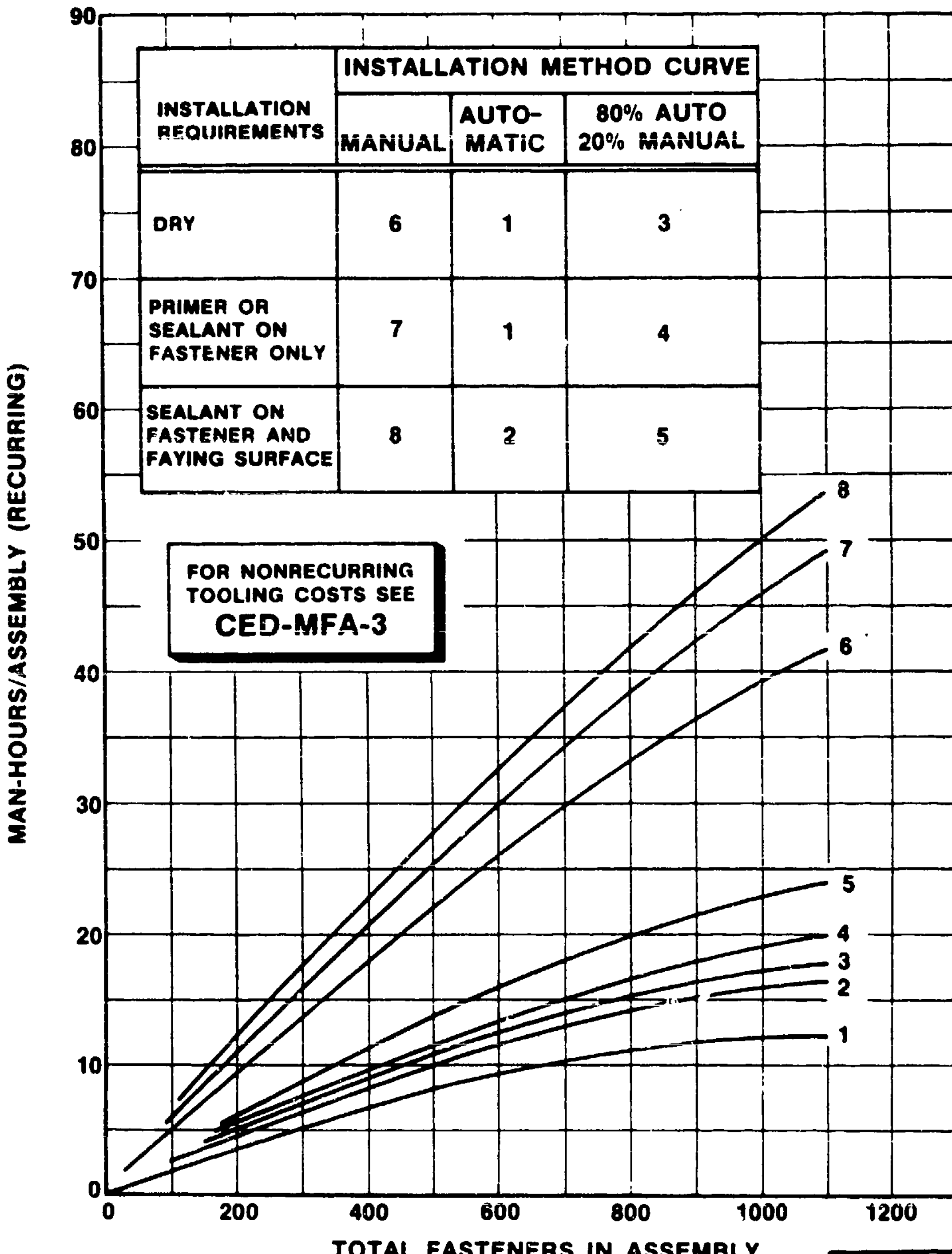
INSTALLATION COSTS FOR ALUMINUM RIVETS



INSTALLATION REQUIREMENTS	INSTALLATION METHOD CURVE		
	MANUAL	AUTO-MATIC	80% AUTO 20% MANUAL
DRY	5	1	2
PRIMER OR SEALANT ON FASTENER ONLY	6	1	3
SEALANT ON FASTENER AND FAYING SURFACE	7	3	4

CED-MFA-1

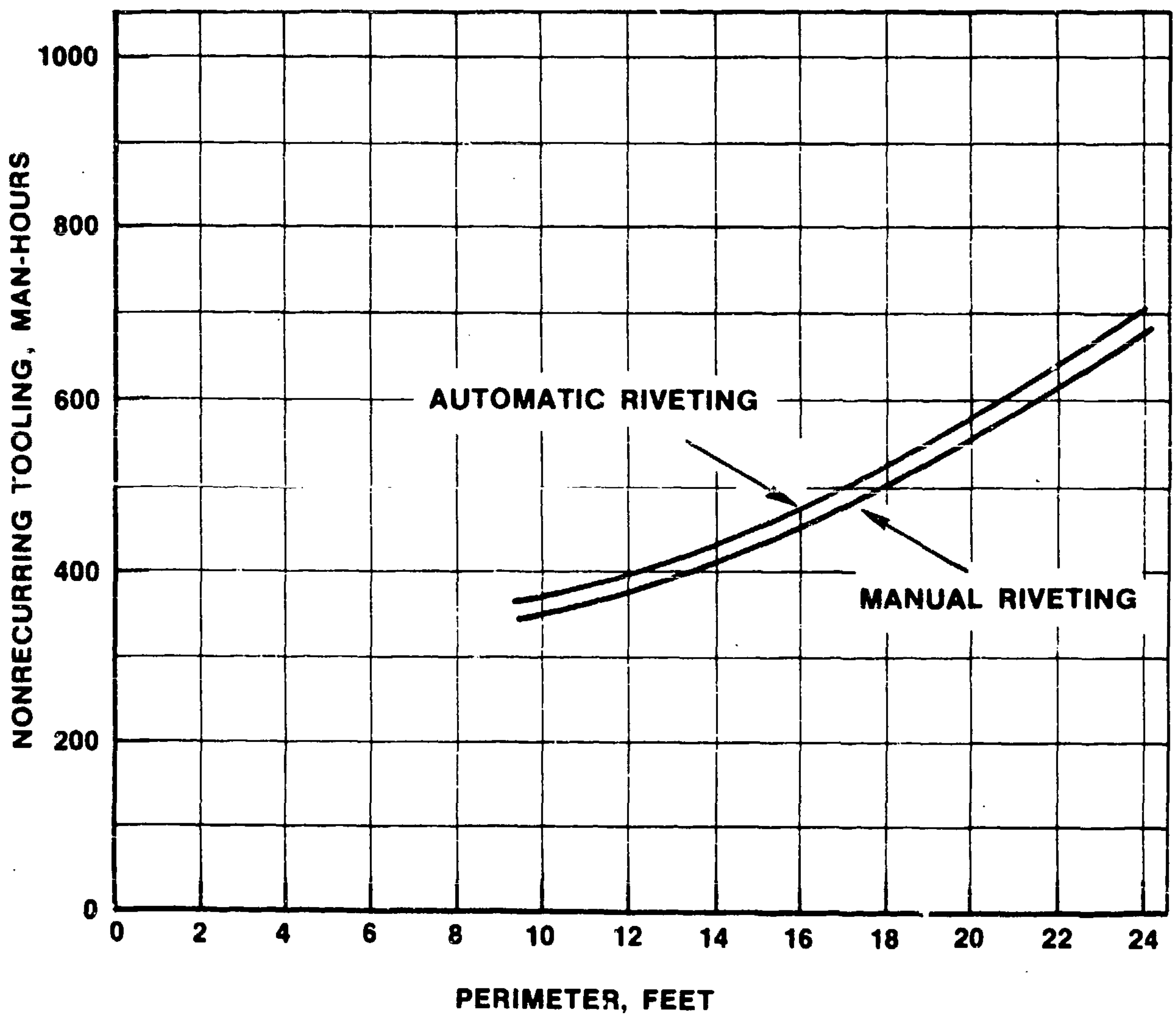
INSTALLATION COSTS FOR TITANIUM RIVETS



INSTALLATION REQUIREMENTS	INSTALLATION METHOD CURVE		
	MANUAL	AUTO-MATIC	80% AUTO 20% MANUAL
DRY	6	1	3
PRIMER OR SEALANT ON FASTENER ONLY	7	1	4
SEALANT ON FASTENER AND FAYING SURFACE	8	2	5

CED-MFA-2

NONRECURRING TOOLING COST FOR ALUMINUM AND TITANIUM ASSEMBLIES



CED-MFA-3

4.2.5 Ground Rules for Mechanically Fastened Assembly Section

The following General and Detailed Ground Rules for the Mechanically Fastened Assembly Section were developed to establish the scope of the data required and to establish guidance to MC/DG application. Ground rules are necessary and important as they promote understanding, ensure consistency, uniformity, and accuracy in generating and integrating data into the formats.

4.2.5.1 General Ground Rules

The general ground rules are categorized under the following major groupings:

(a) First-Level Mechanically Fastened Assemblies (MFA)
(b) Materials
(c) Assembly Methods
(d) Facilities
(e) Data Generation - Recurring Costs
(f) Data Generation - Nonrecurring Costs
(g) Test and Evaluation of Data
(h) Support Function Modifiers.

(a) First-Level Mechanically Fastened Assemblies (MFA)

(1) The MFA were selected to provide, where possible, data for more than one manufacturing assembly method to enable the designer to select the most cost-competitive method in trade-off studies by making cost comparisons.

(2) The assemblies selected are representative of common first-level structural assemblies required in both small and large aircraft. The majority of discrete parts utilized in these assemblies was selected from the Demonstration Section for "Sheet Metal Aerospace Discrete Parts", to form the foundation so that the designer can modify the part, as required, to achieve

the desired structural foundation and configuration. The assemblies selected were an avionics bay panel, a fuselage panel with a cutout, and a fuselage door assembly.

(3) Drawings were developed defining the selected assemblies in the required detail to conduct the cost estimating analysis.

(b) Materials

(1) The materials selected for the assemblies are:

- Aluminum - 2024
- Titanium - 6A1-4V.

(2) Raw materials and fastener costs are not included in the MC/DG formats for MFA but were addressed in the Fuselage Shear-Panel Trade-Off Studies.

(3) The material cost for the tooling was not included.

(c) Assembly Methods

(1) Only conventional methods of assembly were evaluated to assemble the parts.

(2) A production environment was assumed for the selected assemblies.

(3) To generate an effective manufacturing man-hour data base for each selected assembly, the operational sequence for the applicable manufacturing technologies was established reflecting the most economical procedure. The operational sequence was standardized then used by each team member, as the standard, to determine the base assembly cost. The operational sequences are indicated in Appendix E.

(4) Nonrecurring tooling costs (NRTC) for the manufacture of the various assemblies were provided on the Data Collection Forms.

(d) Facilities

(1) Only conventional or standard manufacturing facilities available in the airframe industry were considered.

(e) Data Generation - Recurring Costs

(1) Recurring man-hour data were generated for the complete assembly process to include all hands-on-factory direct labor operations from initial preparation for jig loading, drilling, and fastener installation, to storage for the next assembly phase.

(2) A base cost was generated for each assembly type. This base part was configuration IIa-1-size A (24 in x 36 in) avionics panel assembly with 100 percent automatic installation of fasteners common to skin and substructure.

(3) Designer-influenced cost elements (DICE) were treated as separate cost elements over and above the base assembly cost.

(4) The quantity for which the base assembly cost was determined was unit 200.

(5) Man-hours associated with DICE and other cost drivers were identified.

(6) The data were represented in man-hours.

(7) Assembly time consists of the direct man-hours to set up and complete the assembly operation.

(8) Recurring tooling costs (tool maintenance, planning, etc.) were not included.

(9) In developing cost data for assemblies, the participating companies used common, but proprietary, learning curves.

(10) The assembly man-hours, as derived by each airframe company, were normalized by BCL to reflect an industry team average value for each assembly.

(11) For proprietary reasons, realization factors, including personal fatigue and delay (PF&D), individual company standards, and other business-sensitive information employed at team member companies were not included in the analysis or on the data sheets or MC/DG formats.

(f) Data Generation - Nonrecurring Costs

(1) Tool fabrication man-hours were developed for each assembly type. Tool design and tool planning man-hours were not included.

(2) The cost of production assembly tooling was restricted to contract or project tools only.

(3) Nonrecurring tooling costs (NRTC) generated by the team companies were normalized by BCL for presentation in the MC/DG formats for MFA.

(g) Test and Evaluation of Data

(1) Test and confirmation of the formats and integrated data were accomplished by two team members. Each of the remaining three team members was provided with the data inserted on the MC/DG formats. In order to gain confidence and ensure the validity of the formatted data, the selected configurations were submitted to cost-estimators in other team companies. These data were then compared to the formatted data generated and evaluated to assess its credibility. Any anomalies were resolved and modifications incorporated, if appropriate.

(h) Support Function Modifiers

(1) Additional efforts other than factory labor, such as quality control and assurance, manufacturing engineering, and planning, were excluded from the assembly man-hour data supplied to BCL. These modifiers may be included later by MC/DG airframe company users.

4.2.5.2 Detailed Ground Rules

(1) Manufacturing assembly methods evaluated:

- Manual installation--impact of squeeze
- ~~Automatic installation--manual positioning.~~

(2) Fastener types evaluated:

- Upset rivets
  - Aluminum panel--AD rivets
  - Titanium panels--bitmetallic titanium rivets
- Pins
  - Titanium
- Collar
  - Aluminum panel--aluminum collar
  - Titanium panel--Cres collar.

(3) Flush fasteners were countersunk:

- No dimpling (skin gages selected were sufficiently thick to make dimpling unnecessary).

(4) Hole preparation accomplished by combination of drill and countersink.

(5) Tolerances--location and hole sizes corresponded to individual company standards.

(6) No shimming, fitup, or trimming of assembly.

(7) Rivet heads were as driven with no shaving required.

(8) No sealing required in baseline assemblies.

(9) No mastered hard points or interchangeability requirements.

(10) Manual assemblies were assumed to be deburred at mating surfaces.

(11) No finishing, e.g., paint or prime, required after driving fasteners.

(12) All assemblies were evaluated in aluminum and titanium materials.

APPENDIX C

MC/DG FORMAT AND GROUND RULE LOCATOR FOR AIRFRAMES AND ELECTRONICS

U.S. Air Force
ICAM "Manufacturing Cost/Design Guide" (MC/DG)

GROUND RULE LOCATOR

Contract Numbers:
- **F33615-75-C-5194**
- **F33615-77-C-5027**
- **F33615-79-C-5102**
- **F33615-85-C-5016**

MC/DG FOR AIRFRAMES

Report Type/Number	Report Date	Manufacturing Technology and Ground Rules	Page Numbers
Final Report No. AFWAL-TR-80-4115 Volume II	September 1980	• Sheet-Metal Aerospace Discrete Parts	1 to 7
		• Mechanically Fastened Assemblies	26 to 30
		• Advanced Composites Fabrication	37 to 44
Final Report No. AFWAL-TR-83-4033 Vol. V-Machining		• Machining	4.10-161 to 4.10-166
Final Report No. AFWAL-TR-88-4049		• Composite Fabrication	A-1 to A-9
		• Mechanically Fastened Assembly	B-1 to B-9
		• Superplastic Forming	C-1 to C-7

U.S. Air Force
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GROUND RULE LOCATOR

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- F33615-79-C-5102
- F33615-85-C-5016

MC/DG FOR AIRFRAMES

Report Type/Number	Report Date	Manufacturing Technology and Ground Rules	Page Numbers
Interim Report No. IR 4502/9-II	2 June 1980	• Test, Inspection and Evaluation (TI&E)	
		- Sheet Metal Parts	A-1 to A-5
		- Mechanically Fastened Assemblies	A-6 to A-9
		- Advanced Composites Fabrication	A-10 to A-13
		- Machining	A-14 to A-18
		• Castings (Includes Castings TI&E)	A-19 to A-25
Interim Report No. IR 4502/9-VIII	November 1981	• Forgings	86 to 91
		• Extrusions	92 to 98

U.S. Air Force

ICAM "Manufacturing Cost/Design Guide" (MC/DG)

FORMAT LOCATOR

Contract Numbers:
- F33615-75-C-5194
- F33615-77-C-5027
- F33615-79-C-5102
- F33615-85-C-5016

MC/DG FOR AIRFRAMES

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Final Report No. AFML-TR-76-227	December 1976	CONCEPTUAL FORMATS		
		• Forgings	-	118-148
		• Castings	-	160-183
		• Machining	-	191-201
		• Chemical Milling	-	206-220
		• Surface Texture and Tolerances	-	236-245
		• Metal Forming	-	253-267
		• Fiberglass Laminates	-	270-292
		• Surface Treatment	-	298-302
		• Welding	-	311-318
		• Adhesive Bonding	-	324-344
		• Mechanically Fastened Assemblies	-	347-357
		• Weld-Bonding	-	361-365
		• Diffusion Bonding	-	373-379

U.S. Air Force
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Contract Numbers:

- **F33615-75-C-5194**
- **F33615-77-C-5027**
- **F33615-79-C-5102**
- **F33615-85-C-5016**

MC/DG FOR AIRFRAMES

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Final Report No. AFWAL-TR-80-4115 Volume I	September 1980	PUBLICATION FORMATS		
		• Sheet-Metal Fabrication Lowest Cost Processes		
		- Aluminum	CED-A-1 to CED-A-24	81-104
		- Titanium	CED-T-1 to CED-T-9	108-116
		- Steel	CED-S-1 to CED-S-10	120-129
		- Designer-Influenced Cost Elements (DICE)	DICE-0 to DICE-13	133-146
		• Comparison of Manufacturing Technologies for Sheet-Metal Aerospace Discrete Parts	CDE-P-I to CDE-P-III	150-152
		• Comparison of Structural Sections for Sheet-Metal Aerospace Discrete Parts	CDE-M-I and CDE-M-II	156 & 157
			CDE-M-1 to CDE-M-15	158-172
		• Mechanically Fastened Assemblies	CDE-MFA-I to CDE-MFA-VIII	193-200
			CED-MFA-1 CED-MFA-3	204-206

U.S. Air Force
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- F33615-77-C-5027
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- F33615-85-C-5016

MC/DG FOR AIRFRAMES

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Final Report No. AFWAL-TR-80-4115 Volume I	September 1980	PUBLICATION FORMATS		
		• Advanced Composites Fabrication		
		- Graphite/Epoxy	CDE-G/E-I to CDE-G/E-VII	225-231
			CED-G/E-1 to CED-G/E-12	235-246
		- Designer Influenced Cost Elements (DICE)	DICE-G/E-1 to DICE-G/E-6	250-255
Final Report No. AFWAL-TR-83-4033 Vol. V-Machining	March 1985	• Machining		
		- Cost Hazards		4.10-26 to 4.10-28
		- Cost Driver Effects	CDE-M/C-I to CDE-M/C-XVII	4.10-37 to 4.10-53
		- Cost Estimating Data	CED-M/C-1 to CED-M/C-66	4.10-55 to 4.10-122
		- General Machining Features	CED-M/C-I to CED-M/C-XXIII	4.10-123 to 4.10-146
		- Nonrecurring Costs	NRC-M/C-1 to NRC-M/C-13	4.10-147 tO 4.10-160

U.S. Air Force
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FORMAT LOCATOR

Contract Numbers:
- **F33615-75-C-5194**
- **F33615-77-C-5027**
- **F33615-79-C-5102**
- **F33615-85-C-5016**

MC/DG FOR AIRFRAMES

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Final Report No. AFWAL-TR-88-4049	May 1989	• Composite Fabrication		
		- Cost Driver Effects (Resin)	CDE-CR-IA to CDE-CR-VIIA	5-9 to 5-15
		- Cost Driver Effects (Configuration)	CDE-C/E-I to CDE-C/E-XII	5-16 to 5-27
		- Cost Driver Effects (TI&E)	CDE-TI&E-C/E-I to CDE-TI&E-C/E-V	5-28 to 5-32
		- Cost Estimating Data (Lineal Shapes)	CED-C/E-L1 to CED-C/E-L34	5-34 to 5-67
		- Cost Estimating Data (Lineal Shapes/TI&E)	CED-TI&E-C/E-L1 to CED-TI&E-C/E-M2	5-68 to 5-79
		- Cost Estimating Data (Panels)	CED-C/E-P1 to CED-C/E-P20	5-81 to 5-100
		- Cost Estimating Data (Panels/ TI&E)	CED-TI&E-C/E-P1 to CED-TI&E-C/E-P8	5-110 to 5-117
		- Cost Estimating Data (Shear Webs)	CED-C/E-W1 to CED-C/E-W16	5-124 to 5-139
		- Cost Estimating Data (Shear Webs/ TI&E)	CED-TI&E-C/E-W1 to CED-TI&E-C/E-W12	5-140 to 5-151
		- Cost Estimating Data (Assembly)	CED-C/E-A1 to CED-C/E-A3	5-153 to 5-155
		- Designer Influenced Cost Elements (Panels)	DICE-C/E-1 to DICE-C/E-9	5-101 to 5-109
		- Designer Influenced Cost Elements (TI&E - Panels)	DICE-TI&E-C/E-1 to DICE-TI&E-C/E-4	5-119 to 5-122

U.S. Air Force
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FORMAT LOCATOR

Contract Numbers:
- **F33615-75-C-5194**
- **F33615-77-C-5027**
- **F33615-79-C-5102**
- **F33615-85-C-5016**

MC/DG FOR AIRFRAMES

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Final Report No. AFWAL-TR-88-4049 (Continued)	May 1989	• Mechanically Fastened Assembly		
		- Cost Driver Effects	CDE-MFA-I to CDE-MFA-XXII	7-8 to 7-29
		- Cost Estimating Data (Aluminum)	CED-MFA-1,2,5,6, 7,10 & 12	7-30,7-31 7-34 to 7-36,7-39 & 7-41
		- Cost Estimating Data (Titanium)	CED-MFA-3,5,8,9, 13 & 15	7-32,7-34, 7-37,7-38, 7-42 & 7-44
		- Cost Estimating Data (TI&E - Aluminum)	CED-MFA-16,18 & 19	7-45,7-47 7-48
		- Cost Estimating Data (TI&E - Titanium)	CED-MFA-17 & 19	7-46 & 7-48
		• Superplastic Forming/Diffusion Bonding (SPF/DB)		
		- Cost Driver Effects	CDE-SPF-I to CDE-SPF-XXXVII	6-17 to 6-53
		- Cost Estimating Data	CED-SPF-1 to CED-SPF-13	6-54 to 6-66
		- Test, Inspection & Evaluation (TI&E)	CED-SPF-14 to CED-SPF-24	6-67 to 6-77

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Contract Numbers:
- F33615-75-C-5194
- F33615-77-C-5027
- F33615-79-C-5102
- F33615-85-C-5016

MC/DG FOR AIRFRAMES

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Interim Report No. IR 4502/9-II	2 June 1980	DRAFT FORMATS		
		• Test, Inspection and Evaluation (TI&E)		
		– Advanced Composites Fabrication -- Graphite/Epoxy	CED-G/E-TI&E-1 to CED-G/E-TI&E-12	35 to 46
		-- Designer-Influenced Cost Elements	DICE-G/E-TI&E-1 to DICE-G/E-TI&E-7	47 to 53
		• Castings	CDE-1C to CDE-9C	64 and 71 to 78
			CED-1C to CED-16C	65 to 70 and 79 to 88
Interim Report No. IR 4502/9-V	March 1981	DRAFT FORMATS		
		• Castings	-	38 to 44
Interim Report No. IR 4502/9-VIII	November 1981	CONCEPTUAL FORMATS		
		• Forgings	-	A-11 to A-39
		• Extrusions	-	B-2 to B-15

U.S. Air Force
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FORMAT LOCATOR

Contract Numbers:
- F33615-75-C-5194
- F33615-77-C-5027
- F33615-79-C-5102
- F33615-85-C-5016

MC/DG FOR AIRFRAMES

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Interim Report No. IR 4502/9-IX	January 1982	PRE-PUBLICATION FORMATS		
		• Test, Inspection and Evaluation (TI&E)		
		- Sheet Metal		
		-- Aluminum	CED-TI&E-A-1 to CED-TI&E-A-24	
		-- Titanium	CED-TI&E-T-1 to CED-TI&E-T-9	
		-- Steel	CED-TI&E-S-1 to CED-TI&E-S-10	
		-- Designer Influenced Cost Elements (DICE)	DICE-TI&E-1 to DICE-TI&E-6	
		- Comparison of Manufacturing Technologies for Sheet-Metal Aerospace Discrete Parts	CDE-TI&E-P-I to CDE-TI&E-P-III	

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FORMAT LOCATOR

Contract Numbers:
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- **F33615-77-C-5027**
- **F33615-79-C-5102**
- **F33615-85-C-5016**

MC/DG FOR AIRFRAMES

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Interim Report No. IR 4502/9-IX	January 1982	PRE-PUBLICATION FORMATS		
		• Test, Inspection and Evaluation (TI&E)		
		- Comparison of Structural Sections for Sheet-Metal Aerospace Discrete Parts	CDE-TI&E-M-I to CDE-TI&E-M-III	
			CED-TI&E-M-1 to CED-TI&E-M-9	
		- Mechanically Fastened Assemblies	CED-TI&E-MFA-1 to CED-TI&E-MFA-3	
			DICE-TI&E-MFA-1	
		- Advanced Composites Fabrication		
		-- Graphite/Epoxy	CDE-TI&E-G/E-I	
			CED-TI&E-G/E-1 to CED-TI&E-G/E-6	
			DICE-TI&E-G/E-1 to DICE-TI&E-G/E-4	

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FORMAT LOCATOR

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- F33615-77-C-5027
- F33615-79-C-5102
- F33615-85-C-5016

MC/DG FOR AIRFRAMES

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Interim Report No. IR 4502/9-IX	January 1982	PRE-PUBLICATION FORMATS		
		• Test, Inspection and Evaluation (TI&E)		
		- Machined Parts		
		-- Aluminum	CED-TI&E-MP-A-1 to CED-TI&E-MP-A-5	
		-- Titanium	CED-TI&E-MP-T-1 to CED-TI&E-MP-T-4	
		-- Steel	CED-TI&E-MP-S-1 to CED-TI&E-MP-S-4	
		-- Comparison of Materials	CED-TI&E-MP-M-1 to CED-TI&E-MP-M-5	
		-- Designer-Influenced Cost Elements (DICE)	DICE-TI&E-MP-1	
		- Raw Castings	CED-TI&E-C-1 to CED-TI&E-C-3	

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FORMAT LOCATOR

Contract Numbers:
- F33615-75-C-5194
- F33615-77-C-5027
- F33615-79-C-5102
- F33615-85-C-5016

MC/DG FOR AIRFRAMES

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Interim Report No. IR 4502/9-IX	January 1982	PRE-PUBLICATION FORMATS		
		• Castings		
		– Raw Castings	CDE-C-I to CDE-C-VII	
			CED-C-1 to CED-C-6	
			DICE-C-1 to DICE-C-3	
		– Machining of Castings	CDE-MC-I to CDE-MC-III	
			CED-MC-1 to CED-MC-6	

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ICAM "Manufacturing Cost/Design Guide" (MC/DG)

FORMAT LOCATOR

Contract Numbers:
- F33615-75-C-5194
- F33615-77-C-5027
- F33615-79-C-5102
- F33615-85-C-5016

MC/DG FOR AIRFRAMES

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Interim Report No. IR 4502/9-IX	January 1982	DRAFT FORMATS		
		• Forgings	-	
		- Aluminum	-	
		- Titanium	-	
		- Steel	-	

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FORMAT LOCATOR

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- F33615-77-C-5027
- F33615-79-C-5102
- F33615-85-C-5016

MC/DG FOR AIRFRAMES

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Monthly Status Report No. 4	5 May 1980	DRAFT FORMATS		
		• Castings	1C to 25C	32 to 56
Monthly Status Report No. 21	3 November 1981	CONCEPTUAL FORMATS		
		• Forgings	-	A-11 to A-39
		• Extrusions	-	B-2 to B-15
Monthly Status Report No. 22	10 December 1981	CONCEPTUAL FORMATS		
		• Extrusions	-	A-1 and A-2

U.S. Air Force
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GROUND RULE LOCATOR

Contract Numbers:
- F33615-75-C-5194
- F33615-77-C-5027
- F33615-79-C-5102
- F33615-85-C-5016

MC/DG FOR ELECTRONICS

Report Type/Number	Report Date	Manufacturing Technology and Ground Rules	Page Numbers
Interim Report No. IR 4502/9-VIII	November 1981	• Electronics Fabrication, Assembly, and Test	66 to 72

U.S. Air Force
ICAM "Manufacturing Cost/Design Guide" (MC/DG)

FORMAT LOCATOR

Contract Numbers:
- F33615-75-C-5194
- F33615-77-C-5027
- F33615-79-C-5102
- F33615-85-C-5016

MC/DG FOR ELECTRONICS

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Interim Report No. IR 4502/9-V	March 1981	DRAFT FORMATS		
		• Electronics Fabrication, Assembly, and Test		
		- Interconnect, Insertion and Soldering Process	-	30-35
Interim Report No. IR 4502/9-VI	May 1981	DRAFT FORMATS		
		• Electronics Fabrication, Assembly, and Test		
		- Conceptual Design Phase	CDE-E-IA CDE-E-IIIB CDE-E-IVA	13-16
		- Interconnect, Insertion and Soldering Process	-	18-26

U.S. Air Force

ICAM "Manufacturing Cost/Design Guide" (MC/DG)

FORMAT LOCATOR

Contract Numbers:

- F33615-75-C-5194
- F33615-77-C-5027
- F33615-79-C-5102
- F33615-85-C-5016

MC/DG FOR ELECTRONICS

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Interim Report No. IR 4502/9-VII	August 1981	PRE-PUBLICATION FORMATS		
		• Electronics Fabrication, Assembly and Test		
		- Insertion Process: Printed Wiring Assembly (PWA)	CED-AD-1 to CED-AD-13	B-1 to B-13
		- Soldering Process: Printed Wiring Assembly (PWA)	CED-AD-I to CED-AD-XIII	C-1 to C-13
Interim Report No. IR 4502/9-VIII	November 1981	PRE-PUBLICATION FORMATS		
		• Electronics Fabrication, Assembly and Test		
		- Conceptual Design Phase	CDE-E-1 to CDE-E-VIB	31-65

U.S. Air Force

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Contract Numbers:
- F33615-75-C-5194
- F33615-77-C-5027
- F33615-79-C-5102
- F33615-85-C-5016

MC/DG FOR ELECTRONICS

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Monthly Status Report No. 12	26 January 1981	CONCEPTUAL FORMATS		
		• Electronics Fabrication, Assembly, and Test		
		– Conceptual Design Phase	-	A-3 to A-10
		– Detailed Circuit Design Phase	-	B-3 to B-11
		– Detailed Mechanical Design Phase	-	C-3 to C-10

U.S. Air Force

ICAM "Manufacturing Cost/Design Guide" (MC/DG)

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Contract Numbers:

- F33615-75-C-5194
- F33615-77-C-5027
- F33615-79-C-5102
- F33615-85-C-5016

MC/DG FOR ELECTRONICS

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Monthly Status Report No. 13	10 March 1981	PRELIMINARY FORMATS		
		• Electronics Fabrication, Assembly, and Test		
		– Conceptual Design Phase	CDE-E-I to CDE-E-V	24 to 36
		– Part Selection	-	A-1 to A-9
		– Interconnect Between Components or Assemblies	-	A-10 to A-15
		– Process Electrical or Mechanical	-	A-16 to A-21

U.S. Air Force

ICAM "Manufacturing Cost/Design Guide" (MC/DG)

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Contract Numbers:
- F33615-75-C-5194
- F33615-77-C-5027
- F33615-79-C-5102
- F33615-85-C-5016

MC/DG FOR ELECTRONICS

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Monthly Status Report No. 14	15 April 1981	DRAFT FORMATS		
		• Electronics Fabrication, Assembly, and Test		
		- Interconnect, Insertion and Soldering Process	-	10 to 15
Monthly Status Report No. 16	15 June 1981	DRAFT FORMATS		
		• Electronics Fabrication, Assembly, and Test		
		- Conceptual Design Phase	CDE-E-IA CDE-E-IIIB CDE-E-IVA CDE-E-IVC	9 to 13
		- Interconnect, Insertion and Soldering Process	-	18 to 26
Monthly Status Report No. 17	23 July 1981	DRAFT FORMATS		
		• Electronics Fabrication, Assembly and Test		
		- Insertion Process: Printed Wiring Assembly (PWA)	CED-AD-1 to CED-AD-13	A-1 to A-13
		- Soldering Process: Printed Wiring Assembly (PWA)	CED-AD-I to CED-AD-XIII	B-1 to B-13

U.S. Air Force
ICAM "Manufacturing Cost/Design Guide" (MC/DG)

FORMAT LOCATOR

Contract Numbers:
- F33615-75-C-5194
- F33615-77-C-5027
- F33615-79-C-5102
- F33615-85-C-5016

MC/DG FOR ELECTRONICS

Report Type/Number	Report Date	Manufacturing Technology and Format Development Stage	Format Number	Page Numbers
Monthly Status Report No. 18	August 1981	DRAFT FORMATS		
		• Electronics Fabrication, Assembly, and Test		
		- Part Selection	-	6 to 9
		- Built-In-Test Equipment (BITE)	-	14 and 15
Monthly Status Report No. 19	28 September 1981	DRAFT FORMATS		
		• Electronics Fabrication, Assembly, and Test		
		- Soldering and Insertion Process	-	7 to 10
Monthly Status Report No. 20	23 October 1981	DRAFT FORMATS		
		• Electronics Fabrication, Assembly, and Test		
		- Part Selection	CED-E-XX and CED-E-YY	11 and 17
		- Interconnect, Insertion and Soldering Process	-	12 to 16
		- Conceptual Design Phase	CDE-E-I to CDE-E-VIB	25 to 55

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