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VOLUME VII

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ICAM MANUFACTURING COST/DESIGN GUIDE

VOLUME VII—TECHNOLOGY TRANSFER SUMMARY

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MATERIALS LABORATORY
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AIR FORCE SYSTEMS COMMAND
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12 Sept 1984

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This technical report has been reviewed and is approved for publication.

Richard R. Preston — Sept 13 1984

RICHARD R. PRESTON, Capt., USAF — Date
Project Technical Manager
Computer Integrated Manufacturing Br.
Manufacturing Technology Division

FOR THE COMMANDER:

N G Tupper — 14 Sep 84

NATHAN G. TUPPER — Date
Chief
Computer Integrated Manufacturing Br.
Manufacturing Technology Division

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Computer Aided Manufacturing	Fuselage Panels	Extrusions
Manufacturing Cost	Sheet Metal Parts	Castings
Cost Drivers	Assemblies	Forgings
Design-to-Cost	Mechanical Fastening	Test, Inspection
Airframe Design	Advanced Composites	& Evaluation

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

The "Manufacturing Cost/Design Guide" (MC/DG) enables airframe and electronic designers to achieve lowest cost by conducting trade-offs between manufacturing cost and other design factors. When fully developed, the MC/DG will, for example, permit airframe designers, at all levels of the design process, to quickly perform cost-trade comparisons of manufacturing processes and structural performance/cost trade-offs on airframe components and subassemblies in metallic and composite materials.

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20. (Continued)

The first program, reported in AFML-TR-76-227, developed a model of the MC/DG, the contents, cost drivers, data requirements and designer-oriented formats for conventional and some emerging manufacturing technologies, and also an implementation plan.

The second program (Contract No. F33615-77-C-5027) consisted of four phases in which manufacturing man-hour data and designer-oriented formats were developed for "Sheet-Metal Aerospace Discrete Parts", "First-Level Mechanically Fastened Assemblies", and "Advanced Composite Fabrication". Further, structural performance/manufacturing cost trade-studies were conducted by designers in industry to demonstrate utilization of the manufacturing man-hour data developed in this program.

The data developed by the five participating aerospace companies were normalized by Battelle's Columbus Laboratories and the data plotted in designer-oriented formats. Data have been developed for base parts and discrete parts. The base part is a structural element in its simplest form and when modified with designer-influenced cost elements (DICE) such as joggles, cutouts, and heat treatment, a discrete part ready for assembly is obtained. Typical DICE analyzed for mechanically fastened assemblies are accessibility, material types, part and fastener counts, and sealing requirements. For composites, typical DICE are orientation and number of plies, overlaps, fiber mix, cutouts, and quality requirements.

The data are presented in the series of formats showing cost-driver effects (CDE) and cost-estimating data (CED) and have been evaluated in trade-offs on various fuselage panels designed in titanium, aluminum, and graphite/epoxy.

The third program (Contract No. F33615-79-C-5102) required the development of MC/DG sections on castings, forgings, extrusions, and test, inspection and evaluation (TI&E). Furthermore, as castings, forgings, and extrusions are normally machined prior to assembly in aerospace structures, data and formats were developed for the machining of typical discrete parts manufactured utilizing these methods. TI&E was included in the MC/DG as, in the case of certain materials such as graphite/epoxy and manufacturing methods such as castings, this can be a cost-driver that needs to be included in trade-off studies comparing various manufacturing methods.

The third program also required the development of an MC/DG for electronics fabrication, assembly, and TI&E. A series of typical discrete parts such as transistors, capacitors, diodes, and hybrids were analyzed and also, typical assemblies such as printed wiring boards. Hand, semiautomatic and automatic soldering and insertion processes were also analyzed. Furthermore, the manufacturing cost to meet typical reliability requirements in electronics is also presented to the designer for the selected discrete parts.

The fourth program required the development of a functional section of the MC/DG for machining of metals and also a section-by-section layout of a model of the MC/DG for utilization in conceptual design. The MC/DG for machining contains CDE formats for part size, material types/removal rates, tolerances, finishes, and hog-outs. The CED formats are presented in three groups showing machining features of frames, bulkheads, wing skins, beams, spars, ribs, stiffeners, and longerons; machining features of pins, bolts, bushings, inserts, sleeves, etc.; and also general machining features applicable to most machined airframe parts. The conceptual design model of the MC/DG draws on the formats developed under earlier programs where data is

20. (Continued)

presented which influences material selection, configuration type, and other considerations at this phase where significant leverage exists to reduce cost.

This volume provides an overview of course contents, press releases, executive summary brochure, press accounts, presentations and briefings given on the MC/DG to accelerate technology transfer of the MC/DG program results. A discussion of the organization of the coalition or team is also included as this was a factor in achieving rapid utilization of the MC/DG by design staff of the aerospace member companies.

This project is reported in a six-volume Final Technical Report as follows:

VOLUME I. **User's Manual - Airframes Volume 1**
Contains:
- **Utilization Procedures**
- **Trade-Off Study Examples**
- **MC/DG Sections for:**
  - **Sheet Metal**
  - **Mechanically Fastened Assembly**
  - **Composites**

VOLUME II. **User's Manual - Airframes Volume 2**
Contains:
- **MC/DG Sections for:**
  - **Extrusions**
  - **Castings**
  - **Forgings**

VOLUME III. **User's Manual - Airframes Volume 3**
Contains:
- **MC/DG Test, Inspection & Evaluation Section for:**
  - **Sheet Metal**
  - **Mechanically Fastened Assemblies**
  - **Castings**
  - **Forgings**
  - **Machining**
  - **Composites**

VOLUME IV. **User's Manual - Electronics Volume 1**
Contains:
- **Design Process Descriptions**
- **Conceptual Design Section for:**
  - **New Technology**
  - **Number of Assemblies**
  - **Common Functions**
  - **Digital Design**
  - **Built-in Test**
  - **Part Count**
  - **Part Selection**
    - -- **Reliability**
    - -- **Package**
- **Detail Design Section for:**
  - **Mechanization**
  - **Processes**
  - **Insertion Process**
  - **Soldering Process**

VOLUME V. User's Manual - Airframes Volume 4

VOLUME VI. Project Summary

VOLUME VII. Technology Transfer Summary

FOREWORD

This Manufacturing Cost/Design Guide document covers the work performed under Air Force Contract F33615-79-C-5102 from 1 October 1979 through 31 August 1984. The contract is sponsored by the Computer Integrated Manufacturing Branch, Manufacturing Technology Division, Materials Laboratory, Air Force Wright Aeronautical Laboratories. The ICAM Project Manager is Capt. Richard R. Preston. In previous phases, the following Air Force personnel directed the program; Mr. John R. Williamson, Capt. Dan L. Shunk, and Capt. Steven R. LeClair.

The organization of the program is comprised of a coalition of seven participating companies with Battelle's Columbus Laboratories (BCL) as the prime contractor. Mr. Bryan R. Noton is the BCL Program Manager. The other participating companies of the coalition are listed below:

Airframe Company Subcontractors	Program Managers
General Dynamics Corporation, Fort Worth Division	Ben E. Kaminski Phillip M. Bunting
Grumman Aerospace Corporation	Vincent T. Padden Anthony J. Tornabe
Honeywell, Incorporated	Robert R. Remski
Lockheed-California Company	Anthony J. Pillera John F. Workman
Metcut Research Associates, Inc.	Robert L. Carlton T. Raj Aggarwal
Northrop Corporation, Aircraft Group	John R. Hendel Al P. Langlois
Rockwell International Corporation, North American Aircraft Operations	Ralph A. Anderson
Rockwell International Corporation, Avionics & Missiles Group, Collins Avionics Division	John G. Vecellio
In Critique Mode: Boeing Commercial Airplane Company	David Weiss Peter H. Bain

Note that the number and date in the upper right corner of each page of this document indicates that the document has been prepared according to ICAM's Configuration Management Life Cycle Documentation requirements for Configuration Items (CIs).

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SECTION 1.0
INTRODUCTION

1.1 Project 4502 Objectives

The "Manufacturing Cost/Design Guide" (MC/DG) Study was initiated by the Air Force to further aid in the attainment of the objectives of the Integrated Computer-Aided Manufacturing (ICAM) program.

The ICAM objectives are to:

1) Reduce aerospace systems cost
2) Provide leadership to industry
3) Increase competence in aerospace manufacturing
4) Provide for ICAM technology transfer
5) Improve mobilization position of the USAF
6) Demonstrate the capability for a totally integrated manufacturing system.

The Project 4502 Objectives are directed at reducing the cost of both airframes and electronics. The specific objectives are to:

1) Provide designers with urgently needed, quantitative cost comparisons of manufacturing processes that are quick and simple to use in the design process
2) Emphasize design orientation of MC/DG formats and manufacturing man-hour data for use at all phases of the design process, i.e., preliminary and detail design, therefore, increasing emphasis on cost as a vital design parameter
3) Enable additional and more extensive manufacturing cost trade-offs to be conducted on aerospace airframe and electronic component fabrication and assembly
4) Indicate cost saving potential of emerging materials and manufacturing methods to accelerate the transfer of these technologies to production hardware
5) Guide the designer to the lowest cost design concepts and manufacturing processes early in the design phase
6) Identify cost-driving manufacturing operational sequences and, hence, provide targets for future computer-integrated manufacturing (CIM) efforts.

1.2 Document Identification

This volume documents the material developed to facilitate the dissemination of the data and concepts developed under ICAM Project Priority 4502 "Manufacturing Cost/Design Guide" Data Development for Airframes and Electronics.

This technology transfer material provides executive overviews of the ICAM "Manufacturing Cost/Design Guide (MC/DG)" data, designer-oriented formats and methodologies developed, and the utilization and benefits to industry and the Air Force. The examples of the various presentations can be used for seminar material for introducing the MC/DG. For example, a briefing, included in Appendix F, provides the background, purpose, organization, examples of data and formats, and a utilization example on an integrated airframe design problem and industry application.

1.3 Functional Description of Document

This volume documents the technology transfer materials developed under ICAM Project Priority 4502; ICAM "Manufacturing Cost/Design Guide" Data Development for Airframes and Electronics. Appendices provide examples of the individual publications.

The following document request order form may be used to request copies of the reports prepared under this program.

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DOCUMENT REQUEST ORDER FORM

SUBMIT DOCUMENT REQUESTS TO: **AFWAL/MLTC**
ICAM Program Library
Wright-Patterson AFB, OH 45433

WITH COPY TO: **Bryan R. Noton**
Battelle's Columbus Laboratories
505 King Avenue, Columbus, Ohio 43201

VOLUME NUMBER AND MANAGEMENT NUMBER	TITLE OF DOCUMENT	INDICATE (✓) DOCUMENT REQUESTED
AFWAL-TR-80-4115 (VOLUMES I, II & III)	ICAM "MANUFACTURING COST/DESIGN GUIDE" (DEMONSTRATION SECTIONS AND COMPUTERIZATION)	
AFWAL-TR-83-4033 (VOLUMES I, II & III)	MC/DG USER'S MANUAL FOR AIRFRAMES	
AFWAL-TR-83-4033 (VOLUME IV)	MC/DG USER'S MANUAL FOR ELECTRONICS	
AFWAL-TR-83-4033 (VOLUME V)	MC/DG USER'S MANUAL FOR AIRFRAMES	
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SECTION 2.0
ACHIEVEMENT OF TECHNOLOGY TRANSFER

2.1 Activities to Achieve Technology Transfer

To shorten the time-span in achieving the utilization of research results, it is desirable to provide the information on cost-drivers and cost avoidance, in a number of ways such as follows:

- Team or Coalition Organization
- Courses and Seminars
- Press Releases by Air Force and Contractor and Accounts in Press
- Presentations at National Conferences (trends and no hard data provided)
- Briefings.

These activities are described, or, where appropriate, listed below.

2.1.1 Team or Coalition Organization

Important advantages are evident in the development of manufacturing man-hour data by a team of major aerospace companies and some of the advantages facilitate technology transfer. The principal advantages are as follows:

- Provides a cross-section of small and large aircraft for the entire industry; both military and commercial
- Present team members have large interface with all levels of designers. Therefore, the MC/DG has been transitioned more rapidly to the design process than customary in industry
- Team draws on each company's expertise related to specific manufacturing facilities which favorably influences the viability of the results
- Team has an extensive source of available data for use in verifying calculated data and therefore a broad base is provided from which to develop manufacturing data for the MC/DG functional sections
- Team provides the required base for deriving average industry data
- Team provides confidence to data and formats for designer use, rather than a parochial point of view of a single company

- Team has established ground rules and methodologies to develop manufacturing man-hour data and designer-oriented formats
- Team provides a broad base for emerging technologies and utilization of Air Force manufacturing technology (MT) program results, e.g., superplastic formed/diffusion bonded titanium.

As indicated in the Foreword to this volume, seven major aerospace companies participated in this team. At each company, between six and ten persons were involved in data development and also the test and evaluation of the final averaged data to be presented in the manufacturing technology function sections of the MC/DG. At the proposal stages, each company agreed to provide highly experienced staff from the different disciplines required to develop documents which will be approved by management and subsequently accepted, with enthusiasm by designers to not only minimize design and manufacturing costs, but also to substantially improve design/manufacturing interaction. The staff provided by the companies to work on the MC/DG were highly qualified and in some cases posessed 30-40 years of experience. The staff represented the following areas:

- Management (concurrence necessary to assure MC/DG utilization)
- Engineering (design and support)
- Manufacturing (fabrication, tooling, and quality control)
- Cost-Estimating
- Procurement (materials, parts, and equipment).

Prior to development of data and with Air Force approval, a survey was conducted in many large aerospace companies and 84 responses were received. The surveys and workshops held in 1976, at the initial industry briefing at Battelle's Columbus Laboratories resulted in the following criteria for development of the cost-driver effect (CDE) and cost-estimating data (CED) formats to achieve designer usage:

- Emphasize cost drivers
- Be simple to use
- Use designer language
- Instill confidence
- Be economical
- Be accessible
- Be maintainable.

2.1.2 Report Distribution Within Team

Throughout the accomplishment of the MC/DGs for Airframes and Electronics, comprehensive monthly reports have been prepared and distributed, not only to the Project Engineers in industry, but also to their managers. Management has therefore, on a monthly basis, had the opportunity to follow the development of the MC/DGs. This has stimulated the interest of management, frequently at Vice-President level and management has subsequently provided encouragement and support to the MC/DG groups within the aerospace company. Furthermore, the detailed monthly reports, with the latest data served as a reference document for each program manager and thus circumvented problems which would otherwise be possible due to the large numbers of memos, letters, tables of data, etc., that must be generated on such a program. The result was that the team-member companies were, in some cases, utilizing the data and formats in design well ahead of the distribution dates for the interim and final reports.

2.1.3 Courses and Seminars

A course has been prepared on "Design and Manufacturing-to-Lowest Cost" and during the 1982-83 time-frame, this course has been given to various groups. The outline of this course is included as Appendix A. The course can be tailored as executive overviews, i.e., 1½-3 hours, as a one-day intensive course or as a three-day course. It is not only suited to experienced designers, but has been found to be particularly informative for unseasoned designers that have not been trained in meeting design requirements at the minimum possible cost. A major objective of this course is to put designers on the lowest cost track in utilizing both conventional and some emerging technologies.

The executive overviews of the course have been given to:

- Northrop Corporation's Aircraft Group
- Goodyear Aerospace Corporation, Akron, Ohio, and Tempe, Arizona.

Three one-day courses have been given at Wright-Patterson Air Force Base and was attended by approximately 280 attendees.

The three-day course has been given to:

- General Dynamics Corporation, Convair Division, and,
- Rockwell International, North American Aircraft Operations, Los Angeles.

2.1.4 Press Releases and Accounts in Press

At various stages in the development and acceptance of the data and formats by designers in industry, it was found to be appropriate and timely to issue press releases, with, in the case of Battelle's Columbus Laboratories, Air Force approval. These press releases indicate, for example, actual and projected cost savings. These press releases have resulted in several accounts in the press and these also follow.

Press Releases

1. "Designer's Guide With A New Approach", United States Air Force, Aeronautical Systems Division, Office of Public Affairs (ASD/PA), Wright-Patterson Air Force Base, Ohio, 30 June 1982.

2. Battelle's Columbus Laboratories, 4 March 1983.

3. Battelle's Columbus Laboratories, 25 May 1984.

Copies of the Press Releases are included in Appendix B.

Accounts in Press

1. "AF Developing Guide for Reducing Airframe Costs", Defense/Space Business Daily, 8 January 1979.

2. "Battelle/Industry Team Trying to Trip Aircraft Manufacturing Costs", Aerospace Daily, 3 January 1980.

3. "Battelle/Industry Team Trying to Reduce Design Costs", The Weekly of Business Aviation, 7 January 1980.

4. Software Digest, 10 January 1980.

5. Technical Survey Weekly, 12 January 1980.

6. Aerospace Project Focuses on Manufacturing Costs, February 1980.

7. "Aircraft Manufacturing Costs Guide", Tooling and Production Business Briefs, 22 February 1980.

8. ICAM "Manufacturing Cost/Design Guide" -- The MC/DG in Education, The ICAM Program Report, Integrated Computer-Aided Manufacturing Branch (AFWAL/MLTC), July 1981.

9. Expansion of ICAM "Manufacturing Cost/Design Guide" (MC/DG), The ICAM Program Report, Integrated Computer-Aided Manufacturing Branch (AFWAL/MLTC), October 1981

10. Potential Payoff of Utilizing ICAM "MC/DG For Electronics", The ICAM Program Report, Integrated Computer-Aided Manufacturing Branch (AFWAL/MLTC), March 1982.

11. "Designer's Guide With A New Approach", The ICAM Program Report, Integrated Computer-Aided Manufacturing Branch (AFWAL/MLTC), August 1982

12. Business Aviation, 23 August 1982.

13. "Guide Available to Determine Airframe, Electronics Costs", Aviation Daily, 8 September 1982.

14. "Guide Speeds Manufacturing Cost Studies", Test and Measurement World Monthly, October 1982.

15. "Guide for Designers Helps Reduce Manufacturing Costs", Production Engineering Monthly, October 1982.

16. "Guide Cuts Costs", Electronic Packaging and Production, October 1982.

17. "Industrial Processes", Battelle Memorial Institute, 1983 Annual Report.

18. "Designer's Guide With A New Approach -- ASD", TIG Brief, The Inspector General, 4 April 1983.

19. "ICAM Success Recognized by OSD", The ICAM Program Report, Integrated Computer-Aided Manufacturing Branch (AFWAL/MLTC), October 1983.

2.1.5 Presentations

Approximately 38 presentations, many invited, have been given on the Air Force ICAM "Manufacturing Cost/Design Guide". The following presentations were frequently given by Mr. Bryan Noton, Program Manager, MC/DG. Those presentations which were co-authored with Air Force and industry project engineers on the guide are also indicated below.

1. "U.S.A.F. Manufacturing Cost/Design Guide for Airframes", Co-authored with Mr. J. R. Williamson, Aircraft Systems & Technology Conference, sponsored by the American Institute of Aeronautics and Astronautics (AIAA), Los Angeles, California, August 1975, 16 pp.

2. "The USAF/AFML Manufacturing Cost/Design Guide", Workshop on Increased Productivity, sponsored by the Aerospace Industries Association of America, Los Angeles, California, 6-7 April 1976.

3. Air Force ICAM "Manufacturing Cost/Design Guide", Co-authored with Capt. Dan L. Shunk, Materials Laboratory, Wright-Patterson Air Force Base, Aircraft Systems and Technology Meeting, American Institute of Aeronautics and Astronautics (AIAA), Dallas, Texas, 27-29 September 1976.

4. "Airframe Project Opportunities to Reduce Cost", Army Aviation Manufacturing Technology Conference, Palo Alto, California, 7-11 November 1977.

5. "Selection of Manufacturing Processes", Seminar on Designing for Low Cost Manufacturing, Sponsored by Society of Manufacturing Engineers (SME), Dayton, Ohio, 15-17 November 1977.

6. "Manufacturing Cost/Design Guide (MC/DG)", Co-authored with Capt. Dan L. Shunk, Integrated Computer-Aided Manufacturing Branch, 23rd National Symposium and Exhibition, sponsored by Society for the Advancement of Material and Process Engineering (SAMPLE), Anaheim, California, 2-4 May 1978, pp. 61-93.

7. Air Force "Manufacturing Cost/Design Guide", Co-authored with Capt. D. L. Shunk, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Fourth DoD/NASA Conference on Fibrous Composites in Structural Design, San Diego, California, 13-17 November 1978.

8. "Air Force - Manufacturing Cost/Design Guide - Its Objectives and Potential", Fifth Structural Composite Manufacturing Applications Conference, Society of Manufacturing Engineers (SME), St. Petersburg, Florida, 5-7 December 1978.

9. "Manufacturing Cost/Design Guide for Metallic and Composite Materials", Department of Engineering Sciences, University of Florida, Gainesville, Florida, 26 January 1979.

10. "Air Force Manufacturing Cost Design Guide (MC/DG)" Co-authored with Capt. D. L. Shunk, 38th Annual Conference of the Society of Allied Weight Engineers (SAWE), New York, N.Y., 7-9 May 1979. SAWE Paper No. 1291, 53 pp.

11. "Manufacturing Cost/Design Guide", Symposium on Advanced Composites: Design and Applications", Mechanical Failures Prevention Group (MFPG), Sponsored by National Bureau of Standards, Office of Naval Research, Naval Air Development Center, Department of Energy, and NASA/Goddard Space Flight Center, Gaithersburg, Maryland, 23-25 May 1979.

12. "Manufacturing Cost/Design Guide (MC/DG)", Air Force ICAM Industry Days, Materials Laboratory (AFWAL/ML), Wright-Patterson Air Force Base, Ohio, and Society of Manufacturing Engineers (SME), Detroit, Michigan, 10-13 September 1979.

13. "Manufacturing Cost/Design Guide" Department of Defense 1979 Manufacturing Technology Advisory Group (MTAG) Conference, Phoenix, Arizona, 22-25 October 1979, 65 pp.

14. "Manufacturing Cost/Design Trade-Studies", Clinic on Design for Low Cost Manufacturing, Society of Manufacturing Engineers (SME), Cleveland, Ohio, 27-29 November 1979, 65 pp.

15. "Design/Manufacturing Interaction" Air Force Integrated Computer-Aided Manufacturing (ICAM) Composites Workshop, 9-11 January 1980, 71 pp.

16. "The ICAM Cost Design Guide and Its Application to NDE" Lockheed Corporation NDE Task Force, Research Laboratory, Palo Alto, California, 14-15 February 1980.

17. "Selection of Manufacturing Processes", Designing for Low Cost Manufacturing Clinic, Society of Manufacturing Engineers (SME), Charlotte, North Carolina, 15-17 April 1980, 65 pp.

18. "ICAM Manufacturing Cost/Design Guide (MC/DG)" Conference on Structural Composite Manufacturing Applications, Society of Manufacturing Engineers (SME), Los Angeles, California, 10-12 June 1980, 71 pp.

19. "Utilization of a Manufacturing Cost/Design Guide to Determine the Cost Impact of Materials Substitution", Workshop on Materials Substitution Methodologies, National Materials Advisory Board (NMAB), Study Center of the National Academy of Sciences, Woods Hole, Massachusetts, 11-12 June 1980.

20. "ICAM Manufacturing Cost/Design Guide (MC/DG) for Airframes and Electronics", ICAM Industry Days Conference, St. Louis, Missouri, 29 September through 1 October 1980, pp. B.291-B.301.

21. "Design and Manufacturing-to-Cost", 1980 Technology Briefing on "Productivity: Status, Impact and Direction", Battelle Memorial Institute, Columbus, Ohio, 2-3 October 1980.

22. "Review of the Air Force Manufacturing Cost/Design Guide", Midwest Chapter, Society for the Advancement of Material and Process Engineering (SAMPLE), Dayton, Ohio, 14 October 1980.

23. "Manufacturing Cost/Design Trade-Off Methodology" First Japan-United States Conference on Composite Materials, Tokyo, Japan, 12-14 January 1981.

24. "Development and Utilization in Design Process of ICAM Manufacturing Cost/Design Guide" (MC/DG). Fifth DoD/NASA Conference on Fibrous Composites in Structural Design, New Orleans Louisiana, 27-29 January 1981.

25. "Manufacturing Cost/Design Guide (MC/DG) for Metallic and Composite Structures", Co-authored with Capt. R. R. Preston, AIAA Paper No. 81-0518-CP, Proceedings of American Institute of Aeronautics and Astronautics (AIAA)/ASME/ASCE/AHS 22nd Structures, Structural Dynamics and Materials Conference, Atlanta, Georgia, 6-8 April 1981, pp. 445-462.

26. "ICAM Manufacturing Cost/Design Guide (MC/DG) Background, Metallic and Nonmetallic Demonstration Sections", Co-authored with Capt. Richard R. Preston, Materials Laboratory (AFWAL/MLTC), 26th National Symposium and Exhibition, sponsored by the Society for the Advancement of Material and Process Engineering (SAMPE), Los Angeles, California, 28-30 April 1981, pp. 578-592.

27. "Utilization in Industry of ICAM Manufacturing Cost/Design Guide (MC/DG) for Composite Structures", Authored by Dean S. Klivans, Rockwell International Corporation, and Co-authored by Bryan R. Noton, Battelle's Columbus Laboratories, 26th National Symposium and Exhibition, sponsored by the Society for the Advancement of Material and Process Engineering (SAMPE), Los Angeles, California, 28-30 April 1981, pp. 593-600.

28. "Utilization in Industry of ICAM Manufacturing Cost/Design Guide (MC/DG) for Metallic Structures", Authored by Anthony J. Pillera, Lockheed California Company, and Co-authored by Bryan R. Noton, Battelle's Columbus Laboratories, 26th National Symposium and Exhibition, sponsored by the Society for the Advancement of Material and Process Engineering (SAMPE), Los Angeles, California, 28-30 April 1981, pp. 601-606.

29. "The ICAM Manufacturing Cost/Design Guide (MC/DG) for Avionics", Authored by John G. Vecellio, Rockwell International Corporation, and Co-authored by Bryan R. Noton, Battelle's Columbus Laboratories, 26th National Symposium and Exhibition, sponsored by the Society for the Advancement of Material and Process Engineering (SAMPE), Los Angeles, California, 28-30 April 1981, pp. 607-619.

30. "Manufacturing Cost Trade-Studies in Avionics", Co-authored with Mr. John G. Vecellio and Mr. Robert Remski, 13th National Technical Conference, Society for the Advancement of Material and Process Engineering (SAMPE), Mount Pocono, Pennsylvania, 13-15 October 1981, pp. 364-379.

31. "Fabrication Development Requirements and Cost Analysis Methodologies", Conference Theme: "Advanced Composites - New Directions in Performance and Reliability", Society of Plastics Engineers (SPE), Louisville, Kentucky, 4-5 November 1981.

32. "ICAM Manufacturing Cost/Design Guide (MC/DG)" Composites in Manufacturing Conference, Society of Manufacturing Engineers (SME), Anaheim, California, 12-14 January 1982, 71 pp.

33. "Manufacturing Cost/Design Guide (MC/DG) Data Development for Air Frames and Electronics", Proceedings of the Air Force Sixth Annual ICAM Industry Days Conference, New Orleans, Louisiana, 17-20 January 1982, pp. 93-153.

34. "Successful Technology Transfer with the Cost/Design Guide", Fifth Technology Briefing, Conference Theme: "Technology Implementation: Capitalizing on R&D", Battelle's Columbus Laboratories, Columbus, Ohio, 19-20 October 1982.

35. "Air Force ICAM Manufacturing Cost/Design Guide (MC/DG) for Electronics", Co-authored with Mr. Robert R. Remski, Honeywell, Inc., Department of Defense Manufacturing Technology Advisory Group (MTAG) Conference, Phoenix, Arizona, 19-20 October 1982, pp. 12-34.

36. "Air Force ICAM Manufacturing Cost/Design Guide (MC/DG) for Airframes", Department of Defense Manufacturing Technology Advisory Group (MTAG) Conference, Phoenix, Arizona, 19-20 October 1982, pp. 3-26.

37. In Plenary Session: "Cost Factors and Approach Methodology in Selecting Structural Materials and Manufacturing Technologies", AIAA Paper No. 83-0791-CP, American Institute of Aeronautics and Astronautics (AIAA)/ASME/ASCE/AHS 24th Structures, Structural Dynamics and Materials Conference, Lake Tahoe, Nevada, 2-4 May 1983, 18 pp.

38. "ICAM Manufacturing Cost/Design Guide (MC/DG)", Proceedings of the Air Force Seventh Annual ICAM Industry Days Conference, New Orleans, Louisiana, 5-9 June 1983, pp. 223-252.

2.1.6 Briefings

The contractual requirements stipulate an end-of-contract briefing to be given. However, through the Air Force Project Engineer, AFWAL/MLTC, invitations have been received to present additional briefings. These are listed below and an example is included in Appendix F.

1. "Manufacturing Cost/Design Guide" Background, Development, Utilization, and Computerization, Briefing to Integrated Computer-Aided Manufacturing Program Office, Air Force Materials Laboratory/LTC, Wright-Patterson Air Force Base, Ohio, 13 December 1978, 250 pp.

2. "Manufacturing Cost/Design Guide (MC/DG), Data Development, Computerization and Utilization", End-of-Contract Briefing for Integrated Computer-Aided Manufacturing Program Office, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, 12 April 1979, 335 pp.

3. "Manufacturing Cost/Design Guide (MC/DG)", Joint MC/DG Coalition Technical Review, Computer Integrated Manufacturing Branch, Materials Laboratory (AFWAL/MLTC), Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, 13-14 August 1980, 186 pp.

4. "The Importance of the ICAM Manufacturing Cost/Design Guide (MC/DG) in Aeronautical Systems Division (ASD) Acquisitions", 28 May 1981.

5. "Air Force ICAM Manufacturing Cost/Design Guide for Airframes and Electronics", Briefing to U.S. Army Missile Command Coalition, Wright-Patterson Air Force Base, Ohio, 1 September 1981, 198 pp.

6. "Air Force ICAM Manufacturing Cost/Design Guide for Airframes and Electronics", Briefing to Directorate of Equipment Engineering, Aeronautical Systems Division (ASD/ENE), Wright-Patterson Air Force Base, Ohio, 11 September 1981, 269 pp.

7. "Manufacturing Cost/Design Guide (MC/DG) for Airframes and Electronics", Co-authored by Capt. Richard R. Preston, Computer Integrated Manufacturing Branch, Materials Laboratory (AFWAL/MLT), Briefing to Aeronautical Systems Division/EN, Wright-Patterson Air Force Base, Dayton, Ohio, 10 February 1983, 81 pp.

APPENDIX A

OUTLINE OF COURSE ON

"Design and Manufacturing-to-Lowest Cost"

1. Evolution of Design/Manufacturing Interaction.
2. Cost-Driver Analysis Related to:
   - Product Performance
   - Design
   - Material
   - Manufacturing.
3. Design Features vs. Manufacturing Technology Requirements.
4. Commonality of Cost-Drivers Throughout:
   - Industry
   - Low Performance Products
   - High Performance Products
   - Component Design
   - Subsystem Design
   - Lightweight Structures
   - Electronic Design.
5. Primary & Secondary Structures; Cost-Driver Examples.
6. Cost-Savings Leverage in Conceptual and Detail Design Phases.
7. Decisions made in Design Process and Their Impact.
8. Approaches to Design-to-Cost.

9. Identification of Cost-Drivers for:
   - Metallic Structures (Aluminum, Steel, etc.) and Mechanical Systems
   - Composite Structures/Products
   - Emerging Technologies - Examples:
     - Net Shapes (Powder Metallurgy, Castings, etc.)
     - Adhesive Bonding.

10. Guidance to use of Cost-Cutting Technologies.

11. Need for Manufacturing Cost/Design (Performance) Trade-Studies. The ICAM "Manufacturing Cost/Design Guide" (MC/DG); Designer-Oriented Formats to Include Following Technologies:
    - Sheet-Metal
    - Extrusions
    - Castings
    - Forgings
    - Composites
    - Mechanically-Fastened Assemblies
    - Test, Inspection & Evaluation (TI&E) for:
      - Sheet-Metal
      - Machining
      - Composites
      - Castings
      - Forgings.

12. Examples of MC/DG Utilization for Above Technologies:
    - Utilization of Cost-Driver Effect (CDE) Formats Providing Qualitative Guidance
    - Utilization of Cost-Estimating Data (CED) Formats Providing Man-Hour Data
    - Designer Worksheets to Determine Program Cost
    - Three-Ring Binder Version of MC/DG
    - Computerized MC/DG Under Development
    - Examples of Hardware Design Showing Utilization of Formats.

13. Detail Trade-Studies Conducted on:
    - Aluminum Sheet-Metal Structures
    - Titanium Sheet-Metal Panels
    - Composite Panels, Including Co-Cured.

14. Trends in Design and Manufacturing-to-Lowest Cost.

15. Future Design-to-Cost Data Requirements:
    - Metal Removal
    - Bonding
    - Superplastic Formed/Diffusion Bonding
    - Composites (e.g., Sine-Wave Webs)
    - Powder Metallurgy

16. Obstacles to Implementing Cost-Saving Emerging Technologies.

NOTE

- The course duration is 2-1/2 days consisting of 2 one-hour lectures each morning and one 1-1/2 hour lecture each afternoon.
- Approximately 200 slides/vugraphs will be shown.
- 30 copies of an 80-page lecture supplement will be provided.

APPENDIX B

MC/DG UTILIZATION IN INDUSTRY

B.1 Applications Cited

Requests for the "MC/DG for Airframes and Electronics" require a description of the applications for which it is intended. The following organizations have identified the uses listed below:

Organization	Application Cited
Aerojet Liquid Rocket Company	• Assist in planning and implementing U.S. Army and U.S. Navy aerial target propulsion programs.
Aircraft Industries Association	• Provide reference for projects and information for association membership and manufacturing committee.
AMEC, Incorporated	• Assist in airframe modification program.
American Can Company	• Develop wire identification methods for harness manufacture.
American Cyanamid Company	• Improve design and prediction of composite costs based on prepregs.
AMETA	• Provide inputs for course preparation, especially in CAD/CAM subjects.
Analytic Decision Corporation	• Develop intimate familiarity with MC/DG and its use, to better serve clients.
Andrews Air Force Base	• Provide supporting data, concepts, and guidelines for implementing Air Force manufacturing policy.
University of Arkansas at Little Rock	• Extend the use of MC/DG data to optimize the design of similar products, such as structural frames and transportation vehicles.

Organization	Application Cited
Astronautics Corporation of America	• Provide better cost controls and criteria for design and manufacture of electronic instruments.
Aviation Technical Support Incorporated	• Guide efforts to manufacture a noise reduction module for the B707 aircraft.
AVCO Aerostructures Division	• Design and fabricate advanced composite/metallic aircraft structure.
AVCO Corporation	• Enhance accuracy and efficiency in bidding and integrating CAM and CAD into operations.
Aydin Controls	• Integrate departments in manufacture of new products; obtain better understanding of project costs.
Ball Aerospace Systems Division	• Cost systems and set standards for the production of aerospace and military antennae.
Barry Controls	• Integrate manufacturing cost/design into value engineering systems for large contracts.
Bath Iron Works	• Reduce costs associated with the design and construction of U.S. Navy combatant ships.
Beech Aircraft Corporation	• Coordinate design and manufacturing methods and procedures. • Support design of missile target systems.
Bell Aerospace Textron	• Provide pricing guidance in development cf proposals for the Air Force.
Bendix Oceanics	• Write manufacturing outlines, estimate standards for P&Ds, estimate tooling costs, develop cost reductions, guide inexperienced engineers.

Organization	Application Cited
BDM Corporation	• Support systems engineering/technical assistance contracts for various U.S. DoD customers.
Boeing Aerospace Company	• Assist in design of an automated electronics factory and numerical simulation of electronics factory. • Identify significant cost elements from another perspective and provide guidelines and comparisons in "make" electronics.
Boeing Commercial Airplane Company	• Control cost on new airplane programs. • Provide cost data base on mechanical and electrical hardware for life cycle cost tasks on MX contracts. • Play key role in integrating CAD/CAM into the normal manufacturing process. • Use in producibility and value engineering studies on new aircraft and major improvements to existing aircraft. • Compare costs of alternate structural configurations for 747 derivatives.
Boeing Military Airplane Company	• Support ICAM projects; REACH TechMod; BEAM TechMod. • Design sheet metal for ISMC. • Provide source material for ECAM activities and internal manufacturing improvements. • Provide framework for a computerized manufacturing cost model to complement the AFFDL Modular Life-Cycle Cost Model.
Boeing Vertol Company	• Conduct design trade-off studies on composites.

Organization	Application Cited
Cablecraft, Incorporated	• In use with other design guides, assist in the design and manufacture of push/pull cable assemblies for the military, and for various commercial and aviation industries.
CAECEM Development	• Provide basis for structuring plans to develop design costing programs as part of new integrated CAE/CAM system.
Carlisle Engineering Management	• Estimate manufacturing operation costs before commitment to investment.
Cessna Aircraft Company	• To be used by producibility group and advanced planning.
Cleveland Pneumatic Company	• Used in development of TechMod Program, Tech Area 3, "Computer-Aided Value Engineering".
Colt Industries	• Assist in automating production lines.
Computer Avionics	• Optimize design and cost variables in development of custom hybrid microcircuits.
CMC Electronics	• Assist in laying out a new avionics manufacturing facility -- presently in the planning stage.
Data Con	• Assist in preparing a guide for use in wire wrapping in electronics.
DATA I/O Corporation	• Aid in reducing manufacturing costs in our production organization.
Deere and Company	• Provide a prototype for a cost design guide within this industry. • Use the concepts, format, and perhaps the data itself, to determine the feasibility of a similar approach tailored to company needs.

Organization	Application Cited
Deere and Company	• Assist in design of electronic systems for tractors, crawlers, graders, scrapers, etc.
Defense Contract Audit Agency	• Aid in developing and enhancing operational audits.
DoD, Cameron Station	• Conduct affordability analyses; evaluate new start systems.
DoD, Defense Logistics Agency	• Assist in technical evaluation of cost proposals submitted by Government contractors manufacturing a variety of aircraft and electronic parts.
Diablo Systems, Incorporated	• Assist in designing office equipment for ease of manufacture.
Digital Equipment	• Improve manufacturing engineering interface with design engineering in the development of new products and processes.
DM Data, Incorporated	• Provide background information to draw on in advising clients.
Douglas Aircraft Company	• Used in Industrial Engineering Dept. to aid in manufacturing methods and cost trade-off studies on aircraft components. • Assist in cost trade-off studies and augment cost data base. • Assist in advanced design of structures and systems for commercial and military transports and trainers. • Improve design and manufacturing methods in ICAM sheet metal cell and high speed machining center. • Aid in developing manufacturing methods and conducting cost trade-off studies on aircraft components.

Organization	Application Cited
Douglas Aircraft Company	• Guide engineering production design, especially for best use and performance of flexible ICAM manufacturing cells for fabrication and assembly.
E. I. DuPont de Nemours Company	• Conduct intracompany cost/performance analyses of composite structures.
Eaton Corporation	• Improve feedback cost/reliability data to the design process through CAD system.
Eder Industries	• Reduce design costs and improve accuracy of cost estimates.
Electronic System Division HAFB, Mass.	• Evaluate technical cost of electronic hardware producers for C^3I systems.
EMCEE Broadcast Products	• Reduce manufacturing costs through improved product design, assist in engineering design for reliability in variable environments.
Emerson Electric Company	• Assist in design and manufacture of power system equipment, power supplies, radar modulations, radar equipment, and test equipment.
Emhart Machinery	• Assist in setting-up automated machining and subassembly center.
Fairchild Republic Company	• Establish a tooling estimating procedure and parts estimating procedure to determine manufacturing costs.
	• Conduct cost estimates/comparisons of manufacturing processes, especially in the CAD/CAM environment.
Fairfield Industries Incorporated	• Improve current cost estimating techniques, thereby reducing estimating expenses, and improving productivity and profits.
	• Assist in design and manufacture of avionics equipment for military aircraft.

Organization	Application Cited
Gandalf Data Corporation	• Better control costs.
GCA Corporation - Industrial Systems Group	• Comparing fabrication/assembly costs. Basis for preparing process planning decision trees.
General Dynamics Corporation	• Provide a baseline and guidance procedures for a CAD/CAM interface and communication medium.
	• Improve producibility of government's cruise missile program.
	• Prepare Life-Cycle Cost analyses for current and proposed weapon systems.
	• Support cost effective CAD/CAM process development to assure productivity increases.
	• Improve communications and data transfer between manufacturing and engineering/design; assist in CAD/CAM and MIS planning and integration.
	• Develop industry trend comparisons of methods and processes; develop potential cost saving approaches to manufacturing methods.
	• Data on composite materials will be transmitted to Nuclear Submarine Structural Application in support of Contract N00076-C-2025, Proj. Ser. SSLA1 Task 19946.
	• Developing cost guidance methods and parametric cost-estimating relationships for submarine design.
General Electric Company	• Education internally and possible use when working with Aircraft Engine Business Group on Automation Projects.
	• Support design-to-cost efforts on MK-21 fuze.
	• Reduce costs and increase quality of medical diagnostic ultrasound equipment.
	• Assist in decisions on process alternatives based on cost for process routing, assembly techniques.

Organization	Application Cited
General Electric Company	• Evaluate costs of industrial and military aerospace printed wiring assemblies. • To study the methodology to determine the feasibility of using the costing approach to estimate electronics manufacturing • Integration with Air Force 1105 projects. • Assist in program management of several electronic control programs, including controls for a number of USAF and Navy programs. • Develop own techniques for engine cost estimating.
General Motors Corporation Detroit Diesel Allison	• Guide manufacturing cost decisions during initial design of gas turbine engines/components.
General Research Corporation	• Assist in understanding cost implications of new manufacturing processes. • Estimate Class II and Class V modifications on tactical aircraft for weapon integration.
Genisco Computer Graphics	• Computer graphic display products; to be used in the Manufacturing Engineering Department; the Design Engineering Department; for use with Product Planning Board.
Goodyear Aerospace Corporation	• Help integrate CAD/CAM in operation-automated processing. • Assist in design and manufacture of aircraft structures, radomes, reflectors, waveguides, electronic packaging, and portable shelter structures.
Gould, Incorporated	• Keep abreast of the Air Force's preferred methods and adapt them to company operations.

Organization	Application Cited
Gould, Incorporated	• Assist in contract, subcontract, and manufacturing administration.
Grumman Aerospace Corporation	• Review producibility of new designs; analyze make/buy decisions; analyze subcontractor costs.
GTE Sylvania	• Analyze producibility of new designs and design to attain cost improvements.
Gulfstream American Corporation	• Conduct preliminary design cost estimates of proposed new aircraft, such as Gulfstream trainer.
	• Estimate preliminary design cost estimates for proposals on aircraft such as the "Peregrine" trainer.
Hanscom Air Force Base	• Evaluate manufacturing cost and design criteria in design of C^3 systems.
Harris Corporation	• Input for design to production (DTP) program.
	• Assist in preparing subcontract bids to major aerospace manufacturers for airframes.
Hercules, Incorporated	• Develop standard data and cost estimates for DoD contracts.
	• Conduct design/analysis studies and design-to-cost life-cycle cost analysis for solid rocket motors and composite structures.
	• Aid in implementing "Design-to-Cost" approaches in ongoing and anticipated rocket motor development programs.
Hill Air Force Base	• Assist in administration of design review of weapon systems and the design handbook program.
HITCO	• Use the MC/DG as a guide for estimating manufacturing costs and determining design/cost trade-offs for composite structures.

Organization	Application Cited
Honeywell, Incorporated	• Increase production engineer involvement in entry design formulation for cost reduction, with increased producibility.
HR Textron	• Assist in conceptual design activities, especially related to spacecraft.
IBM Corporation	• Teach manufacturability impacts to mechanical designers.
ITT Defense Communications	• Analyze design to unit production costs; provide guidelines for program estimating; conduct next-generation design cost reduction studies.
King Radio	• Use in costing for government contracts; general guide for manufacturing engineering.
Kirkland Air Force Base	• Conduct cost studies; TechMod studies; producibility studies; and evaluate pricing proposals.
Lawrence Livermore National Laboratory	• Provide a teaching tool to improve estimating skills.
Lear Fan, Limited	• Estimate costs of new composite aircraft projects
Lockheed Aircraft Service Company	• Analyze both subcontract costs and internal costs.
Lockheed-California Company	• Improve design and fabrication of advanced composite structures for production.
	• Conduct material and manufacturing trade-off studies on ATF advanced design, NASA composite wing, and advanced anti-submarine patrol designs.
Lockheed Electronics Company	• Estimate subcontractor costs for componentry and system.

Organization	Application Cited
Lockheed Electronics Company	• Assist in upgrading manufacturing capabilities and keeping ICAM Committee up-to-date on latest developments in the field.
Lockheed-Georgia Company	• During ISMC project review, locate any potential applications that may be useful to Computer-Aided Manufacturing Systems. • Assist in R&D work on composites and composite cost reductions; reduce metal AIC costs. • Guide in preparing a handbook on design alternatives for achieving design-to-cost targets. • Improve existing computerized estimating technique.
Lockheed Missiles & Space Company	• Conduct preliminary design tradeoffs for D5 (Trident II) fleet ballistic missile. • Apply to all new design decisions, which are dependent on lower repetitive production costs.
Loral Electronic Systems	• Investigate alternative strategies during the design phase of a program to integrate our design and manufacturing processes, via a CAD/CAM system. • Provide reference material and data source for decision making involving military avionics.
Management Enterprises Incorporated	• Use for awareness and understanding of various cost relationships in aircraft manufacturing.
Martin-Marietta Corporation	• Assist in productivity analysis; conceptual designs; manufacturing engineering pre-planning. • Automate producibility and cost-effectiveness analysis in computer-aided engineering department.

Organization	Application Cited
Martin-Marietta Corporation Denver Division	• Prepare independent cost estimates for our Design-to-Cost/Life-Cycle estimates. • Evaluation for potential cost estimating and cost control for use on various contracts. • Estimate costs of composite fabrication and introduce cost reductions.
Martin-Marietta Corporation Michoud Division	• Redesign of space shuttle external tank; new design of shuttle derived vehicles; space station; orbital transfer vehicle; etc.
Massachusetts Institute of Technology	• Help generate report to Office of Technology Assessment on potential for composites and ceramics used as substitutes for critical materials (cobalt, platinum, manganese, and chromium).
Maul Technology Corporation	• Provide a guide for planning an upgraded computer-integrated manufacturing system within a $20 million capitalization program.
McDonnell Douglas Aircraft Company	• Guide the modeling of operations -- target and cost data. • Improved advanced design cost models. • Use as model for in-house manual to direct design engineers toward cost effective designs. • Conduct "should cost" evaluations and estimate advanced design cost estimates. • Assist in manufacturing methods cost studies, manufacturing equipment procurement decisions, tooling studies, and establishment of manufacturing criteria. • Design planning and reference documents; conduct value engineering program; assist in DTUPC programs.

Organization	Application Cited
McDonnell Douglas Aircraft Company	• Compare both manufacturing and quality assurance methods; analyze automated vs. manual processing.
McDonnell Douglas Astronautics Company	• Producibility engineering -- SMAW; "Dragon"; cruise missile programs.
MDS - Qautel Corporation	• Assist in implementing the concept of flexible manufacturing systems in computer business.
Memorex Communications Corporation	• Restructure material/manufacturing flow; segregate materials flow into minute elements.
Midland Ross Corporation	• Use as design and cost estimating tool on annunciator units, exterior lights, crew station lights, interior lights, and landing lights.
Miniscribe Corporation	• Assist in electromechanical value engineering and establish labor standard guidelines.
Motorola, Incorporated	• Review current concepts of manufacturing planning. • Optimize manufacturing philosophy and its implementation.
NASA Lewis Research Center	• Help guide design and development of composite propulsion components.
NASA - George C. Marshall Center	• Assist in preliminary design and detail design trade-offs of structures for shuttle payloads and experiments.
National Waterlift Company	• Assist in design and manufacture of fly-by-wire electronic control systems.
Naval Air Development Center	• Estimate costs of Naval aircraft and aerial target drones.

Organization	Application Cited
Naval Air Development Center	• Provide design information for aircraft modifications and instrumentation systems.
Naval Materiel Command	• Develop design process sequences on Navy programs.
Naval Underwater Systems Center	• Control costs of underwater weapon systems acquisition.
Newport News Shipbuilding	• Investigate use in the shipbuilding business.
University of New York	• Assist in continuing work with National Academy of Science committees and panels.
Northrop Corporation	• Aid in selecting R&D projects to improve low cost production capability and in selecting lowest cost processes for modernization; as guide to development of Factory-of-the-Future. • Use as integration tool in ICAM projects. • Improve engineering/manufacturing producibility and cost avoidance on F/A-18A programs.
OECO Corporation	• Estimating costs for electronic equipment (MIL use) and internal manufacturing cost comparisons.
OMNIA	• Assist clients in making cost estimates on commercial and industrial composite parts.
Peat, Marwick, Mitchell and Company	• Assist in advising clients on feasibility of computer-integrated manufacturing.
Pennsylvania State University	• Provide educational aids for classes and research resource in subject areas.

Organization	Application Cited
Perkin Elmer Croporation	• Assist in developing a portable wear analyzer for an atmospheric monitor for the Navy and a cardiopulmonary measurement system for NASA.
Pillar Corporation	• Improve manufacturing costs in production of induction heating equipment.
Piper Aircraft Corporation	• Assist in planning and designing production version of the Enforcer project.
Pitney Bowes	• Analyze costs for equipment and processes for automatic assembly of printed wiring boards.
Pratt & Whitney Aircraft Group	• Establish similar guidelines for engines.
PRC Systems Services Company	• Inclusion in a NASA Data Base System covering research on materials, lead-times, etc.
Procter & Gamble Company	• Provide background for corporate team tasked with developing methods for master planning of advanced integrated manufacturing systems.
Ramsey Controls	• Aid in designing electronic components and sine assemblies for use in industrial motor control centers.
Raytheon Data Systems Company	• Reduce costs, simplify manufacturing operations, exemplify least cost design, and improve efficiency and and competitive posture. • Integrate into the division's manufacturing function. • Provide a baseline for CAD/CAM implementation, construction cost trade-offs, and development of component ranking.

Organization	Application Cited
Reliance Electric	• Integrate cost estimation procedures into R&D activities.
Rockwell International Corporation	• Support development of new aircraft designs such as VMX and ATP.
	• Determine feasibility of economically converting machined parts to castings and forgings.
	• Provide an aid for planning/implementing the fabrication of Global Positioning Satellites, which contain composite materials.
	• Supplement life-cycle cost analysis programs.
	• Provide guidance in research efforts on automation.
	• Conduct producibility improvements on B-1B hardware.
	• Support development of lightweight spacecraft structures.
	• Assist in preliminary design of shuttle upper-stage vehicle configurations and subsystems.
	• Project new WGA004 system costs and support trade-off studies.
	• Expedite and improve structural trade-off studies; train recent college graduates.
Rohr Industries, Incorporated	• Determine cost-drivers, conduct cost estimates, and compare costs of manufacturing processes.
SAB Harmon Industries	• Enhance the cost and performance effectiveness of our design/development efforts.
St. Louis University	• Support instruction in aerospace programs.
Schaevitz Engineering	• Assist in bidding and cost analysis for aerospace contracts with government contractors.

Organization	Application Cited
Scheldahl	• Conduct cost trade-offs on design of flexible printed wiring assemblies for commercial and military applications.
Schindler Haughton Elevator Corporation	• Cost avoidance in the design of our product -- electronic controls for elevators.
A. H. Schlueter, Incorporated	• Guide consulting efforts dealing with DTC, LCC, and systems management activities.
Science Applications, Inc.	• Assist in modernization study of small arms plant under DoD contract.
Shaban Manufacturing	• Improve the design of industrial instruments and reduce costs.
The Singer Company	• Provide reference for analyses of new inertial guidance product designs for producibility.
Sperry Defense	• Design changes; producibility studies; cost estimating; cost/benefit trade-off studies.
SRI International	• Provide guidelines in industry profile and market evaluations, acquisition/diversification reviews, and technology development-manufacturing.
Structural Dynamics Research Corporation	• Familiarize organization with the character of interaction between design and manufacturing functions.
Systems Research Laboratories, Incorporated	• Provide guidance in combining several small shops to establish a manufacturing facility that follows ICAM methodology.
Technology Service Corporation	• Provide a cost-estimating reference and/or cross check for the design and development of advanced radar systems and simulators for DoD programs.

Organization	Application Cited
Teledyne Brown Engineering	• Review all ongoing projects for cost improvement. • Improve computer design and producibility, as well as reduce costs. • Enhance and/or modify current cost estimation procedures for electronic products.
Thiokol Corporation	• Evaluate low cost techniques for propulsion systems and gas generator applications.
Tracor, Incorporated	• Aid in design and fabrication of penetration aids deployment system for Peacekeeper and similar missile systems and of countermeasure dispenser systems.
TRW, Incorporated	• Stimulate increased use of computer-integrated manufacturing disciplines.
TRW Harrisburg Airfoils	• Provide reference documents for efforts to install computer designed forging dies and manufacturing process tooling; reduce production costs.
U.S. Army	• Technology transfer, identify areas where manufacturing technology work is required.
U.S. Army Armament Research and Development	• Provide a cost/design reference for use with aircraft and related weapon system and fire control component use.
U.S. Army Aviation R&D Command	• Assist in estimating and evaluating cost estimates for composite components for Army aviation weapon systems and subsystems.
U.S. Department of Transportation	• Conduct research in manufacturing processes.
U.S. MICOM, Redstone Arsenal	• Evaluate MMET project and provide project management support through production engineer-analysis.

Organization	Application Cited
United Technologies Corporation	• Assist in meeting design-to-cost objectives and improving producibility.
	• Promote producibility activity; foster engineering design and manufacturing engineering cooperation.
	• Provide reference in the design and manufacture of diesel fuel injection systems.
	• Guide modernization of cost estimating program and evaluate future equipment requirements.
Vertex Peripheral	• Obtain more efficient and cost-conscious designs for disk drives.
Vought Corporation	• Develop cost forecasting tools for use in proposals to various government agencies.
	• Establish conceptual framework for the Factory-of-the-Future.
	• Guide for continued emphasis on cost reduction.
	• Assess state-of-art in this area and compare to current company estimating techniques.
	• Conduct early trade-off studies, preliminary design, and production design of aerospace and military products.
	• Improve new products selection and planning; institute total cost control.
Westinghouse Electric Corporation	• Forecast, monitor, and control costs of vendor and in-house parts and components on new apparatus; reduce costs on existing designs.
Whittaker Corporation	• Implement design/cost goals on many programs.

Organization	Application Cited
Williams International	• Incorporate into technology modernization planning for production of cruise missile engine.
Worldway Postal Center	• Evaluate various proposals, develop estimates on projects; assess opportunities for cost reduction in areas.

APPENDIX C

PRESS RELEASES ON "MANUFACTURING COST/DESIGN GUIDE"

TTD450260000
12 Sept 1984

News Release
United States Air Force

AERONAUTICAL SYSTEMS DIVISION, OFFICE OF PUBLIC AFFAIRS (ASD/PA)
WRIGHT-PATTERSON AFB, OH 45433 (513) 255-2725/2726

ASD/PAM 82-165

DESIGNER's GUIDE WITH
A NEW APPROACH

WRIGHT-PATTERSON AFB, Ohio, June 30, 1982 --- A "Manufacturing Cost/Design Guide" (MC/DG) is being established by the Materials Laboratory so that airframe and electronic designers have available--within one reference source--cost estimating data on aerospace parts manufacturing, assembly and test, inspection and evaluation.

Providing such a guide to designers, Air Force engineers say, ensures the lowest cost product for new weapon systems. The MC/DG enables more extensive manufacturing trade-offs on airframe components and aerospace electronic fabrication and assembly than previously possible.

The laboratory's Manufacturing Technology Division, Computer Integrated Manufacturing Branch, began development of the new guides in 1975 with Battelle's Columbus Laboratories, Columbus, Ohio. The sections completed to date are: sheet metal discrete parts; composites; mechanically fastened assemblies; castings; forgings; extrusions; test, inspection and evaluation; and electronics fabrication and assembly.

Air Force project engineer Capt. Richard R. Preston says that since the laboratory "constantly receives reports of implementation and resulting improvements from users of the guide, we feel the time and funds spent during the last seven years have been very cost-effective.

"Based on this good acceptance," he continued, "we are planning additional sections of the MC/DG for machining, adhesive bonding, and superplastic forming/diffusion bonding, and we want to expand the section on composite materials."

The guide can be used by the design, manufacturing and procurement departments. It improves communication and interaction between manufacturing engineers and designers throughout the airframe and avionic design processes.

The guide is particularly useful at the preliminary design phase where the leverage exists to achieve maximum cost savings and affordable performance: i.e., funds expended are low, yet the decisions made have significant impact throughout the manufacturing, operations and maintenance of an aircraft.

Cost information in the guides is provided on formats that are developed to; emphasize cost-drivers, be simple to use, use designer language, instill designer confidence, and be accessible and maintainable.

In addition to technical reports prepared on the MC/DG, the guides will be available soon as three-ring binder desk versions and as a pocket-size edition that uses color coding to indicate cost hazards in design.

The MC/DGs also are time savers, Captain Preston said, as revealed in a recent study by Rockwell International (North American Aircraft Operations) of Los Angeles, California, on a composite material, stiffened panel-type structure. While more than 30 calculations were required using conventional cost-estimating methods for the panel, only two calculations were necessary using the MC/DGs. Similar studies conducted by General Dynamics Corp., Fort Worth, Texas, on F-16 aluminum stiffened panels resulted in the same time savings.

Captain Preston also said that engineers in Rockwell International's North American Aircraft Operations used the MC/DG to conduct a trade study during replacement of an aluminum isogrid shell structure door designed as a baseline for the MX Missile Stage 4 shell structure.

The engineer, using the MC/DG cost-driver effect and cost-estimating data formats, performed the cost trade analysis on ten different advanced composite designs. It is estimated that the trade study was conducted in eight hours using the MC/DG; with the normal method of working with manufacturing engineering and cost-estimators, the task would have required approximately 40 hours of labor and a calendar span of one week.

Designers of avionic/electronic systems also have indicated benefits of the MC/DG and its role in a computer aided manufacturing environment. Those benefits include: influencing design decisions early in the design phase, emphasizing low cost processes within a broad range of available data providing qualitative/quantitative manufacturing cost data, imparting senior design experience on new engineers, and providing direct feedback of manufacturing cost implications of design choices.

The following aerospace companies support Battelle's Columbus Laboratories as prime contractor for the MC/DG:

Collins Avionics & Missiles Group, Rockwell International Corporation, Cedar Rapids, Iowa

Grumman Aerospace Corporation, Bethpage, New York

Honeywell, Inc., Minneapolis, Minn.

Lockheed-California Company, Burbank, Calif.

Northrop Corporation, Hawthorne, Calif.

Rockwell International Corporation, North American Aircraft Operations, Los Angeles, Calif.

U. S. companies and government agencies can access the MC/DG from Capt. Preston or Battelle's Columbus Laboratories. The addresses are:

Capt. Richard R. Preston
AFWAL/MLTC
W-PAFB, Ohio 45433

Mr. Bryan R. Noton
Battelle's Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

Defense Technical Information Center, Cameron Station, Alexandria, VA., 22314 will also carry the MC/DG at the normal government cost.

##AFWAL##

CONTACT: Helen Kavanaugh/255-2725

TTD450260000
12 Sept 1984

INFORMATION FROM

Battelle
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201
Telephone 614/424-6424
Telex 24-5454
3/4/83

For Immediate Release

A design guide developed at Battelle's Columbus Laboratories for determining manufacturing costs of airframes and electronic equipment has been named one of the "Top 10" manufacturing technology economic success stories by the U.S. Department of Defense.

The "Manufacturing Cost/Design Guide" was developed during the past seven years by Battelle as prime contractor for the Air Force Wright Aeronautical Laboratories' Computer Integrated Manufacturing Branch, Material Laboratory. Battelle was supported by seven major aerospace companies.

The "Top 10" list consists of projects that have significantly reduced the costs of military systems.

As a result of the guide, more than 600 applications for quickly and inexpensively determining costs for manufacturing methods, parts, assemblies, and inspection techniques have been identified by military and aircraft manufacturers.

Estimates show the guide can potentially save the government $30 million in procuring forgings, extrusions, and castings and is being used for this purpose on the B-1B bomber. It is projected the guide will save $63 million or 15 additional airframes) for procuring airframes for 300 supersonic aircraft. Similar savings are expected in future electronic and other procurements.

The guide includes manufacturing cost comparative information, which designers can use to quickly determine cost-drivers and estimate total cost of hardware. This puts the designers on the lowest cost track early in the design process and provides them with direct feedback on manufacturing costs.

Guide sections now in use include sheet-metal discrete parts; composites, mechanically fastened assemblies; castings, forgings, and extrusions; test, inspection, and evaluation methods; and electronics fabrication and assembly.

Additionally, sections are being planned for machining, adhesive bonding, superplastic forming-diffusion bonding; and composites.

Captain Richard R. Preston serves as the Air Force project engineer for the guide. Bryan R. Noton serves as the Battelle program manager.

Comp s that helped Battelle develop the guide include: Collins Avionics & Missiles Group, Rockwell International Corporation, Cedar Rapids, Iowa; General Dynamics Corporation, Fort Worth Division, Fort Worth, Texas; Grumman Aerospace Corporation, Bethpage, New York; Honeywell, Inc., Minneapolis, Minnesota; Lockheed-California Company, Burbank, California; Northrop Corporation, Hawthorne, California; and Rockwell International Corporation, North American Aircraft Operations, Los Angeles.

Battelle-Columbus is the original contract research and development center of Battelle Memorial Institute, headquartered in Columbus, Ohio. The world's largest independent research institute, Battelle also has major laboratories in Richland, Washington; Frankfurt, Germany, and Geneva, Switzerland.

TTD450260000
12 Sept 1984

MD: 5/25/84
45-84

Contact: Ilene Zeldin
Telephone 614-424-7728

INFORMATION FROM
Battelle
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201
Telephone (614) 424-6424
Telex 24-5454

<u>For Immediate Release</u>

More than $200 million is projected to be saved during the next two years by Department of Defense contractors using the **Manufacturing Cost/Design Guide**, according to the U.S. Air Force.

The guide allows companies to analyze manufacturing costs and select the most cost-effective alternative designs of airframe and electronic parts and systems.

Already employed in more than 800 applications, the guide was developed by Battelle Memorial Institute's Columbus Division and a coalition of major airframe and avionics companies for the Air Force Wright Aeronautical Laboratories' Computer Integrated Manufacturing Branch, Materials Laboratory.

In its **Overview of the Integrated Computer-Aided Manufacturing Program**, the Air Force estimates that $200 million will be saved on Department of Defense acquisitions of aircraft and missile systems.

As an example, the Air Force says that Rockwell International has estimated a 1983 savings on the B-1B aircraft in excess of $300,000 using data on castings and forgings from the guide.

According to Battelle program manager Bryan R. Noton, the guide includes cost comparisons of manufacturing methods, materials, parts, assemblies, and inspection techniques. Industry-wide information is presented in easy-to-use formats for designers.

"With this information, designers can quickly determine cost-drivers, conduct cost estimates, and compare manufacturing processes by going to a single reference," Noton says. "This puts designers on the lowest cost track early in the design process and provides them with direct feedback on manufacturing costs."

The guide is particularly useful for inexperienced designers who have not been trained in cost reduction. Also, it can benefit those involved with computer-aided manufacturing and procurement departments.

Cost information is provided on sheet metal discrete parts; composites; mechanically fastened assemblies; extrusions, forgings, and castings; test, inspection, and evaluation; and electronics fabrication and assembly.

Noton says a section on machining of aerospace parts is now being prepared. Also, the guide is being extended so that designers will be able to use it at the conceptual design phase, where the most leverage exists for reducing costs of new systems.

The Air Force **Manufacturing Cost/Design Guide** was recognized in 1983 by the Office of the Secretary of Defense as a "Top-of-the-Line" manufacturing technology success story.

Companies that assisted Battelle in the project, include: General Dynamics Corporation, Fort Worth Division; Grumman Aerospace Corporation; Honeywell, Incorporated; Lockheed-California Company; Northrop Corporation, Aircraft Group; Rockwell International Corporation, North American Aircraft Operations; and Rockwell International Corporation, Collins Avionics Division. The Boeing Commercial Airplane Company served as reviewer of the guide.

The four-volume guide is available in three-ring binder desk versions and is easily accessible and maintainable. U.S. companies and government agencies can access it by contacting: the Air Force Project Manager, Captain Richard R. Preston, AFWAL/MLTC, W-PAFB, Ohio 45433.

APPENDIX D

ACCOUNTS IN PRESS

SA-26 DEFENSE/SPACE
BUSINESS DAILY
5 TIMES/WEEK

JAN 8 1979

AF DEVELOPING GUIDE FOR REDUCING AIRFRAME COSTS

A manufacturing manual which is designed to help reduce the costs of future aircraft by providing the manufacturing costs of a large number of alternate design configurations of airframes at both the conceptual and detailed design phases is being developed for the Air Force Materials Laboratory by Battelle's Columbus Laboratories.

Seven of the nation's major aircraft contractors will support the Battelle study: 1) General Dynamics/Fort Worth Division; 2) Grumman Aerospace Corp.; 3) Honeywell Inc.; 4) Lockheed-California Co.; 5) Northrop Corp.; 6) Rockwell International/North American Aviation; and 7) Rockwell/Collins Government Avionics Division.

Expansion of the "Manufacturing Cost/Design Guide" is a follow-on to a program begun in 1975 by Battelle with aerospace support to develop manufacturing man-hour data and designer-oriented formats and to conduct structural performance/manufacturing cost trade-off studies on fuselage panels. According to Battelle, several aerospace companies are already using demonstration sections of the initial guide in their aircraft design activities. Work to computerize the guide is underway.

The follow-on study will develop manufacturing cost data to expand the guide for test, inspection and evaluation techniques. Battelle notes that testing accounts for 10 to 25 percent of the direct labor costs of airframe manufacture and a higher percentage for engine manufacturer.

Cost data will be provided for TI&E techniques for sheet metal, castings, machining, assembly, composites and electronic parts in aerospace manufacturing, and for such emerging technologies as primary adhesive-bonded structures, cast aluminum structures, and built-up low-cost advanced titanium structures.

Manufacturing and design costs will also be established for aerospace electronic parts fabrication and assembly.

The Battelle effort is directed by Bryan R. Noton.

5A-7 AEROSPACE DAILY
DAILY

JAN 3 1980

BATELLE/INDUSTRY TEAM TRYING TO TRIM AIRCRAFT MANUFACTURING COSTS

Seven U.S. aerospace companies are working with Battelle's Columbus Laboratories to develop for the Air Force a guide aimed at reducing cost of aircraft systems.

Assisting Battelle is a team including General Dynamics, Fort Worth Div.; Grumman Aerospace Corp.; Honeywell, Inc.; Lockheed-California Co.; Northrop Corp., Aircraft Group; Rockwell International's North American Div.; and Collins Government Avionics Divisions.

Contracted for by the AF Materials Laboratory, Wright-Patterson AFB, Ohio, the guide, according to an AF spokesman, "will enable designers to compare manufacturing costs of a large number of alternative design configurations of airframes at both the conceptual and detail design phases. This should reduce overall costs of aircraft as well as promote improved communications and interaction between manufacturing engineers and designers."

An announcement from Battelle last week noted that the guide project is part of an onging program begun at Columbus in 1975, when the Laboratories and aerospace company engineers developed man-hour data and designer-oriented formats, as well as studies of structural performance/-manufacturing cost trade-offs on fuselage panels. Several aerospace firms are already using demonstration sections of the guide in their own aircraft design work, Battelle reported, and the guide is being computerized.

The current follow-on study will develop manufacturing cost data to expand the guide for test, inspection and evaluation techniques, Battelle said. It pointed out that testing requirements presently account for about 10-25% of the direct labor cost of airframe manufacture, and a higher percentage in engine manufacture.

Battelle's Bryan R. Noton, who heads the project, said the team will also gather and develop data on several emerging technologies, including primary adhesive-bonded structures; cast aluminum structures; and built-up, low-cost advanced titanium structures.

In addition, he said, engineers will establish manufacturing and design costs for aerospace electronics fabrication and assembly, which due to systems sophistication have been increasing

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12 Sept 1984

5A-54 THE WEEKLY OF
BUSINESS AVIATION
WEEKLY

JAN 7 1980

BATTELLE/INDUSTRY TEAM TRYING TO REDUCE DESIGN COSTS — Seven U.S. aerospace companies are working with Battelle's Columbus Laboratories to develop for the Air Force a guide aimed at reducing the cost of aircraft systems. Those companies participating include: General Dynamics; Grumman Aerospace Corp.; Honeywell Inc.; Lockheed-California Co.; Northrop Corp., Aircraft Group; and the North American and Collins Government Avionics Divisions of Rockwell International. An Air Force spokesman said the guide "will enable designers to compare manufacturing costs of a large number of alternative design configuration of airframes at both the conceptual and detail design phases. This should reduce overall costs of aircraft as well as promote improved communications and interaction between manufacturing engineers and designers," the spokesman said.

SOFTWARE DIGEST
1/10/80

A "Manufacturing Cost/Design Guide," intended to provide aircraft designers with manufacturing cost information on how to keep the cost of aircraft systems down, is being developed for the Air Force Materieals Laboratory Wright-Patterson (Ohio) Air Force Base. Developing the guide is a team of U.S. aerospace companies working with Battelle's Columbus Laboratories, the prime contractor.

According to the Air Force's Capt. Steven LeClair, the guide will enable designers to compare manufacturing cos of a large number of alternative design configurations of airframes at both the conceptual and detail design phases. This should reduce overall costs of aircraft as well as promote improved communications and interaction between manufacturing engineers and designers.

41A-71 TECHNICAL SURVEY
WEEKLY

JAN 12 1980

A Manufacturing Cost/Design Guide is being developed for he Air Force Materials Lab, Wright-Patterson (Ohio) Air Force Base by Battelle Labs (Columbus, Ohio) and the aerospace industry. It will enable designers to compare manufacturing costs of a large number of alternative design configurations of airframes at both the conceptual and detail design phases. This should reduce overall costs of aircraft and improve communications and interaction between manufacturing engineers and designers. Assisting Battelle in the program are: General Dynamics, Fort Worth Div; Grumman Aerospace Corp; Honeywell Inc; Lockheed-California Co; Northrop Corp, Aircraft Group; Rockwell International's N American Aviation; and Collins Govt Avionics Divs. (Battelle Labs news release)

NR 12/27/79 p1-3

FEB 1980

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12 Sept 1984

Aerospace project focuses on manufacturing costs

"Manufacturing Cost/Design Guide" is being developed for the Air Force Materials Laboratory, Wright-Patterson (Ohio) Air Force Base, by a team of U.S. aerospace companies working with Battelle's Columbus Laboratories.

The guide will enable designers to compare manufacturing costs of a large number of alternative design configurations of airframes at both the conceptual and detail design phases. The intent is to reduce overall costs of aircraft as well as promote improved communications and interaction between manufacturing engineers and designers.

The guide development is part of an ongoing program begun in 1975. Initial efforts dealt with manufacturing man-hour data and structural performance/manufacturing cost trade-off studies on fuselage panels. Several aerospace companies are already using demonstration sections of the guide in their own aircraft design activities. The guide is also being computerized.

In the current effort, the team will develop manufacturing cost data to expand the guide for test, inspection, and evaluation techniques for sheet metal, castings, machining, assembly, composites, and electronic parts in aerospace manufacturing. Cost drivers, cost-eliminating data, and designer-influenced cost elements will be identified.

Information also will be gathered and developed on several emerging technologies which include primary adhesive-bonded structures; cast aluminum structures; and built-up, low-cost, advanced titanium structures.

And because electronic costs are increasing as a percentage of total aircraft costs, electronic parts will be studied to establish manufacturing and design costs for aerospace electronics fabrication and assembly.

Tooling & Production

2-22-80

Tooling & Production Business Briefs

Aircraft manufacturing costs guide

A manufacturing cost/design guide intended to provide aircraft designers with manufacturing cost information is being developed for the Air Force by a team of US aerospace companies working with Battelle Columbus Laboratories, Columbus, OH. The guide will enable designers to compare manufacturing costs of a large number of alternative design configurations of airframes at both the conceptual and detail design phases. This should reduce overall costs of aircraft as well as promote improved communications and interaction between manufacturing engineers and designers.

Information also will be gathered and developed on several emerging technologies which include primary adhesive-bonded structures, cast aluminum structures and built-up low-cost advanced titanium structures.

THE ICAM PROGRAM REPORT
INTEGRATED COMPUTER-AIDED MANUFACTURING
VOL. 2, NO. 6, July '81

ICAM "MANUFACTURING COST/DESIGN GUIDE"

The MC/DG in Education

At the present time, it is difficult for the aerospace industry to recruit qualified design engineers. The shortage of engineers is caused by the fact that several new projects are currently under way in industry - both commercial and military. Because of this and other factors, university and college graduates will have to play an increasingly important role in the aerospace industry.

One of the other factors that will require university graduates to play a significant role in aerospace design is shown in Figure 1. This diagram, courtesy of Mr. R. H. Hammer, Boeing Commercial Airplane Company, shows the experience distribution of aerospace industry designers as a function of age. The theoretical curve implies that when an engineer retires, a new person would join the company. This allows time for the inexperienced designer to develop and gain knowledge from the seasoned designers he is associated with. The optimum curve takes into account early retirement and persons transferring from the aerospace industry to other industries. The problem is that the actual situation is not represented by this optimum curve. This is caused by basically two factors. One factor is the large influx of engineers that occurred during World War II, and the other is that during layoffs, such as experienced during the late 1960's, and to some extent, in recent years, the last persons entering the aerospace industry were the first ones released. As the curve shows, the average age of designers is approximately 55 years. Furthermore, many experienced engineers are considering early retirement within the next few years, and unless some method is developed to transfer the vast amount of knowledge acquired by retiring designers over the years to less experienced designers, a valuable resource will be lost. The Air Force ICAM MC/DG is one means of documenting and retaining this experience, thus achieving the needed transfer of design and manufacturing knowledge.

A further problem is that industry has been generally disappointed by the lack of design understanding of graduates from our universities and colleges. This has resulted in industry having to conduct expensive and time-consuming training programs for new hires to familiarize them with the design process and manufacturing methods employed in the aerospace industry.

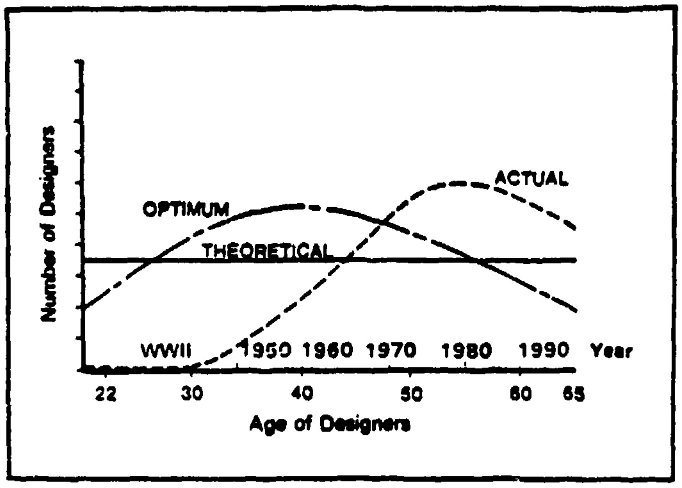

Figure 1. Experience Distribution of Aerospace Designers

Because the recent graduate will be expected to become involved in design earlier in his career, tools are needed to help speed up the process of transitioning graduates to the aerospace design team. The ICAM MC/DG is such a tool. It can be integrated into the university engineering curricula and industry training programs.

An important area in which the MC/DG can be used for training is the design-to-cost (DTC) programs. The MC/DG introduces the designer to design — to lowest cost objectives, manufacturing cost-drivers, and methodologies seldom covered in his education. It not only introduces the designer to DTC, but it indicates how to achieve that goal by the airframe application examples contained in the MC/DG, tutorials on the computerized system, and by the actual trade-studies conducted and included in the appendices to the MC/DG hard copy.

The MC/DG also introduces the less experienced designer to shop floor activities. The MC/DG provides an insight on how parts are manufactured and will help graduates design a part for lower cost manufacture. This information will improve communication between the less experienced designer and his co-workers, both in the design and manufacturing offices.

Benefits of the Air Force ICAM MC/DG to university professors and students are summarized below:

To the Professor:

- Provides a realistic, easy-to-use source of manufacturing cost information for aerospace discrete parts and subassemblies
- Provides a generally applicable, up-to-date source of information, as opposed to specific information from the brochures of vendors
- Provides a link between theoretical design courses and industry by enabling structural performance/manufacturing cost trade-studies to be conducted in the classroom
- The computerized MC/DG will provide an additional dimension to computer activities in engineering schools.

To the Student:

- Introduces students to systematic methodologies for performing trade-studies
- Teaches students the impact of manufacturing technology selection, comparative costs, and manufacturing facility requirements
- Familiarizes students with the use of manufacturing cost data at all stages of the design process
- Aids students in the transition from the classroom or laboratory environment to industry.

The following is a brief course outline on the use of the MC/DG:

- Introduction to the background and need of the MC/DG
- How the MC/DG complements "design-to-cost"
- Explanation of Cost-Driver Effects (CDE), Cost-Estimating Data (CED), Designer Influenced Cost-Elements (DICE), and other information presented in the MC/DG
- Illustration of how the MC/DG is used and applied by:
  - Addressing each manufacturing technology for sheet metal, castings, composites, and test, inspection and evaluation (TI&E).
  - Stressing the cost-drivers and illustrating these with examples
  - Creating theoretical trade-off situations in airframe structure development
  - Illustrate results with diagrams showing cost of structural performance.

Examples of common trade-off situations, with engineering drawings that confront designers, are used. Direction would be provided on how to proceed and significance of results explained. The trades would be extended to include both cost and weight (requiring application of theoretical course work on, for example, mechanics of materials and structural analysis).

MC/DG Courses Scheduled

Presentations by the Air Force and the Prime Contractor, Battelle's Columbus Laboratories (BCL), and the airframe industry team members on the MC/DG Data Development Program (Air Force Contract No. F33615-79-C-5102) have been given at a number of recent important engineering societies' conferences which include:

- AIAA 22nd Structures, Dynamics & Materials Conference
- AIAA 1981 Annual Meeting "Frontiers of Achievement"
- 26th National SAMPE Symposium, "Materials and Process Applications - Land, Sea, Air and Space"
- 18th International Technical Conference of the Numerical Control Society

As the MC/DG is intended for designer use, presentations at conferences are important to accelerate technology transfer of the results of these Air Force programs, as well as to achieve approval and acceptance by management in industry. The MC/DG has been used, for example, by Lockheed-California Company and Rockwell-International's North American Aircraft Division in actual trade-studies on Navy aircraft control surfaces and MX-missile composite fuselage panels.

Another important opportunity to achieve technology transfer is through the presentation of courses in universities. A course on "Structural Performance/Manufacturing Cost Trade-Studies Using Composite Materials and the Manufacturing Cost/Design Guide (MC/DG)" will be given at Texas A&M, College Station, Texas, for one week, beginning 10 August 1981. The course is for students participating in the Air Force Office of Scientific Research (AFOSR) program and provides an introduction to composite design and applications. The course will be similar to that indicated in the brief outline above and will be given by Mr. Bryan R. Noton, Program Manager, MC/DG, Data Development Program at Battelle's Columbus Laboratories.

A similar course is scheduled 19-20 Oct 1981 at the Air Force Institute of Technology (AFIT), Wright-Patterson Air Force Base, Dayton, Ohio, and will be again presented by Mr. Noton and is being organized by Capt. Richard R. Preston, ICAM Project Manager, Computer Integrated Manufacturing Branch, Material Laboratory.

A major missile design and manufacturing corporation has scheduled a course by Battelle on the MC/DG for airframe and mechanical preliminary and detail designers. This course will be given in September, 1981.

A course will also be presented by the MC/DG Subcontractor, Rockwell International, at both the North American Aircraft and the North American Space Operations Divisions.

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12 Sept 1984

THE ICAM PROGRAM REPORT
INTEGRATED COMPUTER-AIDED MANUFACTURING
VOL. 3 NO. 1 October '81

EXPANSION OF ICAM "MANUFACTURING COST/ DESIGN GUIDE" (MC/DG)

The Computer Integrated Manufacturing Branch recently took the necessary action to initiate the development and implementation of two additional manufacturing technology sections of the MC/DG. These sections will be developed under the MC/DG Data Development project, Contract No. F33615-79-C-5102. These sections are:

- forgings
- extrusions.

The data requirements and designer-oriented formats identifying manufacturing cost-drivers, both qualitatively and in man-hours, were prepared under Contract No. F33615-75-C-5194, enabling development of a model of the MC/DG, a section-by-section lay-out of all formats, etc., and an implementation plan. This program is reported in the final technical report (AFML-TR-76-227). The additional MC/DG sections will now enable manufacturing cost trade-studies to be conducted between sheet metal assemblies, such as sheet metal panels with built-up stringer sections and one piece extrusion-stiffened panels. Furthermore, it will be possible to compare the manufacturing cost of castings and forgings with built-up sheet metal assemblies. Earlier completed programs required development of the following MC/DG sections, which have been demonstrated in the airframe design process:

- sheet metal discrete parts
- mechanically-fastened assemblies
- composites (a limited, four-month program)
- castings
- test, inspection and evaluation (TI&E).

Several companies which have utilized the above demonstration sections for applications such as the MX-missile, have shown enthusiasm about expanding this design tool to include forgings and extrusions.

The criteria for developing the MC/DG are:

- **emphasize cost-drivers**
- **be simple to use**
- **use designer language**
- **instill confidence**
- **be economical**
- **be accessible**
- **be maintainable.**

A recent comparison between the MC/DG and conventional cost-estimating methods revealed that for a stiffened panel type structure, only two calculations were necessary with the MC/DG, but over 30 calculations were required utilizing conventional cost-estimating methods. This clearly demonstrates the degree of success achieved in meeting several of the above design criteria. However, conventional cost-estimating methods were utilized in establishing the Battelle Industry Data (BID) which provided the foundation for the designer-oriented formats.

The Air Force focal point for this project is AFWAL/MLTC, Capt. R. R. Preston, (513) 255-6976.

ICAM REPORT October '81 page 2

THE ICAM PROGRAM REPORT
INTEGRATED COMPUTER-AIDED MANUFACTURING
VOL. 3 NO. 2, Mar.

POTENTIAL PAYOFF OF UTILIZING ICAM "MC/DG FOR ELECTRONICS"

Experienced designers in industry were requested to estimate the cost-savings impact of utilizing the ICAM "Manufacturing Cost/Design Guide" (MC/DG) through all phases of electronic systems development:

- Conceptual design phase
- Engineering design phase
- Prototype phase
- Preproduction phase
- Production phase.

The following are the estimated payoffs from using the MC/DG on an inertial navigation system:

- Buy 600
- $60,000 each
- $36,000,000 program
- Engineering design and development program, typically 2-year effort costing $2,000,000
- MC/DG increases design activity by 10 percent, i.e., $200,000 but is more efficient
- Use of ICAM MC/DG predicted to reduce material and labor cost of each system by 10 percent to $54,000
- Cost of total program now $32,000,000
- Savings estimated to be $4,000,000
- At manufacturing level, savings are greater (percentage)

The avionic/electronic designers were also requested to indicate general benefits of the ICAM MC/DG, and its role in the CAM environment. The responses were:

MC/DG Benefits

- Influences design decisions
- Emphasizes low cost processes
- Provides qualitative/quantitative manufacturing cost data
- Imparts senior designer experience on new engineers
- Direct feedback of manufacturing cost implications of design choices.

MC/DG Role in CAM Environment

- Provides link between CAD and CAM
  - Design/manufacturing interaction
- Highlights lowest cost process flow
- Design trades with known manufacturing cost impacts
- Immediate cost impact of documentation change notice.

MC/DG reports containing airframe and electronics formats and data have been requested through the Air Force Computer Integrated Manufacturing Branch (AFWAL/MLTC) for use in conjunction with the following projects. The requesting organizations and related programs are indicated below:

- Advanced Composite Airframe Program (ACAP)
  - AVRADCOM, Ft. Eustis, Virginia
- Advanced Robotic Systems
  - Fairchild Republic Company, Farmingdale, New York
- Computerized Printer
  - RCA, Morristown, New Jersey
- Effective Analysis Program
  - Western Electric, Greensboro, North Carolina
- Flap Structural Configurations
  - Lockheed-California Company, Burbank, California
- Liquid Rocket Engine Propulsion System
  - Rockwell International (NAAD), Los Angeles, California
- MX Stage 4 Shell Structure Door
  - Rockwell International (NAAD), Los Angeles, California
- Seek-Talk Technical Modernization Program
  - Hazeltine Corporation, Greenlawn, New York
- Sheet-Metal Fabrication Systems
  - Fairchild Republic Company, Farmingdale, New York
- Space Shuttle External Tank Project - NASA
  - Martin-Marietta Aerospace Corporation, New Orleans, Louisiana
- YAH-64 Advanced Attack Helicopter
  - Hughes Helicopters, Inc., Culver City, California
- F/A-18 Technical Modernization Program N00019-75-C-0424
  - Hughes Aircraft Company, Culver City, California
- Ballistic Intercept Missile Concept Study
  - General Research Corporation, Santa Barbara, California

- Future Torpedo Requirements Study, Contract NICRAD-81-NVSC-0007
  — Gould, Inc., Cleveland, Ohio

The MC/DG program is being developed by Battelle's Columbus Laboratories (BCL), as prime contractor, supported by the following subcontractors: General Dynamics Corporation, Fort Worth Division; Grumman Aerospace Corporation; Honeywell, Inc.; Lockheed-California Company; Northrop Corporation, Aircraft Group; Rockwell International Corporation, North American Aircraft Division; and Rockwell International Corporation, Avionics & Missiles Group, Collins Avionics Division.

The USAF project manager for this program is Capt R. R. Preston, (513)255-6976.

THE ICAM PROGRAM REPORT
INTEGRATED COMPUTER-AIDED MANUFACTURING
VOL. 3 NO. 3 Aug. '82

DESIGNER'S GUIDE WITH A NEW APPROACH

The ICAM "Manufacturing Cost/Design Guide" (MC/DG) has been established by the Materials Laboratory so that airframe and electronic designers have available, within one reference source, cost estimating data on aerospace parts manufacturing, assembly and test, inspection and evaluation. Providing such a guide to designers ensures the lowest cost product for new weapon systems by enabling more extensive manufacturing trade-offs on airframe components and aerospace electronic fabrication and assembly than previously possible.

The Computer Integrated Manufacturing Branch began development of the new guides in 1975 with Battelle Columbus Laboratories, Columbus, Ohio. The sections completed to date are: sheet metal discrete parts; composites; mechanically fastened assemblies; castings; forgings; extrusions; test, inspection and evaluation; and electronics fabrication and assembly. Based upon excellent industry acceptance of the guide, the Program Office is planning to develop additional sections of the MC/DG for machining, adhesive bonding, and superplastic forming/diffusion bonding, and to expand the section on composite materials.

The guide can be used by the design, manufacturing and procurement departments. It improves communication and interaction between manufacturing engineers and designers throughout the airframe and avionic design processes. It is particularly useful during the preliminary design phase where the leverage exists to achieve maximum cost savings and affordable performance: i.e., funds expended are low, yet the decisions made have significant impact throughout the manufacturing, operations and maintenance of an aircraft.

Cost information in the guides is provided on formats that are developed to: emphasize cost-drivers, be simple to use, use designer language, instill designer confidence, and be accessible and maintainable. In line with this philosophy, the guides will be available soon as three-ring binder desk versions and as a pocket-size edition that uses color coding to indicate cost hazards in design.

Many users have reported significant time savings as a result of using the guide. For example, in a recent design exercise by Rockwell International (North American Aircraft Operations) of Los Angeles, California, of a composite material, stiffened panel-type structure, more than 30 calculations were required using conventional cost-estimating methods for the panel, while only two calculations were necessary using the MC/DG3. Similar studies conducted by General Dynamics Corp., Fort Worth, Texas, on F-16 aluminum stiffened panels resulted in time savings of the same relative magnitude. In another study, the MC/DG was used to conduct a trade study for replacement of an aluminum isogrid shell structure door designed as a baseline for the MX Missile Stage 4 shell structure. An engineer, using the MC/DG cost-driver effect and cost-estimating data formats, performed the cost trade analysis on ten different advanced composite designs. It was estimated that the trade study was conducted in eight hours using the MC/DG, whereas with the normal method of working with manufacturing engineering and cost-estimators, the task would have required approximately 40 hours of labor and a calendar span of one week.

Designers of avionic/electronic systems also have indicated benefits of the MC/DG and its role in a computer aided manufacturing environment. Those benefits include: influencing design decisions early in the design phase, emphasizing low cost processes within a broad range of available data providing qualitative/quantitative manufacturing cost data, imparting senior design experience on new engineers, and providing direct feedback of manufacturing cost implications of design choices. The ICAM Program Office focal point for the MC/DG project is Capt R. R. Preston, (513) 255-7371.

5A-18 AVIATION DAILY
DAILY

SEP 8 1982

GUIDE AVAILABLE TO DETERMINE AIRFRAME, ELECTRONICS COSTS

Battelle's Columbus Laboratories has developed a guide that allows designers of airframe and electronic equipment to quickly and inexpensively *determine manufacturing* costs. Guide was developed by Battelle with a coalition of major airframe and avionics companies and is now being used by a number of military and civil aircraft manufacturers. "Manufacturing Cost/Design Guide" was developed *during* the past seven years for the Air Force Wright Aeronautical Laboratories' Computer Integrated Manufacturing Branch, Materials Laboratory. Guide includes cost comparisons of manufacturing methods, parts assemblies and inspection techniques. For a copy of the report, contact Capt. Richard R. Preston, AFWAL/MLTC, W-PAFB, Ohio 45433, or Bryan R. Noton at Battelle.

41C-34N TEST & MEASUREMENT
WORLD
MONTHLY
OCTOBER 1982

Guide Speeds Manufacturing Cost Studies

Developed along with a coalition of major airframe and avionics companies, a guide that allows designers of airframes and electronic equipment to quickly and inexpensively determine manufacturing costs has been published by Battelle Laboratories. Including cost comparisons of manufacturing methods, parts assemblies and test, inspection and evaluation methods, the guide is particularly useful for inexperienced designers and those involved with computer-aided manufacturing. Presently in use, the guide reportedly has reduced the time to perform some studies by as much as 80 percent. *The Manufacturing Cost/Design Guide* is available from Bryan R. Norton, Battelle Columbus Laboratories, 505 King Ave., Columbus, OH 43201, or from the Defense Technical Information Center, Cameron Station, Alexandria, VA 22314.

418-10 PRODUCTION ENGINEERING
MONTHLY 90.000
OCTOBER 1982

Guide for designers helps reduce manufacturing costs

A guide that allows designers of airframe and electronic equipment to quickly and inexpensively determine manufacturing costs has been developed at Battelle's Columbus Laboratories with a coalition of major airframe and avionics companies. It is currently being used by a number of military and civil aircraft manufacturers.

The guide includes cost comparisons of manufacturing methods, parts, assemblies, and inspection techniques. With the information in the guide, designers can quickly determine cost-drivers, conduct cost estimates, and compare manufacturing processes—early in the design process.

Guide sections now in use include sheet-metal descrete parts; mechanically fastened assemblies; castings, forgings, and extrusions; test, inspection, and evaluation methods; and electronics fabrication and assembly. Sections are being planned for machining, adhesive bonding, superplastic forming-diffusion bonding, and composites.

The guide currently is in report-style, but soon will be available in three-ring binder desk versions and as a pocket-size edition.

U.S. companies and government agencies can access the guide by contacting: Captain Richard R. Preston, AFWAL/ MLTC, W-PAFB, Ohio 45433, or Bryan R. Noton, Battelle's Columbus Laboratories, 505 King Avenue; Columbus, Ohio 43201. In addition, "Manufacturing Cost/Design Guide" is available from the Defense Technical Information Center, Cameron Station; Alexandria, Virginia 22314.

August 23, 1982 BUSINESS AVIATION Page 63

BATTELLE'S Columbus Laboratories has developed a guide that allows designers of airframe and electronic equipment to quickly and inexpensively determine manufacturing costs. Guide was developed by Battelle with a coalition of major airframe and avionics companies and is now being used by a number of military and civil aircraft manufacturers. "Manufacturing Cost/Design Guide" was developed during the past seven years for ti. Air Force Wright Aeronautical Laboratories' Computer Integrated Manufacturing Branch, Materials Laboratory. Guide includes cost comparisons of manufacturing methods, parts assemblies and inspection techniques. For a copy of the report, contact: Capt. Richard R. Preston, AFWAL/MLTC, W-PAFB, Ohio 45433, or Bryan R. Noton at Battelle.

ELECTRONIC PACKAGING and PRODUCTION
OCTOBER 1982

Guide cuts costs

A guide that allows designers of electronic and airframe equipment to quickly and inexpensively determine manufacturing costs has been developed at Battelle's Columbus Laboratories in cooperation with a coalition of major airframe and avionics companies. The *Manufacturing Cost/Design Guide* was developed during the past seven years for the Air Force Wright Aeronautical Laboratories' Computer Integrated Manufacturing Branch, Materials Laboratory. According to Battelle program manager Bryan R. Noton, the guide includes cost comparisons of manufacturing, parts, assemblies and inspection techniques.

This information is designed to enable designers to quickly determine cost-drivers, conduct cost estimates, and compare manufacturing processes by going to a single reference. This puts designers on the lowest cost track early in the design process and provides them with direct feedback on manufacturing costs.

While generally targeted for manufacturing and procurement departments, the guide is particularly useful for inexperienced designers and those involved with computer-aided manufacturing. Guide sections now in use include electronics fabrication and assembly, and test, inspection, and evaluation methods. According to Air Force project engineer Captain Richard R. Preston, several companies already have reduced design time and costs by using the new guide. U.S. companies and government agencies can obtain the guide by contacting: Captain Richard R. Preston, AFWAL/MLTC, W-PAFB, Ohio 45433, or Bryan R. Noton, Battelle's Columbus Laboratories, 505 King Avenue, Columbus, Ohio 43201. In addition, it is available from the Defense Technical Information Center, Cameron Station, Alexandria, Virginia 22314.—*D.E.*

BATTELLE MEMORIAL INSTITUTE 1983 ANNUAL REPORT

INDUSTRIAL PROCESSES

Battelle served as the prime contractor in developing the U.S. Air Force's Manufacturing Cost/Design Guide which will help reduce the cost of airframe structures and electronics in aerospace systems. This accomplishment was recognized by the U.S. Secretary of Defense as a "Top-of-the-Line" Manufacturing Technology Success Story. The guides are developed with industry-wide cooperation to distill industrial practice in easy-to-use formats and make key connections with computer-aided design and computer-integrated manufacturing systems. Used in all design phases, including procurement, the guide also provides cost comparisons of manufacturing processes, imparts senior designer experience to inexperienced engineers, and emphasizes potential cost advantages of emerging technologies.

Improving productivity in today's highly competitive manufacturing climate requires managers to face some difficult questions about their operations. Battelle has developed a computer-simulation system to provide important information about productivity. The system enables assessment of the impact of individual or combinations of factors before costly changes are made. Examples include current or proposed process functions, major plant renovation, or personnel requirements. A decision-maker, working at a computer terminal, can use the modeling technique to test alternative solutions to problems, immediately observing the effect of the proposed change. Potential applications include parts manufacturing, food processing, and factory automation.

A Battelle study is under way to utilize rapid solidification technology in producing steel strip products directly from molten steel. The new process, known as direct strip casting, has the potential to provide the "leap-frog" technology needed to obtain a competitive advantage in world steel markets. In the Battelle-developed process, molten metal is "dragged" from a tundish onto a cooled rotating metal wheel where the metal solidifies instantly into a strip of uniform thickness and width. The process offers the potential to reduce capital investment and operating and energy costs as well as to improve yield and quality.

Battelle scientists have developed an electroplating device to deposit flawless, well-bonded protective coatings on the internal surfaces of hollow components. The functional coatings, which consist of a metallic matrix containing finely dispersed nonmetallic particles, offer a number of useful properties, including combined wear and corrosion resistance, dry lubrication, and mechanical strength. In contrast to conventional brush electroplating, in the new process, the electrolyte suspension is pumped continuously to the cathode—the hollow part—in a circuit that includes a wad of spongy material, mounted on an exchangeable, rotating, or oscillating anode. This prevents sedimentation of the particles, coagulation, or clogging of the spongy material. The plating process can be integrated into an automated production line.

TTD450260000
12 Sept 1984

TIG BRIEF 7, VOLUME XXXV, 4 APRIL 1983

TIG BRIEF

The INSPECTOR GENERAL

DESIGNER'S GUIDE WITH A NEW APPROACH—ASD

A "Manufacturing Cost/Design Guide" (MC/DG) is being established by the Materials Laboratory, Wright-Patterson AFB, Ohio, so that airframe and electronic designers have available—within one reference source—cost-estimating data on aerospace parts manufacturing, assembly and test, inspection, and evaluation.

Air Force engineers say that providing such a guide to designers ensures the lowest cost product for new weapon systems. The MC/DG enables more extensive manufacturing trade-offs on airframe components and aerospace electronic fabrication and assembly than previously possible.

The laboratory's Manufacturing Technology Division, Computer Integrated Manufacturing Branch, began development of the new guides in 1975. The sections completed to date are: sheet metal discrete parts; composites; mechanically fastened assemblies; castings; forgings; extrusions; test, inspection, and evaluation; and electronics fabrication and assembly.

Based on good acceptance of the new guide, additional sections of the MC/DG are planned for machining, adhesive bonding and superplastic forming/diffusion bonding, and an expansion of the section on composite materials.

The guide can be used by the design, manufacturing, and procurement departments. It improves communication and interaction between manufacturing engineers and designers throughout the airframe and avionic design processes.

The guide is particularly useful at the preliminary design phase where the leverage exists to achieve maximum cost savings and affordable performance: i.e., funds expended are low, yet the decisions made have significant impact throughout the manufacturing, operation, and maintenance of an aircraft.

Cost information in the guides is provided on formats that are developed to: emphasize cost-drivers, be simple to use, use designer language, instill designer confidence, and be accessible and maintainable.

In addition to technical reports prepared on the MC/DG, the guides will be available soon as three-ring binder desk versions and as a pocket-size edition that uses color coding to indicate cost hazards in design.

The MC/DGs are time savers. In a recent study by Rockwell International, 30 calculations were required, using conventional cost-estimating methods for the panel, while only two calculations were necessary using the MC/DGs. Similar studies conducted by General Dynamics Corporation on F-16 aluminum-stiffened panels resulted in the same time savings.

Designers of avionic/electronic systems also have indicated benefits of the MC/DG and its role in a computer-aided manufacturing environment. Those benefits include: influencing design decisions early in the design phase, emphasizing low-cost processes within a broad range of available data providing qualitative/quantitative manufacturing cost data, imparting senior design experience on new engineers, and providing direct feedback of manufacturing cost implications of design choices.

US companies and Government agencies can gain access to the MC/DG by contacting Capt Preston or Mr Noton at the following addresses:

Capt Richard R. Preston
AFWAL/MLTC
Wright-Patterson AFB, OH 45433

Mr Bryan R. Noton
Battelle's Columbus Laboratories
505 King Avenue
Columbus, OH 43201

Defense Technical Information Center, Cameron Station, Alexandria, VA 22314, will also carry the MC/DG at Government cost. (Ms Kavanaugh, AFWAL/MLTC, AUTOVON 785-2725) ■

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TTD450260000
12 Sept 1984

THE ICAM PROGRAM REPORT
INTEGRATED COMPUTER-AIDED MANUFACTURING
October 83

ICAM SUCCESS RECOGNIZED BY OSD

Two ICAM projects were recently recognized by the Office of the Secretary of Defense (OSD) as "Top-of-the-Line" Manufacturing Technology Success Stories. The two projects, "ICAM Definition (IDEF) Methodologies" and "ICAM Manufacturing Cost/Design Guide (MC/DG)", have been identified in numerous applications yielding cost saving improvements.

The IDEF Methodologies are a set of tools which both government and industry personnel can use to better understand and analyze current manufacturing activities, propose system design changes for future operations and manage alternatives available in a systematic, organized pattern. In addition, the IDEF Methodologies have been used to assess cost benefits and risks associated with the implementation of new technology. This enables managers who are introducing emerging technologies to optimize their return on investment while avoiding unworkable solutions. The IDEF Methodologies, since their introduction by SofTech, Inc. in 1979, have been used on more than 100 Air Force, Army, Navy and NASA projects. Independent industry applications have been reported by numerous companies including: Boeing Military Airplane Company, International Harvester, General Dynamics/Ft. Worth, Vought Corporation, General Electric/Aerospace and Electronics Systems Division, Rockwell International, and Kaiser Aluminum. These methodologies are currently being taught as a part of the Industrial Engineering curriculum at Texas A&M, Arizona State and Purdue Universities.

In summary, the IDEF Methodologies have emerged as new management and analysis techniques that will allow managers and engineers to address problems in a total systems context and cope with the complexity of change in the modernization of today's manufacturing environment.

The Manufacturing Cost/Design Guide (MC/DG) was established by Battelle Columbus Laboratories to identify the lowest cost manufacturing alternatives during the design process. The MC/DG is a tool that enables designers to conduct quick and simple design configuration/manufacturing process cost comparisons based on industry averaged data.

More than two thousand requests for MC/DG Documents have been received and over six hundred applications have been identified by MC/DG users. Examples of end product applications and sponsoring companies include: B-1B Bomber (Rockwell), Ballistic Intercept Missile Concepts (General Research Corporation), YAH-64 Advanced Attack Helicopter (Hughes), Space Shuttle External Fuel Tanks (Martin-Marietta), Seek-Talk Technology Modernization (Hazeltine Corporation), M-X Missile Stage 4 (Rockwell), Liquid Rocket Engine Propulsion Components (Rockwell), Computerized Printer (RCA), Advanced Composite Airframes (AVRADCOM), Torpedoes (Gould, Inc.), M-1 Tank (A. T. Kearney), Boeing 757 and 767 Aircraft (Boeing), Long Range Combat Aircraft (LRCA) (General Research Corporation), Joint Technology Demonstrator Engine Program (JTDEP) (General Electric Company), and many more.

Single applications of the MC/DG have resulted in savings of $50,000-$75,000. Potential savings across industry over the next few years are projected to exceed $30 million on DoD acquisitions.

The success to date of the MC/DG for Airframes and Electronics has exceeded original expectations in reducing cost associated with both designing for manufacturing and reducing the designers cost trade-off labor hours necessary to analyze a broad range of manufacturing activities.

The IDEF Methodologies and the MC/DG can be obtained by request from the ICAM Program Office or from the Defense Technical Information Center.

For further information contact the ICAM Project Manager, Capt R. R. Preston at (513) 255-6976.

APPENDIX E

EXAMPLES OF PRESENTATIONS

ICAM "MANUFACTURING COST/DESIGN GUIDE" (MC/DG)

Air Force Contract F33615-79-C-5102
ICAM Project Priority 4502/9

Bryan R. Noton
Engineering & Manufacturing Technology Department
Battelle's Columbus Laboratories
Columbus, Ohio

and

Capt. Richard R. Preston
Computer Integrated Manufacturing Branch (AFWAL/MLTC)
Manufacturing Technology Division
Air Force Wright Aeronautical Laboratories
Dayton, Ohio

ABSTRACT

An urgent need exists for methodologies that can be used by designers to reduce the cost of aerospace systems. Cost drivers can be related to performance, design, materials, and manufacturing. Manufacturing cost data are required for metal and composite parts and assemblies, and also designer-influenced cost elements, which, for composites, include hybrids, ply count, curing method, and quality requirements. To meet these needs, a "Manufacturing Cost/Design Guide" (MC/DG) is under development. The designer-oriented formats comparing manufacturing processes have been used in trade-off studies of structural performance and cost. Examples are given of applications of the MC/DG in industry. When fully developed, the MC/DG will be capable of indicating potential cost savings of emerging technologies which will accelerate technology transfer. Development of a guide for electronics is also included as a task in this program.

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5-9 June 1983

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ICAM "MANUFACTURING COST/DESIGN GUIDE"

Bryan R. Noton
Battelle's Columbus Laboratories

and

Capt. Richard R. Preston
Computer Integrated Manufacturing Branch
Materials Laboratory, WPAFB

1. INTRODUCTION

The need to arrest and reduce costs at all levels of the aircraft system life cycle is becoming increasingly important. To meet this need, qualitative and quantitative data on cost drivers for use in the design, manufacture, operation, and maintenance of aircraft systems are essential. This is particularly true because the reduced number of newly developed aircraft types creates a demand for improved performance; implying reduced weight, better quality, and lower ownership cost, including decreased energy consumption. Furthermore, performance improvements must be affordable.

Improved aircraft performance depends upon the excellence of engineering design. Affordable aircraft performance depends upon recognizing cost drivers in both design and manufacture--avoiding cost drivers in new designs and improving manufacturing methods for existing products. Cost drivers can be avoided in aircraft design by applying design to cost (DTC) methods. Likewise, early identification of cost drivers and corrective action in existing and new products depends upon proficiency in applying manufacturing to cost (MTC) principles. There is a need for proven innovative manufacturing technology ahead of the development of new aerospace systems.

Cost drivers can be grouped in four categories of aircraft system development:

Mr. Bryan R. Noton is the Program Manager, MC/DG, Battelle's Columbus Laboratories, 505 King Avenue, Columbus, Ohio 43201; Tel. (614) 424-4588 or 424-5608. The Air Force Project Engineer is Capt. Richard R. Preston, Computer Integrated Manufacturing Branch (AFWAL/MLTC), Manufacturing Technology Division, Air Force Wright Aeronautical Laboratories, Dayton, Ohio 45433; Tel. (513) 255-7371.

- Performance
- Design
- Material Selection
- Manufacturing.

As examples, cost drivers for auxiliary components are:

- Performance related
  - Reduced weight
  - Higher operating speeds
  - Increased reliability and maintainability
- Design related
  - High part count
  - Nonstandardization
  - Close tolerances
- Material related
  - Cost
  - Availability
  - Utilization
  - Energy
  - Inventory
- Manufacturing related
  - Inspection
  - Equipment
  - Cyclic production
  - Small lot sizes
  - Job shop environment
  - Highly skilled labor
  - Metal removal
  - High scrap rate
  - Deburring/hand finishing
  - Heat treatment
  - Hand fit up
  - Energy requirements.

Tables 1 and 2 show the significant differences between the design and manufacturing requirements and, hence, cost drivers, for low- and high-speed aircraft types.

Individual designers seldom have the training or experience to conduct structural performance/manufacturing cost trade-off studies in their daily efforts. Nonetheless, today's designers are rated not only on their ingenuity in meeting weight and cost objectives, but also on their ability to do so within design schedule limitations (Figure 1). Design to lowest cost is now a design discipline. Design teams must, therefore, be provided with:

- **Tools**--identification and documentation of cost drivers and cost reduction methods in airframe design and manufacture.

- **Incentives**--cost targets against which performance of design personnel can be measured.

In the past, the designer had only one resource to determine cost: the cost estimator. The cost estimator is still an important factor in the final iteration of the design prior to production commitment. However, it is often difficult to meet scheduling requirements, and also consider an adequate number of design alternatives, while ascertaining, with confidence, that the selected design is actually the lowest cost alternative. The recently developed ICAM "Manufacturing Cost/Design Guide" for composite and metallic airframes now provides an unprecedented opportunity for the designer to study a large number (e.g., ten) of alternative design configurations for airframe subassemblies to obtain the lowest manufacturing cost. It also provides a design approach that meets the needs described above.

Of prime importance, use of the MC/DG leads to the strong interaction between design and manufacturing elements that is essential to achieve the required advances in manufacturing sophistication. While the MC/DG will eventually be applicable at all levels of the design process, the importance of the preliminary design phase, the "window of opportunity", needs to be emphasized. Figure 2, shows the cost importance of decisions and of the number of decisions as a function of time. The impacts are much greater in the early stages. Figure 3 illustrates the application of the MC/DG from airframe concept development through concept selection.

TABLE 1.

**LOW SPEED AIRCRAFT DESIGN FEATURES
VERSUS
MANUFACTURING TECHNOLOGY REQUIREMENTS**

	DESIGN FEATURES	MT REQUIREMENTS
SUBSYSTEMS/ COMPONENTS	• USE EXISTING ENGINE – AVIONICS – ACCESSORIES, ETC.	• MINIMUM – METHODS IMPROVEMENTS ONLY
STRUCTURE	• PRIMARILY S/M – MINIMUM MACHINED PARTS • CONSTANT SECTION FUSELAGE • CONSTANT SECTION CONTROL SURFACES • USE LH/RH INTERCHANGEABLE COMPONENTS (LANDING GEAR, CONTROL SURFACES)	• MINIMUM – LOW COST S/M TOOLING • COMMON USE TOOLING • MINIMUM EQUIPMENT REQUIREMENTS
ASSEMBLY AND INSTALLATION	• CONVENTIONAL ALUMINUM FASTENERS • LAP SKIN – JOINTS • LOW PRESSURE HYDRAULIC SYSTEMS • DESIGNED FOR BREAK-BACK SUBASSEMBLIES	• PERMITS MAXIMUM USE OF AUTOMATIC RIVETING: • M.T. IS AVAILABLE, PROVEN, AND ONLY REQUIRES CONTINUED MANUFACTURING-TO-COST IMPROVEMENTS

TABLE 2.

**HIGH SPEED AIRCRAFT DESIGN FEATURES
VERSUS
MANUFACTURING TECHNOLOGY REQUIREMENTS**

	DESIGN FEATURES	MT REQUIREMENTS
SUBSYSTEMS/ COMPONENTS	• ENGINE IN DEVELOPMENT PARALLEL WITH AIRFRAME – ADVANCED AVIONICS-HIGH PERFORMANCE ACCESSORIES	• NEW MT REQUIREMENTS – NEW TOOLING – EQUIPMENT INVESTMENTS • CONTINUED MT – MTC
STRUCTURE	• EXTENSIVE USE OF EXOTIC METALS • DOUBLE CURVATURE FUSELAGE • EXTENSIVE S/M AND MACHINE PROFILING • TAPERED WINGS, CONTROL SURFACES • COMPOSITES	• NEW MT FOR MACHINING EXOTIC METALS • EXPENSIVE MACHINE TOOLS • CAM REQUIREMENTS • NEW MT FOR COMPOSITE MANUFACTURE • CONTINUED MT – MTC
ASSEMBLY AND INSTALLATION	• EB WELDING • SPECIAL PURPOSE FASTENERS • BUTT JOINTS – FAYING SURFACES • PRESSURE SEALING • HIGH PRESSURE HYDRAULIC SYSTEMS • HIGH DENSITY WIRING/TUBING • WIRE SHIELDING	• LIMITED USE OF AUTOMATIC RIVETING • MT FOR EB WELDING • HIGH MAN-HOURS FOR CLOSE TOLERANCE ASSEMBLY • MT FOR DEVELOPMENT OF HIGH PRESSURE HYDRAULIC FITTINGS AND TUBING • AVOID RF PROBLEMS

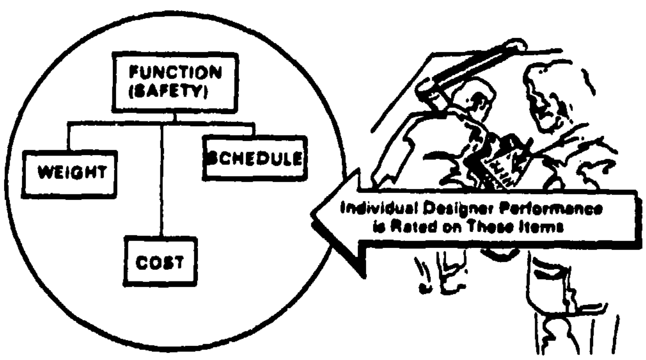


FIGURE 1.

PRESENT AIRCRAFT DESIGN TEAM PRIORITIES

IMPACT OF DECISIONS ON COST

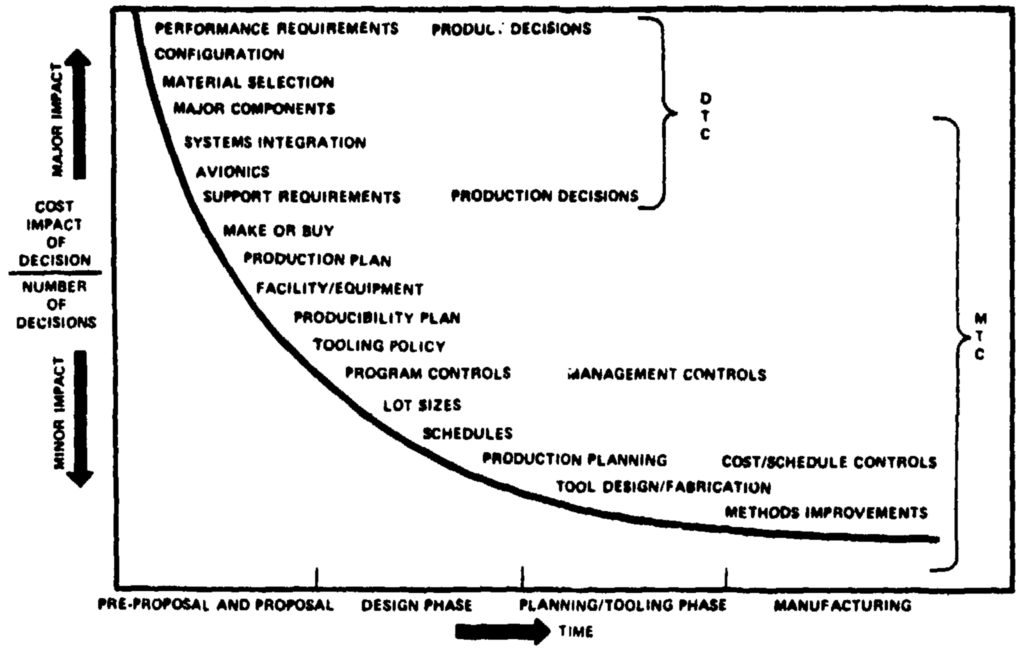


FIGURE 2.

AIRFRAME TRADE-OFF STUDY FLOW DIAGRAM

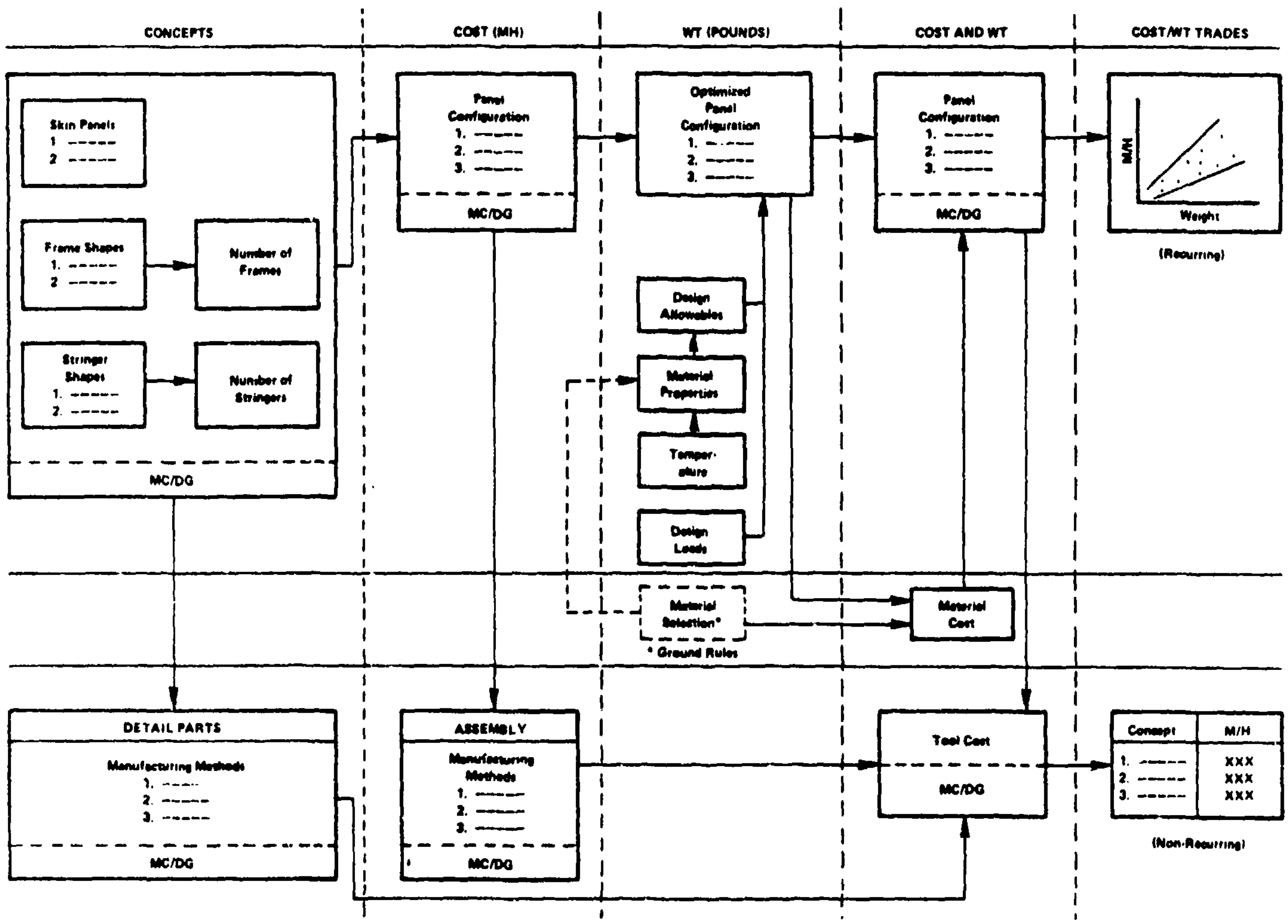


FIGURE 3.

2. OBJECTIVES OF DESIGN GUIDE

The objectives of the MC/DG are to:

- Provide designers with urgently needed, quick, simple, and quantitative cost comparisons of manufacturing processes.
- Emphasize design orientation in formats and manufacturing man-hour data for use at all phases of the design process, i.e., preliminary and detail design, therefore increasing the emphasis on cost as a vital parameter.
- Enable designers to conduct more extensive manufacturing cost trade-offs for airframe components and aerospace electronics fabrication and assembly.
- Emphasize potential cost advantages of emerging materials and manufacturing methods, accelerating the transfer of these technologies to production hardware.
- Guide the designer to the lowest cost manufacturing processes early in the design phase to avoid cost drivers.
- Identify cost driving manufacturing operational sequences which provide targets for future computer-aided manufacturing (CAM) efforts.

The contents of the MC/DG for airframes are shown in Table 3. A guide for electronics is also under development and the contents are shown in Table 4.

3. MC/DG PROGRAM ORGANIZATION

The MC/DG Data Development program is administered under the technical direction of Capt. Richard R. Preston, Computer Integrated Manufacturing Branch, Manufacturing Technology Division, Materials Laboratory (AFWAL/MLTC).

Battelle's Columbus Laboratories (BCL) is the prime contractor. The Program Manager at BCL is Mr. Bryan R. Noton. The effort is supported by a team comprising the following airframe and electronic industry subcontractors:

TABLE 3.

MC/DG VOLUME CONTENTS: MANUFACTURING TECHNOLOGIES FOR AIRFRAMES

I	II	III	IV	V	VI
PROCURED ITEM COSTS	MATERIAL REMOVAL COSTS	DETAIL FABRICATION COSTS	MATERIAL TREATMENT COSTS	ASSEMBLY* COSTS	TEST, INSPECTION, AND EVALUATION COSTS
EXTRUSIONS CASTINGS FORGINGS	MACHINING (UNDER DEVELOPMENT)	SHEET METAL COMPOSITES	HEAT TREATMENT SURFACE TREATMENT	METALLIC ASSY. NON-METALLIC ASSY. *MAJOR AND FINAL ASSEMBLY	SHEET METAL ASSEMBLY CASTINGS FORGINGS MACHINING COMPOSITES

CATEGORIES = PROCURED ITEM COSTS, ETC.
SECTIONS = FORGINGS, ETC.
SUBSECTIONS = MACHINING, ETC.

TABLE 4.

MC/DG VOLUME CONTENTS: MANUFACTURING TECHNOLOGIES FOR ELECTRONICS

I	II	III		IV
PROCURED ITEMS	DETAIL FABRICATION	ASSEMBLY		TEST, INSPECTION, AND EVALUATION (TI&E)
SCHEMATIC PARTS INTERCONNECT PARTS HARDWARE FABRICATED PARTS	METALLICS NON-METALLICS SURFACE TREATMENT COATINGS MARKING	MECHANICAL ASSEMBLY COMPONENT ASSEMBLY (PRE-WAVE AND POST-WAVE) CLEANING SOLDERING SHEET METAL/ STANDOFF ASSEMBLY (HARD WIRING) CABLE/WIRE HARNESSS ASSEMBLY	HYBRIDS CHASSIS ASSEMBLY FINAL EQUIPMENT ASSEMBLY POST-ASSEMBLY PROCESSES POTTING ADHESIVES	CARD/MODULE LEVEL TEST BURN-IN/SCREENING TEST DEVICE/EQUIPMENT TEST

Airframe/Avionic Company	Program Managers
General Dynamics Corporation, Fort Worth Division	P.M. Bunting B.E. Kaminski
Grumman Aerospace Corporation	V.T. Padden A.J. Tornabe
Honeywell, Incorporated	R. Remski
Lockheed-California Company	A.J. Pillera J.F. Workman
Northrop Corporation, Aircraft Group	J.R. Hendel A.P. Langlois
Rockwell International Corporation, North American Aircraft Operations	R.A. Anderson
Rockwell International Corporation, Collins Avionics Division	J.G. Vecellio

The Boeing Commercial Airplane Company also participated in the first two MC/DG contracts. Mr. R. H. Hammer, Mr. David Weiss, and Mr. Peter H. Bain were the Program Managers at Boeing during these phases.

The team approach to development of manufacturing cost data offers several important advantages. Principally, this approach:

- Provides data for a cross section of small and large aircraft for the entire industry; both military and commercial.
- Assures interface with all levels of designers. Industry has therefore utilized the MC/DG rapidly in the design process.
- Draws on each company's expertise, making results more viable. Expertise and installed manufacturing facilities vary across industry.
- Provides a broad base from which to collect and develop data.
- Provides the required base for deriving average industry data (which cannot be achieved without the team approach).

- Lends credibility to data and formats for designer use, as compared to the parochial point of view of a single company.

- Provides a broad base for utilizing the results of DoD manufacturing technology (MT) programs to reduce acquisition cost.

4. GROUND RULES FOR DATA DEVELOPMENT

To promote understanding and ensure consistency, uniformity, and accuracy in generating and integrating data into the formats, the team developed general and detailed ground rules for each MC/DG section. Major groupings of ground rules are:

(a) Definition of Aerospace Discrete Parts
(b) Material Selection
(c) Manufacturing Methods
(d) Facilities Required
(e) Data Generation--Recurring Costs
(f) Data Generation--Nonrecurring Costs
(g) Support Function Modifiers.

5. AIRFRAME PART DEFINITIONS

For determining manufacturing man-hours (composites selected), the MC/DG subdivides airframe parts as follows:

1. **Base Part**: A part in its simplest geometric form, i.e., without complexities such as strip-plies, cutouts, and doublers.

2. **Designer-Influenced Cost Elements (DICE)**: Includes strip-plies, cutouts, doublers, and special tolerances that add cost through the increased fabrication operations and tooling required over the standard manufacturing method for the base part.

3. **Detailed or Discrete Parts**: A distinct airframe structural part which may incorporate complexities, e.g., a base part plus DICE, ready for assembly to perform its required function in the airframe.

The MC/DG man-hour information is presented in basically three forms: the lowest cost processes for the designer; manufacturing methods for multiple discrete parts; and multiple manufacturing methods for single discrete parts. This leads to the building-block approach illustrated in Figure 4.

6. MANUFACTURING COST DRIVERS

To develop this model, with a section-by-section layout of the MC/DG for airframes, it was necessary to identify the cost drivers for each conventional and emerging manufacturing technology included in the list of contents, Table 3.

The following are examples of cost drivers in typical fabrication processes:

Forgings

- Forging process
- Material
- Quality requirements
  - Tolerances
  - Metallurgical properties
  - NDI/NDE
- Quantity, lead time, and lot releases
- Complexity
- Size

Casting

- Casting process
- Material
- Quality requirements
  - Tolerances and surface texture
  - Metallurgical properties
  - NDI/NDE
- Quantity

UTILIZATION OF DATA IN SHEET METAL DISCRETE PART AND MECHANICALLY FASTENED ASSEMBLY SECTIONS

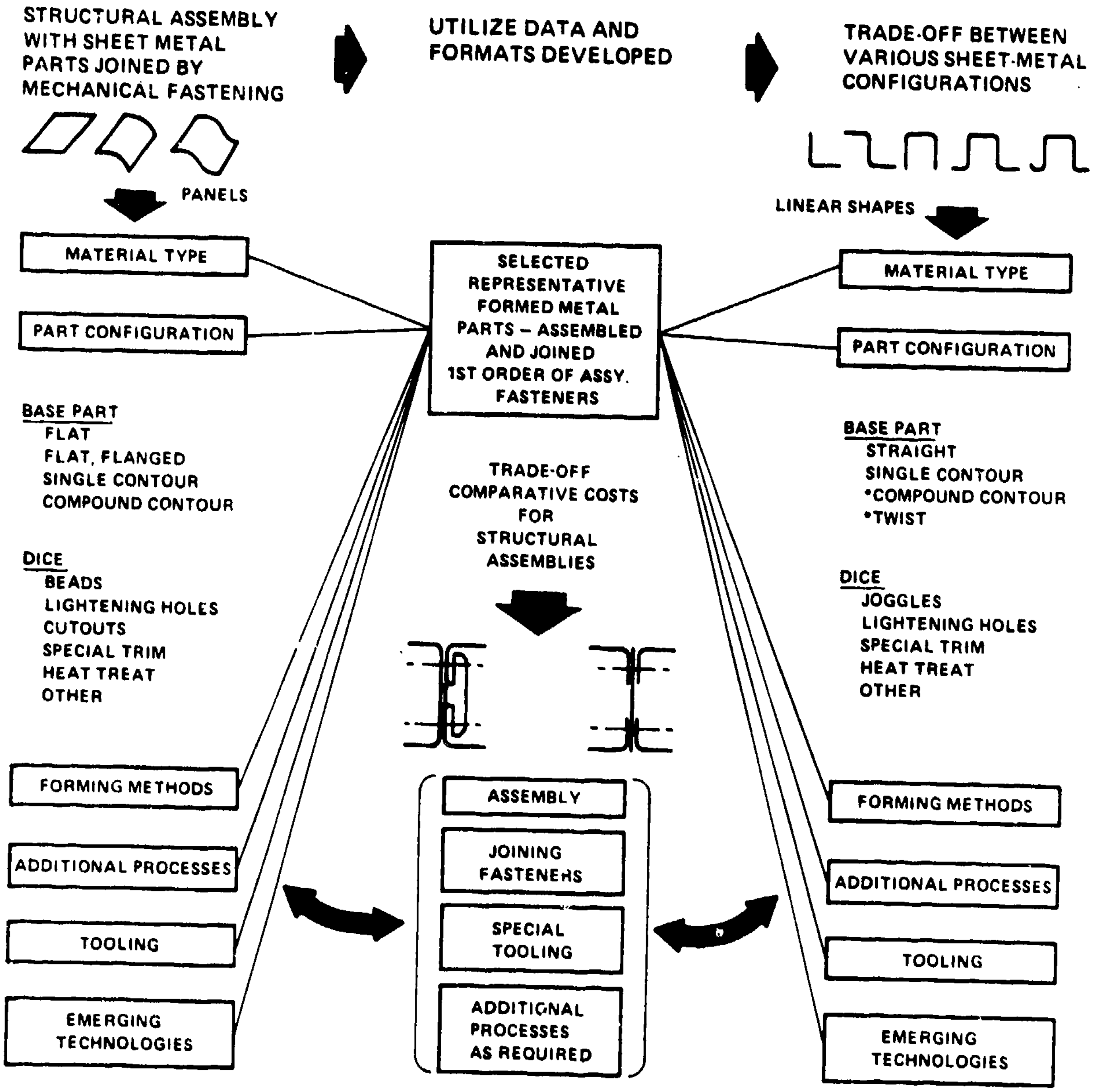


FIGURE 4. BUILDING-BLOCK APPROACH OF MC/DG

- Complexity
- Size
- Subsequent machining

Mechanical Fastening

- Accessibility
- Jigging requirements
- Sequencing requirements
- Materials joined
- Sealing
- Quantity
- Stack-up of parts
- Number of parts
- Number and types of fasteners
  - Hand rivets
  - Drivematic rivets
  - Threaded fasteners
- Tolerances
- Assembly size

Surface Treatment

- Surface preparation
- Size
- Complexity
- Energy requirements
- Quantity
- Materials
- Tolerances

Advanced Composite Fabrication

- Fiber types
- Fiber mix (hybrids)
- Resin systems
- Part type and function

- Part size
- Number of plies
- Overlaps
- Gaps
- Lot size
- Automatic versus manual lamination
- Curing method
- Facility requirements
- Tooling concepts
- Quality requirements

Sheet Metal Forming

- Material type (formability)
- Complexity of configuration
- Size
- Tolerances
- Quantity
- Heat-treatment
- Inspection.

Based on these cost drivers, data requirements were specified for subsequent development of the designer-oriented formats to present cost and man-hour data. Examples of these formats are shown in Figures 5 to 7.

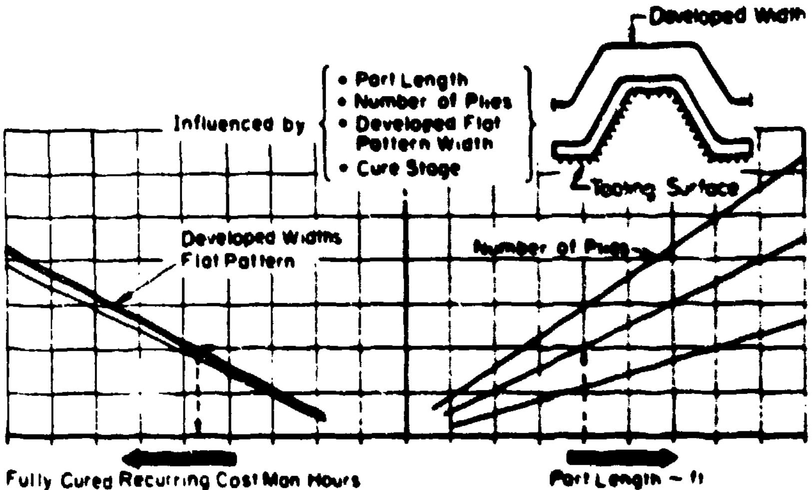
7. METHODOLOGIES FOR PRESENTING DATA TO DESIGNERS

The MC/DG presents manufacturing cost data to designers in terms of:

- Cost Driver Effects (CDE)
- Cost Estimating Data (CED).

The objectives of the CDE and CED methodologies are to provide:

COMPOSITE HAT SECTION RECURRING COST/PART



Fully Cured Recurring Cost Man Hours
For "B" Staged Recurring Cost,
Multiply by X
See Ground Rules for Limitations and Considerations

FIGURE 5.

COMPOSITE HAT SECTION TOTAL NONRECURRING TOOLING COST/PART

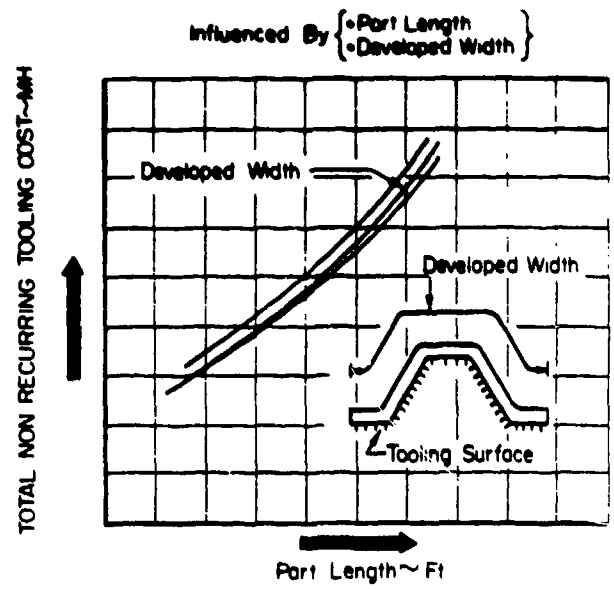


FIGURE 6.

CUTOUT-HOLE RECURRING COST/DETAIL

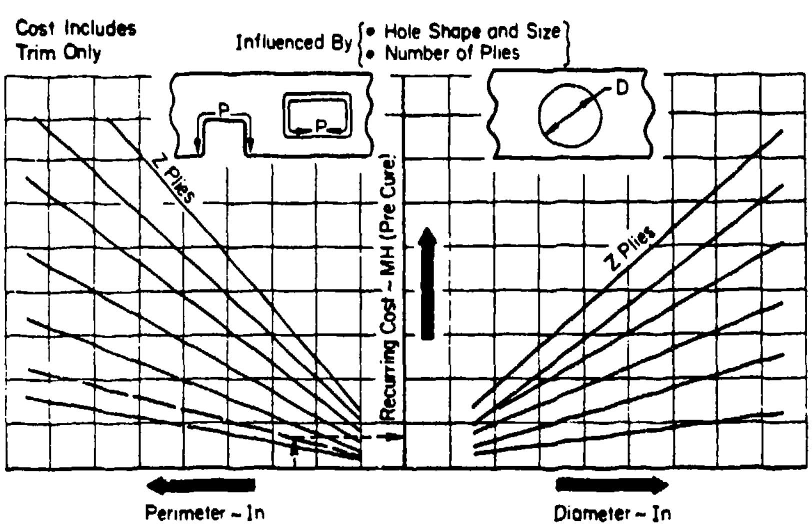


FIGURE 7.

• A simple approach for designer use of formatted data to achieve lower fabrication costs: both CDE and CED.	**DIRECTION**
• Qualitative cost guidance while developing low cost design configuration alternatives for parts and assemblies: CDE	**COMPARISON**
• The designer with the capability of performing trade-offs to estimate actual fabrication man-hours or costs: CED.	**COST**

Thus, the CDE and CED methodologies can provide the designer with guidance for obtaining lower manufacturing costs at the preliminary and detail design phases:

- Cost-Driver Effects (CDE) provide qualitative guidance.
- Cost-Estimating Data (CED) provide quantitative results.

The CDE approach enables designers to:

- Identify the intensive cost drivers that increase the manufacturing cost of the design
- Determine the relative effects of cost drivers over which they have control
- Reduce the impact of the cost drivers.

8. FORMAT DEVELOPMENT CRITERIA

The BCL industry team developed the MC/DG formats to meet the following criteria:

- Emphasize cost drivers
- Be simple to use
- Use designer language
- Instill confidence
- Be economical
- Be accessible
- Be maintainable.

An overview selection aid indicating the sections available in the guide is shown in Figure 8. An example of a format selection aid for a specific section (composites) in the MC/DG is shown in Figure 9.

9. PROCEDURE TO CONDUCT AIRFRAME TRADE-OFF STUDIES UTILIZING MC/DG

The MC/DG will point designers to the lowest cost structural part or configuration meeting the other design objectives, which may include:

- Strength and stiffness
- Minimum weight
- Elevated temperature performance
- Fatigue strength
- Damage tolerance
- Low maintenance
- Crashworthiness
- Corrosion resistance
- Ease of repair.

To accomplish this, the designer can use the following procedure to conduct manufacturing cost trade-off studies:

(a) Develop concepts (Figure 10), which, in the case of a fuselage panel, requires determining the:

- Material
- Skin panel sizing
- Frame shapes
- Number of frames
- Stringer shapes
- Number of stringers
- Joining methods, e.g., bonding versus rivets
- Candidate manufacturing methods for each discrete part in the assembly.

(b) Determine manufacturing costs for each panel configuration.

(c) Determine assembly cost for each configuration.

MC/DG SECTION SELECTION AID

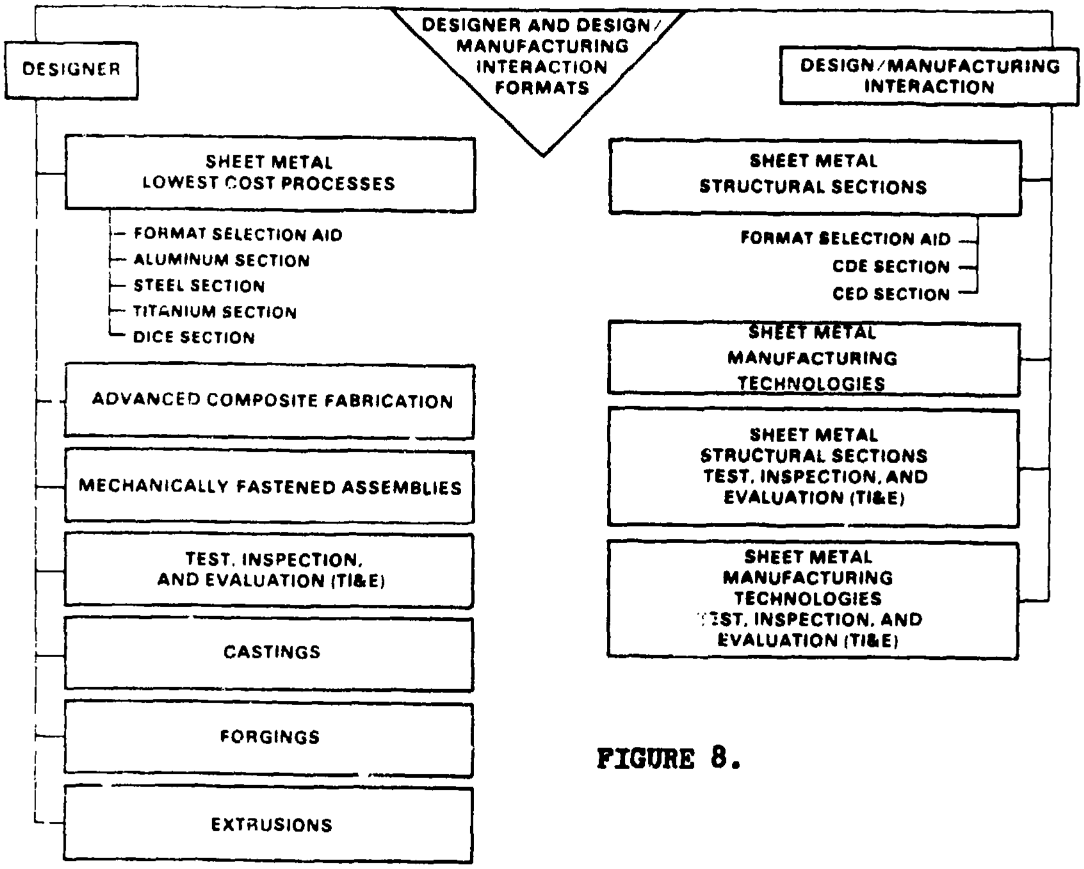


FIGURE 8.

FORMAT SELECTION AID MECHANICALLY FASTENED ASSEMBLIES

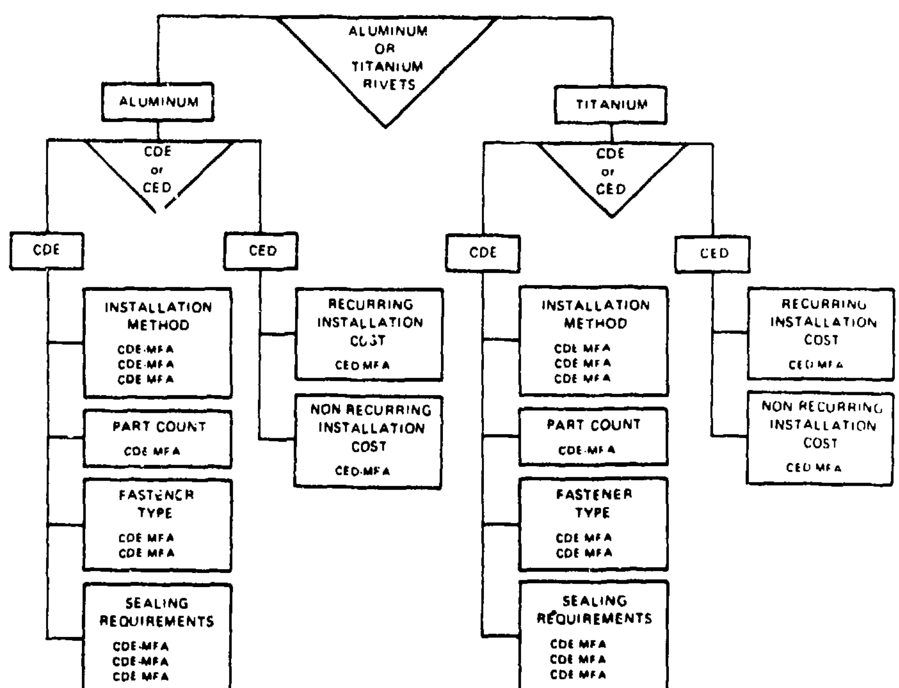
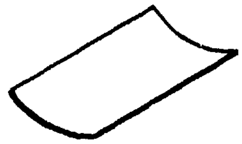
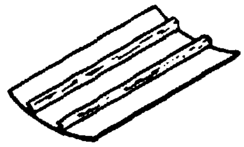
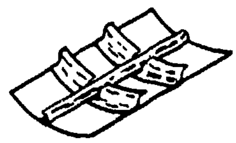
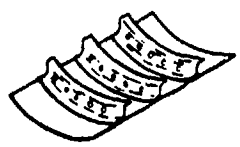


FIGURE 9.

SINGLE CURVATURE PANELS

CONCEPT NO.	DESCRIPTION	
1	UNSTIFFENED SKIN	
2	2 STRINGERS	
3S	1 STRINGER, 2 FRAMES	
4	3 FRAMES	
5	3 FRAMES WITH CUTOUTS	

COMPOUND CURVATURE, TAPERED WIDTH PANEL

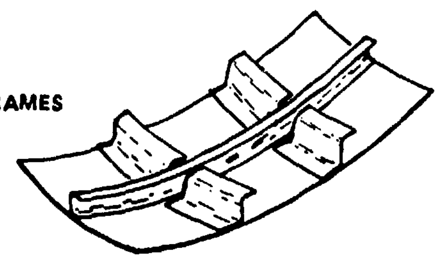
CONCEPT NO.	DESCRIPTION	
3C	1 STRINGER, 2 FRAMES	

FIGURE 10. **EXAMPLES OF CANDIDATE AIRFRAME CONCEPTS FOR AN ALUMINUM FUSELAGE PANEL**

(d) Determine test, inspection, and evaluation (TI&E) costs.

(e) Determine total manufacturing costs, which include materials and tooling.

(f) Determine weight of each panel assembly.

(g) Present manufacturing man-hours or costs and structural weight in summary tables and, if appropriate, on design charts that, for example, show structural weight on the ordinate versus manufacturing cost on the abscissa.

The designer and management selects the optimum structure (discrete part, subassembly, or assembly) with respect to structural weight, other design factors, and manufacturing costs. If a manufacturing facility is committed for the manufacture of other components, or if a facility is not available, decisions to procure parts from other sources or to utilize a substitute, but higher cost method, can be made quickly.

In following this procedure, the designer, once having developed candidate structural configurations to meet all design requirements, such as those listed above, utilizes the MC/DG. The following steps are typical of those taken to arrive at an airframe design with the lowest manufacturing cost:

<u>Step 1</u>: Select materials that meet corrosion, elevated temperature, and other requirements, and review the section ground rules for those materials, e.g., titanium sheet metal or carbon/epoxy.

<u>Step 2</u>: Review the MC/DG ground rules for the discrete parts and assemblies to be analyzed.

<u>Step 3</u>: Record on the designer's worksheet, the Concept No., Part No., description, labor rate, number of parts per aircraft, design quantity, and date. Use one worksheet for each part when conducting the trade-off between parts or a separate worksheet for each subassembly.

Step 4: Using the MC/DG overview selection aid, select MC/DG sections representing the pertinent material types and/or joining methods, e.g., sheet metal or mechanically fastened assemblies.

Step 5: Study the selection aid for each MC/DG section to be used. The selection aid will indicate the CDE formats, CED formats for the manufacturing methods, and also the test, inspection, and evaluation (TI&E) methods for the materials and parts analyzed in the MC/DG in accordance with the ground rules.

Step 6: Review CDE formats providing relative cost information for the materials, parts, and assemblies being analyzed. These CDE formats will provide qualitative information leading to the lowest cost.

Step 7: Utilize the format selection aid to determine the lowest cost manufacturing process and select the format to use. Selection aids and utilization examples precede the formats.

Step 8: Study CED formats for the base parts and any required Designer-Influenced Cost Elements (DICE) using the required dimensions, e.g., length for stringers or area for panels. Note on the designer's worksheet the total labor man-hours/part (including applicable DICE) for each discrete part in the assembly.

Step 9: Check for applicable DICE. The format will indicate which DICE are applicable and in some cases DICE will be incorporated in the manufacturing methods for the base part.

Step 10: Apply the learning curve tables in the MC/DG as required. The manufacturing man-hours figure for each part and assembly in the MC/DG is the average value for the aerospace industry. In most cases, the average value will be sufficiently accurate for comparisons between candidate concepts meeting the design requirements. However, when a company considers it has greater or less experience than the industry average, or if the quantity is greater or less than the 200th unit analyzed in the MC/DG in accordance with the ground rules, the learning curve tables may be required.

Step 11: From the CED chart selected, read the value (man-hours) for the nonrecurring tooling costs (NRTC). Note again that these values are for 200 parts or assemblies. Record the man-hours per part on the designer's worksheet.

Step 12: Record the current manufacturing labor rate, including direct labor fringe benefits and overhead charges, on the designer's worksheet.

Step 13: Using the same procedure as for manufacturing methods, determine TI&E man-hours from that section of the MC/DG and record the TI&E recurring and nonrecurring tooling costs on the designer's worksheet.

Step 14: Insert cost of materials based on furnished data and enter material costs per part in dollars on the designer's worksheet.

Step 15: Consult instructions accompanying the designer's worksheet to determine aerospace vehicle program cost for the discrete part and assembly.

Step 16: Compare results from the designer's worksheets for each part and/or subassembly and, if desired, enter on a diagram (graph) showing weight versus manufacturing cost and compare each concept. In the case of a supersonic aircraft, management and the customer may elect to sacrifice some manufacturing cost for improved performance and, in the case of a low-speed aircraft, to sacrifice some performance for lower manufacturing cost.

Using this procedure, the designer will have compared different design concepts, possibly using different materials, e.g., sheet metal versus composites or castings versus a built-up metal assembly. With each analysis conducted in accordance with the same general ground rules, e.g., lot sizes, design quantity, etc., the designer and management can be confident in the results.

10. COST WORKSHEET FOR AIRFRAME DESIGNERS

Airframe designers can utilize the MC/DG data in a number of ways. The Cost Worksheet shown in Table 5, developed for determining the total cost of an aircraft subassembly, can be used at the discretion of the designer. The designer can determine the program recurring and nonrecurring costs and also the cost per aircraft. Instructions for utilizing this worksheet are shown in Table 6.

TABLE 5.
MC/DG COST WORKSHEET

PAGE ______ OF ______

DESIGN CONCEPT		RECURRING COST (RC)										NONRECURRING COST (NRC)				PROGRAM COST		
		(L . LC + TI&E) LR = L$ + M$ = RC . P/AC . DQ = PRC										(NRC + TI&E) LR = PNRC				10 + 14	DQ = COST/AC	
PART NO	DESCRIPTION	LABOR MC/DG MH/PT (1)	LC FACTOR (2)	LABOR TI&E MH/PT (3)	LABOR RATE $/MH (4)	LABOR RC $/PT (5)	MAT'L $/PT (6)	REC. COST/ PT. $ (7)	PARTS PER AC (8)	DES. QTY. (9)	PROG. RC $ (10)	NRC MC/DG MH (11)	NRC TI&E MH (12)	LABOR RATE $/MH (13)	PROG. NRC $ (14)	PROG COST $ (15)	DES. QTY. (16)	COST AC $ (17)
	TOTALS																	

REMARKS ______________________________

BY: ______________________________

DATE: ______________________________

TABLE 6. INSTRUCTIONS FOR USING MC/DG COST WORKSHEET

Worksheet Column	Input	Procedure
	Part no.	Enter identification, if available.
	Description	Enter brief description, e.g., stiffener, Z & J sections, etc.
1	Manufacturing labor	Enter man-hours per part at 200 units determined from CED format.
2	Learning curve (LC) factor	Enter LC factor based upon learning curve percentage and design quantity. Factor provided by user company.
3	TI&E labor	From MC/DG, enter RC for TI&E (man-hours).
4	Labor rate	Enter current manufacturing labor rate, including direct labor fringe benefits and overhead charges.
5	Labor recurring costs (RC)	Enter the product of Column 1 times Column 2 plus Column 3 times Column 4.
6	Material cost	Based upon furnished data in company utilizing MC/DG enter material cost per part in dollars.
7	Recurring cost (RC) per part	Total of columns 5 and 6.
8	Parts per aircraft	Enter number of identical parts per aerospace system.
9	Design quantity	Enter number of aerospace systems in buy considered.
10	Program recurring cost (RC)	Enter the product of Column 7 times Column 8 times Column 9.
11	Nonrecurring tooling cost (NRTC) for part/assembly	From MC/DG enter NRTC in man-hours.
12	NRTC for TI&E	From MC/DG, enter NRTC for TI&E in man-hours.
13	Labor rate	See Column 3.
14	Program nonrecurring tooling costs (NRTC)	Enter the product of Column 13 times the total of Column 11 and 12.
15	Program cost	Enter the sum of Column 10 and Column 14.
16	Design quantity	See Column 9.
17	Cost per aircraft	Enter the quotient of Column 15 divided by Column 16.

11. DESIGN GUIDE COMPUTERIZATION

Computerization of the cost data and formats obviously represents a very important step in the creation of a tool that will make manufacturing costs associated with various design solutions quickly visible to the design engineer. A sister program has therefore been funded by the Integrated Computer-Aided Manufacturing Branch (ICAM) of the Materials Laboratory, Air Force Wright Aeronautical Laboratories (AFWAL), to develop an automated system--the Manufacturing Cost/Design System (MC/DS). The prime contractor for the MC/DS is Grumman Aerospace Corporation. This company is supported by Rockwell International, Northrop, Vought, Bell Helicopter, Control Data, and SofTech, Inc.

Designers will also be able to use the computerized MC/DG, the MC/DS, to:

- Determine impacts of
  - Material price fluctuations
  - Learning curve base, e.g., aircraft quantity ordered
  - Lot sizes other than the detailed ground rule of 25
  - Labor rate increases
- Retrieve earlier design trade-off data in a readily usable and recognized form
- Extrapolate and interpolate dimensional data for part and assembly manufacture.

Without the computer, designers find evaluation of sometimes critical information of this type to be time-consuming, intricate, and bothersome.

12. EXAMPLES OF TRANSITIONING MC/DG DATA IN DESIGN PROCESS TODAY

- MX-missile stage 4 composite door
  - 10 concepts studied in 8 hours
  - Normal procedure requires 40 hours
  - Cost/weight effective design easily selected
- Composite, titanium, and aluminum fuselage shear panels
  - 4 simple calculations required for each concept
  - 20 to 40 calculations normally required
  - Young engineering graduate designed aluminum panels
- Procurement of B-1B castings and forgings
  - Provides procurement with cost driver guidance
  - Improves interaction with vendors
  - Leads to cost savings for prime contractor and customer.

13. POTENTIAL APPLICATIONS OF MC/DC

Through this development effort, industry has identified a range of potential MC/DG uses. The MC/DG can be used:

- As a working reference for evaluating the impact of engineering changes at various phases of system development
- For decisions on process alternatives based on costs of process routing and assembly techniques
- For use in various manufacturing-engineering operations to meet producibility requirements and to reduce cost
- As an authoritative standard and reference for cost and design information and for guidance in component design and fabrication
- As an aid in understanding cost implications of new manufacturing processes
- For estimating costs of group technology part families

- To guide planning of upgraded, computer-integrated manufacturing facilities within a specific capitalization program.
- To design new products to help meet cost objectives
- To conduct value analysis of manufacturing methods
- As a baseline for CAD/CAM implementation, construction cost trade-offs, and component ranking
- For design/manufacturing/cost reduction and production-readiness reviews; from proposal to production
- To familiarize the organization with the character of interaction between design and manufacturing.

14. POTENTIAL COST SAVINGS

- MC/DG can reduce airframe acquisition costs by 2 to 5 percent.
- On a supersonic attack/fighter costing $14M, the estimated airframe cost is 30 percent.
- The estimated program savings would be:

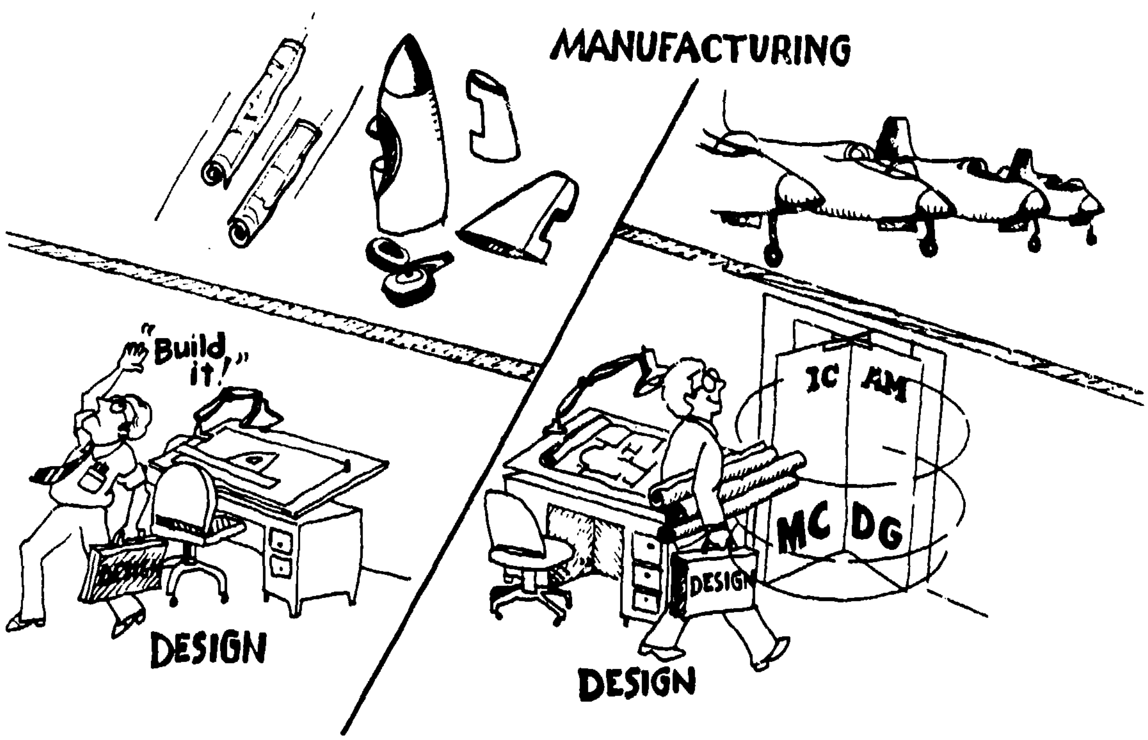
Number of Aircraft:	1	100	300	500
2 percent reduction:	$84,000	$8.4M	$25.2M	$42M
Equivalent airframes:		2	6	10
5 percent reduction:	$210,000	$21M	$63M	$105M
Equivalent airframes:		5	15	25.

15. MC/DG BENEFITS

Summarizing, the MC/DG can benefit industry in many ways. It's use:

- Influences design decisions
- Emphasizes application of low-cost processes
- Provides qualitative/quantitative manufacturing cost data
- Imparts senior designer experience on new engineers
- Provides direct feedback on manufacturing cost impacts
- Bridges CAD and CAM by fostering design/manufacturing interaction
- Allows design trade-offs with known manufacturing cost impacts
- Provides immediate feedback on the cost impact of a documentation change notice.

The ICAM MC/DG payoff on return of investment is cumulative on all electronic and airframe subassemblies and systems; Army, Navy, and Air Force.



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1982 MANUFACTURING TECHNOLOGY ADVISORY GROUP CONFERENCE

AIR FORCE ICAM "MANUFACTURING COST/DESIGN GUIDE" (MC/DG) FOR AIRFRAMES

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Columbus, OH

ABSTRACT

A study of design/manufacturing interaction reveals the need for design methodologies to reduce aerospace systems cost. Cost-driver identification related to performance, design, materials, and manufacturing reinforces the importance of the preliminary design phase. Data are required on designer-influenced cost elements, for example, with composites these are, hybrids, ply count, curing method, and quality requirements. A "Manufacturing Cost/Design Guide" (MC/DG) for composite and metallic airframes is reviewed. The utilization of MC/DG designer-oriented formats for manufacturing processes in trade-studies involving structural performance is shown. The MC/DG can, when fully developed, also indicate potential cost savings of emerging technologies which will accelerate technology transfer.

INTRODUCTION

The need to arrest and reduce costs at all levels of the aircraft system life-cycle is becoming increasingly important. Qualitative and quantitative data on cost-drivers useful during the design, manufacture, operation, and maintenance of aircraft systems, are essential. This is particularly so, because the reduction of newly developed aircraft types has required a need for increased performance; implying reduced weight, better quality, lower ownership cost, including lower energy consumption. Performance must be provided which is affordable.

Increased aircraft performance depends upon the excellence of engineering design. Affordable aircraft performance depends upon manufacturing technology recognizing cost-drivers, in both design and manufacture--avoiding cost-drivers in new designs, and by improving manufacturing methods for existing products. Cost-drivers can be avoided in aircraft design by design-to-cost (DTC). Early identification of cost-

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drivers and corrective action in existing and new products depends upon proficiency in manufacturing-to-cost (MTC). There is a need for proven innovative manufacturing technology ahead of the aerospace systems design phases.

Cost-drivers can be grouped in various categories of aircraft system development, such as:

- Performance
- Design
- Material selection
- Manufacturing.

To provide examples, the cost-drivers for auxiliary components are listed below:

- Performance related
  - Reduced weight
  - Higher operating speeds
  - Increased reliability and maintainability
- Design related
  - High part-count
  - Nonstandardization
  - Tight tolerances
- Material related
  - Cost
  - Availability
  - Utilization
  - Energy
  - Inventory
- Manufacturing related
  - Inspection
  - Equipment
  - Cyclic production
  - Small lot sizes
  - Job shop environment
  - Highly skilled labor
  - Metal removal
  - High scrap rate
  - Deburring/hand-finishing
  - Heat treatment
  - Hand fit-up
  - Energy (autoclave curing).

The individual designer has seldom been trained or has the experience to conduct structural performance/manufacturing cost trade-studies in his daily efforts. However, today the designer is rated not only on his ingenuity to meet the weight and cost objectives but also to achieve this within design schedule limitations (Figure 1). Design-to-lowest cost is now a design discipline. However, Tables 1 & 2 show the significant differences between aircraft types. Design teams must therefore be provided with:

- Tools
  - Identification and documentation of cost-drivers and cost reduction methods in airframe design and manufacture

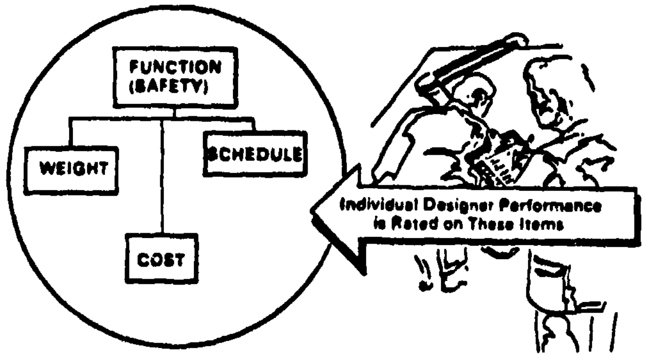


FIGURE 1.
PRESENT AIRCRAFT DESIGN TEAM PRIORITIES

TABLE 1.

LOW SPEED AIRCRAFT DESIGN FEATURES VERSUS MANUFACTURING TECHNOLOGY REQUIREMENTS

	DESIGN FEATURES	MT REQUIREMENTS
SUBSYSTEMS COMPONENTS	• USE EXISTING ENGINE – AVIONICS – ACCESSORIES, ETC.	• MINIMUM – METHODS IMPROVEMENTS ONLY
STRUCTURE	• PRIMARILY S/M – MINIMUM MACHINED PARTS • CONSTANT SECTION FUSELAGE • CONSTANT SECTION CONTROL SURFACES • USE LH/RH INTERCHANGEABLE COMPONENTS (LANDING GEAR, CONTROL SURFACES)	• MINIMUM – LOW COST S/M TOOLING • COMMON USE TOOLING • MINIMUM EQUIPMENT REQUIREMENTS
ASSEMBLY AND INSTALLATION	• CONVENTIONAL ALUMINUM FASTENERS • LAP SKIN – JOINTS • LOW PRESSURE HYDRAULIC SYSTEMS • DESIGNED FOR BREAK-BACK SUBASSEMBLIES	• PERMITS MAXIMUM USE OF AUTOMATIC RIVETING: • M.T. IS AVAILABLE, PROVEN, AND ONLY REQUIRES CONTINUED MANUFACTURING-TO-COST IMPROVEMENTS

TABLE 2.

HIGH SPEED AIRCRAFT DESIGN FEATURES VERSUS MANUFACTURING TECHNOLOGY REQUIREMENTS

	DESIGN FEATURES	MT REQUIREMENTS
SUBSYSTEMS	• ENGINE IN DEVELOPMENT PARALLEL WITH AIRFRAME – ADVANCED AVIONICS-HIGH PERFORMANCE ACCESSORIES	• NEW MT REQUIREMENTS – NEW TOOLING – EQUIPMENT INVESTMENTS • CONTINUED MT – MTC
STRUCTURE	• EXTENSIVE USE OF EXOTIC METALS • DOUBLE CURVATURE FUSELAGE • EXTENSIVE S/M AND MACHINE PROFILING • TAPERED WINGS, CONTROL SURFACES • COMPOSITES	• NEW MT FOR MACHINING EXOTIC METALS • EXPENSIVE MACHINE TOOLS • CAM REQUIREMENTS • NEW MT FOR COMPOSITE MANUFACTURE • CONTINUED MT – MTC
ASSEMBLY AND INSTALLATION	• EB WELDING • SPECIAL PURPOSE FASTENERS • BUTT JOINTS – FAYING SURFACES • PRESSURE SEALING • HIGH PRESSURE HYDRAULIC SYSTEMS • HIGH DENSITY WIRING/TUBING • WIRE SHIELDING	• LIMITED USE OF AUTOMATIC RIVETING • MT FOR EB WELDING • HIGH MAN-HOURS FOR CLOSE TOLERANCE ASSEMBLY • MT FOR DEVELOPMENT OF HIGH PRESSURE HYDRAULIC FITTINGS AND TUBING • AVOID RF PROBLEMS

- Incentives

  - Cost targets against which performance of design personnel can be manufactured.

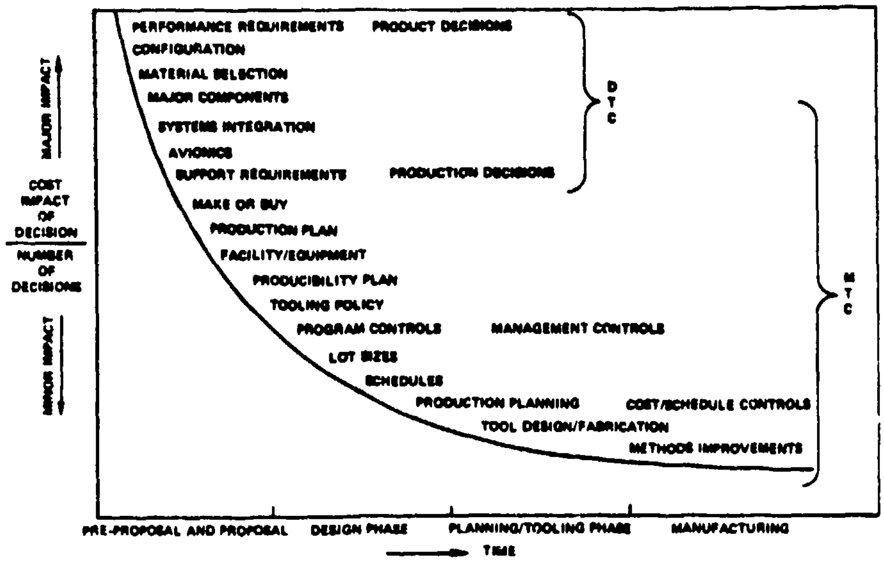
In the past, the designer had only one resource to determine cost: the cost estimator. The cost estimator is still an important factor in the final iteration of the design prior to production commitment. However, it is often difficult to meet scheduling requirements, as well as, to consider an adequate number of design alternatives while ascertaining, with confidence, that the selected design is actually the lowest cost alternative. The MC/DG now provides an unprecedented opportunity for the designer to study a large number of alternative design configurations, e.g., 10, of airframe subassemblies to achieve the lowest manufacturing cost.

Strong interaction between design and manufacturing is essential to achieve the required advancement in manufacturing sophistication. While the MC/DG will eventually be applicable at all levels of the design process, the importance of the preliminary design phase, the "window of opportunity", needs to be emphasized. Figure 2 shows the cost impact of decisions as a function of the number of decisions. Figure 3 illustrates the applicability of the MC/DG from airframe concept development through concept selection.

OBJECTIVES OF DESIGN GUIDE

The objectives of the MC/DG are to:

- Provide to designers urgently needed, quick, simple and quantitative cost comparisons of manufacturing processes
- Emphasize design orientation of MC/DG formats and manufacturing man-hour data for use at all phases of design process, i.e., preliminary and detail design, therefore, increasing emphasis on cost as a vital parameter
- Enable more extensive manufacturing cost trade-offs to be conducted on airframe components and aerospace electronics fabrication and assembly
- Emphasize potential cost advantages of emerging materials and manufacturing methods accelerating the transfer to production hardware of these technologies
- Guide the designer to the lowest cost manufacturing processes early in the design phase to avoid cost-drivers

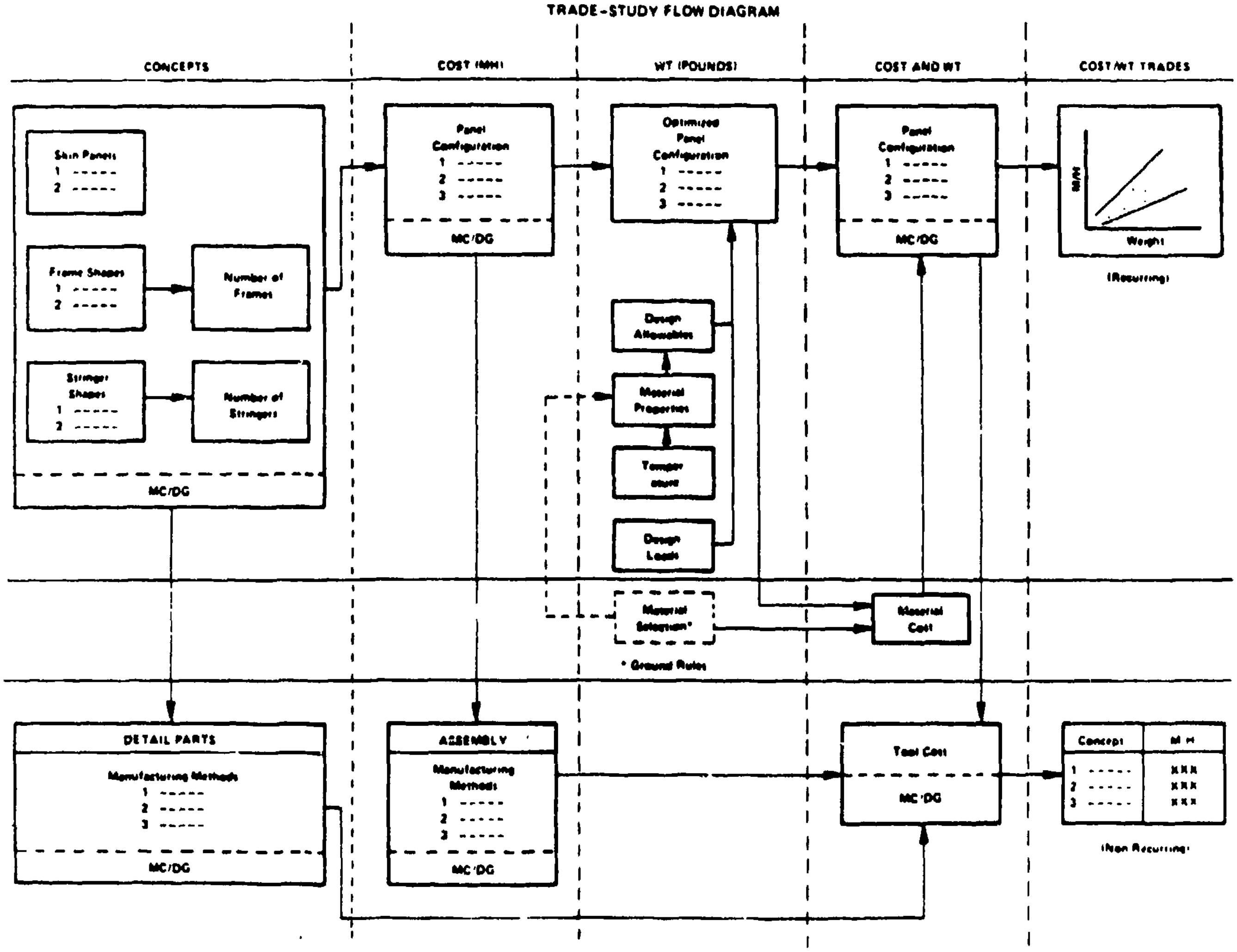


IMPACT OF COST VS DECISION

FIGURE 2.

FIGURE 3.

TRADE-STUDY FLOW DIAGRAM



- Identify cost-driving manufacturing operational sequences which provide targets for future computer-aided manufacturing (CAM) efforts.

The contents are shown in Table 3. Using advanced composite fabrication as the example, Figure 4 illustrates the interaction between various Air Force cost analysis programs.

The MC/DG will be available in both hard copy and as a computerized manufacturing cost/design system (MC/DS) being developed by another coalition headed by Grumman Aerospace Corporation.

TABLE 3.

MC/DG VOLUME CONTENTS: "MANUFACTURING TECHNOLOGIES FOR AIRFRAMES"

I	II	III	IV	V	VI	VII
PROCURED ITEM COSTS	MATERIAL REMOVAL COSTS	DETAIL FABRICATION COSTS	MATERIAL TREATMENT COSTS	PERMANENT JOINING* COSTS	ASSEMBLY* COSTS	TEST, INSPECTION AND EVALUATION COSTS
FORGINGS CASTINGS EXTRUSIONS MATERIALS FASTENER SYSTEMS EMERGING PROC.	MACHINING CHEM MILLING EDM ECM EMERGING PROC.	METALLIC NON-METALLICS EMERGING PROC.	HEAT TREATMENT SURFACE TREATMENT EMERGING PROC.	WELDING ADHESIVE BONDING BRAZING EMERGING PROC. *SUB-ASSEMBLY	METALLIC ASSY. NON-METALLIC ASSY. EMERGING PROC. *MAJOR AND FINAL ASSEMBLY	METALLIC NON-METALLICS

CATEGORIES = MATERIAL REMOVAL, ETC.
SECTIONS = MACHINING, ETC.
SUBSECTIONS = TURNING AND MILLING, ETC.

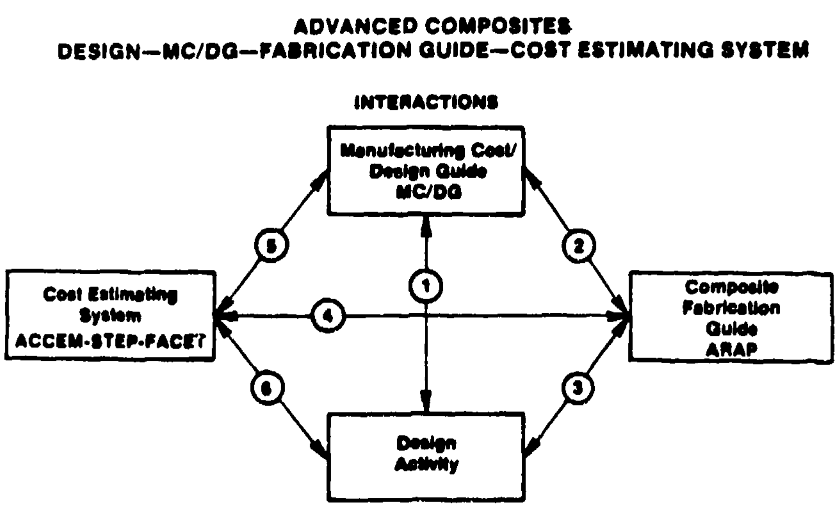


FIGURE 4. INTERACTION BETWEEN AIR FORCE PROGRAMS

GUIDE PROJECT ORGANIZATION

This program is administered under the technical direction of Capt. Richard R. Preston, Computer Integrated Manufacturing Branch, Materials Laboratory (AFWAL/MLTC), Air Force Wright Aeronautical Laboratories, AFSC, Wright-Patterson Air Force Base, Ohio 45433.

Battelle's Columbus Laboratories (BCL) is the prime contractor on the MC/DG Data Development Program. The Program Manager at BCL is Mr. Bryan R. Noton. The program is supported by the following airframe and electronics industry subcontractors:

Airframe/Avionic Company	Program Managers
General Dynamics Corporation, Fort Worth Division	P. M. Bunting B. E. Kaminski
Grumman Aerospace Corporation	V. T. Padden A. J. Tornabe
Honeywell, Incorporated	R. Remski
Lockheed-California Company	J. F. Workman
Northrop Corporation, Aircraft Group	J. R. Hendel A. P. Langlois
Rockwell International Corporation, North American Aircraft Operations	R. A. Anderson
Rockwell International Corporation, Avionics & Missiles Group, Collins Avionics Division	J. G. Vecellio

Boeing Commercial Airplane Company also participated in the first two MC/DG contracts. Mr. R. H. Hammer, Mr. David Weiss, and Mr. Peter H. Bain were the Program Managers at Boeing during various phases.

Multi-Company Approach

Important advantages are evident in the development of manufacturing man-hour data by a team of major aerospace companies. The principal advantages are as follows:

- Provides a cross-section of small and large aircraft for the entire industry; both military and commercial
- Present team members have large interface with all levels of designers. Industry will, therefore utilize the MC/DG rapidly in the design process

- Team draws on each company's expertise making results more viable (expertise and installed manufacturing facilities vary across industry).
- Team has an extensive source of available data and provides a broad base from which to collect and develop data.
- Team provides the required base for deriving average industry data (which cannot be achieved without the team approach).
- Team can verify and thus provide confidence to data and formats for designer use, rather than a parochial point of view of a single company.
- Team provides a broad base for emerging technologies and utilization of DoD manufacturing technology (MT) research program results.

GROUND RULES FOR DATA DEVELOPMENT

General and detailed ground rules for each MC/DG section were developed by the team. Ground rules are necessary and important as they promote understanding, ensure consistency, uniformity, and accuracy in generating and integrating data into the formats. The following are examples of ground rules for sheet-metal aerospace discrete parts.

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

(a) Sheet-Metal Discrete Parts
(b) Materials
(c) Manufacturing Methods
(d) Facilities
(e) Data Generation - Recurring Costs
(f) Data Generation - Nonrecurring Costs
(g) Support Function Modifiers.

AIRFRAME PART DEFINITIONS

The following indicates the subdivison of airframe parts to determine manufacturing man-hours (composites selected):

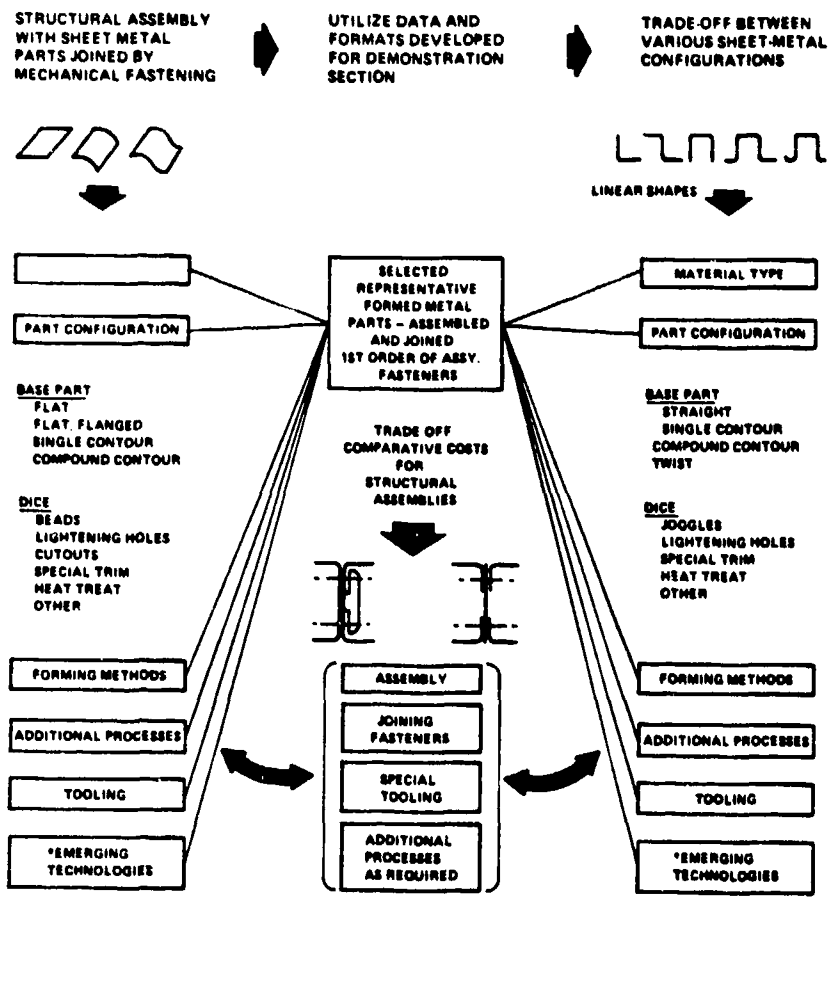
1. Base Part: A detailed part in its simplest form, i.e., without complexities such as strip-plies, cut-outs, and doublers.
2. Designer-Influenced Cost Elements (DICE): Includes strip-plies, cut-outs, doublers, and special tolerances that add cost to the increased fabrication operations and tooling required over the standard manufacturing method (SMM) for the base part.

3. Detailed or Discrete Parts: A distinct airframe structural part which may incorporate complexities, e.g., a base part plus DICE, ready for assembly to perform its required function in the airframe.

The MC/DG man-hour information is presented in basically three forms. These are the lowest cost processes for the designer; manufacturing methods for multiple discrete parts; and multiple manufacturing methods for single discrete parts. This building-block approach is illustrated in Figure 5.

FIGURE 5.

UTILIZATION OF SHEET METAL AEROSPACE DISCRETE PART DEMONSTRATION SECTION



MANUFACTURING COST-DRIVERS

To develop the model, or section-by-section layout of the MC/DG, it was necessary to identify the cost-drivers for each conventional and emerging manufacturing technology included in the list of contents, Table 3.

The following are examples of cost-drivers in typical fabrications processes:

Forgings

- Forging processes
- Material
- Quality requirements
  - Tolerances
  - Metallurgical properties and NDI/NDE
- Quantity, lead-time and lot releases
- Complexity
- Size.

Castings

- Casting process
- Material
- Quality requirements
  - Nondestructive testing
  - Destructive testing
  - Finished part tolerances and surface texture
  - Metallurgical properties
- Quantity
- Complexity
- Size
- Subsequent machining.

Mechanically Fastened Assemblies

- Accessibility
- Jigging requirements
- Sequencing requirements
- Materials joined
- Sealing
- Quantity
- Stack-up of parts
- Number of parts
- Number and type of fasteners
  - Hand rivets
  - Drivematic rivets
  - Threaded fasteners
- Tolerances
- Assembly size.

Surface Treatment

- Surface preparation
- Size
- Complexity
- Energy requirements
- Quantity
- Materials
- Tolerances.

<u>Welding</u>

- Material
- Welding processes
- Weld method
  - Manual
  - Mechanized
  - Automatic
- Type of joint
- Weld classification
  - Primary structure
  - Secondary structure
  - Non-load bearing, non-structural
- Size of assembly
- Length and number of passes
- Path complexity, e.g., straight, curved, irregular
- Pre- and post-weld processing (heat treatment and straighten)
- Tooling complexity
- Inspection
- Proof loading
- Weld repair.

<u>Advanced Composites</u>

- Fiber types
- Part type and function
- Part size
- Number of plies
- Overlaps
- Gaps
- Lot size
- Resin systems
- Fiber mix (hybrids)
- Quality requirements
- Automatic vs. manual lamination
- Curing method
- Facility requirements
- Tooling concept.

<u>Sheet-Metal Forming</u>

- Material type (formability)
- Complexity of configuration
- Size
- Tolerances
- Quantity
- Heat-treat conditions and other process requirements.

The above cost-drivers enabled the data requirements to be specified for subsequent development of the designer-oriented formats. Examples of these formats are shown in Figures 6 to 12.

METHODOLOGIES FOR PRESENTING DATA TO DESIGNERS

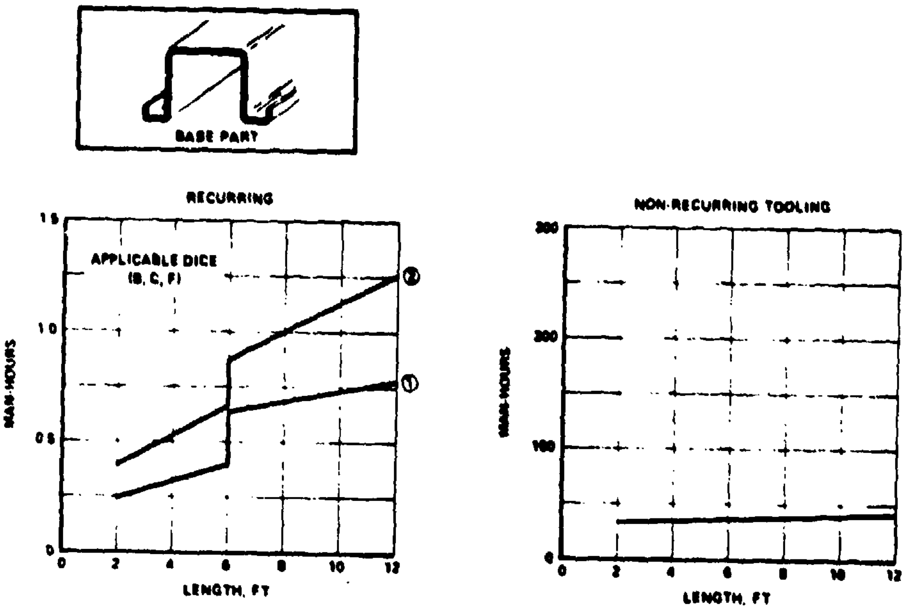
When presenting cost-drivers and manufacturing man-hour data to designers, the following terminologies were selected:

- Cost-Driver Effects (CDE)
- Cost-Estimating Data (CED).

FIGURE 6.

ALUMINUM LIPPED HAT, STRAIGHT MEMBER, LOWEST COST PROCESS

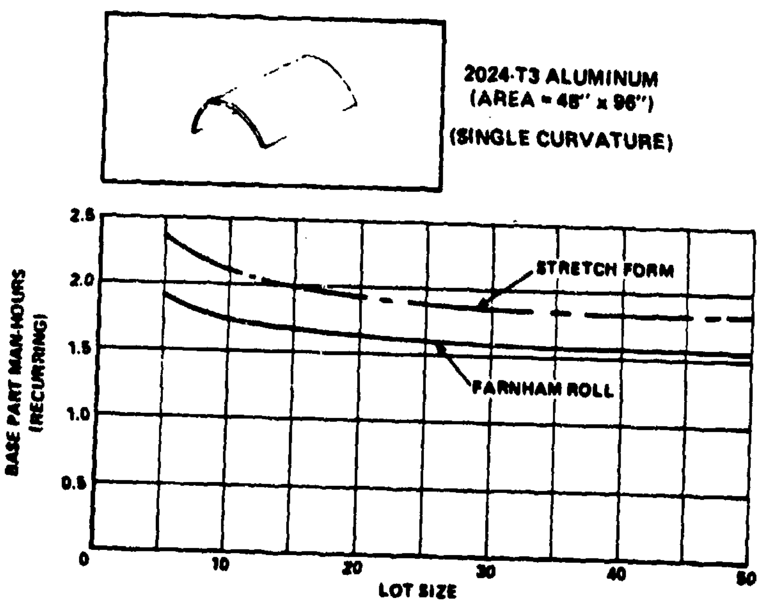
BRAKE FORM



(1) PART FORMED IN T3 CONDITION (NO SOLUTION HEAT TREAT), MINIMUM BEND RADIUS = 3.5t
(2) PART FORMED IN "O" OR "W" CONDITION T62 FINAL TEMPER, MINIMUM BEND RADIUS = 1.5t

FIGURE 7.

COST EFFECT OF LOT SIZE—SKIN PANEL



COMPOSITE HAT SECTION RECURRING COST/PART

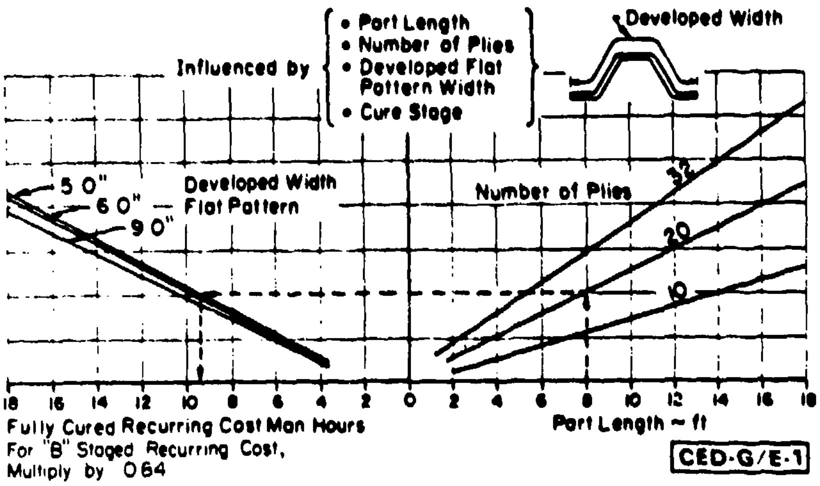


FIGURE 8.

COMPOSITE HAT SECTION TOTAL NONRECURRING TOOLING COST/PART

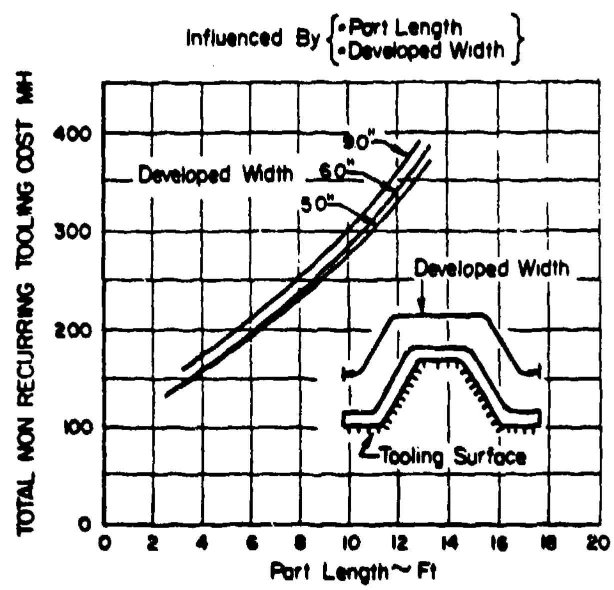


FIGURE 9.

See Ground Rules for Limitations and Considerations

CED-G/E-2

CUTOUT-HOLE RECURRING COST/DETAIL

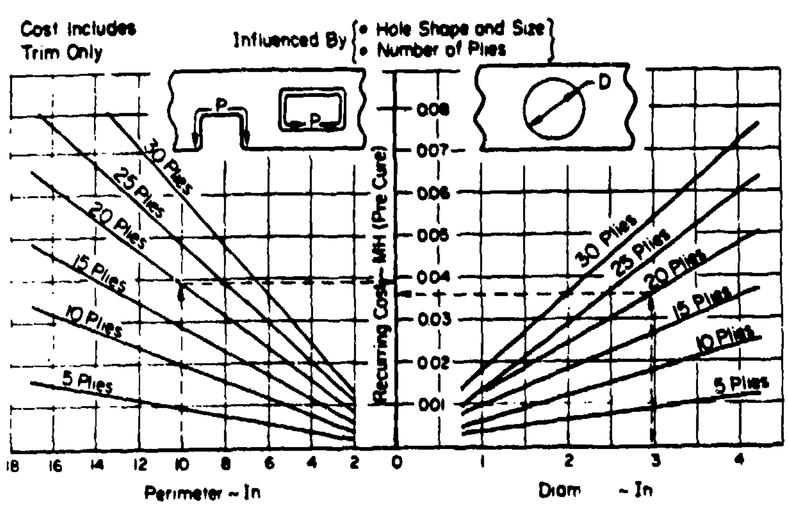
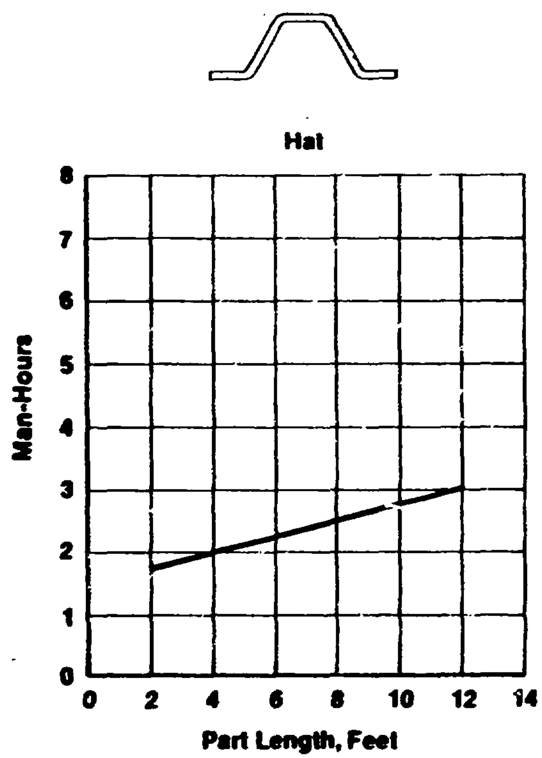


FIGURE 10.

FIGURE 11.

**TEST, INSPECTION AND EVALUATION (TI&E)
COMPOSITE HAT SECTION
RECURRING COST/PART**

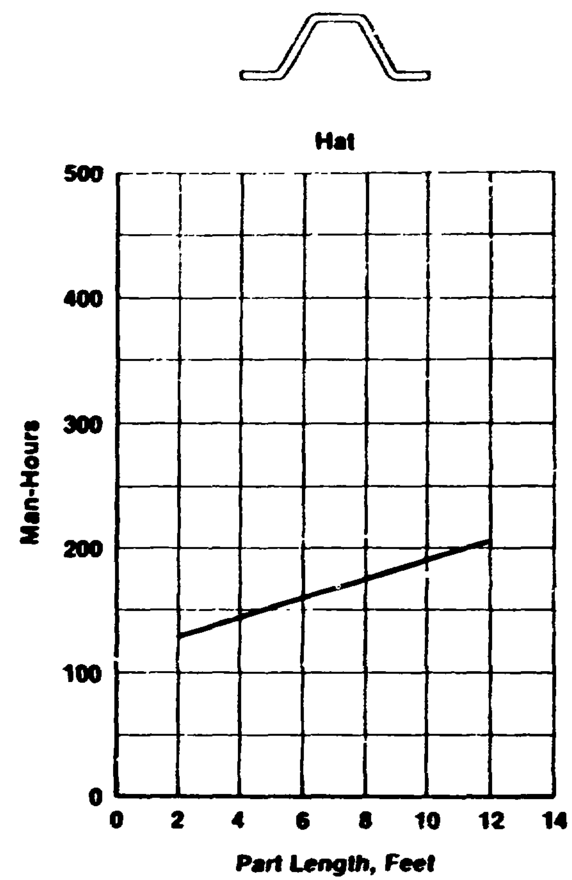


- **Applies to laminates up to 32 plies.**

CED-TI&E-G/E-1

FIGURE 12.

**TEST, INSPECTION AND EVALUATION (TI&E)
COMPOSITE HAT SECTION
NONRECURRING COST/PART**



- **Includes tooling, first article acceptance, ultrasonic reference standard (URS), and tool proof.**

CED-TI&E-G/E-2

The objectives of the CDE and CED methodologies are:

• To develop a simple approach for the use of formatted data by designers to achieve lower fabrication costs during design phases: both CDE and CED	DIRECTION
• To provide qualitative cost guidance to perform simple trade-offs to achieve lowest fabrication cost: CDE	COMPARISON
• To provide the designer with the capability to perform trade-offs to achieve quantitative rough-order-of magnitude (ROM) estimated fabrication costs: CED.	COST

The CDE and CED methodologies provide the designer with cost guidance for achieving lower manufacturing costs at the preliminary and detail design phases. Summarizing:

- Cost-Driver Effects (CDE) provides qualitative guidance
- Cost-Estimating Data (CED) provides quantitative results.

The CDE approach enables preliminary and production designers to:

- Identify the intensive cost-drivers that increase the manufacturing cost of the design
- Determine the relative effects of cost-drivers over which he has control
- Utilize cost data enabling simple trade-offs to be performed to achieve comparative costs for those configurations considered.

DESIGNER-ORIENTED FORMAT/CHART DEVELOPMENT CRITERIA

The BCL/industry team agreed that the MC/DG formats must be created in accordance with the following criteria:

- Emphasize cost-drivers
- Be simple to use
- Use designer language
- Instill confidence
- Be economical
- Be accessible
- Be maintainable.

An example of a format selection aid for the MC/DG is shown in Figure 13. A typical selection aid for an MC/DG section is shown in Figure 14.

FIGURE 13.

MC/DG SECTION SELECTION AID

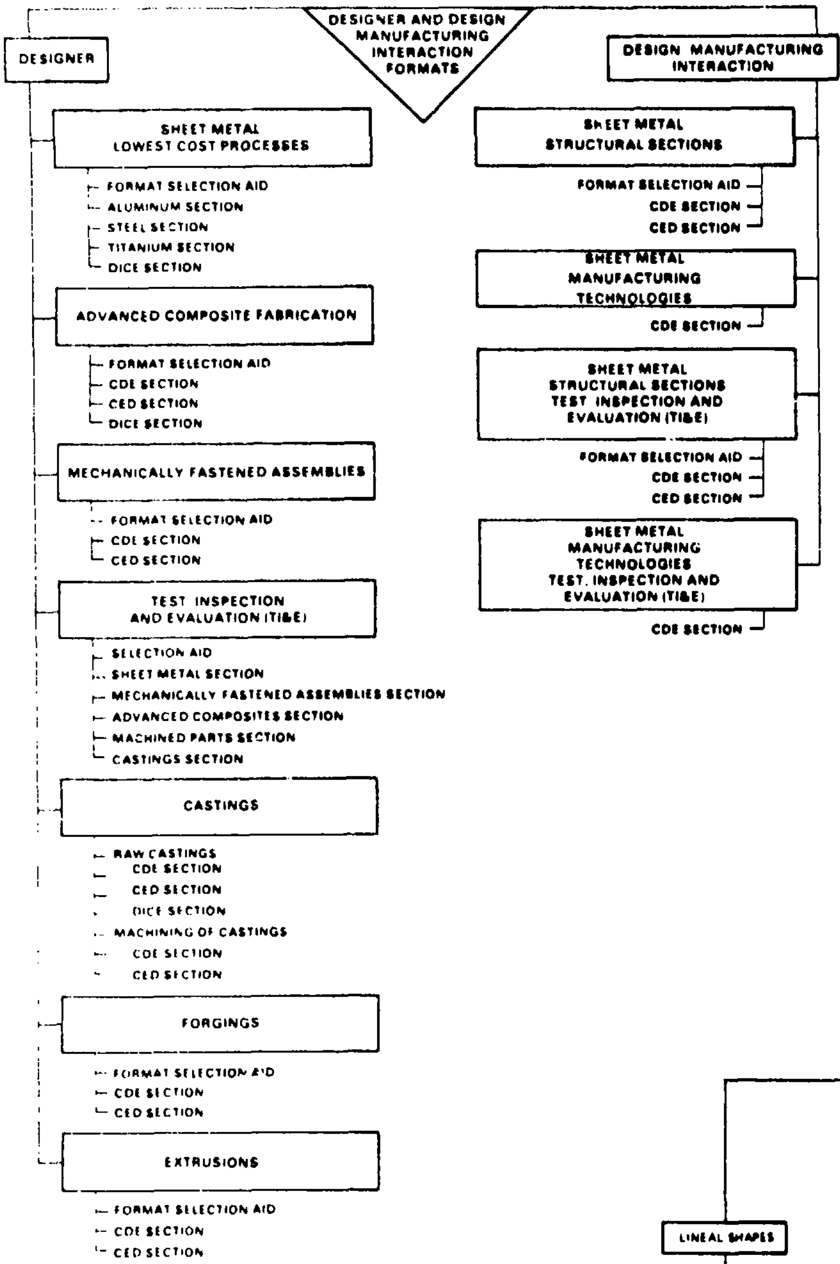
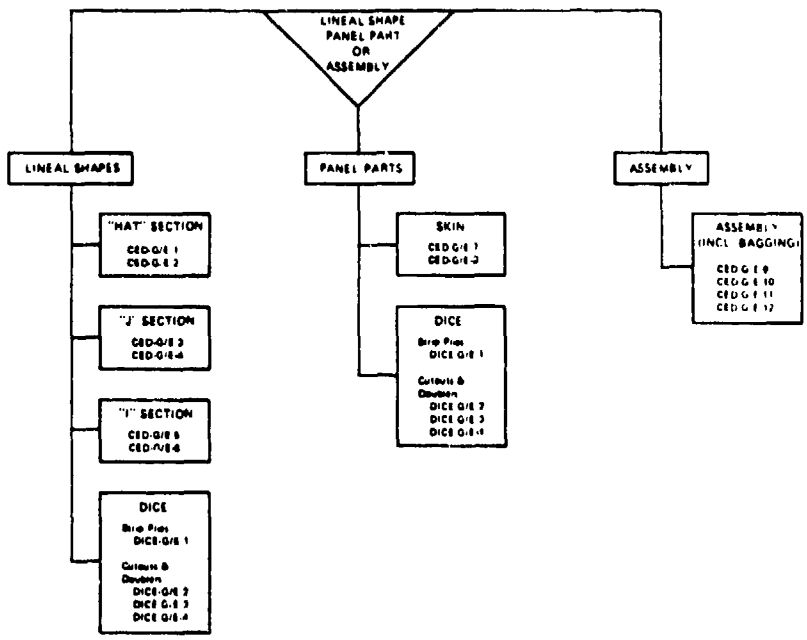


FIGURE 14.

FORMAT SELECTION AID
ADVANCED COMPOSITES



ALUMINUM FUSELAGE SHEAR PANEL TRADE-STUDY

The following illustrates the methodology and results of a trade-study conducted on the aluminum fuselage panel. The approach used can be summarized in five steps. First, a basic panel was defined. Next, structural concepts were developed as candidates for the panel designs. Third, the ground rules and assumptions for the study were specified. Fourth, the MC/DG data display formats were utilized to obtain the cost of the concepts. Finally, conclusions were drawn concerning the effectiveness of the MC/DG in conducting a typical trade-study performed in industry.

The panel chosen for this trade-study is from the fuselage of the Air Force F-16 aircraft. Figure 15 shows the location of the panel on this aircraft. The panel concepts selected for evaluation are illustrated in Figure 16 which shows concepts having single and compound curvature concept. The aluminum alloy selected was 2024 aluminum. Skins and brake formed discrete parts were in the T-3 condition. The parts formed on the rubber press were in the "O" or "W" condition and solution heat-treated to a final condition of T-42. The brake formed parts were straight channels and Z-sections. Curved channels and Z-sections were formed on the rubber press. All skins were Farnham rolled.

The design/analysis assumptions were:

- Shear buckling permitted
- No inter-fastener buckling
- No frame or stringer buckling
- No crippling of stringers in compression.

Examples of the concepts are given in Figure 17 through 20.

The weight of each concept was determined using conventional methods of calculation. The MC/DG was utilized to determine the manufacturing cost of each concept.

The MC/DG cost worksheet was used, along with the supporting data sheet, to calculate the cost per aircraft of each panel. These worksheets are shown in Tables 4 and 5 for concepts IA and IB. The data obtained from the MC/DG formats were entered onto the worksheet in the appropriate columns. Examples of how the data were determined from the formats for concepts IA and IB are shown following the trade-study summary (Figures 21 and 22). It is interesting to note that the cost for both concepts IA and IB is the same.

This is because facility limitations constrained the contoured parts to be formed using the rubber press method, instead of the less expensive brake and roll method. The only difference between the two concepts is the addition of lightening holes to the frames in concept IB. For the rubber press operation, the addition of lightening holes does not require any additional operations, and therefore does not require the addition of a DICE cost. These results provided the cost per pound for each concept.

Table 6 lists the cost, weight, and cost per pound of the single curvature concepts. The compound curvature concept was similar to one of the single curvature concepts, and as expected, the MC/DG shows the compound curvature concept to be more expensive (Table 6). These data will allow the design team to select the cost-optimized fuselage shear panel that will satisfy all other program parameters. Table 7 indicates the cost of weight saved for the F-16 panel concepts.

This and other studies show that the MC/DG is an effective aid to the design engineer. The designer can easily and quickly use the qualitative and quantitative manufacturing cost formats provided in the MC/DG. The MC/DG is sensitive to configuration variations. A further conclusion was that additional CDE and CED formats for other manufacturing processes are required to analyze more complex airframe subassemblies.

The MC/DG plays an important role in the CAM environment, e.g.:

- Provides bridge between CAD and CAM
  - Design/manufacturing interaction
- Highlights lowest cost process flow
- Allows design trades with known manufacturing cost impacts
- Provides immediate cost impact of documentation change notice.

The ICAM MC/DG payoff on return of investment is cumulative on all subassemblies and systems; airframes and avionics/electronics.

FIGURE 15.
LOCATION OF ALUMINUM CONCEPTUAL PANEL ON F-16 FUSELAGE

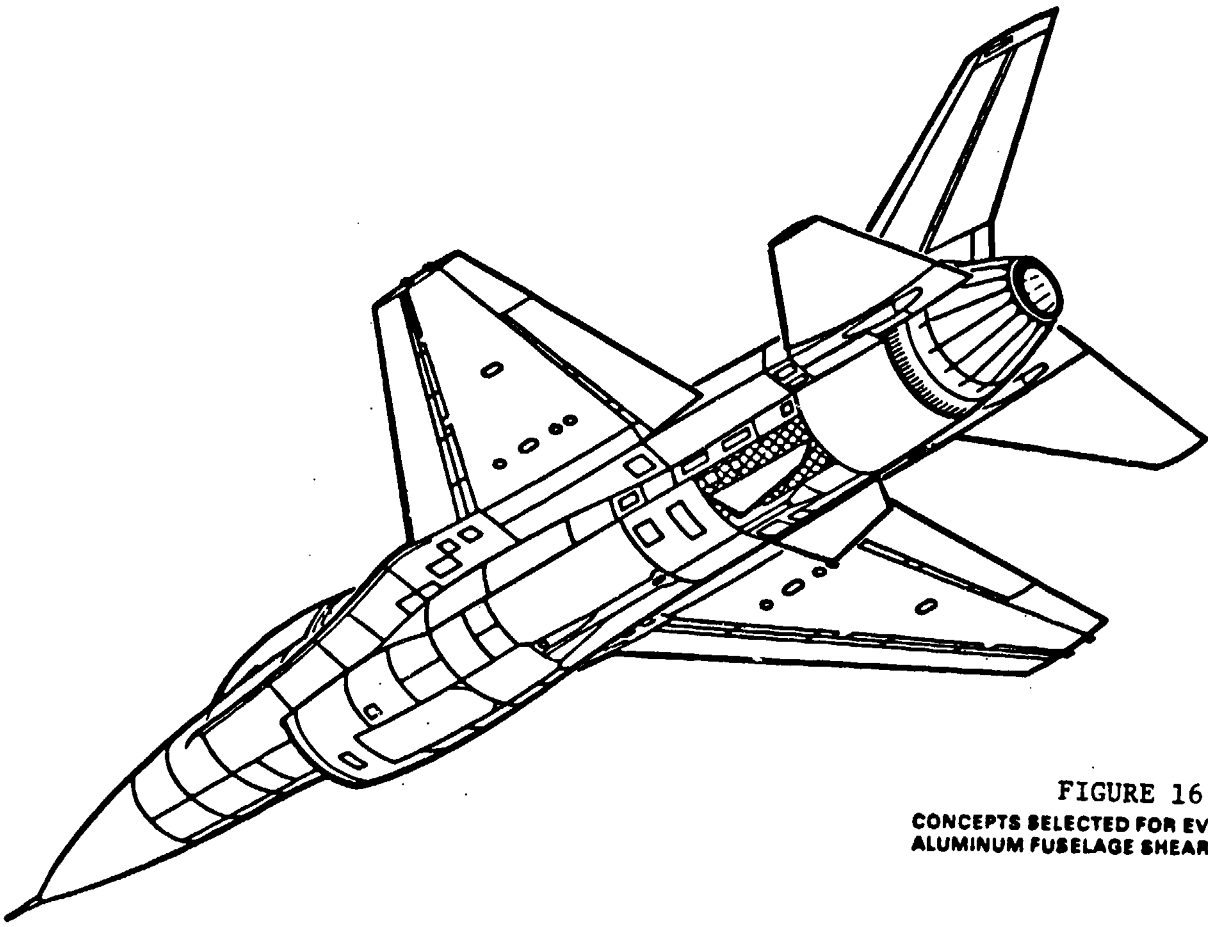


FIGURE 16.
CONCEPTS SELECTED FOR EVALUATION IN ALUMINUM FUSELAGE SHEAR-PANEL TRADE-STUDY

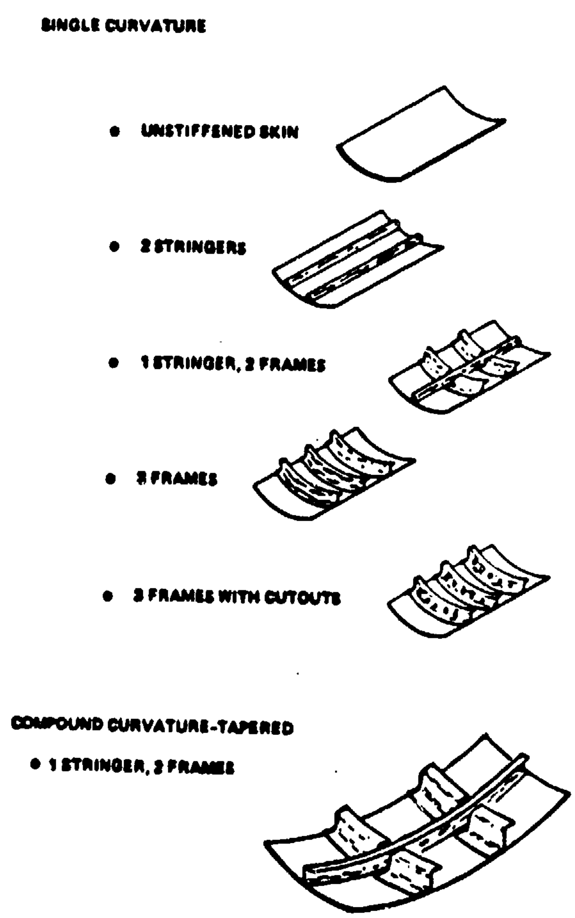
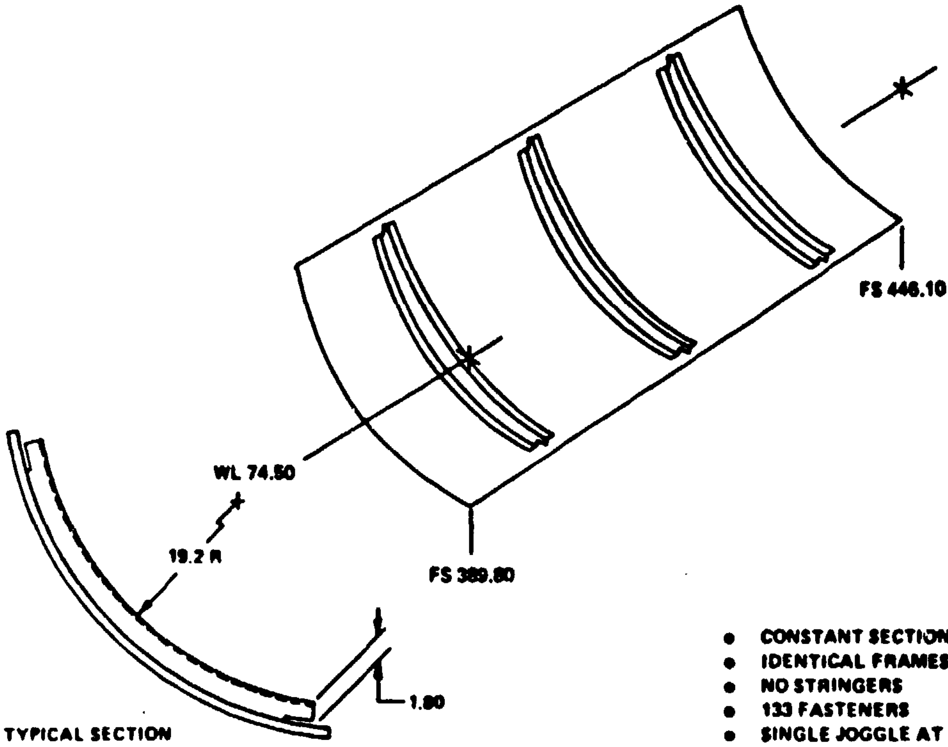
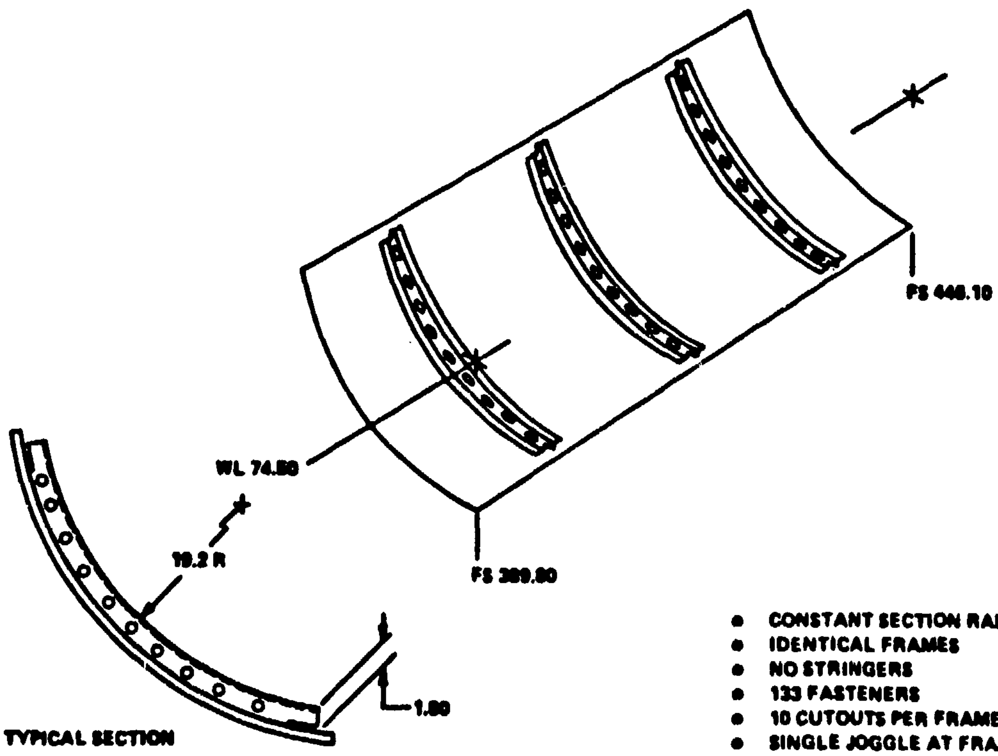


FIGURE 17.
THE F-16 SIMPLIFIED ENGINE ACCESS COVER (16B6530)
CONCEPT IA



- CONSTANT SECTION RADIUS
- IDENTICAL FRAMES
- NO STRINGERS
- 133 FASTENERS
- SINGLE JOGGLE AT FRAME ENDS

FIGURE 18.
THE F-16 SIMPLIFIED ENGINE ACCESS COVER (16B6530)
CONCEPT IB

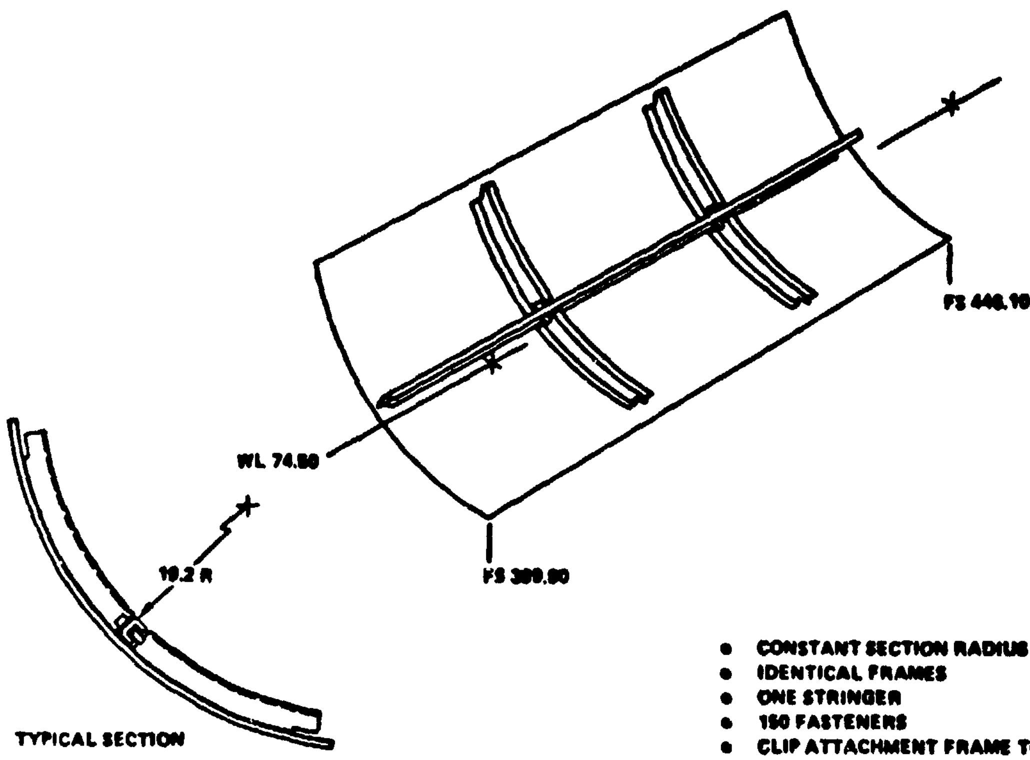


- CONSTANT SECTION RADIUS
- IDENTICAL FRAMES
- NO STRINGERS
- 133 FASTENERS
- 10 CUTOUTS PER FRAME
- SINGLE JOGGLE AT FRAME ENDS

FIGURE 19.

THE F-16 SIMPLIFIED ENGINE ACCESS COVER (16B6530)

CONCEPT IIA

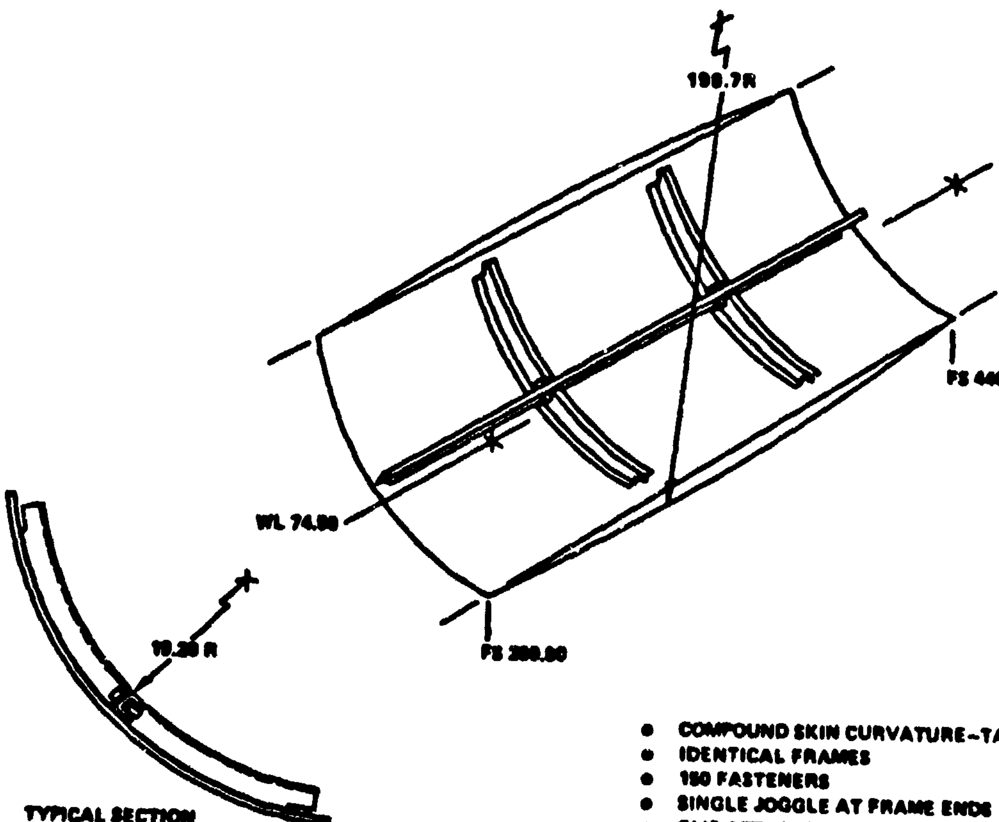


- CONSTANT SECTION RADIUS
- IDENTICAL FRAMES
- ONE STRINGER
- 150 FASTENERS
- CLIP ATTACHMENT FRAME TO STRINGER

FIGURE 20.

THE F-16 SIMPLIFIED ENGINE ACCESS COVER (16B6530)

CONCEPT IIB



- COMPOUND SKIN CURVATURE–TAPERED WIDTH
- IDENTICAL FRAMES
- 150 FASTENERS
- SINGLE JOGGLE AT FRAME ENDS
- CLIP ATTACHMENT – FRAME TO STRINGER

TABLE 4.

MC/DG COST WORKSHEET

CONCEPT NO. IA: 3 FRAMES
CONCEPT NO. IB: 3 FRAMES WITH CUTOUTS

PAGE 1 of 2

DESIGN CONCEPT		RECURRING COST (RC)									NON-RECURRING COST (NRC)			PROGRAM COST		
		L . LC . LR = LS + MS = RC . P/AC . DQ = PRC									NRC . LR = PNRC			9 + 12 + DQ = COST/AC		
PART NO.	DESCRIPTION	LABOR MC/DG MH/PT (1)	LC FACTOR (2)	LABOR RATE $/MH (3)	LABOR RC $/PT (4)	MAT'L $/PT (5)	REC. COST/PT. $ (6)	PARTS PER AC (7)	DES. QTY. (8)	PROD. RC $ (9)	NRC MC/DG MH (10)	LABOR RATE $/MH (11)	PROD. NRC $ (12)	PROD. COST $ (13)	DES. QTY. (14)	COST/AC $ (15)
1	SKIN	1.08	1.00	25	27.00	21.93	48.93	1	200	9786	68	25	1700			
2	FRAMES	0.498	1.00	25	12.45	0.91	13.36	3	200	8016	84	25	2100			
	ASSEMBLY	3.0	1.00	25	75.00	33.25	108.25	1	200	21650	462	25	11550			
	TOTALS									39452			15350	54802	200	274

BY:
DATE FEB '82

TABLE 5.

COST WORKSHEET – SUPPORTING DATA

CONCEPT NO. IA:
CONCEPT NO. IB:

PAGE 2 OF 2

PART: SKIN → T3 CONDITION BASE PART - CED-A-20 - 1.08 MH/PART TOOL - 68MH MATERIAL: 14.15 SQ.FT. @ $1.55/SQ.FT. $21.93	**PART:**
PART: FRAME - ZEE (RUBBER PRESS) BASE PART - CED-A-9 0.498 MH/PART TOOL 84MH MATERIAL: 0.91 SQ.FT. @ $1.00/SQFT. = $0.91/PART	**PART:**
PART:	**PART:**
ASSEMBLY: CED-MFA-1 and CED-MFA-3 133 RIVETS 3 MH/ASSEMBLY TOOL 462 15.38 FT OF PERIMETER MATERIAL: 133 RIVETS @ $0.25/RIVET = $33.25/ASSEMBLY	**ASSEMBLY:**

TABLE 6.

SUMMARY OF COST-WEIGHT RELATIONSHIPS IN ALUMINUM FUSELAGE SHEAR-PANEL TRADE – STUDY

CONCEPT	COST, $	WEIGHT, LBS	COST PER LB, $/LB
UNSTIFFENED	63	21.22	3
2 STRINGERS	243	19.88	13
2 FRAMES 1 STRINGER	309	19.83	16
3 FRAMES	274	19.06	14
3 FRAMES (WITH CUTOUTS)	274	19.03	14

CONCEPT	COST, $	WEIGHT, LB	COST PER LB WEIGHT, $/LB
SINGLE CURVATURE	309	19.83	16
COMPOUND CURVATURE	362	18.96	19

TABLE 7.

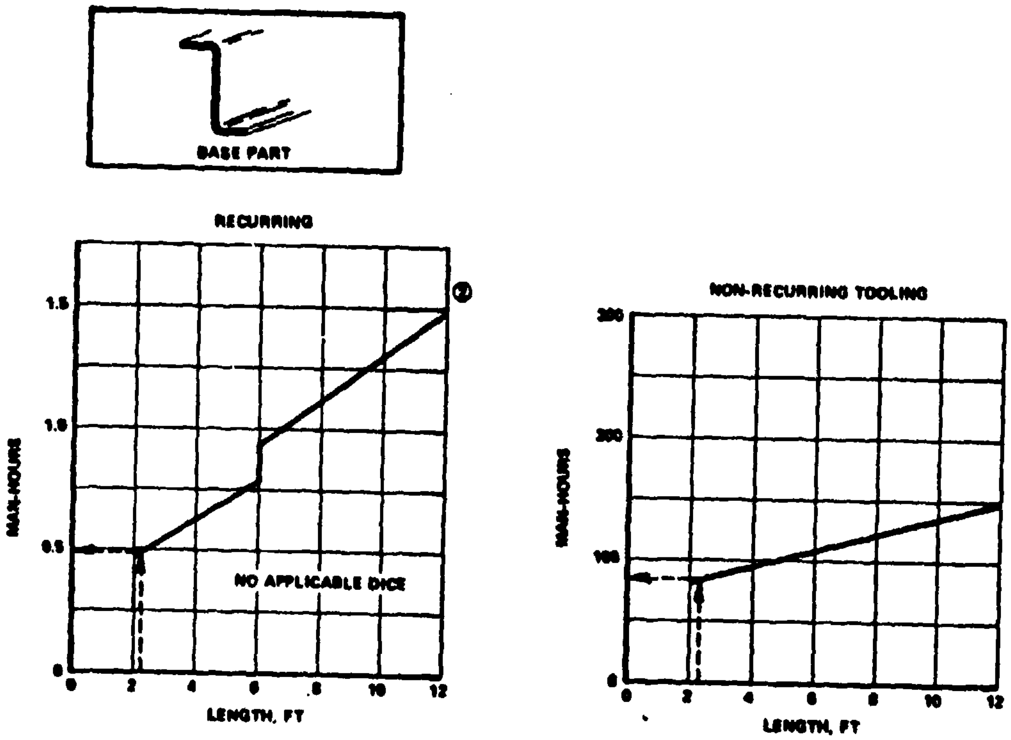
SUMMARY OF RESULTS IN ALUMINUM FUSELAGE SHEAR-PANEL TRADE – STUDY

CONCEPT	COST		WEIGHT		COST OF WEIGHT SAVED, $/LB
	$/PART	Δ$/PART	LBS/PART	ΔLBS/PART	
UNSTIFFENED	63	BASE	21.22	BASE	BASE
2 STRINGERS	246	183	19.38	1.84	119
2 FRAMES 1 STRINGER	309	246	19.83	1.39	177
3 FRAMES	274	211	19.06	2.16	98
3 FRAMES (WITH CUTOUTS)	274	211	19.03	2.19	96

FIGURE 21.

ALUMINUM ZEE, NON-CYLINDRICALLY CONTOURED MEMBER,* LOWEST COST PROCESS

RUBBER PRESS



*NO REVERSE CURVES
(2) PART FORMED IN "O" OR "W" CONDITION; T62 FINAL TEMPER, MINIMUM BEND RADIUS = 1.0t

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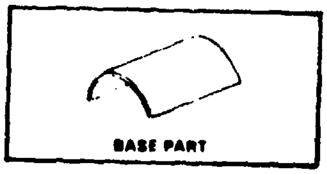
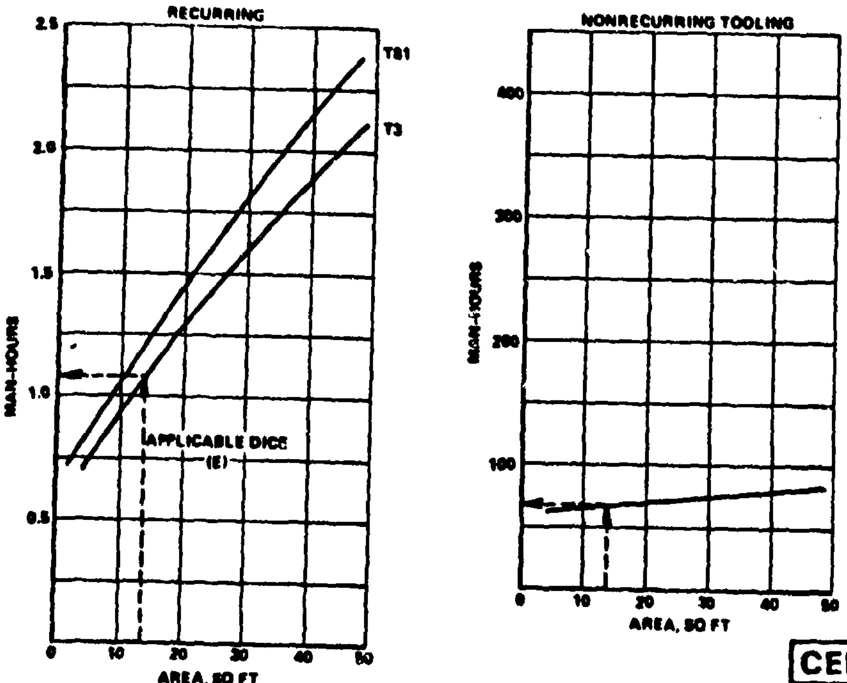
FIGURE 22.



ALUMINUM CYLINDRICAL CURVATURE SKIN, LOWEST COST PROCESS FARNHAM ROLL

(PERIMETER TRIM INCLUDED)



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TTD450260000
12 Sept 1984

DEPARTMENT OF DEFENSE
1982 MANUFACTURING TECHNOLOGY ADVISORY GROUP CONFERENCE

AIR FORCE ICAM "MANUFACTURING COST/DESIGN GUIDE" (MC/DG) FOR ELECTRONICS

Bryan R. Noton*
Battelle's Columbus Laboratories
Columbus, OH

and

Robert Remski
Honeywell Inc., Avionics Division
Minneapolis, MN

ABSTRACT

A "Manufacturing Cost/Design Guide" (MC/DG) for electronics is under development for the Computer Integrated Manufacturing Branch (AFWAL/MLTC), Materials Laboratory, WPAFB, Ohio. The data analysis methodologies established for the "MC/DG for Airframes" are being used. General and detailed ground rules are developed, which include specifications of electronic discrete parts, materials, assemblies and manufacturing methods. Examples of assemblies are power supply, hybrids and chassis. Examples of discrete parts are substrates and printed wiring boards. The paper includes an overview of the aerospace electronic design processes, indicating how the MC/DG will be utilized to conduct trade-studies at the conceptual and detailed design phases for the circuitry, etc. An overview is included of typical trade-studies and data requirements to achieve affordable performance for avionic systems. This data must be presented to designers so that the cost trade-studies can be conducted within scheduling constraints.

INTRODUCTION

The need to arrest and reduce costs at all levels of the aircraft system life-cycle is becoming increasingly important. Qualitative and quantitative data on cost-drivers useful during the design, manufacture, operation, and maintenance of aircraft systems are essential. This is particularly so, because, at the same time, the number of new aircraft being developed is reducing while there is a need for increased performance in terms of reduced weight, improved reliability, and lower ownership costs, including reduced fuel consumption. The customer must be provided with performance which is affordable.

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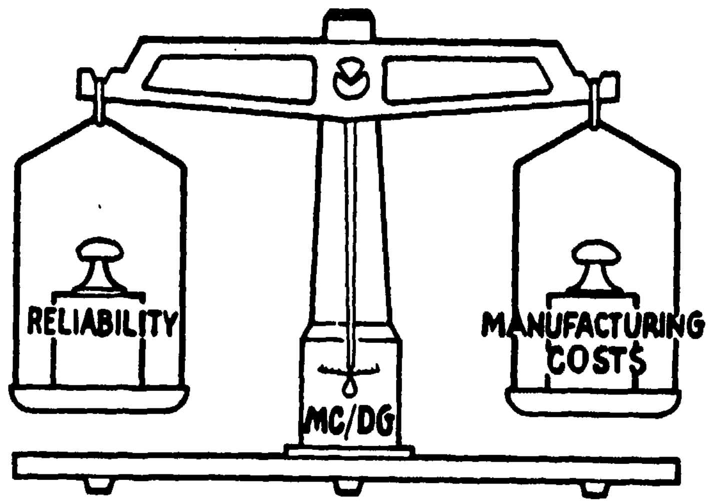
MANUFACTURING COST
-- A DESIGN OBJECTIVE FOR ELECTRONICS



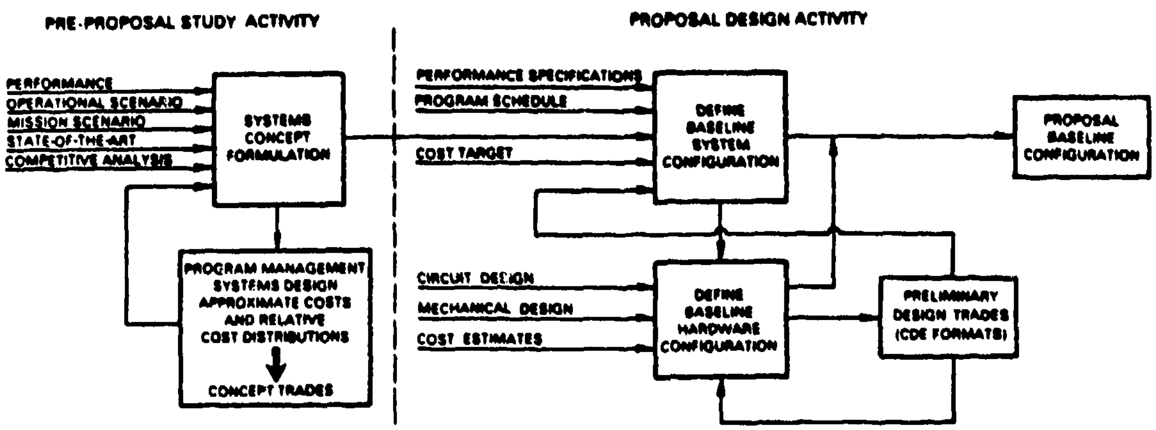
Strong interaction between design and manufacturing is essential to achieve these required advancements in manufacturing sophistication and refinements. The "Manufacturing Cost/Design Guide" (MC/DG) Data Development Program for airframes and electronics, a follow-on of earlier Air Force contracts (F33615-75-C-5194 and F33615-77-C-5027) provides an unprecedented opportunity for the designer to study a larger number, than before, of alternative design configurations for airframes and electronics to achieve the lowest manufacturing cost.

The MC/DG identifies the cost-drivers over which the designer has control and which can be traded back for performance once the basic performance requirements of the system have been exceeded. The MC/DG also provides the mechanism to improve interaction between manufacturing and design, for example, regarding the selection and use of alternative manufacturing facilities that may be necessary due to shop loading requirements.

The MC/DG is intended for utilization throughout the aerospace electronics/avionics design process. The design process is depicted in Figure 1 for the conceptual and detail design (circuit and mechanical) phases. The decreasing leverage to influence cost, as systems develop, is shown in Figure 2.

FIGURE 1.

TYPICAL DESIGN FLOW FOR AEROSPACE ELECTRONICS INDUSTRY



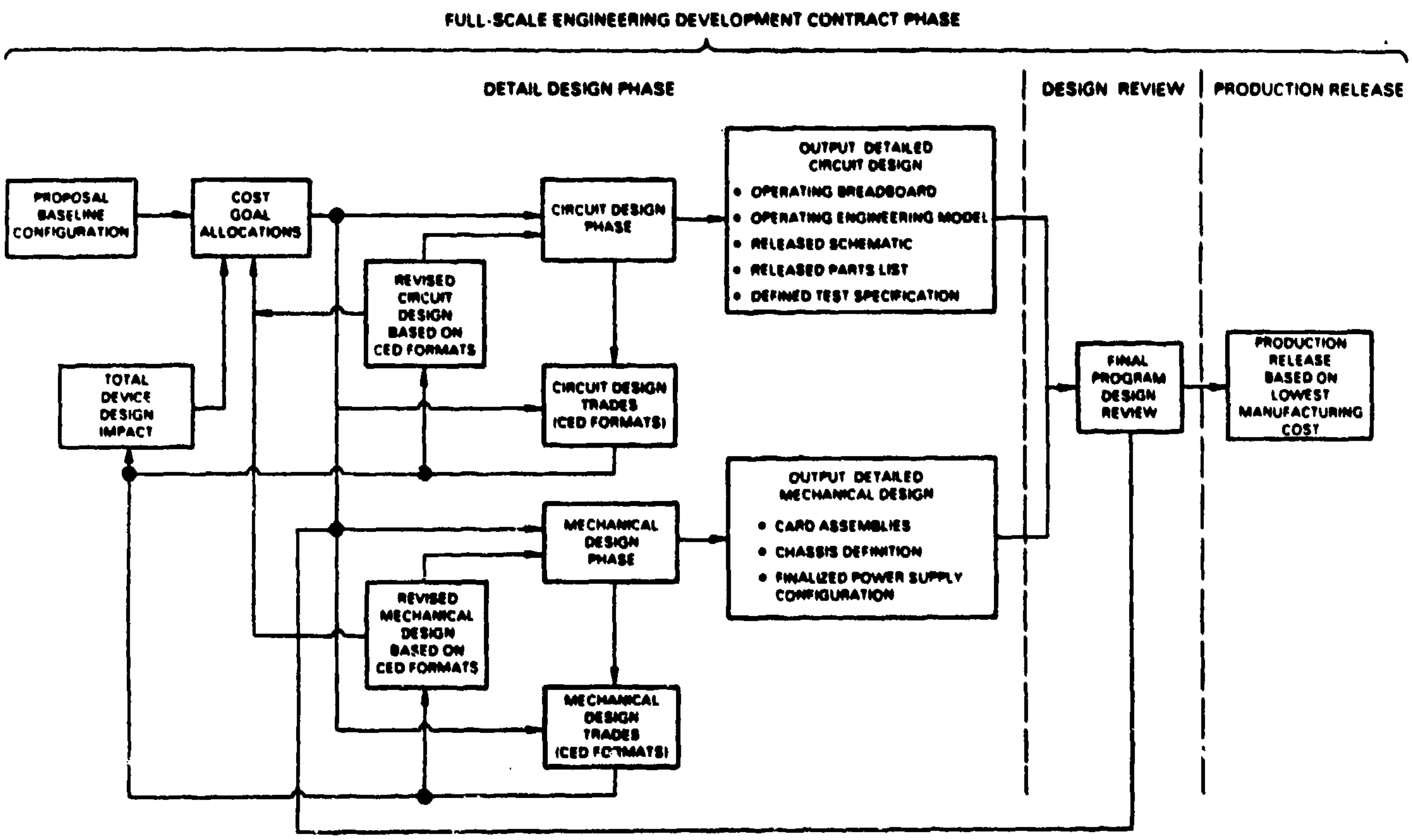
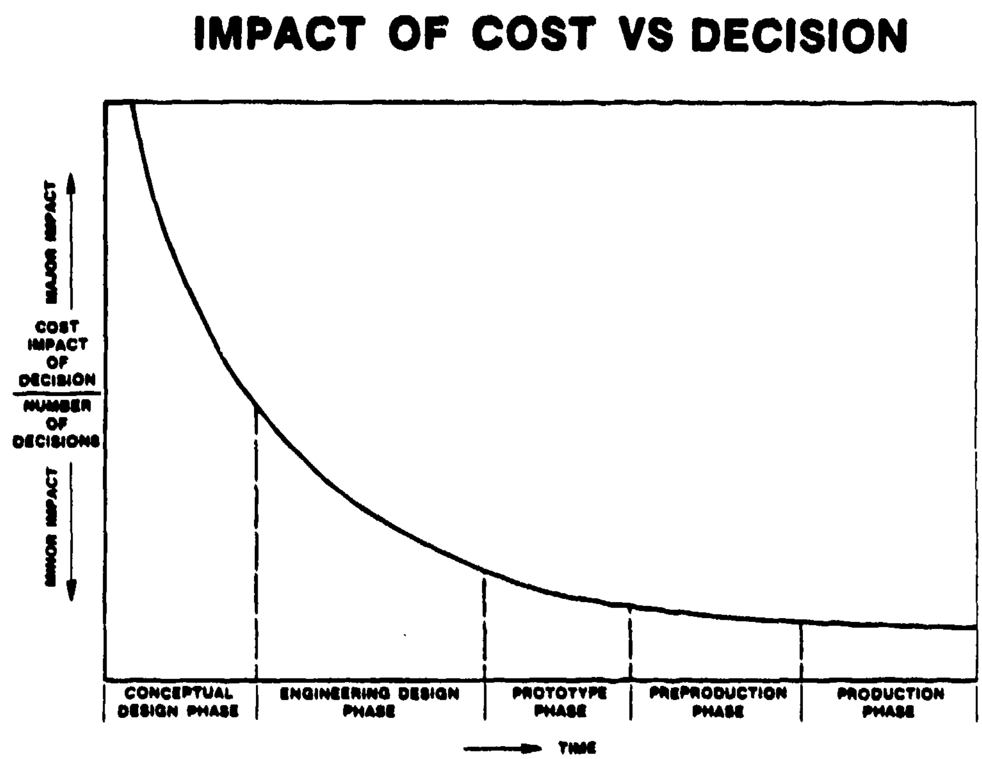


FIGURE 2.



THE MC/DG TEAM

The development of the "MC/DG for Electronics" is being accomplished by the Battelle's Columbus Laboratories (BCL)/Electronics Industry Coalition for the Computer Integrated Manufacturing Branch, Materials Laboratory (AFWAL/MLTC), Wright-Patterson Air Force Base, Ohio 45433.

A. USAF TECHNICAL DIRECTION

This program is administered under the technical direction of Capt. Richard R. Preston, AFWAL/MLTC.

B. MC/DG COALITION

BCL is the prime contractor on the MC/DG Data Development Program. The Program Manager is Mr. Bryan R. Noton, BCL, supported by the following subcontractors:

Aerospace Industry Subcontractors	Program Managers
Honeywell, Incorporated	R. Remski
Lockheed-California Company	J. F. Workman
Rockwell International Avionics & Missiles Group, Collins Avionics Division	J. C. Vecellio

OBJECTIVES OF THE MC/DG

The objectives of the "MC/DG for Electronics" are to:

- Provide electronic designers with simple, relative, and quantitative cost comparisons of manufacturing processes
- Emphasize design orientation of MC/DG formats and manufacturing man-hour data for use at all phases of design process, e.g., conceptual and detail design, therefore, increasing emphasis on cost; a vital design parameter
- Expand electronic performance/manufacturing cost trade-offs conducted by designers on electronic discrete parts and subassemblies
- Emphasize potential cost advantages of emerging materials and manufacturing methods accelerating the transfer of these technologies to production hardware
- Put electronic designers on lowest cost track early in design process
- Identify cost-driving manufacturing operational sequences which provide targets for future computer-aided manufacturing (CAM) efforts.

MC/DG VOLUME CONTENTS - ELECTRONICS

The contents for the MC/DG Volume, "Manufacturing Technologies for Electronic Fabrication, Assembly and Test" are subdivided (Table 1) into the following broad categories:

I. Procured Items
II. Detailed Fabrication
III. Assembly
IV. Test, Inspection and Evaluation (TI&E).

A designer's cost worksheet (Table 2) and selection aids for the electronic/avionic manufacturing data have been developed. The first selection-tree, Figure 3, is similar to that included in Report No. AFWAL-TR-80-4115 and also, a second type, which indicates the formats required for designer guidance at the conceptual design phase, when addressing specific design parameters, is shown in Table 3.

TABLE 1.

MC/DG VOLUME CONTENTS: "MANUFACTURING TECHNOLOGIES FOR AEROSPACE ELECTRONIC FABRICATION, ASSEMBLY, AND TEST"

I	II	III		IV
PROCURED ITEMS	DETAIL FABRICATION	ASSEMBLY		TEST, INSPECTION, AND EVALUATION (TI&E)
SCHEMATIC PARTS	METALLIC	MECHANICAL ASSEMBLY	HYBRIDS	CARD/MODULE LEVEL TEST
INTERCONNECT PARTS	NONMETALLIC	COMPONENT ASSEMBLY (PRE-WAVE AND POST-WAVE)	OTHER ASSEMBLY TECHNIQUES	TESTABILITY
HARDWARE	TREATMENT/ COATING/MARKING	CLEANING	CHASSIS ASSEMBLY	BURN-IN/SCREENING TEST
FABRICATED PARTS	EMERGING TECHNOLOGIES	SOLDER	FINAL EQUIPMENT ASSEMBLY	DEVICE/EQUIPMENT TEST
EMERGING TECHNOLOGIES		SHEET METAL/ STANDOFF ASSEMBLY (HAND WIRING)	POST-ASSEMBLY PROCESSES	EMERGING TECHNOLOGIES
		CABLE/WIRE HARNESS ASSEMBLY	POTTING	
			ADHESIVES	
			EMERGING TECHNOLOGIES	

TABLE 2.

MC/DG AVIONIC DESIGNER'S COST WORKSHEET

Baseline Configuration: Interface Assembly LRU
Indenture Level: RF Module Subassembly SRU

Baseline Manufacturing Cost Allocation $ ________

DESIGN DECISION Part Selection	1	2	3	4	5	6	7
Piece Part Type	% Total Electronic Part Cost	Baseline Approach	Reference CED No	Study Approach	Ratio Baseline to Study Approaches From CED	Cost Factor (%) (1 - 8)	Cost* Change (%) (1 - 6)

Total ________

Cost Impact: Baseline Manufacturing Cost (9) x Cost Change Total (%) = (8) ________ x ________ (% Total of Column 7) = (8) ________

New Cost: Baseline Manufacturing Cost (8) - Cost Impact = (9) ________ - (8) ________ = (8) ________

*Notes: Positive Value = Cost Savings
Negative Value = Cost Increase

Remarks ________

By ________

Date ________

FIGURE 3.

ELECTRONIC DETAIL DESIGN PHASE DESIGNER FORMAT SELECTION CHART

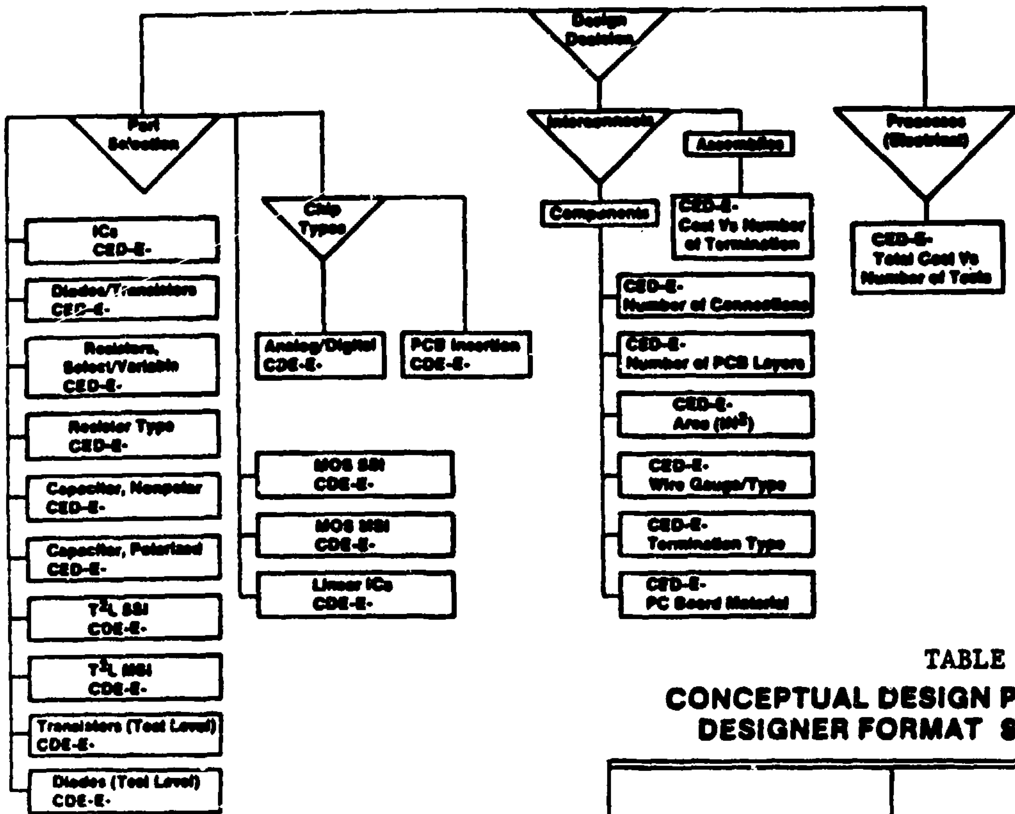


TABLE 3.

CONCEPTUAL DESIGN PHASE TRADE STUDY DESIGNER FORMAT SELECTION CHART

System Design Parameters	Parameters Known	Impact of: I New Technology	II Assembly Number	III Commonality	IV Digital Design	V Built-in Test
Reliability		●	●	●	x	●
Maintainability		●	x	o	x	●
Environmental		o	●	o	x	o
Density		●	x	●	x	o
Part Costs		●	x	o	x	x
Factory Special Handling		●	o	o	o	o
Assembly Cost		●	x	x	x	x
Test Cost		●	x	x	x	●
Aircraft Configuration		o	●	x	x	●
Redundancy		x	●	x	●	●
Maintenance Concept		x	●	o	x	●
Interface		x	●	●	●	x
Partitioning, Functional		x	●	x	●	x
Fault Isolation		x	x	●	●	●
Mission Length		o	o	●	o	o
Part Count		x	o	x	●	x
Number of Functions		o	o	o	●	x
Vulnerability Levels		o	●	x	x	x

Parameters Required for Use of CDE Formats I-V

● = Required Data
x = Secondary Data
o = Not Used

Designer: ____________

Date: ____________

MAJOR SYSTEM DESIGN PARAMETERS

In the design process for electronics, a series of systems parameters or objectives must be considered at the conceptual and preliminary design phases. Examples of these parameters are:

1. Reliability ⟶ Goal MTBF
2. Maintainability ⟶ Goal MITR
3. Cost ⟶ Cost Bogie or DTC Coal
4. Environmental ⟶ Quality Levels
   a. Temperature
   b. Vibration
   c. Shock
   d. Radiation
   e. Altitude
5. Operation/Mission Requirements
   a. Fault Tolerance
   b. Power-on Cycles
   c. Mission/Flight Critical
6. Mounting Configuration
7. Vehicle Power Requirements
8. Location in Vehicle
9. Volume
10. Weight
11. Interface Requirements
12. Field Maintenance Concept
13. Build Schedule
14. Part Lead-Time
15. Design Schedule
16. Design Costs.

MANUFACTURING DATA PRESENTATION FOR DESIGNERS

As was previously the case for the "MC/DG for Airframes," the manufacturing man-hour data for materials, discrete parts, assembly and test, inspection and evaluation (TI&E) are presented in two ways. Firstly, cost-driver effects (CDE), and secondly, cost-estimating data (CED) are given. The objectives of the CDE and CED methodologies are:

- To develop a simple approach for the use of formatted data by designers to achieve lowest manufacturing costs during all design phases (CDE and CED)
- To provide qualitative cost guidance to the designer to assure lowest manufacturing cost (CDE)
- To provide the designer with the capability, through quantitative guidance, to perform simple trade-offs on manufacturing costs (CED).

The CDE cost relationships, providing qualitative direction, have the following objectives:

- Identify cost-drivers that increase the manufacturing cost of the design
- Show relative effects of cost elements over which designers have control
- Motivate designers to reduce the impact of the cost-drivers by avoiding such design and manufacturing features.

Using the CDE approach, the designer should realize the lowest cost, while satisfying the performance requirements.

The CED cost relationships, providing quantitative information, have the following objectives:

- Provide designers with manufacturing man-hour data to allow trade-offs to be quickly performed to achieve comparative costs for candidate electronic systems
- Motivate electronic designers to conduct trade-offs.

The CDE approach also motivates designers. Low cost designs can be realized providing full advantage was taken of the CDE data and the lower end of the cost range used wherever possible, while satisfying the performance and reliability requirements.

The CED approach provides preliminary and detail designers with:

- Ability to perform cost-estimates through the use of simplified formats showing manufacturing man-hour data.

The utilization of the formats is indicated in Figure 1.

ELECTRONIC FORMAT DESIGN CRITERIA

The designer-oriented formats and methodologies reported in the model of the MC/DG (AFML-TR-76-227) have been used as the basis for format development for the "MC/DG for Electronics Fabrication, Assembly and TI&E".

The MC/DG designer-oriented formats must meet the following criteria:

- Emphasize cost-drivers
- Be simple to use
- Use designer language
- Instill confidence
- Be economical
- Be accessible
- Be maintainable.

GROUND RULES FOR ELECTRONICS

Prior to the development of manufacturing cost data, it is necessary to establish both general and detailed ground rules. Ground rules are important as they promote understanding, ensure consistency, uniformity, and accuracy in generating and integrating data into the formats. Examples of the ground rule categories follow.

1. <u>General Ground Rules</u>

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

(a) Electronic Assemblies
(b) Discrete Parts
(c) Materials
(d) Manufacturing Methods
(e) Facilities
(f) Data Generation - Recurring Costs
(g) Data Generation - Nonrecurring Costs
(h) Support Function Modifiers
(i) Test, Inspection, and Evaluation (TI&E).

2. <u>Detailed Ground Rules</u>

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

(a) Material (Purchased Items)
(b) Configuration
(c) Specification Requirements
(d) Manufacturing Methods
(e) Facilities
(f) Test, Inspection and Evaluation (TI&E)
(g) Data Generation - Recurring
(h) Data Generation - Nonrecurring.

EXAMPLES OF DESIGN TRADE-OFFS

a) Conceptual Design

A. Standard Circuits vs. New Technology

- Cost
- Weight
- Size
- Reliability
- Maintainability
- Availability
- Factory Capability to Handle
- Multiple Source (for Candidate Circuits)

B. Analog vs. Digital Processing

- Interface
  - I/O
  - Required Conversions
- Part Availability
- Part Costs
- Reliability
- Hardware/Software Integration
- Number of Functions
- Operational Definition
- Test Costs

C. Common Functions vs. Unique Functions

- Multi-Mode Computational Capability
- Reliability and Flight/Mission Critical
- Space Availability
- Data Transmission
- Fault Isolation Capability

b) Detail Design

D. Interconnect: Hard-Wire Auto Wire Wrap vs. Wire Lay-up vs. Printed Circuit Board (PCB)

- Quantity
- Size
- Assume Production (Firm) Design
- Density
- Nonrecurring Costs
- Recurring Costs
- Repairability

E. Auto-Insertion vs. Hand-Insertion

- Quantity of Assemblies
- Type of Component
- Number of Axes - Component Orientation
- Number of Boards per Blank
- Footprint
- Lot Sizes
- Assume Production (Firm Design)

F. Adding Cuts/Jumpers vs. Redesigning Printed Wiring Board

- Quantity of Cuts and Jumpers
- Cost per Cut & Jumper (Labor)
- Cost of Redesign of PWA
- Volume of Assembly Remaining

ELECTRONIC INTERCONNECT, INSERTION AND SOLDERING PROCESSES DATA DEVELOPMENT

The interconnect, insertion and soldering processes for electronics include several materials, part types, and also manufacturing methods. Some processes are accomplished by hand, while others are semi-automated or fully automated.

Designer guidance formats have been prepared for insertion, soldering, and interconnect between components. Examples of such formats are included (Tables 4 & 5). These formats resemble that earlier developed for sheet-metal designer-influenced cost elements (DICE).

For the insertion and soldering processes, each part type is listed in the MC/DG, e.g., resistors, capacitors, transistors, integrated circuits, and coils. For the interconnect between components, various materials were included, e.g., Teflon, polyimide and ceramic. The man-hours have been subsequently calculated for each process. Other typical formats are shown in Figures 4 to 9 for cost analysis of discrete parts.

TABLE 4.

INSERTION PROCESS FOR AVIONIC PARTS (PWA RELATED)

RELATIVE COST	LOW	MEDIUM	HIGH
INSERTION PROCESS	Auto	Semi-Auto	Hand
PART TYPE			
RESISTORS			
Axial Leaded	A	A	A
DIP	S	A	A
SIP	N	A	A
Chip	A	S	A
VARIABLE RESISTORS			
Sealed	N	A	A
Open	N	A	A
CAPACITORS			
Axial Leaded	A	A	A
Radial Leaded	A	A	A
DIP	A	A	A
SIP	N	A	A
Chip	A	S	A
VARIABLE CAPACITORS			
Opened	N	A	A
Sealed	N	A	A
COILS			
Axial Leaded	S	A	A
Variable	N	N	S
DIODES	A	A	A
TRANSISTORS			
Standard Leaded	N	A	A
Ribbon Leaded	N	N	A

A Applicable
S Applicable (May Require Special Processing/Equipment)
N Not Applicable

TABLE 5.

SOLDERING PROCESS FOR AVIONIC PARTS (PWA RELATED)

RELATIVE COST	LOW	LOW	MEDIUM	MEDIUM	HIGH
SOLDERING PROCESS	Infrared*	Laser*	Wave	Vapor Phase*	Hand
PART TYPE					
RESISTORS					
Axial Leaded	A	A	A	A	A
DIP	A	A	A	A	A
SIP	A	A	A	A	A
Chip	A	N	A	A	S
VARIABLE RESISTORS					
Sealed	A	A	A	A	A
Open	A	S	N	N	A
CAPACITORS					
Axial Leaded	A	A	A	A	A
Radial Leaded	A	A	A	A	A
DIP	A	A	A	A	A
SIP	A	A	A	A	A
Chip	A	N	A	A	S
VARIABLE CAPACITORS					
Sealed	A	A	A	A	A
Open	S	N	N	N	A
COILS					
Axial Leaded	A	A	A	A	A
Variable	S	N	A	A	S
DIODES	N	N	A	A	A
TRANSISTORS					
Standard Leaded	A	A	A	A	A
Ribbon Leaded	A	N	N	A	A

*Pre-Applied Solder/Flux Required

A Applicable
S Applicable (May Require Special Processing/Equipment)
N Not Applicable

RESISTORS (ESTABLISHED RELIABILITY)

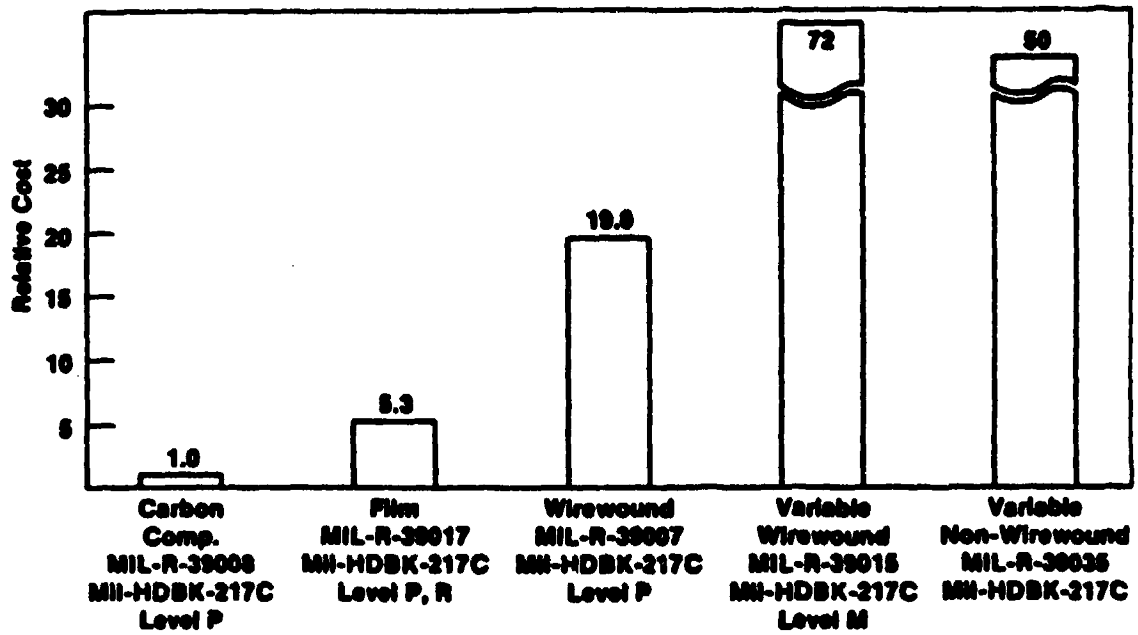


FIGURE 4.

SOLDERING PROCESS FOR AVIONIC PARTS (PWA RELATED)

CAPACITORS

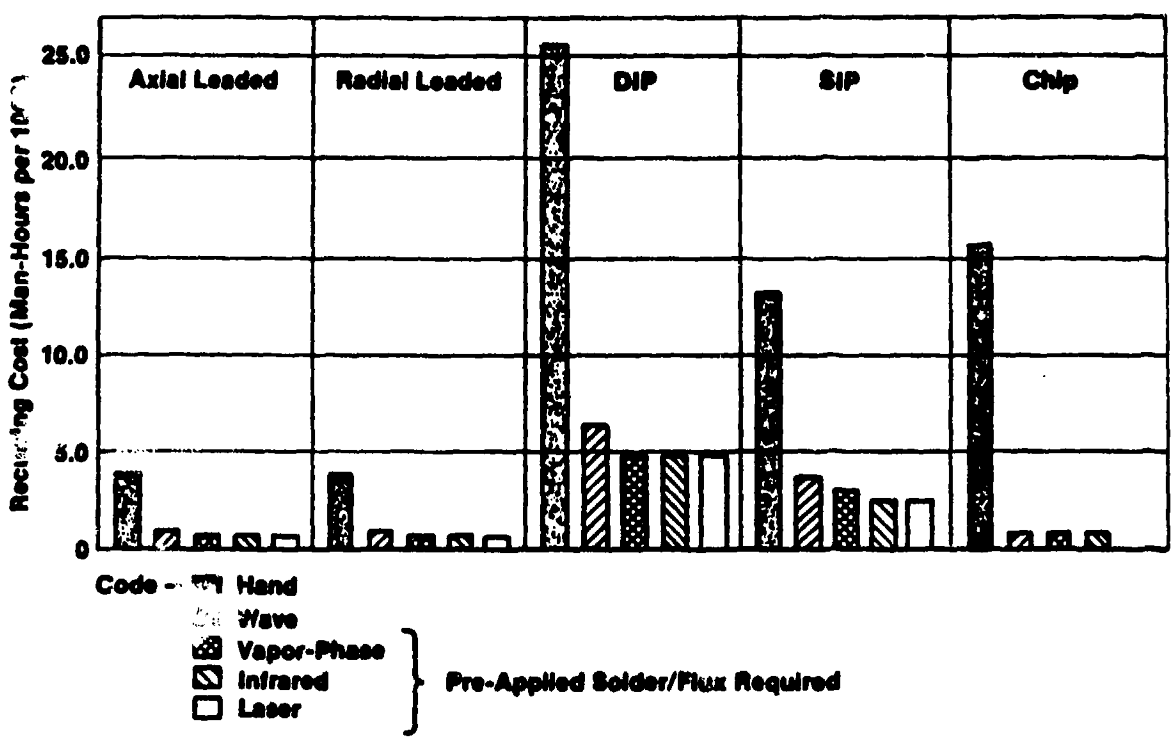


FIGURE 5.

CED-AD-I

145

INSERTION PROCESS FOR AVIONIC PARTS (PWA RELATED)

CAPACITORS

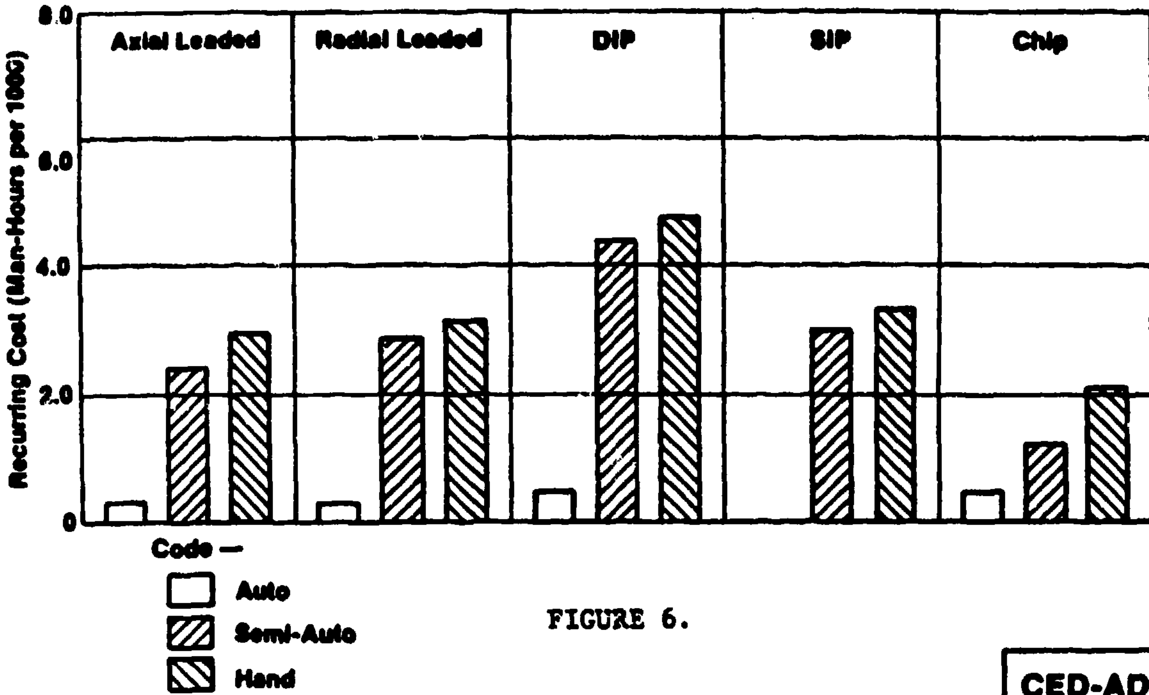
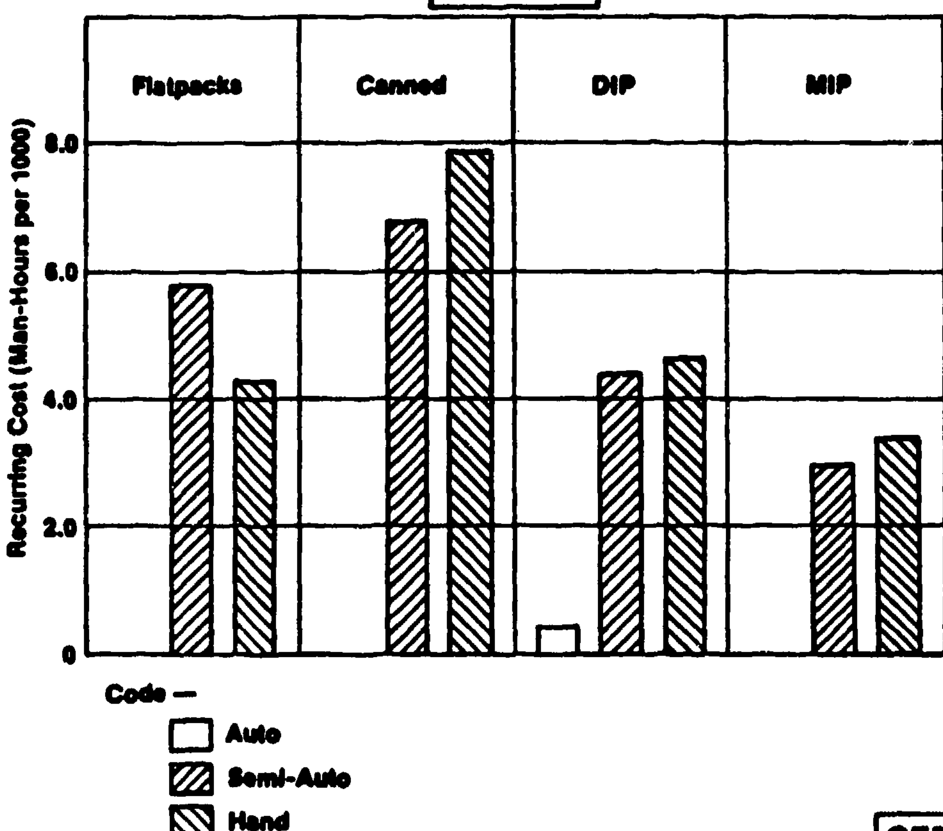


FIGURE 6.

CED-AD-1

INSERTION PROCESS FOR AVIONIC PARTS (PWA RELATED)

HYBRIDS



CED-AD-6

FIGURE 7.

SOLDERING PROCESS FOR AVIONIC PARTS (PWA RELATED)

CONNECTORS

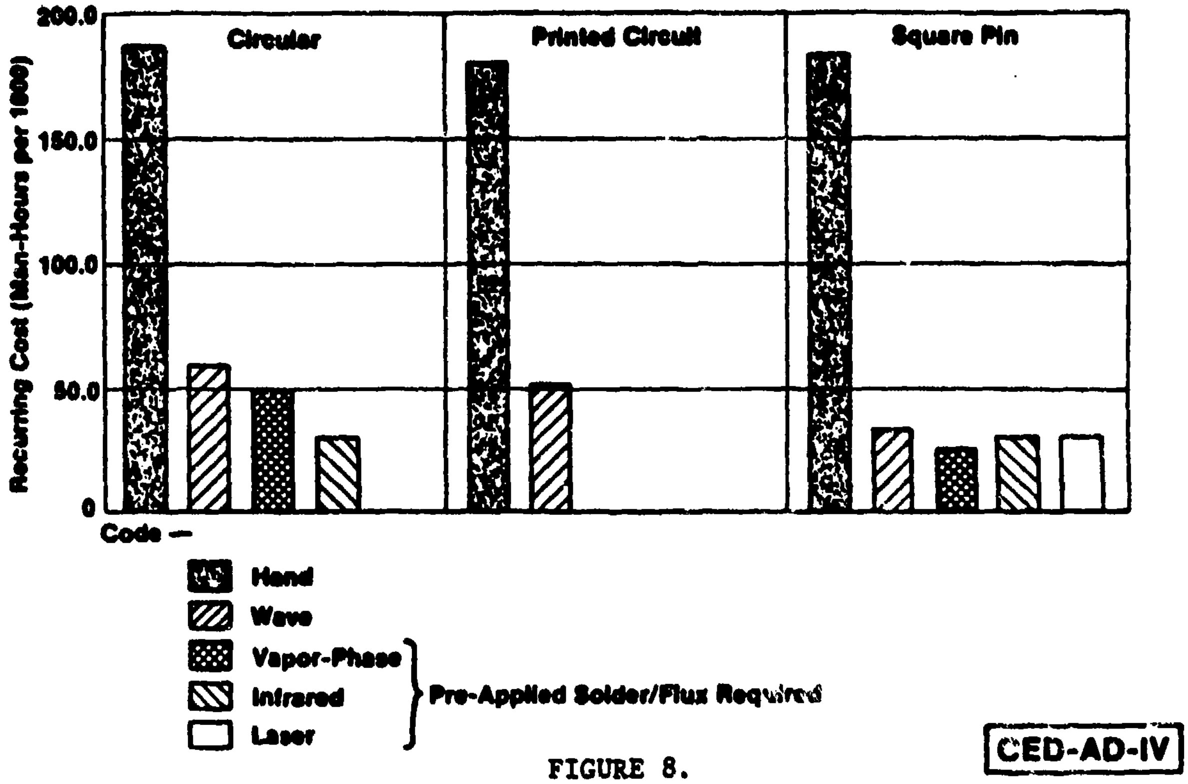


FIGURE 8.

SOLDERING PROCESS FOR AVIONIC PARTS (PWA RELATED)

HYBRIDS

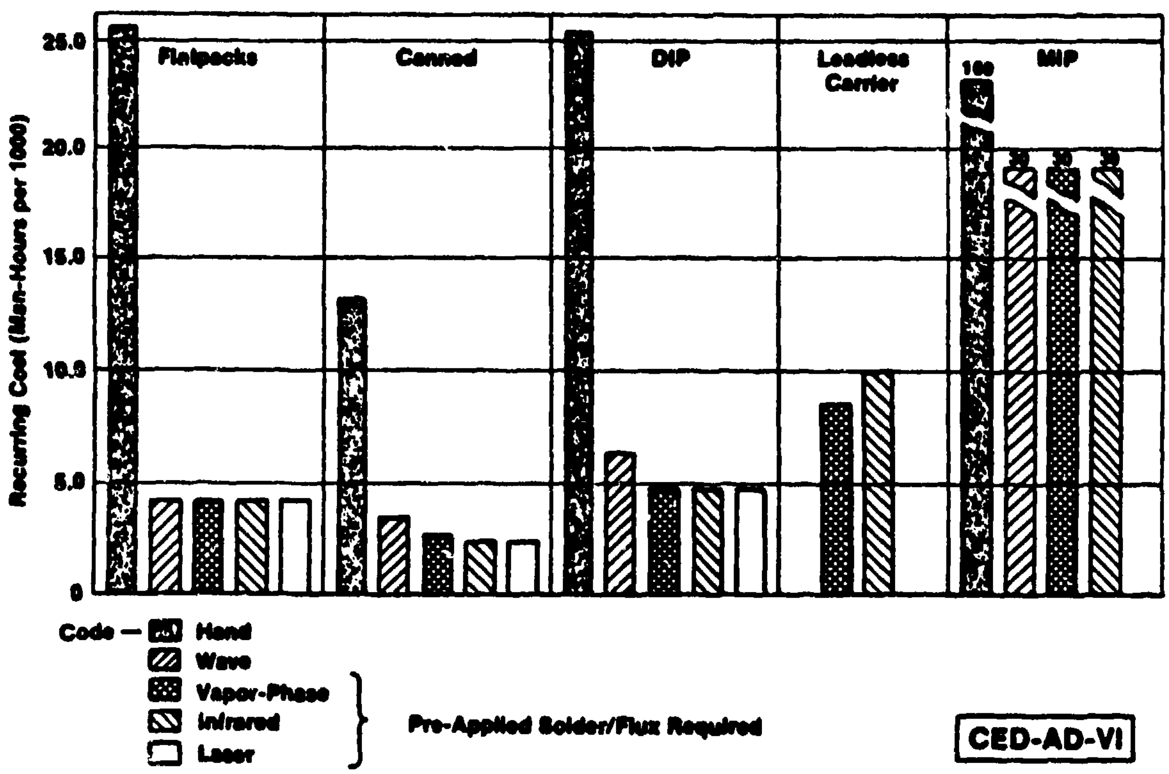


FIGURE 9.

EXAMPLES OF CONCEPTUAL DESIGN TRADE-STUDIES USING MC/DG

1. IMPACT OF BUILT-IN TEST EQUIPMENT ON MANUFACTURING COSTS

The interaction of LRU-BITE, manufacturing test, and related equipment, has the potential of providing a reduction in associated manufacturing costs. Four possible benefits of this interaction are:

- Simple ATE to item interface - many interfaces that would have to be brought out of the LRU to the ATE are now examined by the BITE.
- Less ATE execution time - more testing is done by the BITE resulting in reduced ATE memory and test time. Also, less software needs to be generated.
- Improved intermittent fault detection - BITE operating continuously has a far greater possibility of detecting an intermittent fault, recording that fault and storing in a fault memory for later interrogation by the ATE.
- A more comprehensive test - the BITE, being an intimate part of the LRU, is responsive to faults the ATE could not detect due to the limits of interfacing, and non real-time monitoring.

In general, the discussion will be directed toward the 15 to 25 board system. Cost impacts vary with system complexity and the required BITE. However, this level of complexity is typical and offers some up-to-date data. The self-test must be capable of annunciating faults it detects such that an operator may isolate the problem to a card or group of cards and/or function. Also assumed is a relatively thorough level of electronic card test such that an operator, on having a fault annunciated, can remove the suspect assembly or assemblies and subject them to a more detailed test.

Prior to examining the cost differentials associated with BITE/manufacturing test interaction, some definitions of the system configuration involved must be discussed. Figure 10 (CDE-E-VA) shows a two-board "system" with two separable functions occupying board #1 and two functions on board #2. Board #2 is also broken into sub-functions which are designated "clusters" of components. Clusters are difficult to define, but would consist of sub-functions within a major function, each having a measurable interface.

An end-to-end test is relatively simple, requiring a minimum of test equipment, and isolating nothing except the system. At the opposite end, the test which isolates clusters of components requires extensive interfacing equipment and diagnostic programming. Board and function isolation fall in between. This relationship is shown in Figure 11 (CDE-E-VB) which depicts the relative BITE sizing for the 3 levels of test.

The growth in time and part count of roughly 7.5 percent for an end-to-end test reflects the additional memory for the program, as well as the buffering electronics necessary to transfer information to the testing processor. To isolate the board or function, an approximate 27 percent increase in parts is required for an isolation ambiguity of 23 percent between two boards or function.

To extend the approximation to a detection of faulty clusters of components requires some assumptions. Each function or board type is listed below, and a "cluster breakdown" is provided.

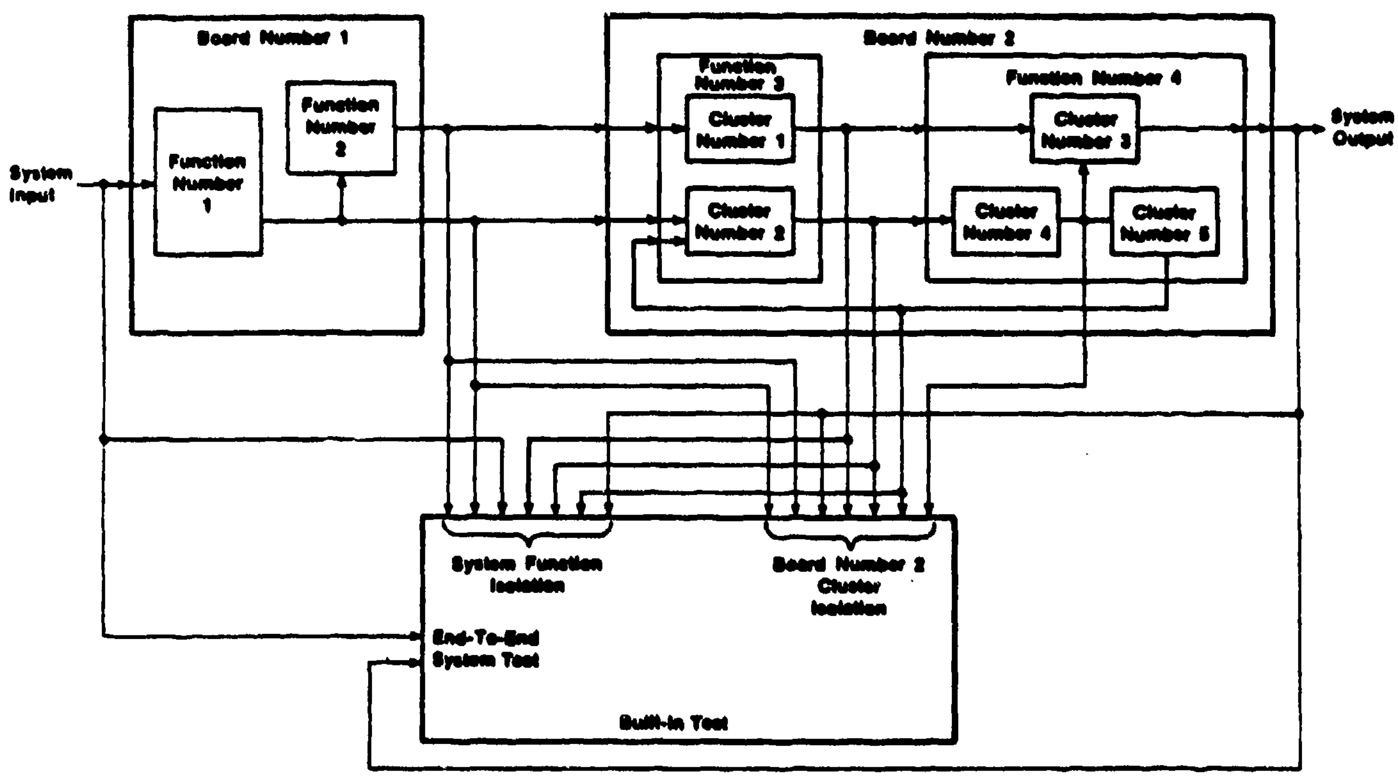
Function	Clusters	Total Clusters	Necessary Tests Added
Processor	ALU, PROM, Logic	3	3
Memory	4 chip address groups	16	0
Analog input	Buffers, A/D	20	1
Analog output	D/A buffers & hold	20	1
Discrete-in	-	10	1
Discrete-out	Each discrete	20	20
Servo amp	Each amplifier	4	4
Resolver input	Each resolver buffer	8	8
Power supply	-	1	6
Demodulator	Each demod	8	8
			52

These tabulations provide the basis for the last data point on Figure 11 (CDE-E-VB).

Once the estimates for the increase in size of the LRU due to BITE are known, an approximation to manufacturing costs can be made. Data indicates that on the average, testing is about 40 percent of the manufacturing cost. This, of course, is a function of board and system complexity, and the type of test equipment involved. The 60 percent balance is composed of parts cost and assembly labor, and is impacted by the level of BITE installed in the LRU. Data also indicates that a reduction in test time of a factor of 5 to 12 can be realized when a comprehensive, well annunciated BITE is used. Using these values, the curve of Figure 12 (CDE-E-V) is plotted. However, these are approximations and are useful for trend indication only. As expected, the test time decreases significantly due to the BITE usage. However, the cost of the increased amount of BITE hardware soon becomes more dominant, and we find that manufacturing costs begin to rise again, having once reached a minimum. Consequently, it would appear that a relatively thorough BITE may not be cost-effective when considering only manufacturing costs.

FIGURE 10.

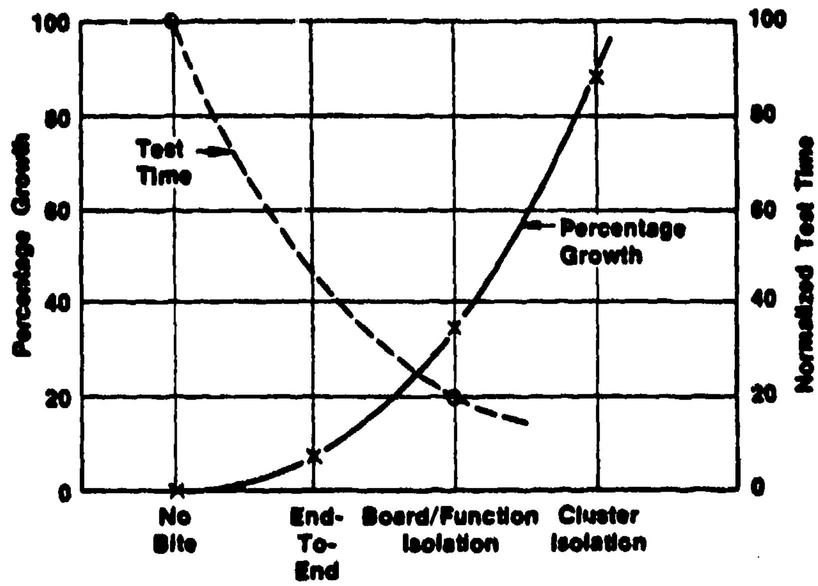
BITE TEST LEVEL DEFINITION



CDE-E-VA

FIGURE 11.

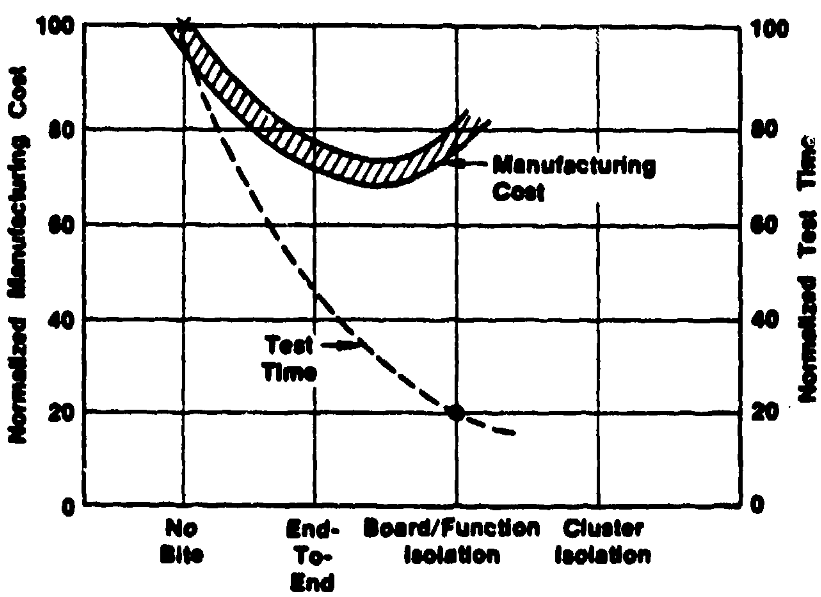
IMPACT OF BIT COMPLEXITY



CDE-E-VB

FIGURE 12.

BITE IMPACT ON MANUFACTURING COST



CDE-E-V

2. ANALOG VS. DIGITAL SYSTEM DESIGN

At the start of the conceptual design phase, an early decision is often required to define the basic configuration as to a digital system or an analog system design. The first design task associated with this study is the definition of functions required to meet operational specifications. The most immediate task is to define an interface list to provide signal types, signal levels, termination impedances, dedicated data transmission or time shared, redundancy levels, power requirements, etc.

A curve, Figure 13 (CDE-E-IVA) was developed from data obtained analyzing seven avionic flight hardware systems. In two cases, an original analog system was replaced by a digital system performing identical functions. The normalized manufacturing costs as a function of part count are plotted in Figure 13 (CDE-E-IVA). This curve is not totally usable since piece part-count alone does not account for the capacity of digital processing equipment to accomodate more functions than analog circuits.

The "K" factor curve of Figure 14 (CDE-E-IVB) was derived by analysis of the various analog and digital system to define a relationship of piece part-count to functional capability.

The final results of the analysis are presented in Figure 15 (CDE-E-IVC). A design engineer can determine relative manufacturing costs of an analog vs. a digital system mechanization by making a piece part-count and locating the point on the appropriate line of Figure 15 (CDE-E-IVC). Using the adjusted piece part-count criteria of a summation of all types of electronic parts, the break point for manufacturing cost consideration is 2100 piece parts.

**ANALOG VS DIGITAL SYSTEMS
UNADJUSTED COST DATA**

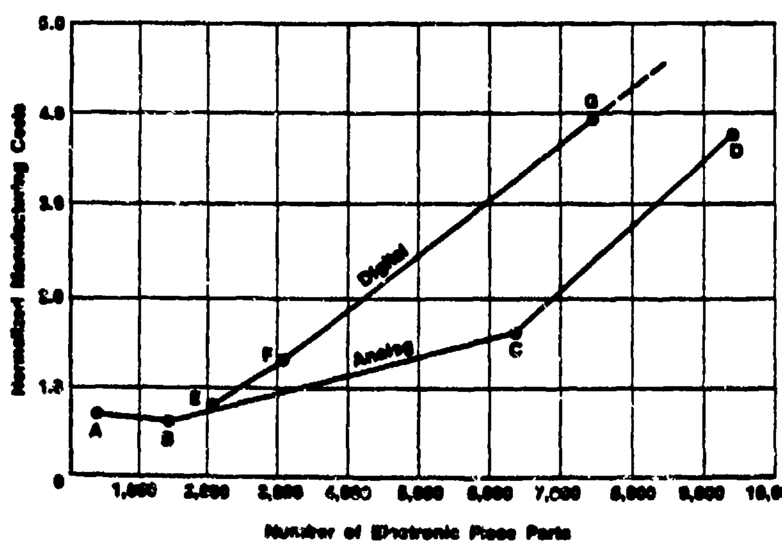
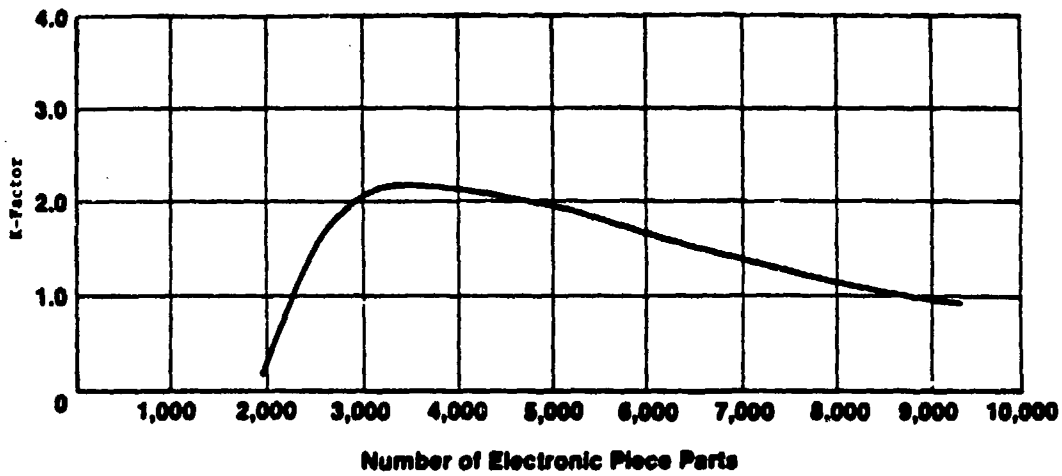


FIGURE 13.

CDE-E-IVA

FIGURE 14.

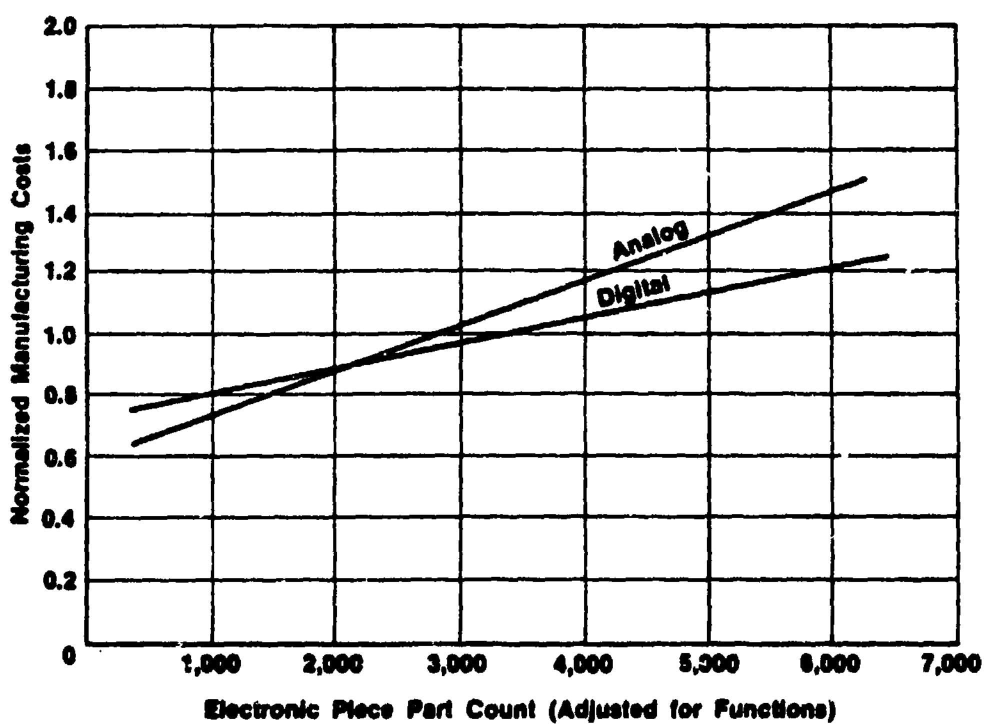
FUNCTION ADJUSTMENT K FACTOR



CDE-E-IVB

FIGURE 15.

ANALOG VS DIGITAL SYSTEMS FUNCTIONALLY ADJUSTED COST DATA



CDE-E-IVC

POTENTIAL COST REDUCTIONS UTILIZING "MC/DG FOR ELECTRONICS"

The following are the approximate costs of various electronic systems:

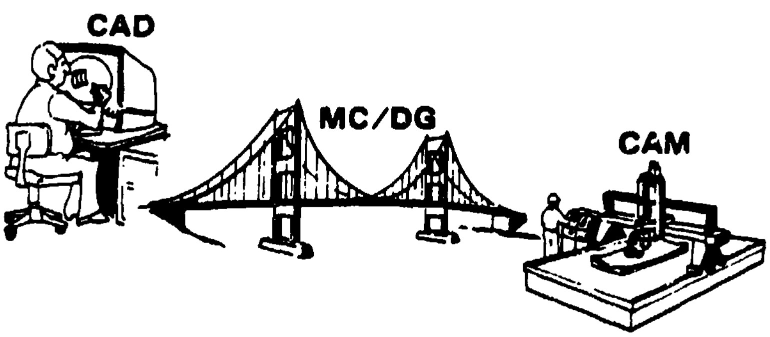
- Commercial Navigation Received (Black Box Level) $10-15k.
- Military Communication Received/Transmitter $15-20k.
- Commercial VHF Communication System (System Level) $30-50k.
- Military Cockpit Management System or Autopilot System $100-200k.

Experienced designers in industry were requested to estimate the cost-savings impact of utilizing the ICAM "Manufacturing Cost/Design Guide" (MC/DG) through all phases of electronic systems development.

The following are the estimated payoffs from using the MC/DG on an inertial navigation or flight control system:

- Buy 600
- $60,000 each
- $36,000,000 program
- Engineering design and development program, typically 2-year effort costing $2,000,000
- MC/DG increases design activity by 10 percent, i.e., $200,000 but is more efficient
- Use of ICAM MC/DG predicted to reduce material and labor cost of each system by 10 percent to $54,000
- Cost of total program now $32,000,000
- Savings estimated to be $4,000,000.

MC/DG IS THE BRIDGE BETWEEN CAD AND CAM



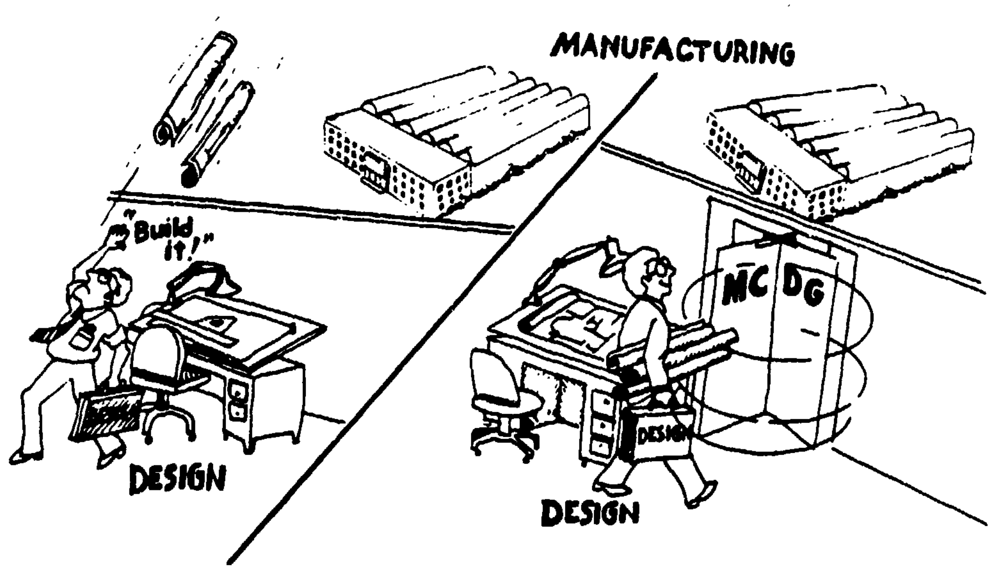
MC/DG FOR ELECTRONICS PROVIDES THE FOLLOWING BENEFITS:

- Influences design decisions
- Emphasizes low cost processes
- Provides qualitative/quantitative manufacturing cost data
- Imparts senior designer experience on new engineers
- Provides direct feedback of manufacturing cost impact.

The MC/DG plays an important role in the CAM environment.

- Provides bridge between CAD and CAM
  - Design/manufacturing interaction
- Highlights lowest cost process flow
- Allows design trades with known manufacturing cost impacts
- Provides immediate cost impact of documentation change notice.

The ICAM MC/DG payoff on return of investment is cumulative on all electronic and airframe subassemblies and systems; Army, Navy and Air Force.



A DESIGN/MANUFACTURING INTERACTION TOOL FOR MATERIAL SUBSTITUTION TRADE-OFFS

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Abstract

Constraints frequently exist in determining cost-effective materials substitution and include lack of manufacturing cost-data to conduct trade-studies, cost of redesign, additional testing and tooling, and requirements to maintain form, fit and function of parts committed to production. Additional design tools are necessary at the conceptual, preliminary and detail design phases. Such guides must, for example, enable conceptual designers to evaluate alternative concepts and the manufacturing technologies needed for emerging materials, when changes have minimal cost impact. Current methods of estimating manufacturing costs are discussed. The application of the "Manufacturing Cost/Design Guide" (MC/DG) to the materials substitution problem, assisting designers and manufacturing engineers to avoid cost-drivers, is reviewed.

Materials Substitution Background

We are now in an age for which we are unprepared, an age of material shortages.

We are all acutely aware of the energy dilemma; many solutions are proposed and just as many controversial objections and constraints toward progress are advanced. However important the energy crisis is, of equal importance is the increasing awareness of materials shortages and the immediate need to find alternative materials.

Some of the contributing factors to material shortages are:

- Up to 90% of the columbium, manganese, tantalum, cobalt, chromium, bauxite, and alumina used in the United States are imported. Up to 50% of many other important materials are imported.
- Political upheavals in some of the exporting countries have disrupted supplies resulting in significant price increases.
- Lead-time for many materials and components has increased by a factor of from 2 to 4 times since 1977. Examples are:
  - Aluminum sheet; 18 weeks in 1977 to 72 weeks in 1980
  - Precision forgings; 27 weeks in 1977 to 80 weeks in 1980
  - Purchased parts (built-to-print); 35 weeks in 1977 to 78 weeks in 1980.

Another important factor which contributes to material substitution and the quest for alternative materials is the necessity for increased performance of complex systems such as jet-engines. The design engineer is driven and assessed by his ability to provide the marketplace with an ever-improved product with increased performance. The complex external forces and internal interactions in the design-to-cost process is shown in Figure 1. To accomplish these objectives, the engineer, using advanced technology, has not only improved existing materials, but has developed new "man-made" materials, new products, and new manufacturing technologies. A few examples in the aerospace industry are:

- Transition of the airframe structure from "wood-wire-cloth" to high-strength sheet metal structures utilizing aluminum and titanium
- High-strength aluminum, steel and titanium alloys
- Development of high-strength, high-modulus composite materials
- Advanced welding technology; e.g., electron-beam, laser, and plasma
- Environmental protection of surfaces
- High-strength fasteners
- High-strength castings and forgings
- Powder metal technology (shape technology)
- Improved metal removal cutting tools
- Numerous applications of computer technology (CAM and CAD)
- Development of solid-state electronics.

The aerospace design team priorities are shown in Figure 2. To continue to meet the requirements for increased performance in face of material shortages and lead-time problems, engineers must have a working knowledge of the cost impact on manufacturing when selecting materials for new designs or when substituting alternative materials to improve performance or to overcome a material shortage. The Air Force ICAM "Manufacturing Cost/Design Guide" (MC/DG) will provide this capability to design-to-cost in all phases of the evolution of the design, as well as in the production phase of the product.

Constraints to Material Substitution

Just as constraints exist in the energy problem, such is also the case with the materials shortage problem. Some of these constraints are:

- Lack of engineering design data
- Lack of adequate manufacturing cost data to conduct trade studies

*Associate Fellow, AIAA

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Preliminary Design Phase

During this phase, the final design concept or configuration is selected. If in preparation for a design competition, the "homework" has been accomplished and the customer's requirements have been defined with a reasonable degree of accuracy, this phase constitutes primarily a review of the conceptual design more closely meeting the requirements of the "Request for Proposal" (RFP) at the most competitive cost. During this critical phase, the overall configuration is "frozen". The following are examples of the major decisions which have to be made:

- Performance parameters
- Envelope the basic configuration and size the design
- Define weight targets
- Material selection for major components
- Major manufacturing subassemblies or break-backs
- Degree of commonality with existing designs
- Major "make-or-buy" decisions
- Major testing requirements, e.g., aerodynamic, acoustic, structural fatigue, and materials
- Optimum master schedule
- Manufacturing plan/tooling policy
- Manpower and skill requirements
- Funding requirements
- Marketing plan.

It is incumbent on the design engineer to indicate, by providing adequate and factual test data, that the projected performance claims made in the initial proposal to the customer will be met. Of equal importance, is the responsibility of manufacturing to satisfy the customer that the product can be built on schedule, at the contractual price, and without overruns. In today's climate of double-digit inflation and material availability uncertainties, this poses a major problem to both the manufacturer and the customer. The cost-estimating methodology and its accuracy must be capable of substantiation with factual back-up data for both in-house supervision and customer review.

Current Methods of Estimating Manufacturing Costs

The bases for most cost estimations of products are "historical data," drawn from a data bank. These costs are in categories such as the following:

- Material cost trends and projections
- Man-hours per pound of structure
- Standard hour data
- Learning curve slopes
- Productivity trends
- Average tooling costs by type of tool
- Average cost per part
- Processing costs
- Production control costs
- Test, inspection, and evaluation (TI&E) costs
- Overhead pools
- Administrative costs.

MC/DG as a Costing Methodology Aid

Historical data, regardless of the constraints, will continue to be used to estimate manufacturing costs. However, the designer can utilize MC/DG formats shown in Figures 8 and 9 to conduct trade-offs between structural performance and manufacturing cost. Such formats showing qualitative data put the designer on the lowest cost track early in the development phase.

The MC/DG is not a cost-estimating manual, but rather a guide toward lower cost, enabling designers and manufacturing engineers to avoid cost-drivers. As such, it becomes a tool to evaluate the compatibility of the proposed design with a market, and customer's accepted "bench-mark" or "baseline" of low cost design. A low manufacturing cost for a design utilizing high cost material or with extensive lead-time, may not meet the criteria for affordable performance. The alternatives can be evaluated with the MC/DG. The design approach is illustrated in Figure 7 for a fuselage shear-panel study. The methodology to define base parts (simplest geometry) and designer-influenced cost elements (DICE) is schematically shown in Figure 10.

Production Design Phase

Although the principal design decisions pertaining to the material to be used on the primary structural components are made in the previous design phase, many important decisions are also necessary during the production design phase.

Detail design of each of the frequently thousands of parts requires a comprehensive knowledge of the effect of designer-influenced cost elements (DICE) on discrete parts. DICE might add 25% to manufacturing man-hours. Selection of material for the detail parts must be compatible with the structural configuration, loading, corrosive, and many other requirements, but the designer frequently has considerable latitude in selecting the material form; e.g., bar, plate, sheet, forging, and casting for metals, or tape and broadgoods for composites.

It is at this critical phase, that the design is "locked-in" and changes made after design release must meet the "form, fit, and function" requirements. This results in added costs for retesting, retooling, scrap or salvage of completed parts, and interruption of the learning curve, resulting in schedule delays.

- Lack of in-service experience with some new materials
- Initial "start-up"; e.g., tooling, new skills, learning curves, and high cost of some materials, such as advanced composites, titanium, and steel alloys.
- Increased logistic inventory required for more than one spare replacement
- Reluctance to change, e.g., "let someone else take the risk" or the "not invented here" syndrome
- Cost of redesign, additional testing, tooling, and also retraining
- Necessity to maintain the "Form, Fit, and Function" of parts designed and already committed to production
- Investment requirements in new facilities and equipment.

Conceptual Design Phase

In today's highly competitive environment, the survival of a company depends primarily on the ability of its design engineers to anticipate the needs and requirements of the customer, and to perceive how to meet those requirements at a lower cost and in a shorter time-span than competitors.

Top priority must be given to performance. Performance is achieved not only by superior knowledge and skill in the application of design theory and engineering disciplines related to the product; but also of importance is the creative and inventive mind. However, the design engineer must also recognize that performance must be achieved at an affordable cost and a major constraint to this necessary goal, among others, is the shortage of strategic materials.

At the preproposal or conceptual design phase, decisions must be made which will ensure that the materials selected, when required, will be readily available and cost-effective to use. The ability to accurately predict technology advances and material requirements is an important factor in the conceptual phase. Examples of these factors are:

- Long-range predictions for materials, including availability and cost projections must be utilized to avoid potential problems
- More time is available to evaluate alternative design approaches
- Several alternative design concepts or options can be evaluated
- Manufacturing technology can be applied to "productionize" any new process/method required to utilize advanced materials
- Material property data can be generated and made available to designers
- Decisions made at the conceptual design phase are more readily changed with little or no cost impact
- Degree of commonality with existing designs can be studied to reduce tooling and manufacturing costs.
- Provides the lead-time for the procurement of new facilities or equipment
- Projected customer performance requirements, funding constraints, and schedule requirements are being generated
- Provides management with the time to evaluate long-term commitments and improve the competitive position of the company.

Importance of MC/DG at the Conceptual Design Phase

Although decisions made by the design engineer at this early phase are subject to change, they normally have a major impact on the total life-cycle costs of the system to be developed. The decreasing leverage to achieve minimum cost, as the investments in a system increase, is shown in Figure 3. Examples of the decisions made throughout the design process and their cost impact is illustrated in Figures 4 and 5. It is most important that the design engineer is provided with qualitative and quantitative manufacturing cost data, besides mechanical property data, etc., if a design is to evolve that not only meets or exceeds performance goals, but does so at an affordable cost and ahead of the competition.

The MC/DG is a source of manufacturing manhour data for both metallic and non-metallic discrete parts and assemblies. It allows the design engineer to evaluate "on paper" the various design approaches envisioned and their relative overall manufacturing cost. The contents of the MC/DG, when fully developed, is shown in Figure 6. Examples of how the MC/DG will be able to aid the design engineer at the conceptual design phase, are:

- Based on long-range material costs and projections of availability, evaluate alternative solutions, such as the application of composites vs. metals
- Avoid cost-drivers by determining the lowest cost manufacturing methods/processes with available materials
- Highlight the potential cost impact resulting from designs utilizing strategic metals and alloys such as titanium, cobalt, and chromium. Study design alternatives to identify cost impact early and avoid "built-in" cost escalation
- Provide management with realistic, timely estimates of projected manufacturing costs
- Facilitate interaction between manufacturing and engineering at the phase when manufacturing input to the design will have the maximum impact on producibility
- Provide design engineers with a comprehensive source of data or a tool to enable trade-offs to be conducted between manufacturing costs, including test, inspection, and evaluation (TI&E), and the performance of the system.

During this phase, schedules are tight and decisions are made rapidly. The designer-oriented formats in the MC/DG have been especially developed to minimize the possibility of schedule slippage. The MC/DG will be available in hard copy (3-ring binder and pocket version), and also as a computerized data base and interactive computerized system (Manufacturing Cost/Design System-MC/DS).

Production Phase

Provided that an acceptable design has been released and every effort has been made to utilize the lowest cost materials and manufacturing technologies, the product should proceed into production at an acceptable cost level. Unfortunately, this is an ideal situation, but continued application of design-to-cost and manufacturing-to-cost principles throughout all design and production phases, as exemplified by the MC/DG, will help to achieve the desired goal of affordable performance.

Most production programs experience a "start-up" and "shake-down" phase to correct engineering and tooling discrepancies and achieve shop learning. This is normal, but the cost and schedule impact can be minimized if corrective action is taken in a timely and organized manner.

An indirect benefit of the MC/DG is the mutual understanding and interaction that results between design engineering and manufacturing. The MC/DG continues to be a valuable tool throughout the production program. For example it:

- Provides data necessary to evaluate the cost impact of proposed or necessary changes brought about, for example, by modifications in system missions.
- Provides justification and a method to evaluate cost impact of necessary changes resulting from the requirement to substitute alternative materials due to shortages, lead-times or increased performance requirements (cost could either be lowered or increased).
- Provides cost analysis data necessary to justify the feasibility of introducing new materials or emerging technologies into ongoing programs.
- Provides a "bench-mark" or "baseline" to document productivity gains.
- Promotes better industry and customer relations by providing a common baseline or starting point for cost vs. performance studies.
- Provides method to determine "break-even" points for introduction of, for example, forgings or precision castings, vs. "hog-outs."

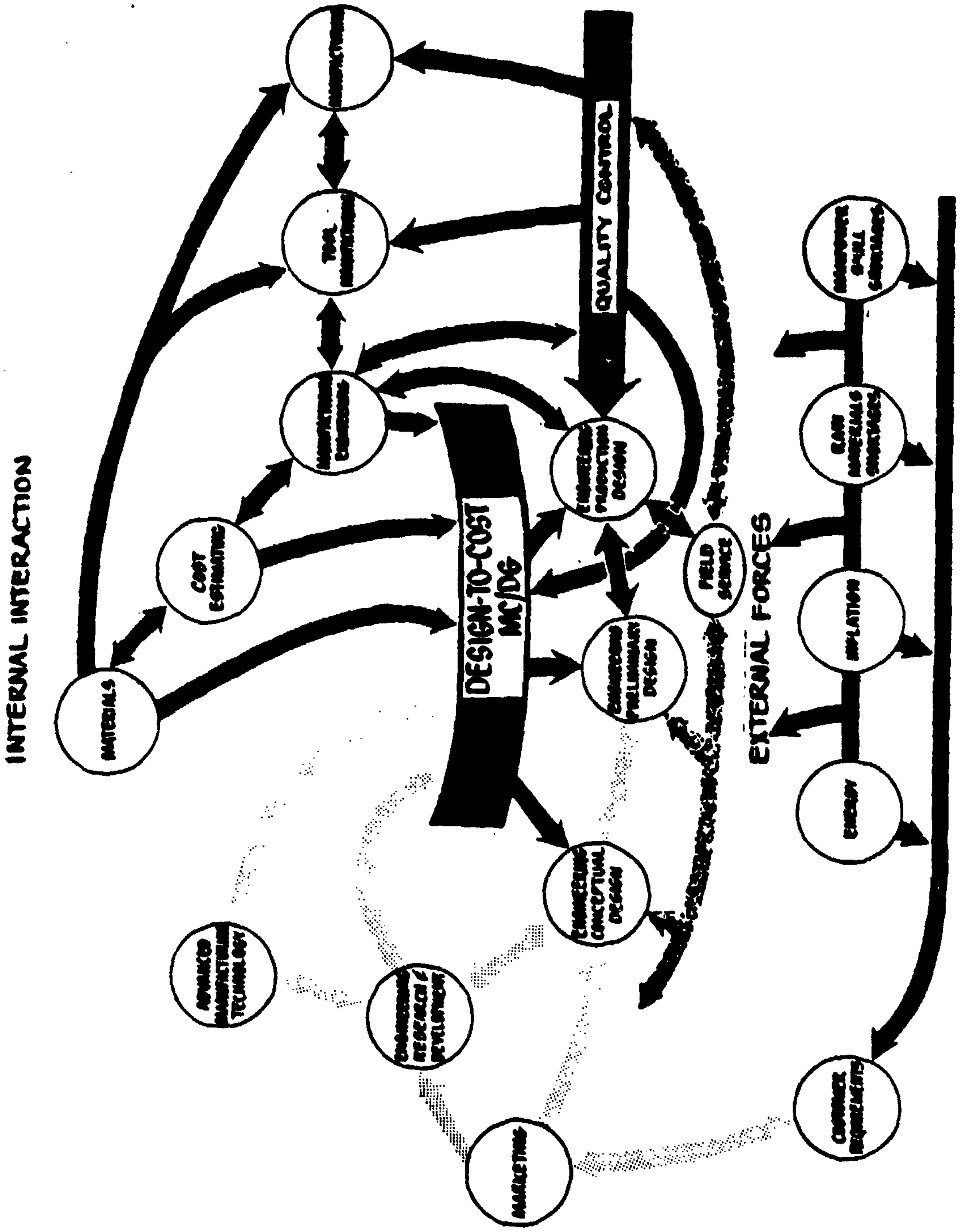


Fig. 1 Impor:ance of recognition of external forces and internal interactions in design-to-cost

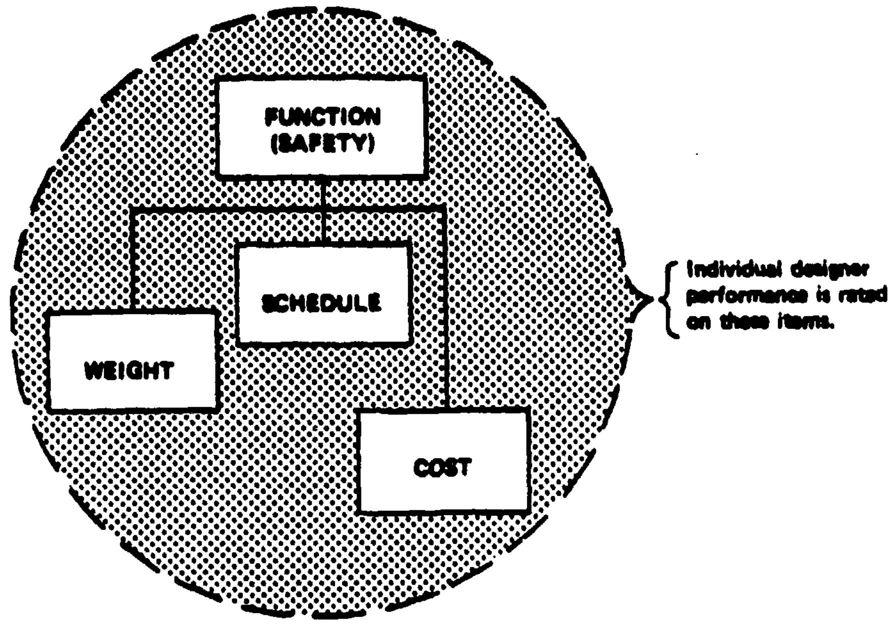


Fig. 2 Present aircraft design team priorities

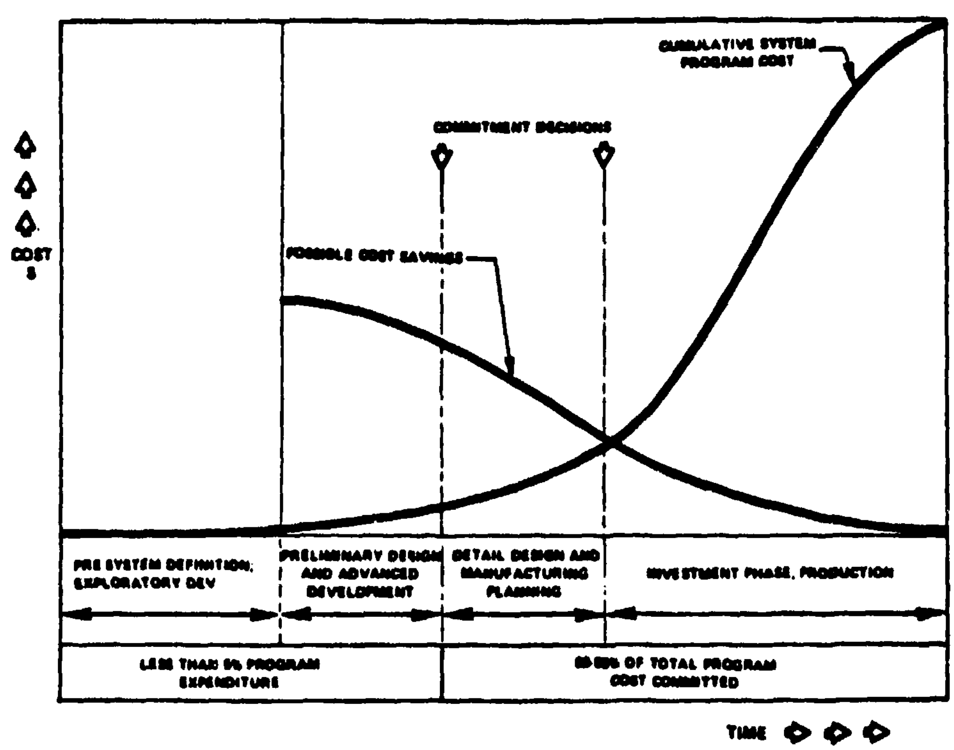


Fig. 3 Decreasing leverage to achieve cost savings as development progresses

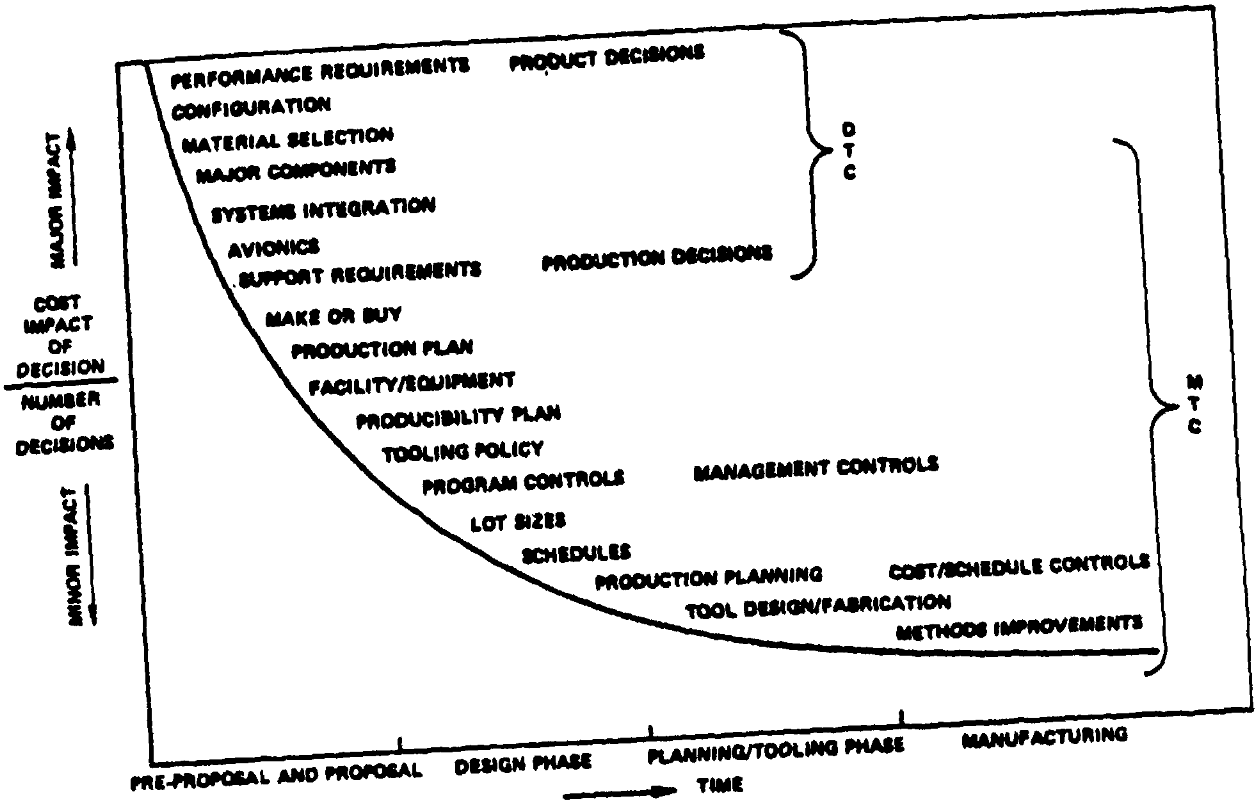


Fig. 4 Major decisions and decreasing cost impact with time

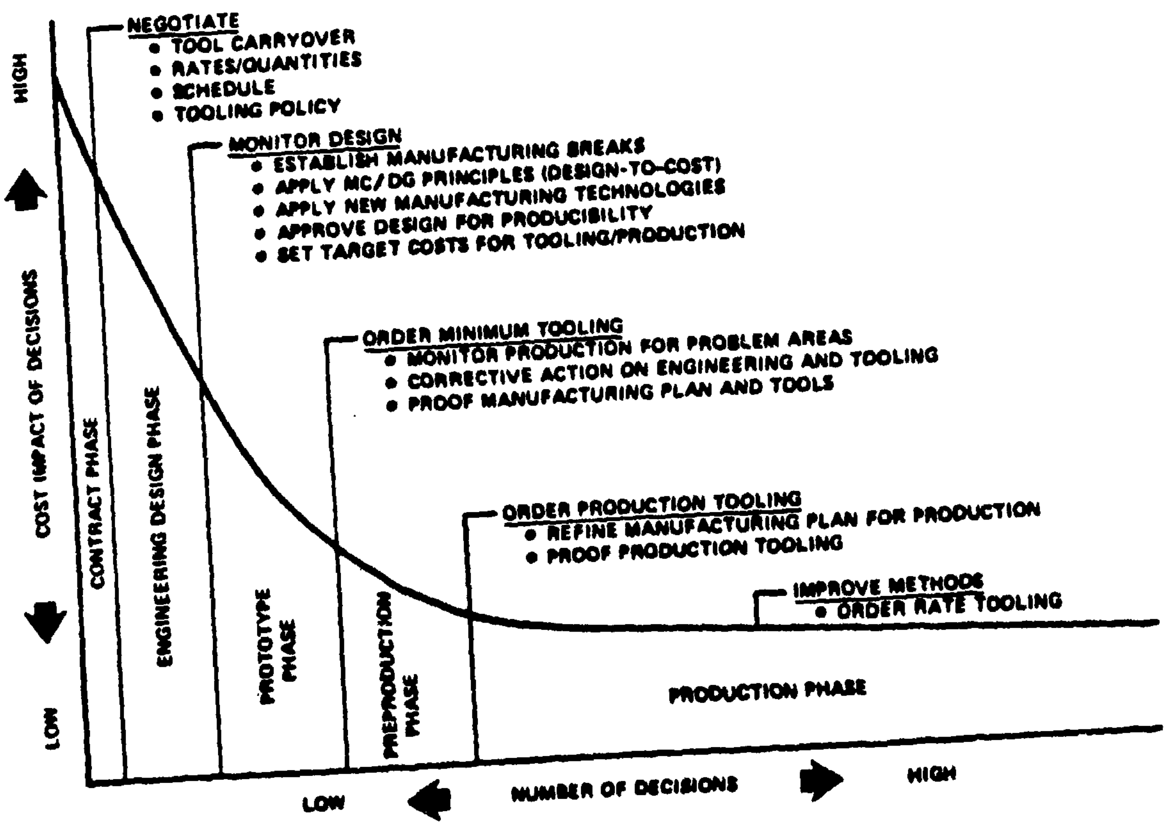


Fig. 5 Manufacturing decisions during various design phases

I	II	III	IV	V	VI
PROCURED ITEM COSTS	MATERIAL REMOVAL COSTS	DETAIL FABRICATION COSTS	MATERIAL TREATMENT COSTS	PERMANENT JOINING* COSTS	ASSEMBLY* COSTS
• Forgings Hand Conventional Blocker Precision • Castings Sand Permanent Mold Investment Die Casting • Extrusions • Materials • Fastener Systems • Emerging Proc. Isothermal Forging Powdered Metal Pultrusion HIP Healing CAM	• Machining Turning Milling Drilling • Chem Milling • EDM • ECM • Emerging Proc. Laser Fluid-Jet CAM EB Cutting	• Metallic Forming Cutting • Non-Metallics Forming Cutting Molding Laminating • Emerging Proc. Superplastic Forming Flow Forming Hydrostatic Forming Thermoplastic Forming CAM	• Heat Treatment • Surface Treatment • Emerging Proc. Laser Treating Nonenvironmental Polluting Treatments	• Welding • Adhesive Bonding • Brazing • Emerging Proc. Diffusion Bonding Weld Bonding Laser Welding Ultrasonic Welding Plasma Arc *Subassembly	• Metallic Assy. Mechanical Fastening • Non-Metallic Assy. Mechanical Fastening • Emerging Proc. Bimetallic Rivets Microwave Curing *Major and Final Assembly

Categories = e.g., Material Removal
Sections = e.g., Machining
Subsections = e.g., Turning and Milling

Fig. 6 MC/DG volume contents: "Manufacturing Technologies for Airframes"

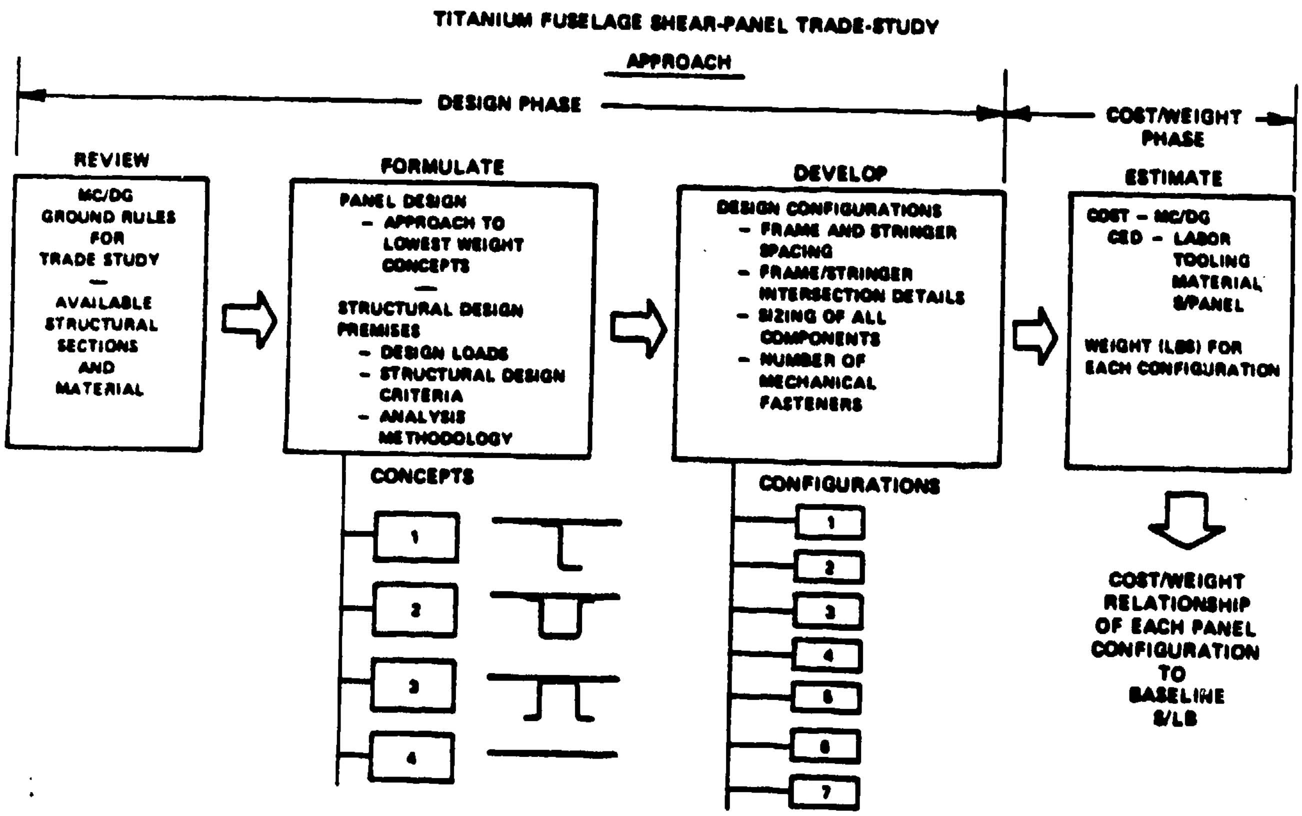
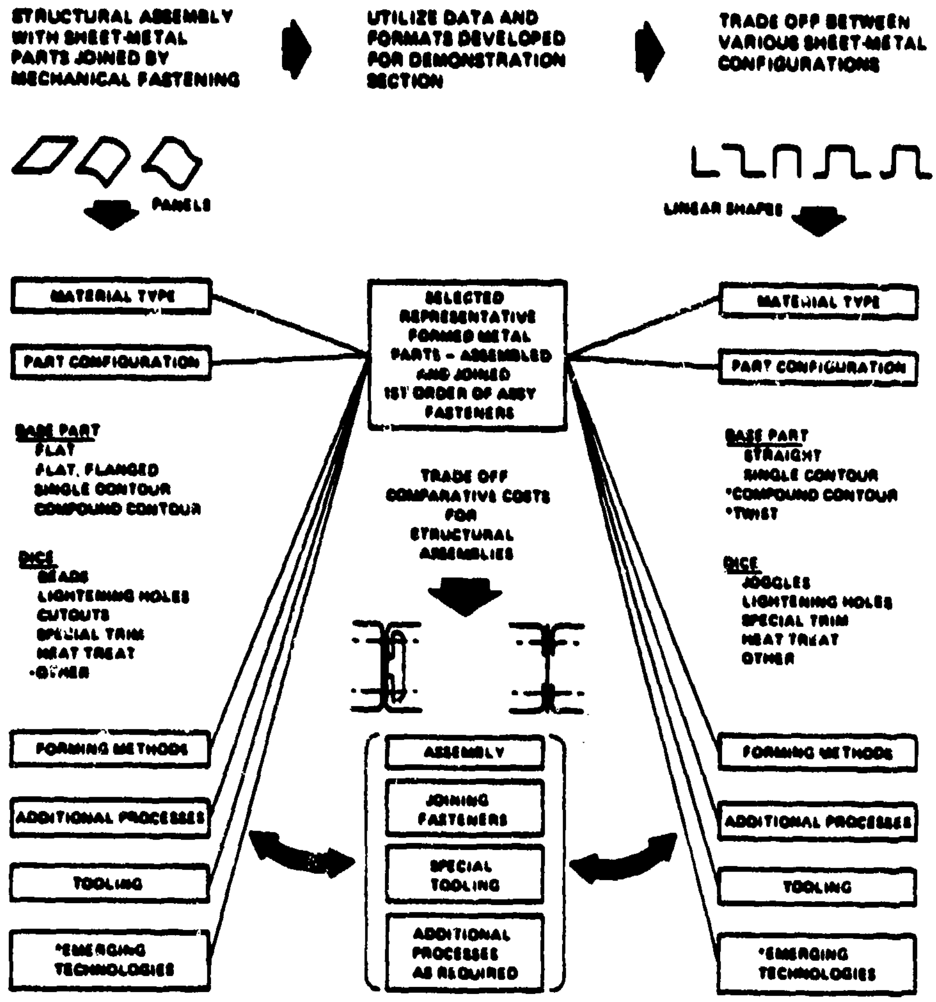


Fig. 7 Typical example of design approach utilizing MC/DG



*Recommended to be developed

Fig. 8 Base part and Designer Influenced Cost Element (DICE) approach in utilizing MC/DG

MC/DG COST WORKSHEET

DESIGN CONCEPT		RECURRING COST (RC)									NON-RECURRING COST (NRC)			PROGRAM COST		
		[illegible]									[illegible]			[illegible]		
PART NO.	DESCRIPTION	LABOR HRS/SHIFT (1)	LC FACTOR (2)	LABOR RATE $/HR (3)	LABOR RC $/PT (4)	MAT'L $/PT (5)	REC. COST/PT. $ (6)	PARTS PER AC (7)	REQ. QTY. (8)	PROG. RC $ (9)	NRC HRS/DG (10)	LABOR RATE $/HR (11)	PROG. NRC $ (12)	PROG. COST $ (13)	REQ. QTY. (14)	COST/AC $ (15)
	TOTALS															

Fig. 9 Proposed MC/DG cost worksheet for evaluating alternative designs and manufacturing technologies

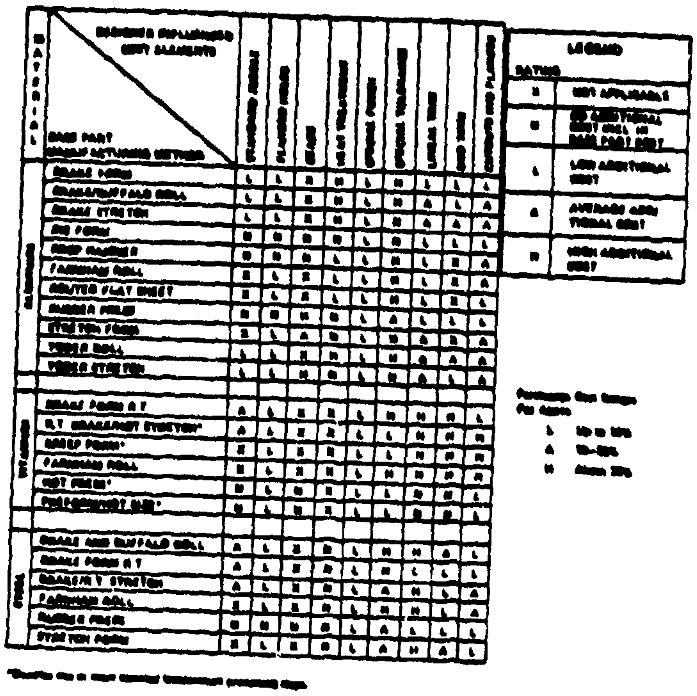


Fig. 10 Typical format showing relative cost impact of various manufacturing technologies for aluminum, steel and titanium

STEEL FRAME, LOWEST COST PROCESS
RUBBER PRESS

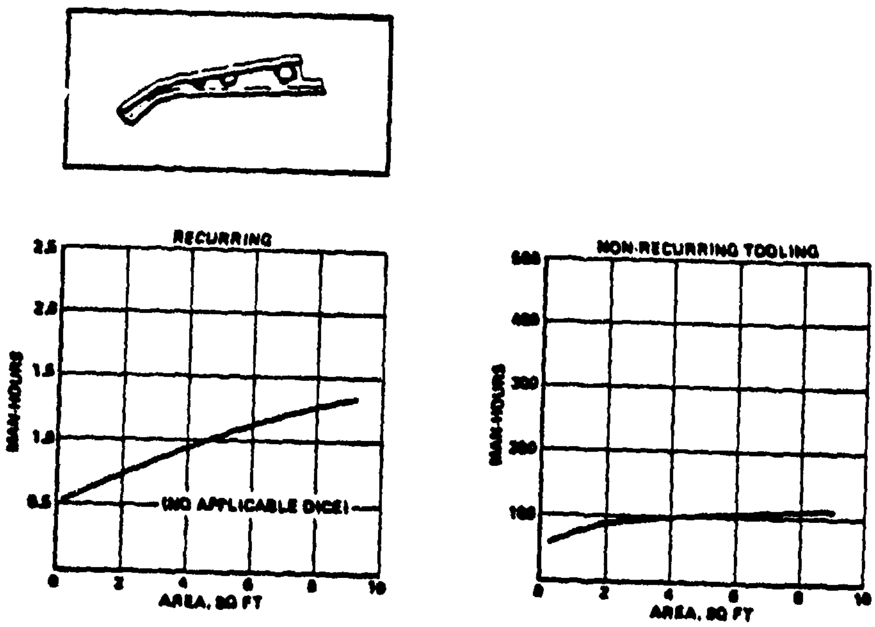


Fig. 11 Typical designer-oriented cost-estimating format showing recurring and non-recurring man-hours

APPENDIX F

EXAMPLE OF BRIEFINGS

AIR FORCE ICAM

"MANUFACTURING COST/DESIGN GUIDE" (MC/DG)

FOR

AIRFRAMES AND ELECTRONICS

BRYAN R. NOTON
BATTELLE'S COLUMBUS LABORATORIES (BCL)

CAPT. RICHARD R. PRESTON
COMPUTER INTEGRATED MANUFACTURING BRANCH
MATERIALS LABORATORY (AFWAL/MLTC)

BRIEFING TO ASD/EN, WPAFB

10 FEBRUARY 1983

AIR FORCE ICAM

"MANUFACTURING COST/DESIGN GUIDE" (MC/DG) FOR AIRFRAMES AND ELECTRONICS

BRIEFING OUTLINE

- BACKGROUND
- PURPOSE
- ORGANIZATION
- DATA & FORMATS — EXAMPLES
- UTILIZATION EXAMPLE
- INDUSTRY APPLICATION

BACKGROUND

AIRCRAFT MANUFACTURE

- DEPENDS HEAVILY ON MANPOWER
- IS A CYCLIC INDUSTRY
- HAS LITTLE AUTOMATION
- HAS FEW CUSTOMERS, EXCESSIVE CAPACITY
- HIGHLY SKILLED INDUSTRY
- HIGH TECHNOLOGY ORIENTED
- DRIVEN BY PRODUCT EXCELLENCE

MAJOR COST DRIVERS

- PERFORMANCE RELATED
  - REDUCED WEIGHT
  - HIGHER OPERATING SPEEDS
  - INCREASED RELIABILITY

- DESIGN RELATED
  - HIGH PART COUNT
  - NON-STANDARDIZATION
  - TOLERANCES

MAJOR COST DRIVERS

- MATERIAL RELATED
  - COST
  - AVAILABILITY
  - UTILIZATION
  - ENERGY
- MANUFACTURING RELATED
  - INSPECTION
  - EQUIPMENT
  - CYCLIC PRODUCTION
  - SMALL LOT SIZES
  - HIGHLY SKILLED LABOR
  - ENERGY IN AUTOCLAVE CURING
  - HIGH TOOL COUNT

MAJOR COST DRIVERS BY SUBSYSTEM

SUBSYSTEM \ COST DRIVER	AEROSPACE INDUSTRY-RELATED COST DRIVERS: WEIGHT REDUCTION OPERATIONS	PERFORMANCE VERSUS COST SYNDROME	LACK OF DTC	CYCLIC PRODUCTION	LACK OF SPECIFICATION/STANDARDIZATION	LACK OF AUTOMATION AND LOW PRODUCTION RATES	HIGH SKILL REQUIREMENTS	HIGHER QUALITY REQUIREMENTS	USE OF COBALT	CONTROLLED MANU-FACTURING CONDITIONS
AIRFRAME	H	H	H	H	A	A	A	A	L	L
ENGINE	H	H	H	H	A	H	A	A	H	L
MECHANICAL SYSTEMS	H	H	A	A	H	A	A	A	L	L
CREW SYSTEMS	H	H	H	H	H	A	H	H	A	A

H — HIGH IMPACT

A — AVERAGE IMPACT

L — LOW IMPACT

O — NO IMPACT

EXAMPLES OF COST-DRIVERS

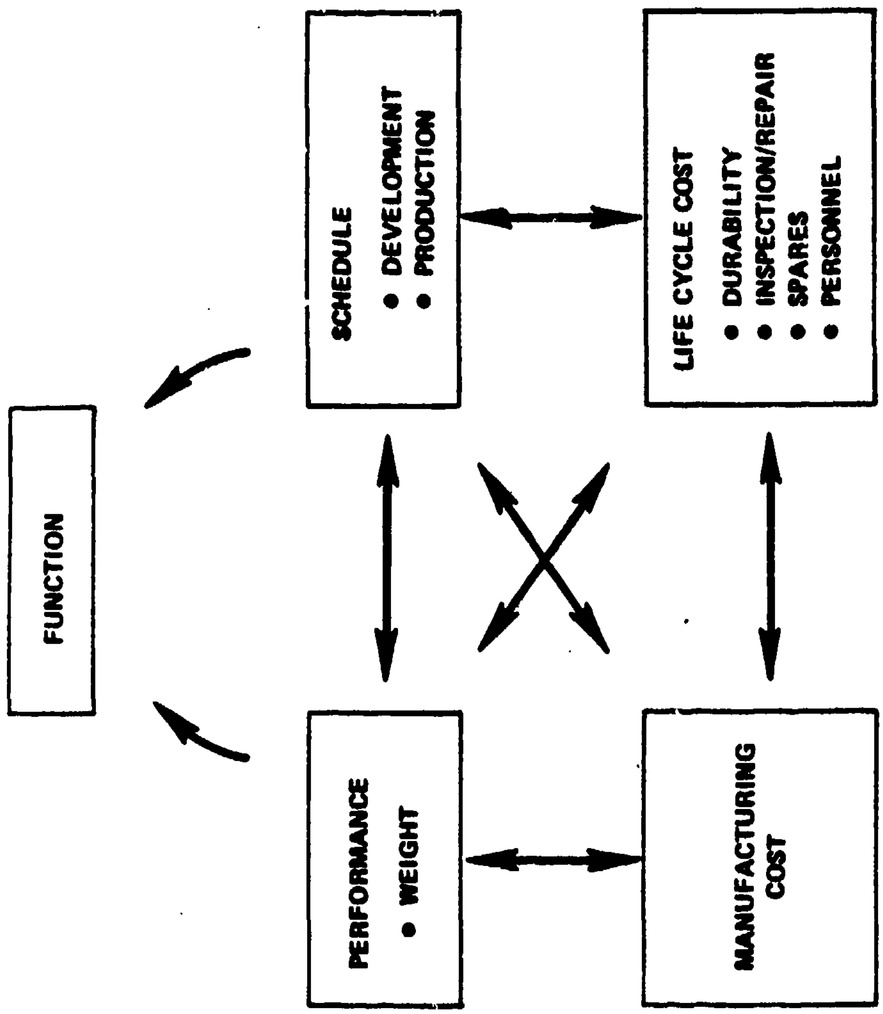
FORGINGS

- FORGING PROCESSES
- MATERIAL
- QUALITY REQUIREMENTS
  - TOLERANCES
  - METALLURGICAL PROPERTIES AND NDT/NDE
- QUANTITY, LEAD-TIME, AND LOT RELEASES
- COMPLEXITY
- SIZE

EXAMPLES OF COST-DRIVERS
(Continued)

TOLERANCES AND SURFACE TEXTURE

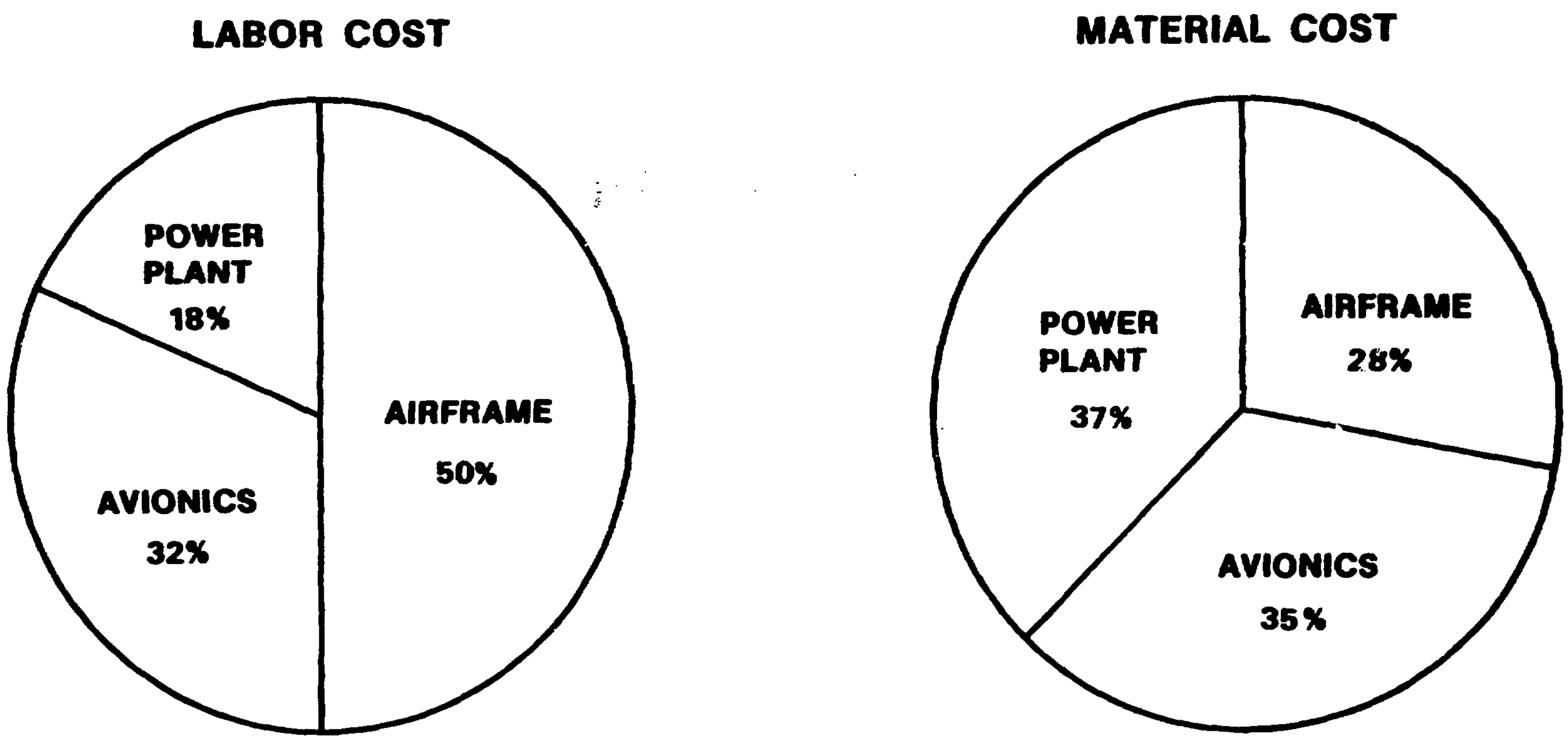
- OVER-SPECIFICATION OF DIMENSIONAL TOLERANCES
- OVER-SPECIFICATION OF SURFACE TEXTURES
- RELATIVE INFLUENCE OF DIMENSIONAL TOLERANCES IN CONJUNCTION WITH SURFACE TEXTURES
- MATERIAL TYPES/MACHINABILITY



INTERACTIONS BETWEEN DESIGN AND OTHER DISCIPLINES

APPROXIMATE COST DISTRIBUTIONS FOR USAF F-16 AIRCRAFT

FISCAL YEAR 1982



PURPOSE

OBJECTIVES OF MC/DG

- PROVIDE DESIGNERS WITH SIMPLE, RELATIVE, AND QUANTITATIVE COST COMPARISONS OF MANUFACTURING PROCESSES
- EMPHASIZE DESIGN ORIENTATION OF MC/DG FORMATS AND MANUFACTURING MAN-HOUR DATA FOR USE AT ALL PHASES OF DESIGN PROCESS
- INCREASE NUMBER OF PERFORMANCE/MANUFACTURING COST TRADE-OFFS CONDUCTED BY DESIGNERS
- EMPHASIZE POTENTIAL COST ADVANTAGES OF EMERGING MATERIALS AND MANUFACTURING METHODS
- PUT DESIGNERS ON LOWEST COST TRACK EARLY IN DESIGN PROCESS
- IDENTIFY COST-DRIVING MANUFACTURING OPERATIONAL SEQUENCES PROVIDING TARGETS FOR COMPUTER-AIDED MANUFACTURING (CAM) THRUSTS

MC/DG FOR AIRFRAMES & ELECTRONICS

HOW DOES THE MC/DG ACHIEVE THIS?

- BUILDING-BLOCK APPROACH
  - PROVIDES DESIGNER WITH COST FLEXIBILITY READILY ADAPTABLE DURING DEVELOPMENT OF AIRFRAME OR ELECTRONIC SYSTEMS
  - PROVIDES DESIGNER WITH UNIQUE BUILDING-BLOCK METHODOLOGIES
  - ENABLES DESIGNERS TO PERFORM, WITHIN THE SCHEDULE LIMITATIONS, TRADE-STUDIES FOR LARGE NUMBERS OF ALTERNATIVE DESIGN CONFIGURATIONS USING DIFFERENT MANUFACTURING TECHNOLOGIES

ICAM "MANUFACTURING COST/DESIGN GUIDE" MC/DG

SUBCONTRACTORS	MANAGERS
• GENERAL DYNAMICS CORPORATION, FORT WORTH DIVISION	P. M. BUNTING
• GRUMMAN AEROSPACE CORPORATION	A. J. TORNABE
• HONEYWELL, INCORPORATED	R. REMSKI
• LOCKHEED-CALIFORNIA COMPANY*	J. F. WORKMAN
• NORTHROP CORPORATION, AIRCRAFT GROUP	A. P. LANGLOIS
• ROCKWELL INTERNATIONAL CORPORATION, NORTH AMERICAN AIRCRAFT DIVISION	R. A. ANDERSON
• ROCKWELL INTERNATIONAL CORPORATION, COLLINS AVIONICS DIVISION	J. G. VECELLIO

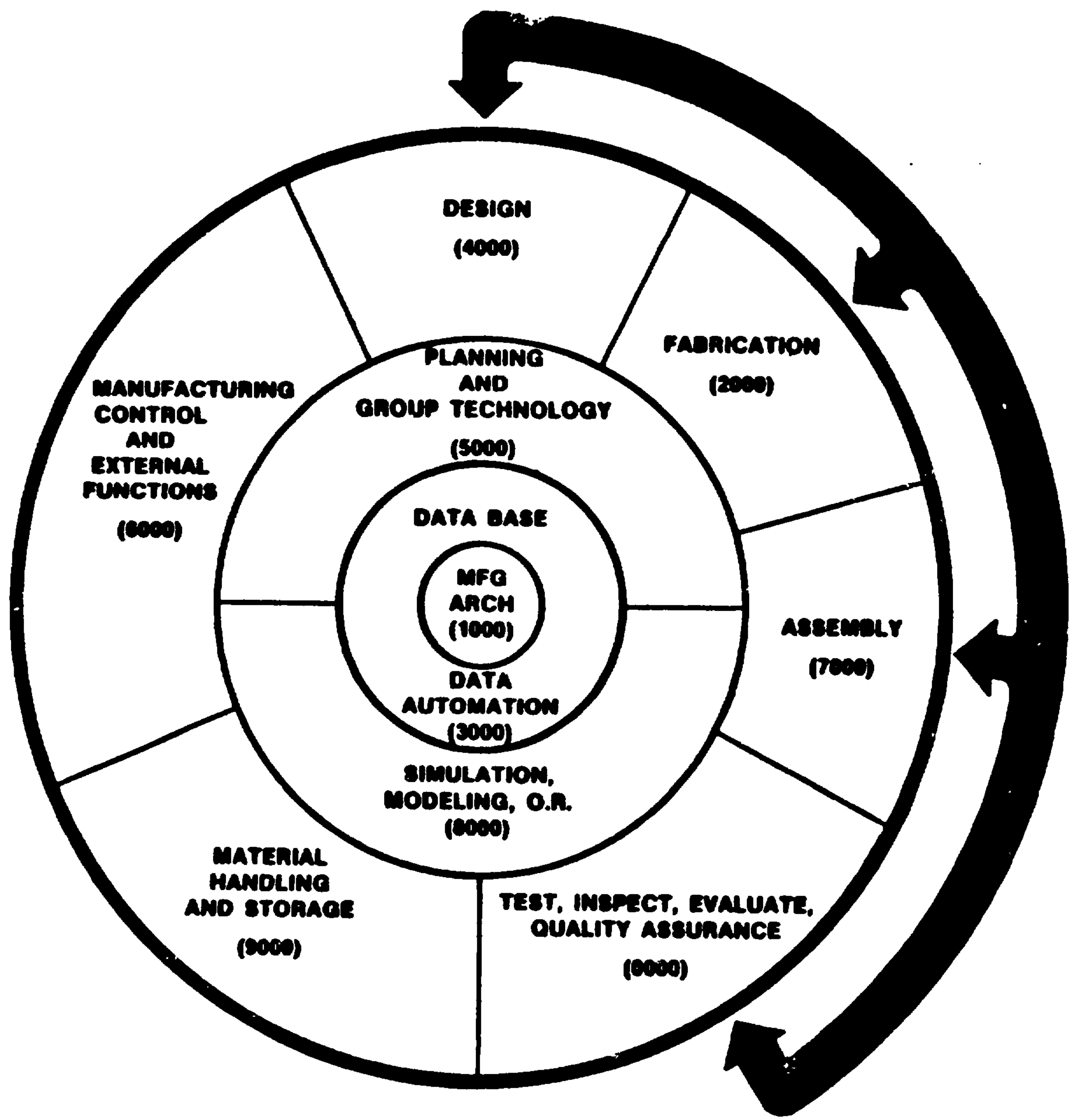
*A. J. PILLERA, CONSULTANT

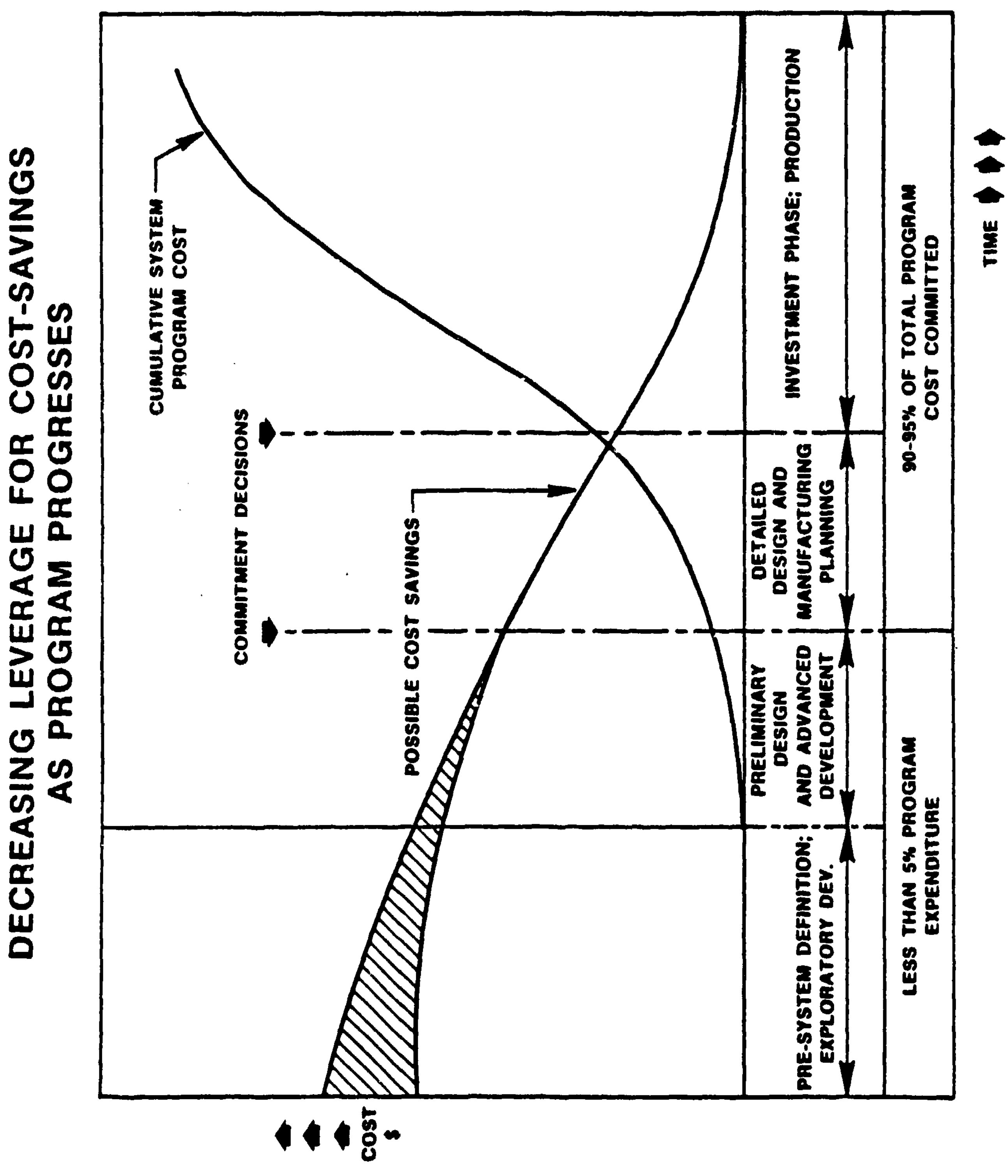
"MANUFACTURING COST/DESIGN GUIDE (MC/DG)"

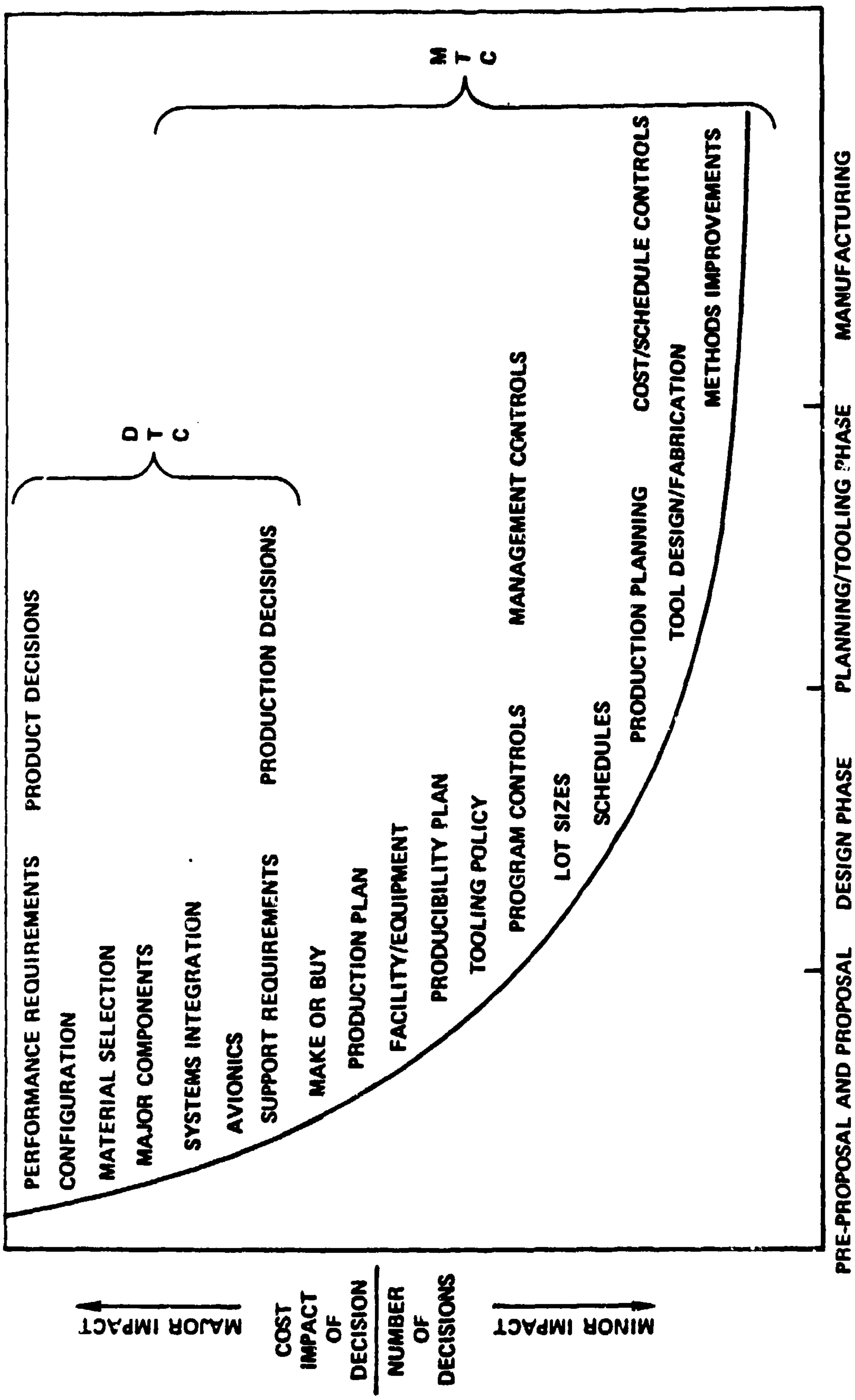
ADVANTAGES OF TEAM APPROACH

- PROVIDES A CROSS SECTION OF SMALL AND LARGE AIRCRAFT FOR THE ENTIRE INDUSTRY; BOTH MILITARY AND COMMERCIAL
- TEAM MEMBERS HAVE LARGE INTERFACE WITH ALL LEVELS OF DESIGNERS
- TEAM DRAWS ON EACH COMPANY'S EXPERTISE MAKING RESULTS MORE VIABLE
- TEAM PROVIDES A BROAD BASE FOR EMERGING TECHNOLOGIES
- TEAM HAS AN EXTENSIVE SOURCE OF AVAILABLE DATA AND PROVIDES BROAD BASE FROM WHICH TO COLLECT AND DEVELOP DATA
- TEAM PROVIDES THE REQUIRED BASE FOR DERIVING AVERAGE INDUSTRY DATA
- TEAM TENDS TO VERIFY AND GIVE CONFIDENCE TO DATA AND FORMATS FOR DESIGNER USE

MC/DG INTERACTION WITH ICAM THRUST AREAS




DECREASING LEVERAGE FOR COST-SAVINGS
AS PROGRAM PROGRESSES
CUMULATIVE SYSTEM
PROGRAM COST
COMMITMENT DECISIONS
POSSIBLE COST SAVINGS
COST
$
PRE-SYSTEM DEFINITION;
EXPLORATORY DEV.
PRELIMINARY
DESIGN
AND ADVANCED
DEVELOPMENT
DETAILED
DESIGN AND
MANUFACTURING
PLANNING
INVESTMENT PHASE; PRODUCTION
LESS THAN 5% PROGRAM
EXPENDITURE
90-95% OF TOTAL PROGRAM
COST COMMITTED
TIME



IMPACT OF COST VS DECISION

ORGANIZATION

MC/DG VOLUME CONTENTS: "MANUFACTURING TECHNOLOGIES FOR AIRFRAMES"

I	II	III	IV	V	VI	VII
PROCURED ITEM COSTS	MATERIAL REMOVAL COSTS	DETAIL FABRICATION COSTS	MATERIAL TREATMENT COSTS	PERMANENT JOINING* COSTS	ASSEMBLY* COSTS	TEST, INSPECTION AND EVALUATION COSTS
FORGINGS CASTINGS EXTRUSIONS MATERIALS FASTENER SYSTEMS EMERGING PROC.	MACHINING CHEM MILLING EDM ECM EMERGING PROC.	METALLIC NON-METALLICS EMERGING PROC.	HEAT TREATMENT SURFACE TREATMENT EMERGING PROC.	WELDING ADHESIVE BONDING BRAZING EMERGING PROC. *SUB-ASSEMBLY	METALLIC ASSY. NON-METALLIC ASSY. EMERGING PROC. *MAJOR AND FINAL ASSEMBLY	METALLIC NON-METALLICS

CATEGORIES = MATERIAL REMOVAL, ETC.
SECTIONS = MACHINING, ETC.
SUBSECTIONS = TURNING AND MILLING, ETC.

MC/DG VOLUME CONTENTS: "MANUFACTURING TECHNOLOGIES FOR AEROSPACE ELECTRONIC FABRICATION, ASSEMBLY, AND TEST"

I	II	III		IV
PROCURED ITEMS	DETAIL FABRICATION	ASSEMBLY		TEST, INSPECTION, AND EVALUATION (TI&E)
SCHEMATIC PARTS INTERCONNECT PARTS HARDWARE FABRICATED PARTS EMERGING TECHNOLOGIES	METALLIC NONMETALLIC TREATMENT/ COATING/MARKING EMERGING TECHNOLOGIES	MECHANICAL ASSEMBLY COMPONENT ASSEMBLY (PRE-WAVE AND POST-WAVE) CLEANING SOLDER SHEET METAL/ STANDOFF ASSEMBLY (HARD WIRING) CABLE/WIRE HARNESS ASSEMBLY	HYBRIDS OTHER ASSEMBLY TECHNIQUES CHASSIS ASSEMBLY FINAL EQUIPMENT ASSEMBLY POST-ASSEMBLY PROCESSES POTTING ADHESIVES EMERGING TECHNOLOGIES	CARD/MODULE LEVEL TEST TESTABILITY BURN-IN/SCREENING TEST DEVICE/EQUIPMENT TEST EMERGING TECHNOLOGIES

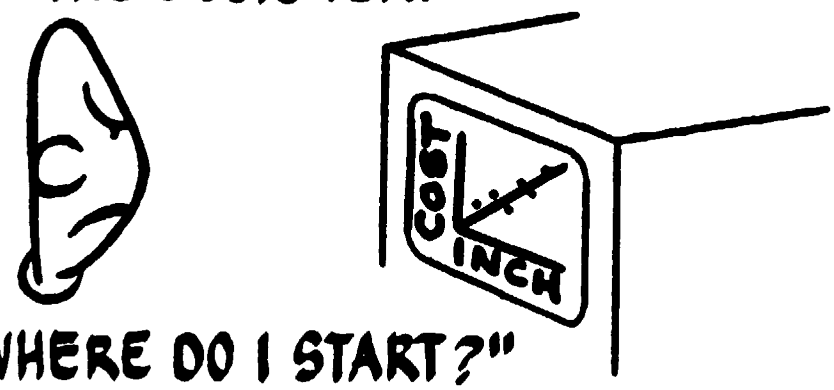
DEVELOPMENT AND SELECTION CRITERIA FOR MC/DG FORMATS

- EMPHASIZE COST-DRIVERS
- USE DESIGNER LANGUAGE
- INSTILL CONFIDENCE
- BE COST-EFFECTIVE TO PRODUCE AND USE
- BE SIMPLE TO USE
- BE ACCESSIBLE TO ALL LEVELS OF DESIGNERS
- BE FLEXIBLE TO ACCEPT NEW AND REVISED DATA
- BE RAPIDLY MAINTAINABLE

ICAM "MANUFACTURING COST/DESIGN GUIDE (MC/DG)"

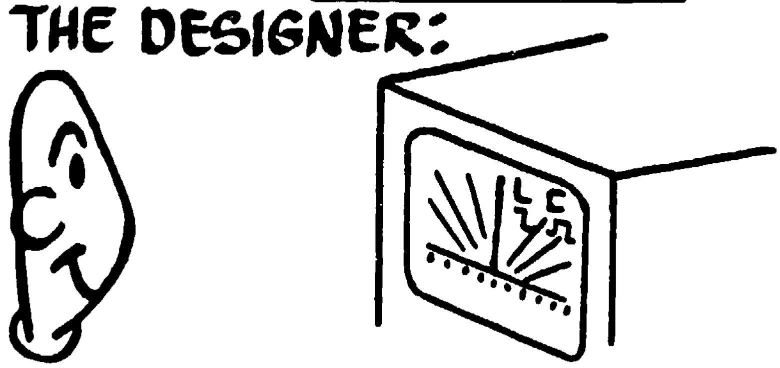
TASK: TO DESIGN A LOW-COST ADVANCED COMPOSITE STRUCTURAL SECTION.

NO MC/DG FORMATS DISPLAYED TO THE DESIGNER:



"WHERE DO I START?"

MC/DG FORMATS & DATA ARE DISPLAYED TO THE DESIGNER:



① CALLS FOR DATA ON STRINGER TYPES, FRAMES, ETC. & FORMATS APPEAR

② NOTES THE LOWEST COST STRUCTURAL ELEMENTS AND COST-DRIVERS

③ DESIGNS TOWARD THE LOWEST COST CONFIGURAT-ION.

THE DESIGNER IS GIVEN GUIDANCE

DATA & FORMATS — EXAMPLES

"MANUFACTURING COST/DESIGN GUIDE (MC/DG)"

GROUND RULES FOR ADVANCED COMPOSITES FABRICATION

GROUND RULES HAVE BEEN DEVELOPED BY THE TEAM FOR EACH PHASE OF THE MC/DG PROGRAM. GROUND RULES ARE ESSENTIAL, AS THEY PROVIDE A COMMON BASE FOR PROMOTING UNDERSTANDING, CONSISTENCY, UNIFORMITY, AND ACCURACY IN GENERATING AND INTEGRATING DATA INTO THE FORMATS AND ALSO FOR INTERRELATING THE VARIOUS PHASES OF THE MC/DG DEVELOPMENT.

"MANUFACTURING COST/DESIGN GUIDE (MC/DG)"

GENERAL GROUND RULES FOR ADVANCED COMPOSITES FABRICATION

MAJOR GROUPINGS

(1) ADVANCED COMPOSITE DISCRETE PARTS
(2) COMPOSITE MATERIAL TYPES
(3) MANUFACTURING TECHNOLOGY
(4) FACILITIES
(5) DATA GENERATION—RECURRING COSTS
(6) DATA GENERATION—NON-RECURRING COSTS
(7) SUPPORT FUNCTION MODIFIERS

THE ADVANCED COMPOSITES FABRICATION GUIDE (ACFG) GLOSSARY WAS USED AS A BASIS FOR TERMINOLOGY. THE ADVANCED COMPOSITES DESIGN GUIDE (ACDG), ADVANCED COMPOSITES COST ESTIMATING MANUAL (ACCEM), AND THE ACFG HAVE BEEN UTILIZED IN THE DEVELOPMENT OF THE MC/DG SECTION, "ADVANCED COMPOSITES FABRICATION".

"MANUFACTURING COST/DESIGN GUIDE (MC/DG)"

DETAILED GROUND RULES FOR ADVANCED COMPOSITES FABRICATION

MAJOR GROUPINGS:

(1) MATERIAL

(2) BASE PART DRAWINGS AND SKETCHES USED TO DEVELOP COST DATA FOR FORMATS

(3) TOLERANCES

(4) ESTIMATING METHOD.

"MANUFACTURING COST/DESIGN GUIDE (MC/DG)"

METHODOLOGIES

FOR

DESIGNER'S GUIDANCE TOWARDS LOWER COSTS

COST-DRIVER EFFECT (CDE)

AND

COST-ESTIMATING DATA (CED)

OBJECTIVES

- TO DEVELOP A SIMPLE APPROACH FOR THE USE OF FORMATTED DATA BY DESIGNERS TO ACHIEVE LOWER FABRICATION COSTS DURING DESIGN PHASES
- TO PROVIDE QUALITATIVE COST GUIDANCE TO THE DESIGNER TO ASSURE LOWEST FABRICATION COSTS
- TO PROVIDE THE DESIGNER WITH A CAPABILITY TO PERFORM SIMPLE TRADE-OFFS TO ACHIEVE QUANTITATIVE ROM DELTA FABRICATION COSTS

"MANUFACTURING COST/DESIGN GUIDE (MC/DG)"

CDE AND CED METHODOLOGIES

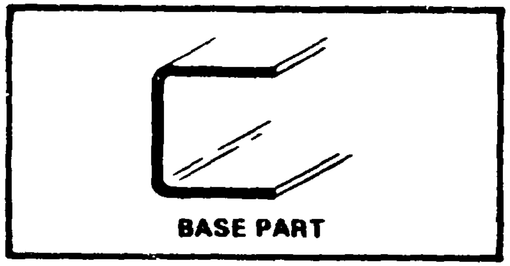
COST-ESTIMATING DATA (CED)

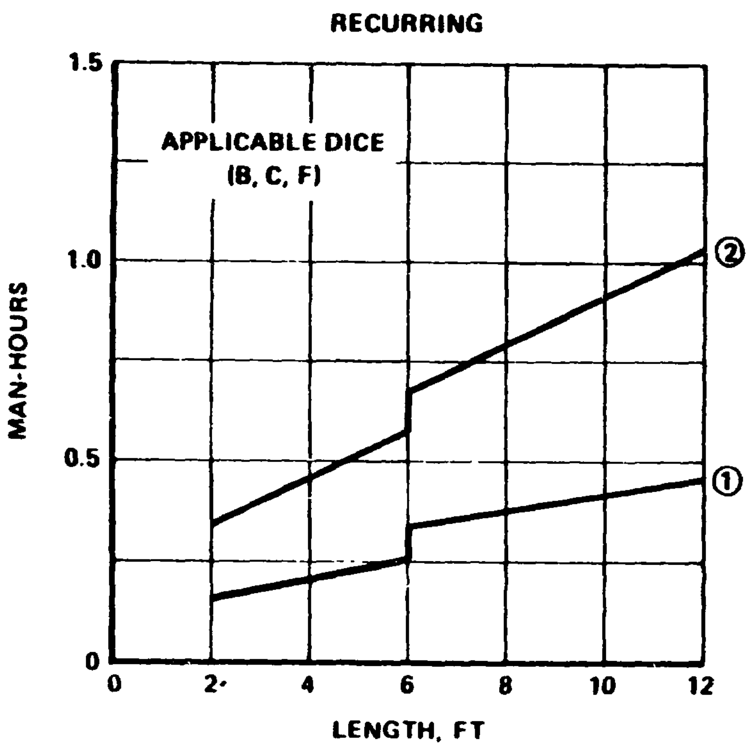
- PROVIDES THE DESIGNER WITH MAN-HOUR COST DATA TO ALLOW HIM TO QUICKLY PERFORM TRADE-OFFS TO ACHIEVE COMPARATIVE COSTS FOR THOSE CONFIGURATIONS EVALUATED
- MOTIVATES THE DESIGNER TO PERFORM TRADE-OFFS THROUGH THE USE OF SIMPLIFED FORMATS AND DATA

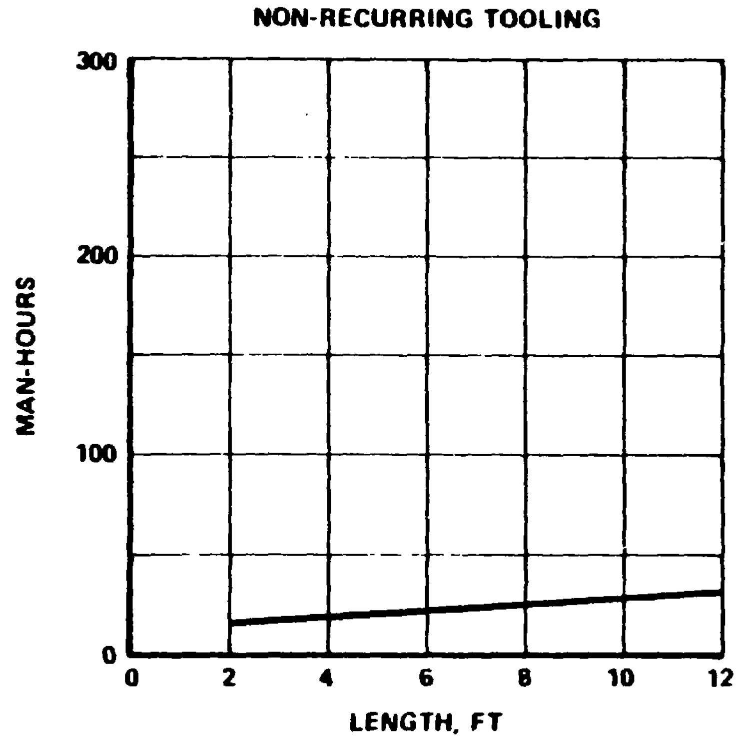
COSTS ARE QUANTITATIVE AND COMPARATIVE

ALUMINUM CHANNEL, STRAIGHT MEMBER, LOWEST COST PROCESS

BRAKE FORM





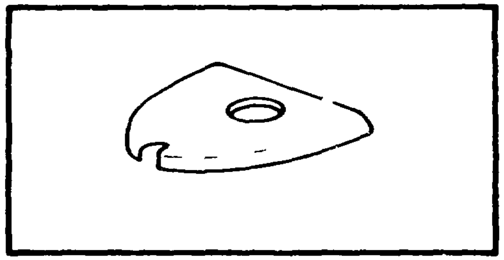


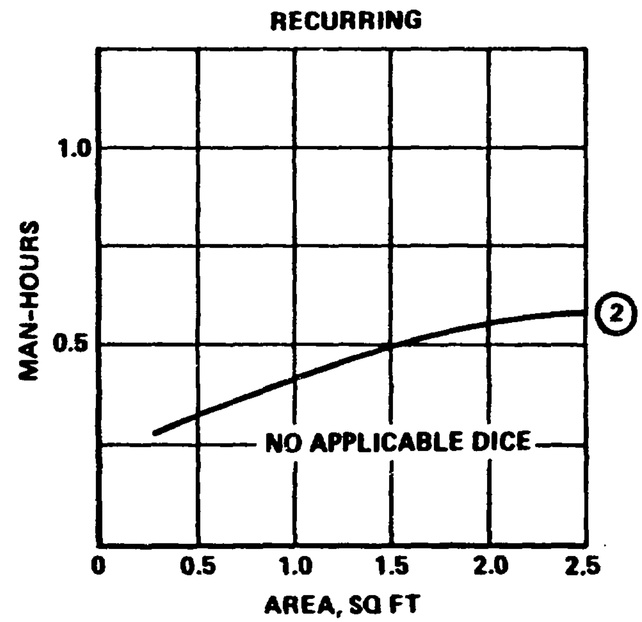
(1) PART FORMED IN T3 CONDITION (NO SOLUTION HEAT TREAT); MINIMUM BEND RADIUS = 3.5t
(2) PART FORMED IN "O" OR "W" CONDITION; T62 FINAL TEMPER; MINIMUM BEND RADIUS = 1.5t

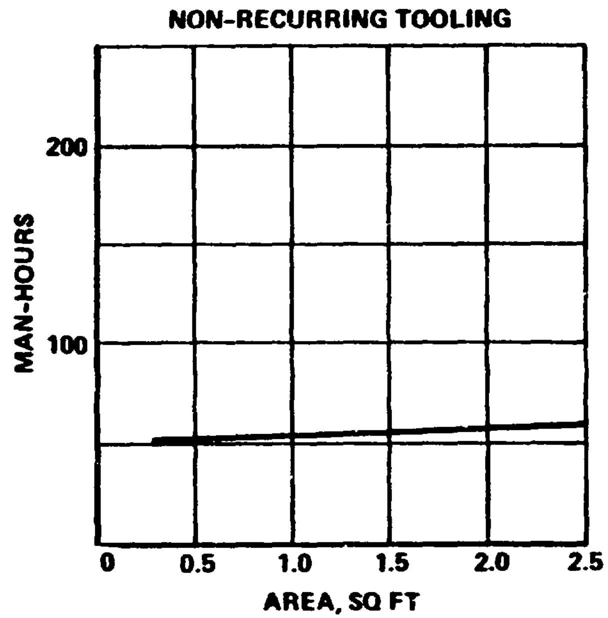
CED—A-4

ALUMINUM RIB, LOWEST COST PROCESS

RUBBER PRESS



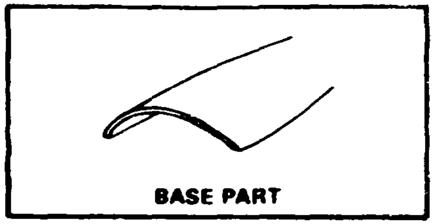


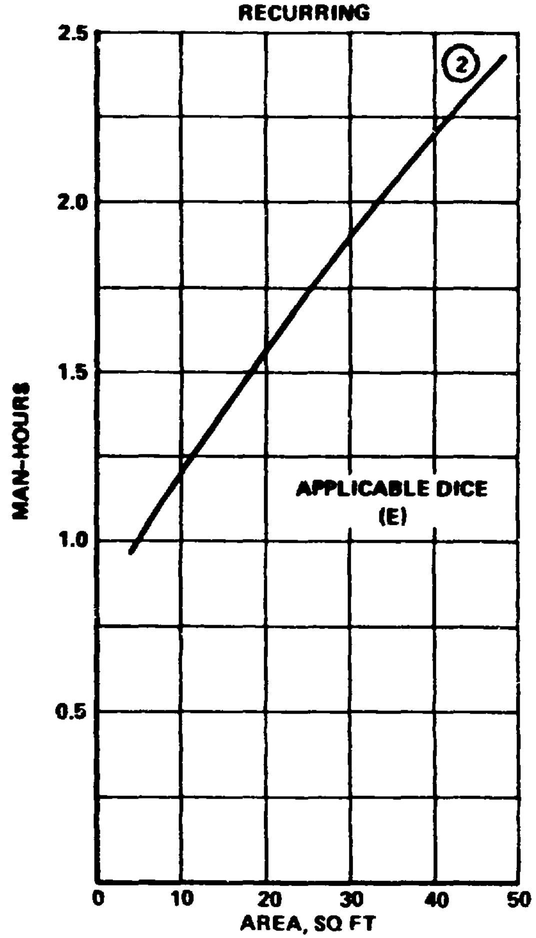


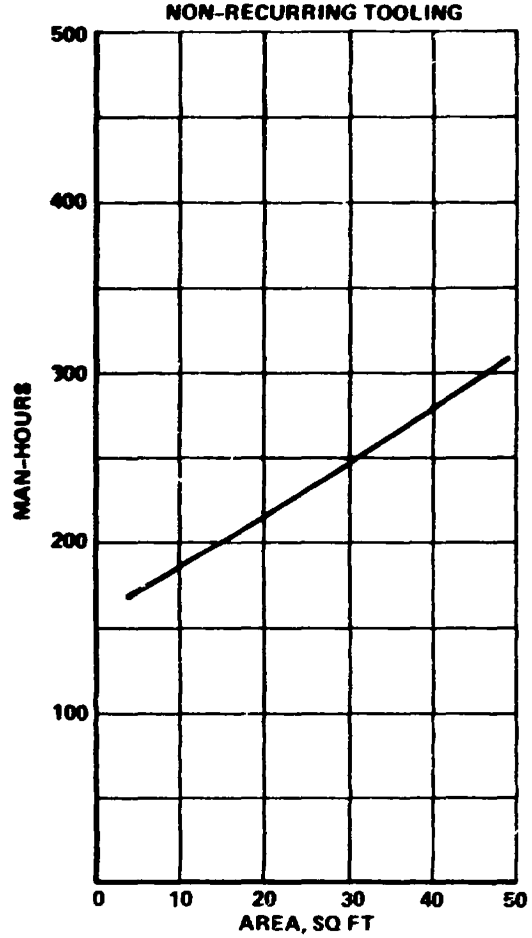
(2) FORMED IN "O" OR "W" CONDITION, FINAL TEMPER T62

CED—A-23

ALUMINUM NON-CYLINDRICAL CURVATURE SKIN*, LOWEST COST PROCESS
STRETCH FORM







*NO REVERSE CURVES

(2) FORMED IN "O" OR "W" CONDITION, FINAL TEMPER T81

CED—A-21

CDE AND CED METHODOLOGIES (CONTINUED)

COST-DRIVER EFFECT (CDE)

- IDENTIFIES THE COST-DRIVERS THAT INCREASE THE MANUFACTURING COST OF THE DESIGN
- SHOWS THE RELATIVE EFFECTS OF COST ELEMENTS OVER WHICH THE DESIGNER HAS CONTROL
- MOTIVATES THE DESIGNER TO REDUCE THE IMPACT OF THE COST-DRIVERS

USING THE CDE APPROACH, THE DESIGNER SHOULD REALIZE THE LOWEST COST WHILE SATISFYING THE PERFORMANCE REQUIREMENTS OF THE AIRFRAME.

QUALITATIVE COST RELATIONSHIPS

GUIDE TO DESIGNER INFLUENCED COST ELEMENTS (DICE)

MATERIAL	DESIGNER INFLUENCED COST ELEMENTS / BASE PART MANUFACTURING METHOD	STANDARD JOGGLE	FLANGED HOLES	BEADS	HEAT TREATMENT	SPECIAL FINISH	SPECIAL TOLERANCE	LINEAL TRIM	END TRIM	CUTOUTS W/O FLANGES
ALUMINUM	BRAKE FORM	L	L	X	H	L	H	L	L	L
	BRAKE/BUFFALO ROLL	L	L	X	H	L	H	A	A	A
	BRAKE STRETCH	L	L	X	H	L	N	A	A	A
	DIE FORM	N	N	N	N	L	N	[illegible]	L	L
	DROP HAMMER	N	N	N	L	L	H	L	X	A
	FARNHAM ROLL	X	L	X	H	L	H	L	X	A
	ROUTED FLAT SHEET	X	L	X	H	L	H	L	X	L
	RUBBER PRESS	N	N	N	H	L	A	L	L	L
	STRETCH FORM	X	L	X	A	L	N	A	X	A
	YODER ROLL	L	L	X	H	L	H	A	A	A
	YODER STRETCH	L	L	X	H	L	N	A	L	A
TITANIUM	BRAKE FORM R.T.	A	L	X	X	L	H	H	H	L
	R.T. BRAKE/HOT STRETCH*	A	L	X	X	L	L	H	H	H
	CREEP FORM*	X	L	X	X	L	L	H	H	H
	FARNHAM ROLL	X	L	X	X	L	H	H	H	H
	HOT PRESS*	N	L	N	X	L	L	N	N	L
	PREFORM/HOT SIZE*	N	L	N	X	L	L	N	N	L
STEEL	BRAKE AND BUFFALO ROLL	A	L	X	X	L	H	H	A	L
	BRAKE FORM R.T.	A	L	X	X	L	H	L	L	L
	BRAKE/R.T. STRETCH	A	L	X	X	L	A	H	L	A
	FARNHAM ROLL	X	L	X	X	L	H	H	L	A
	RUBBER PRESS	N	N	N	X	L	A	L	L	L
	STRETCH FORM	X	L	X	X	L	A	H	A	L

LEGEND

RATING	
X	NOT APPLICABLE
N	NO ADDITIONAL COST INCL. IN BASE PART COST
L	LOW ADDITIONAL COST
A	AVERAGE ADDITIONAL COST
H	HIGH ADDITIONAL COST

Percentage Cost Ranges For Above

L	Up to 10%
A	10–30%
H	Above 30%

*Denotes one or more elevated temperature processing steps.

DICE-0

"MANUFACTURING COST/DESIGN GUIDE (MC/DG)"

DEFINITIONS

BASE PART

A DETAILED PART IN ITS SIMPLEST FORM, I.E., WITHOUT COMPLEXITIES SUCH AS HEAT TREATMENT, CUTOUTS, AND JOGGLES.

DESIGNER—INFLUENCED COST ELEMENTS (DICE)

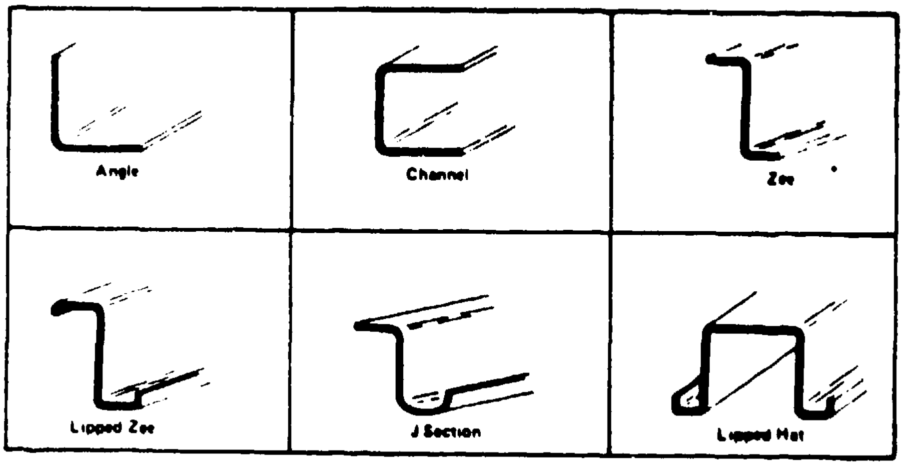
DESIGNER—INFLUENCED COST ELEMENTS (DICE) WHICH INCLUDE JOGGLES, HOLES, LIGHTENING HOLES, AND SPECIAL TOLERANCES, AND ADD COST TO THE BASE PART CONFIGURATION. THESE ADDITIONAL COSTS ARE DUE TO INCREASED FABRICATION OPERATIONS AND TOOLING REQUIRED OVER THE STANDARD MANUFACTURING METHOD (SMM) FOR THE BASE PART.

DETAILED OR DISCRETE PART

A DISTINCT AIRFRAME STRUCTURAL PART WHICH MAY INCORPORATE DESIGN COMPLEXITIES, E.G., A BASE PART PLUS DICE.

SAMPLE PARTS USED TO DERIVE COST DATA FOR MC/DG

Sheet Metal Aerospace Base Parts
Example:
Aluminum Stringers



- Aluminum
- Steel
- Titanium

Part Lengths
24" to 144"

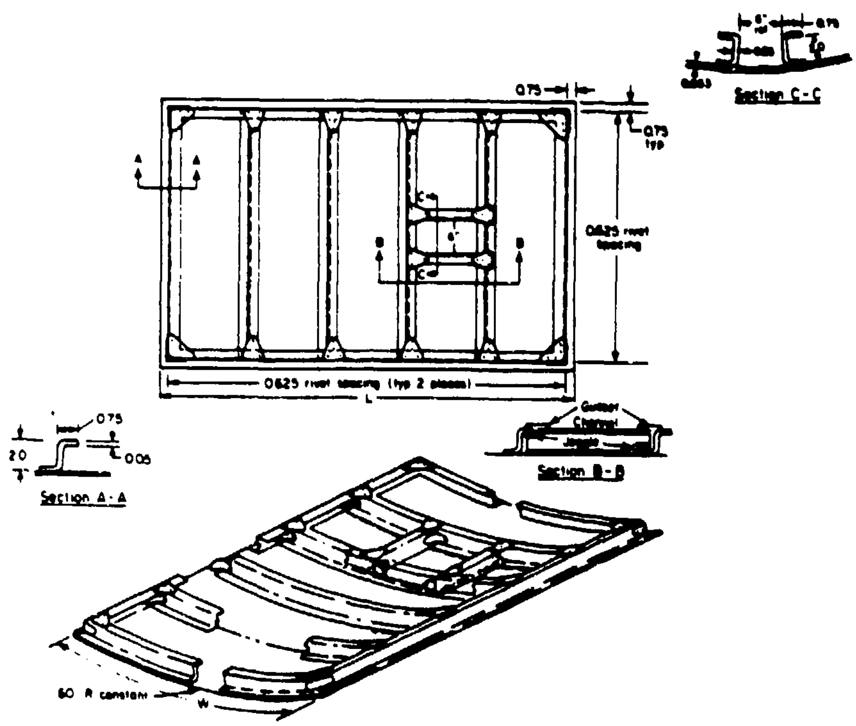
Manufacturing Methods

Straight Parts
- Brake Form
- Rubber Press

Contoured Parts
- Brake/Buffalo Roll
- Brake/Stretch
- Rubber Press

Mechanically Fastened Assemblies

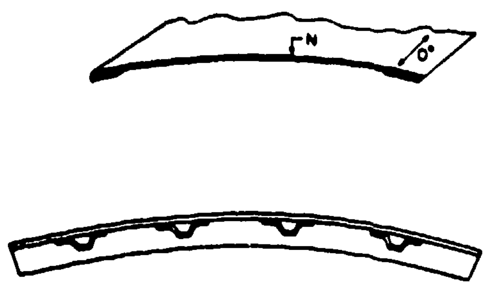
Example:
Fuselage Door Assembly



Advanced Compsites

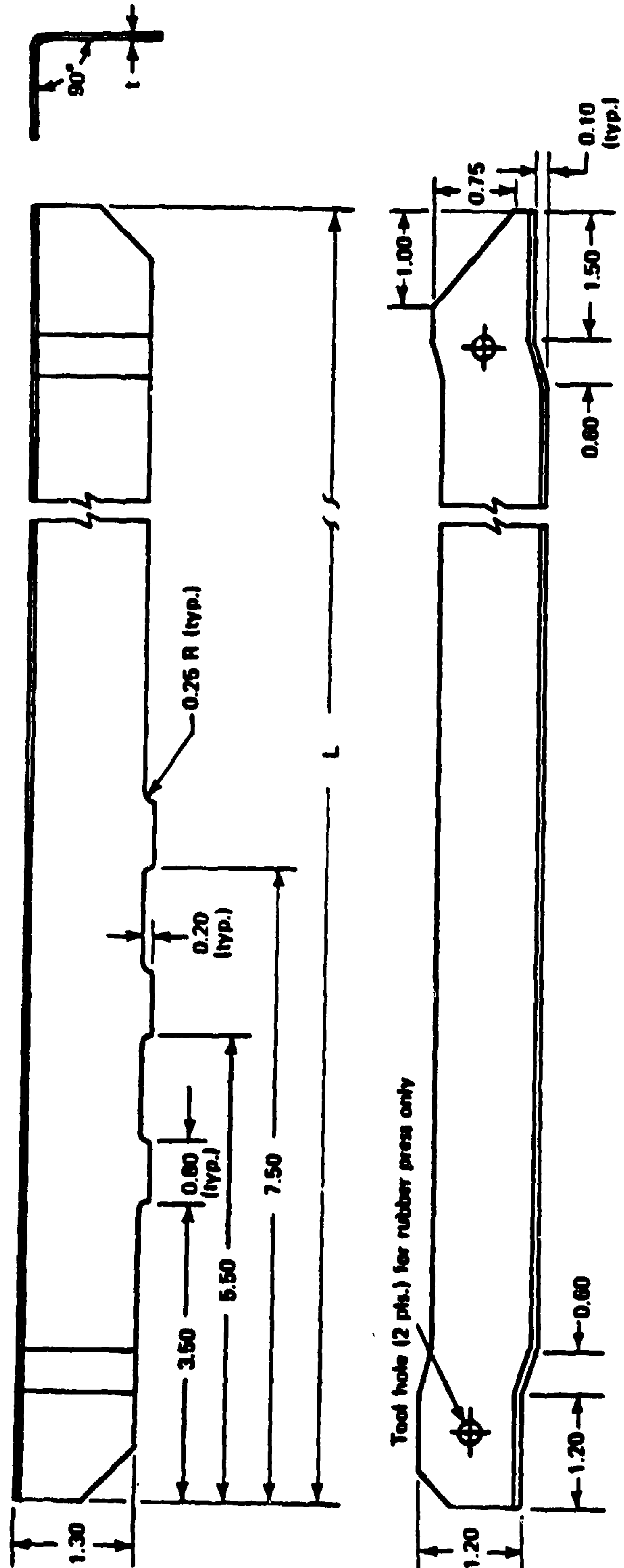
Example:
Panel Structures

- Graphite/epoxy



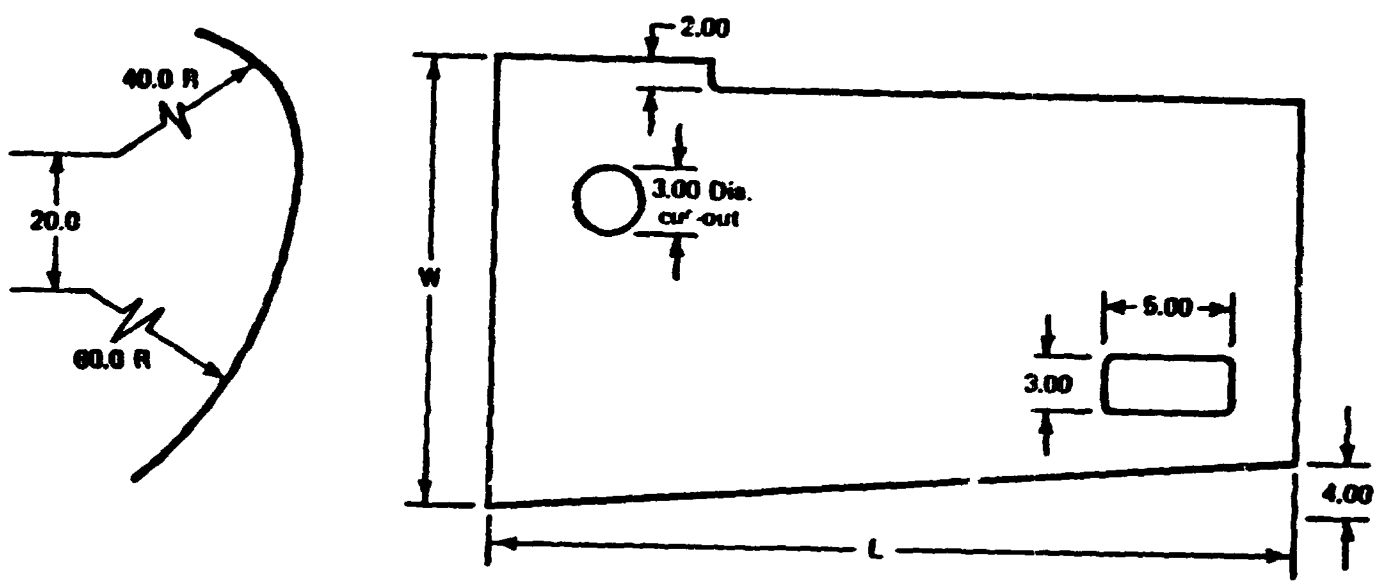
MC/DG-A-1A

ALUMINUM ANGLE
CONSTANT SECTION
STRAIGHT



ALUMINUM SKIN PANEL

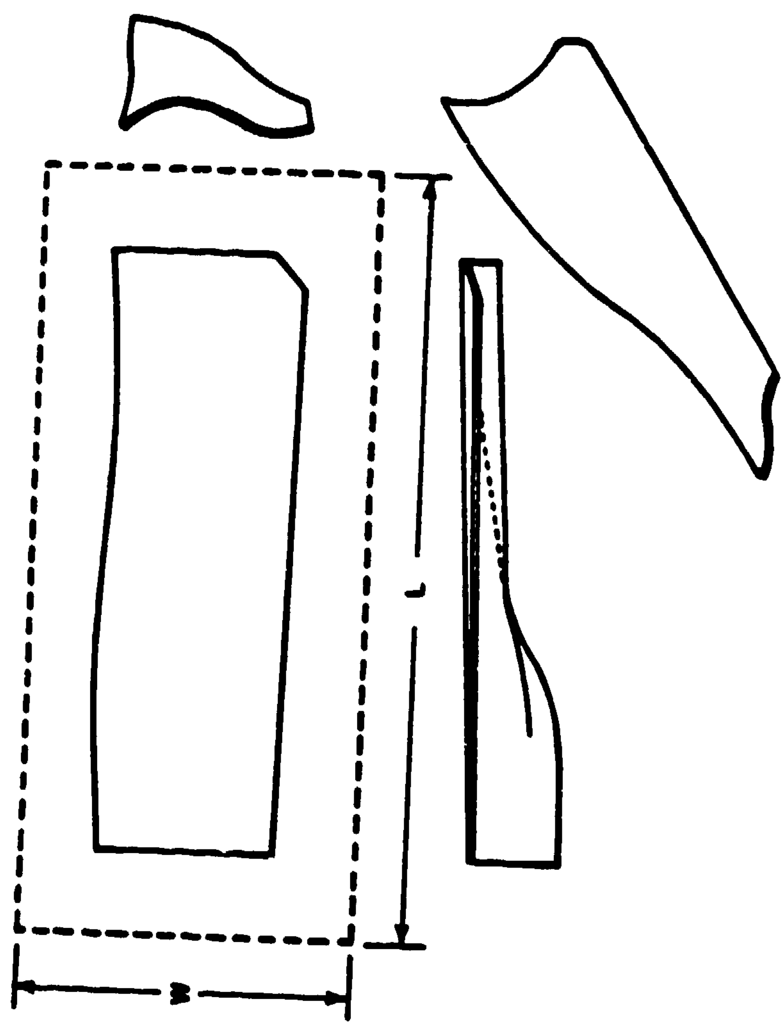
CONSTANT THICKNESS
SINGLE CURVATURE—NONCIRCULAR



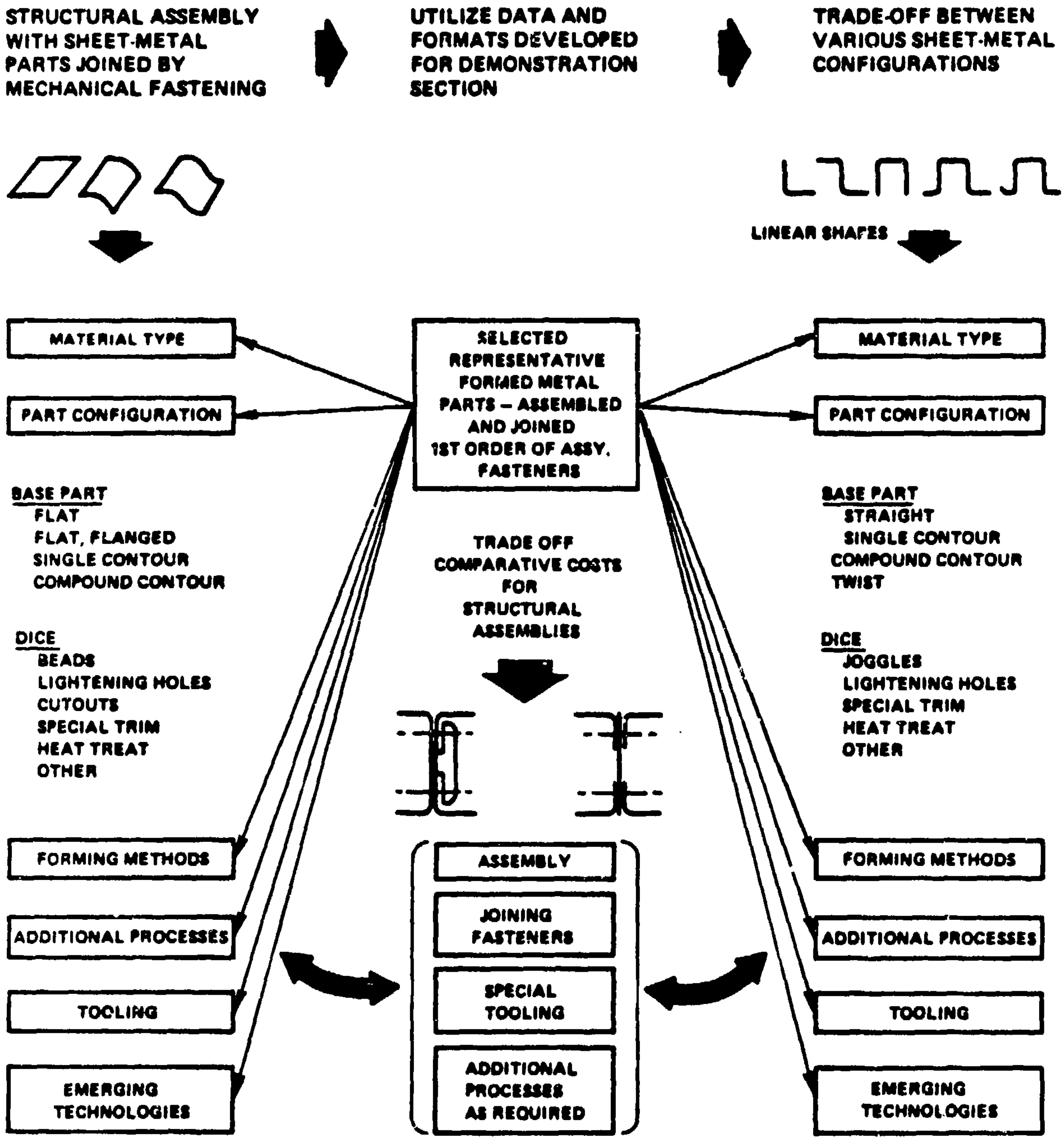
MC/DG-A-9

MC/DG-A-11

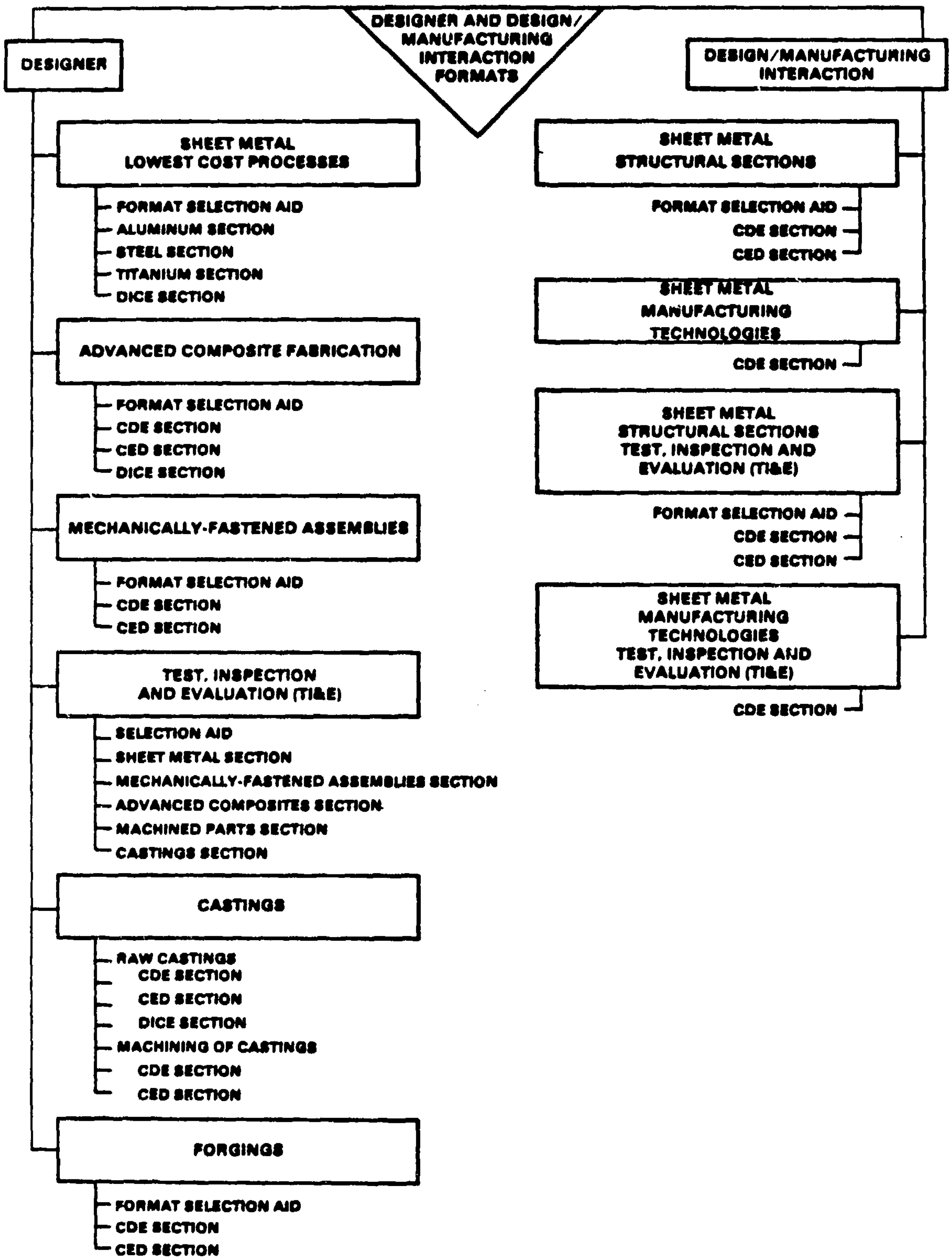
ALUMINUM FAIRING
COMPOUND CURVATURE



DECISION CONSIDERATIONS FOR SHEET-METAL DESIGNS
UTILIZING MECHANICALLY FASTENED ASSEMBLIES SECTION



MC/DG SECTION SELECTION AID



EXAMPLE OF SECTION CONTENTS: SHEET-METAL AEROSPACE DISCRETE PART DEMONSTRATION SECTION (AFWAL-TR-80-4115)

- OVERVIEW SELECTION AID
- FORMAT SELECTION AIDS
- BASE PARTS ANALYZED
  - ALUMINUM
  - TITANIUM
  - STEEL
- DESIGNER-INFLUENCED COST ELEMENTS (DICE)
- MANUFACTURING TECHNOLOGIES
- EXAMPLES OF UTILIZATION
  - ALUMINUM FAIRING
  - STEEL SKIN
  - TITANIUM STRINGER
- FORMATS
  - ALUMINUM: LOWEST COST PROCESSES
  - TITANIUM: LOWEST COST PROCESSES
  - STEEL: LOWEST COST PROCESSES
  - DESIGNER-INFLUENCED COST ELEMENTS (DICE)
  - COMPARISON OF MANUFACTURING TECHNOLOGIES
  - COMPARISON OF STRUCTURAL SECTIONS

"MANUFACTURING COST/DESIGN GUIDE (MC/DG)"

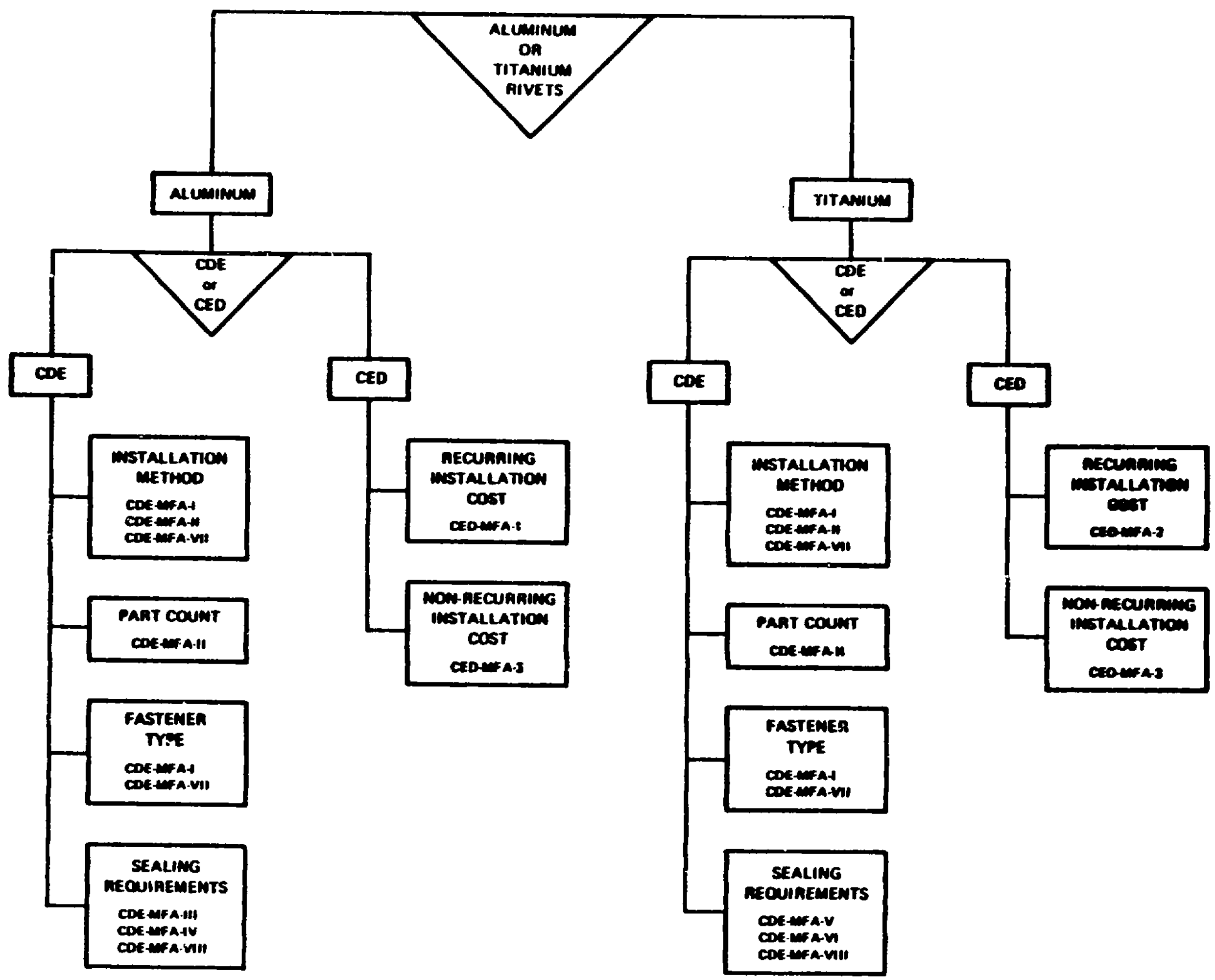
COST-DRIVERS IN MECHANICALLY FASTENED ASSEMBLY FABRICATION

COST-DRIVERS ANALYZED IN PHASE II(A)

- ACCESSIBILITY
- MATERIALS JOINED
- FASTENER COUNT
- PART COUNT
- SEALING

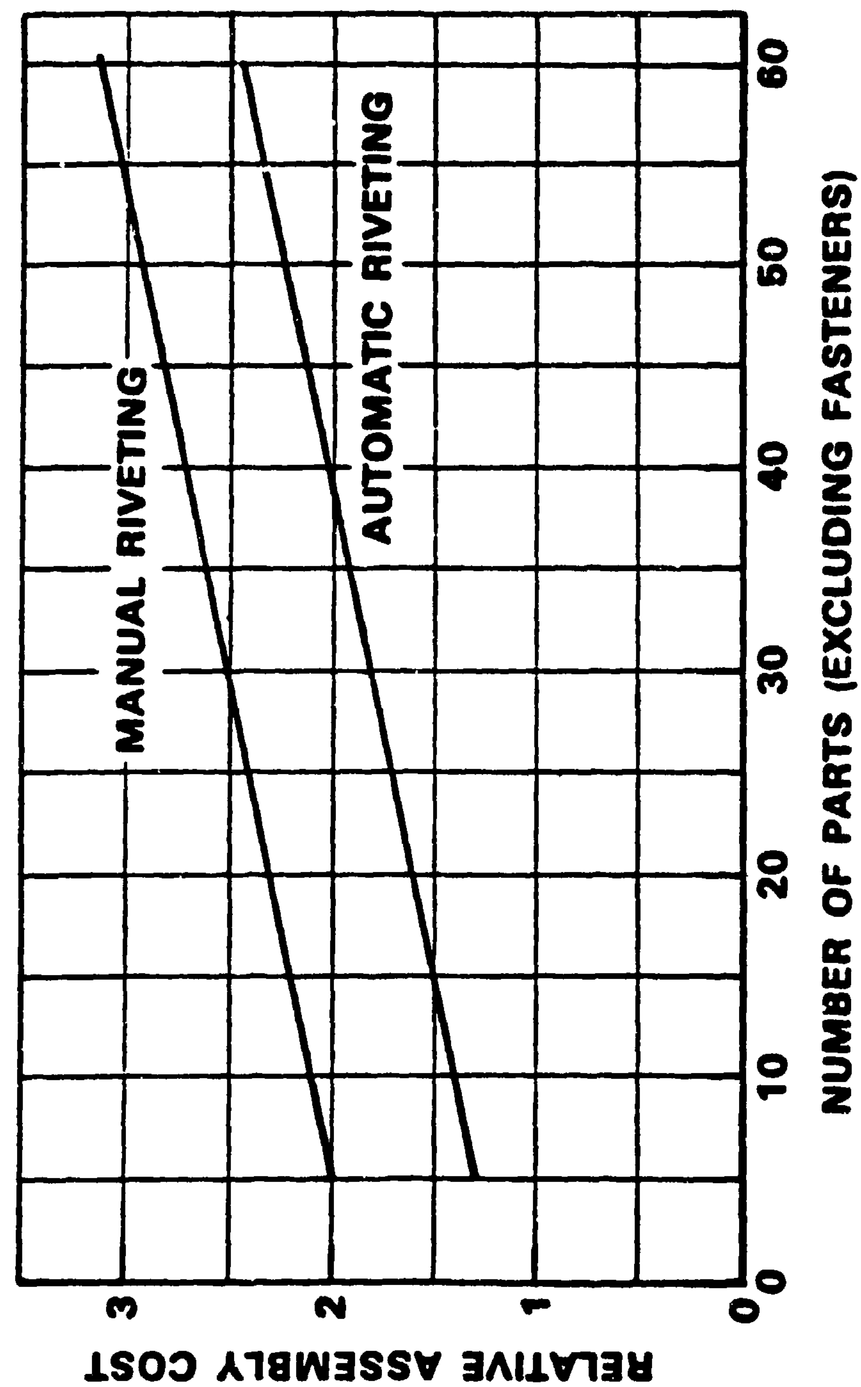
FORMAT SELECTION AID

MECHANICALLY FASTENED ASSEMBLIES

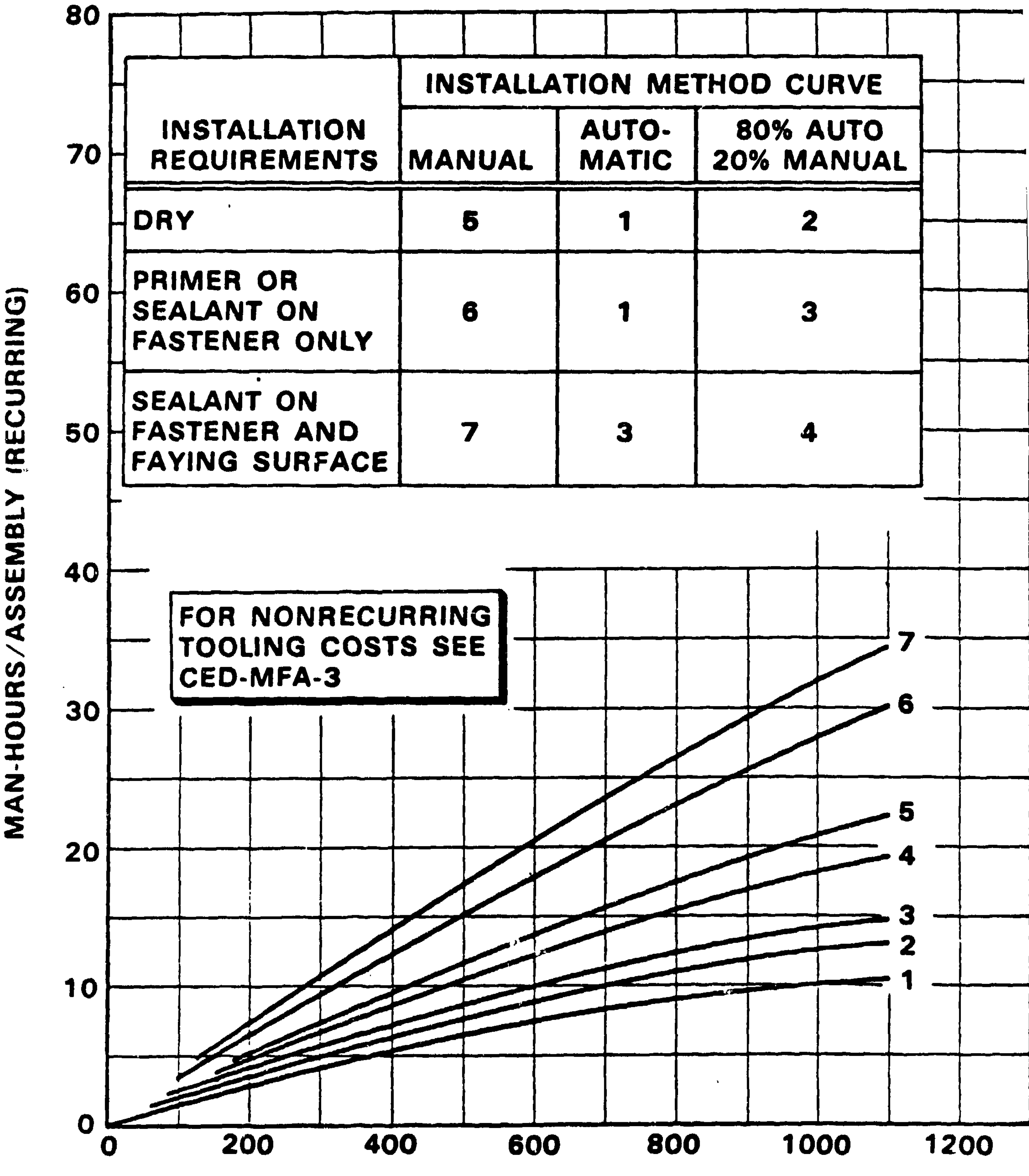


CDE-MFA-II

EFFECT OF PART COUNT AND FASTENING METHOD



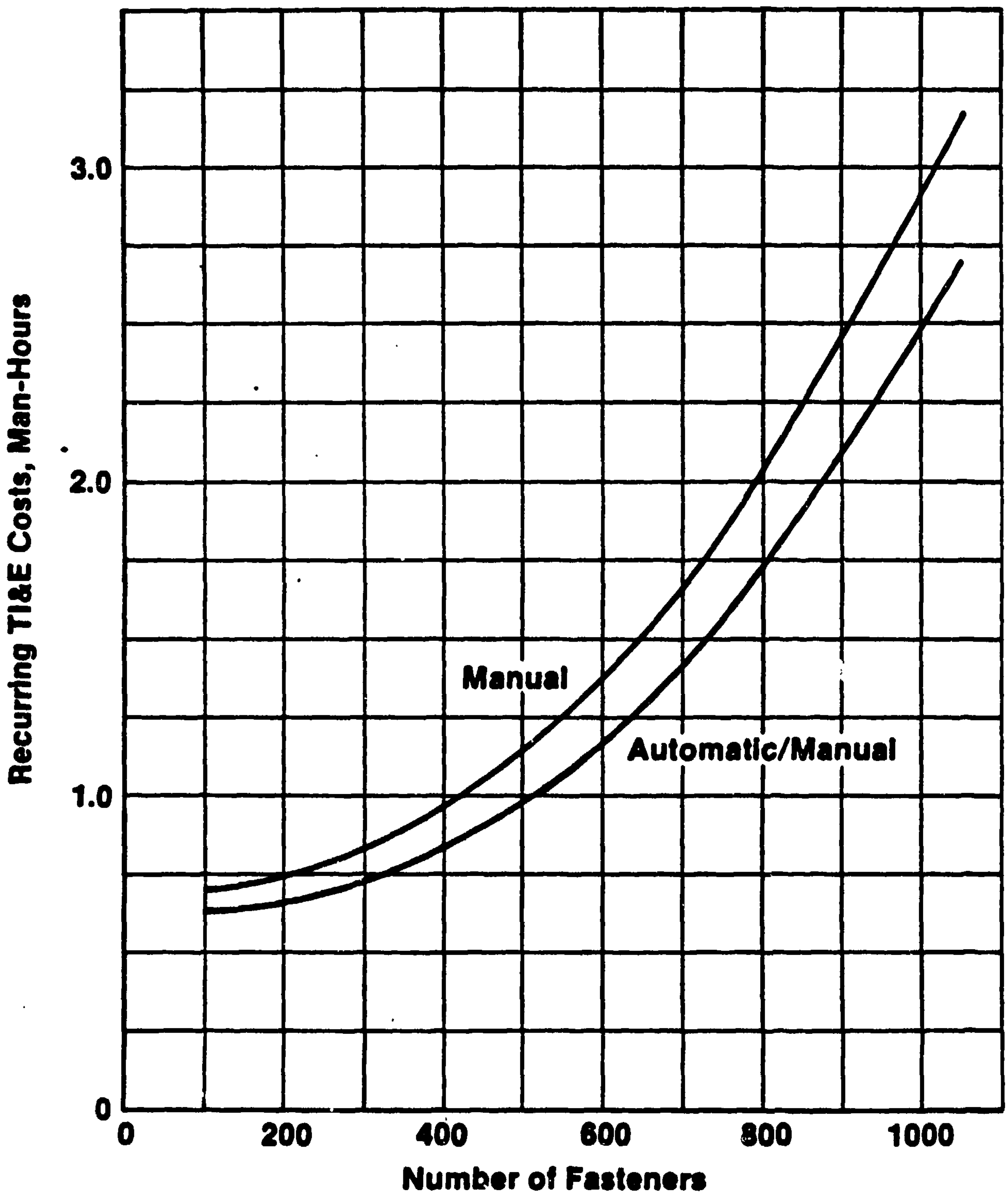
INSTALLATION COSTS FOR ALUMINUM RIVETS



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

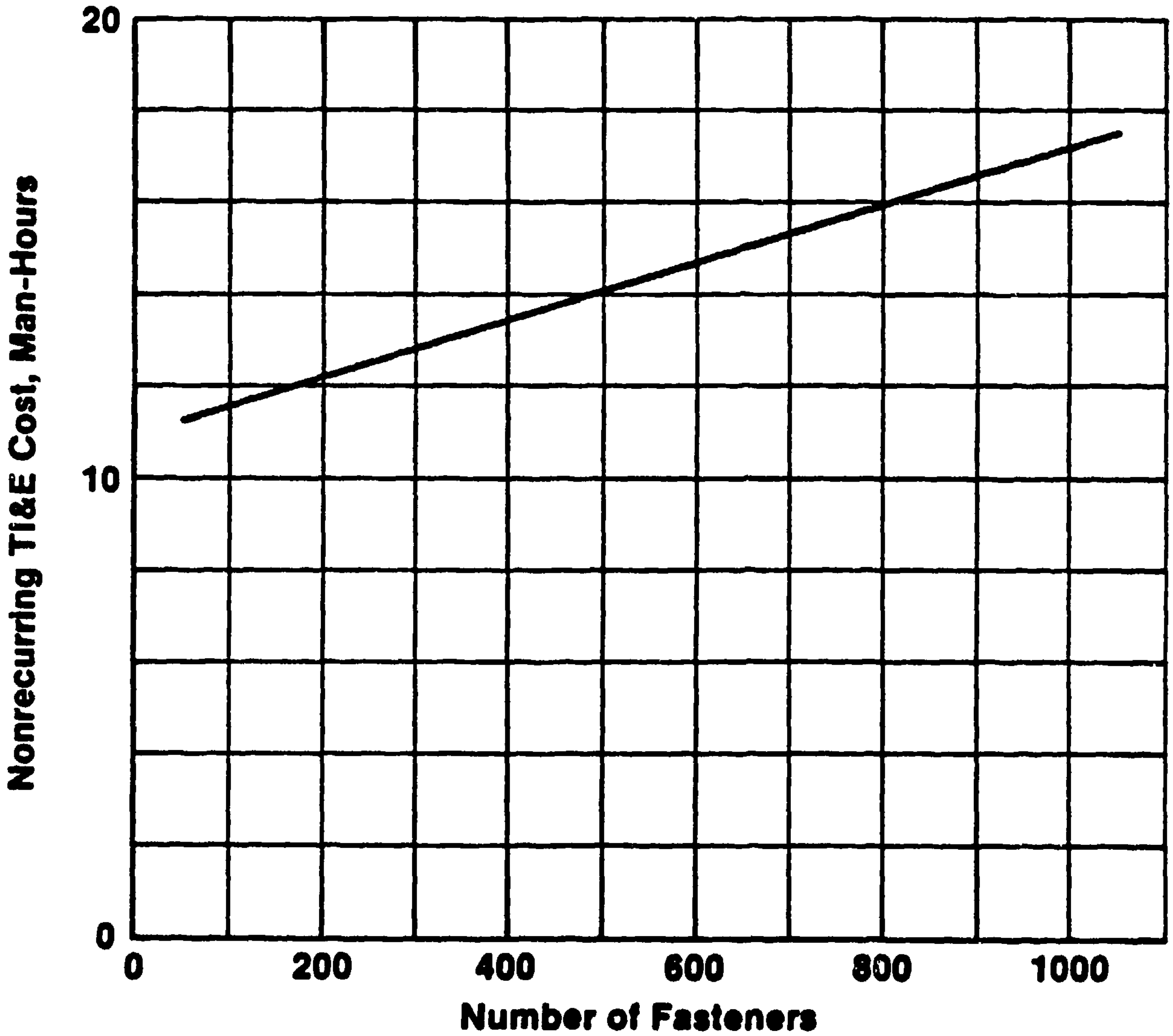
CED-MFA

TEST, INSPECTION AND EVALUATION (TI&E) RECURRING MAN-HOURS FOR MECHANICALLY FASTENED ALUMINUM ASSEMBLIES



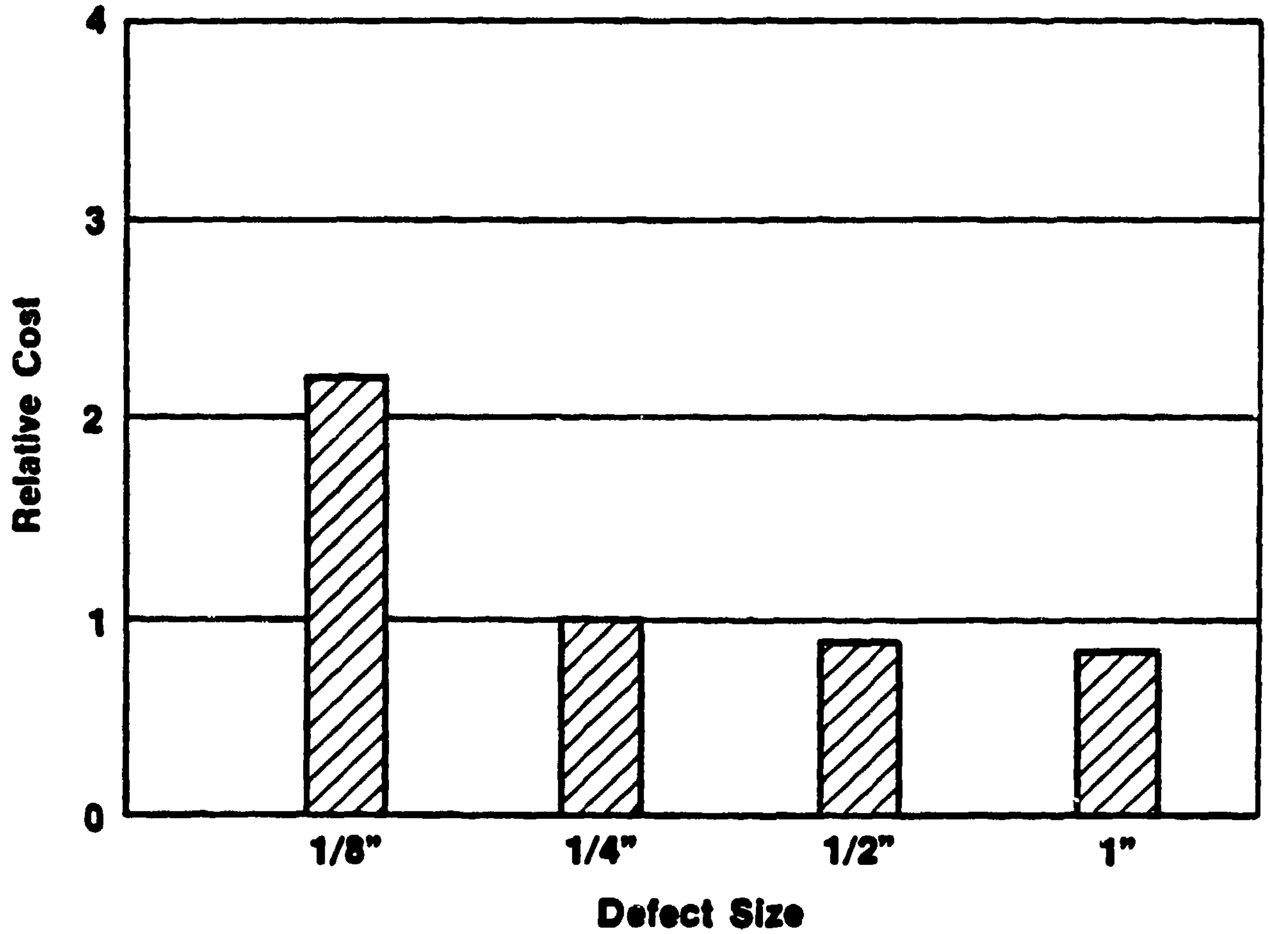
CED-TI&E-MFA-1

TEST, INSPECTION AND EVALUATION (TI&E) NONRECURRING TI&E MAN-HOURS FOR ALUMINUM AND TITANIUM ASSEMBLIES USING MANUAL OR COMBINED AUTOMATIC/ MANUAL FASTENING METHODS



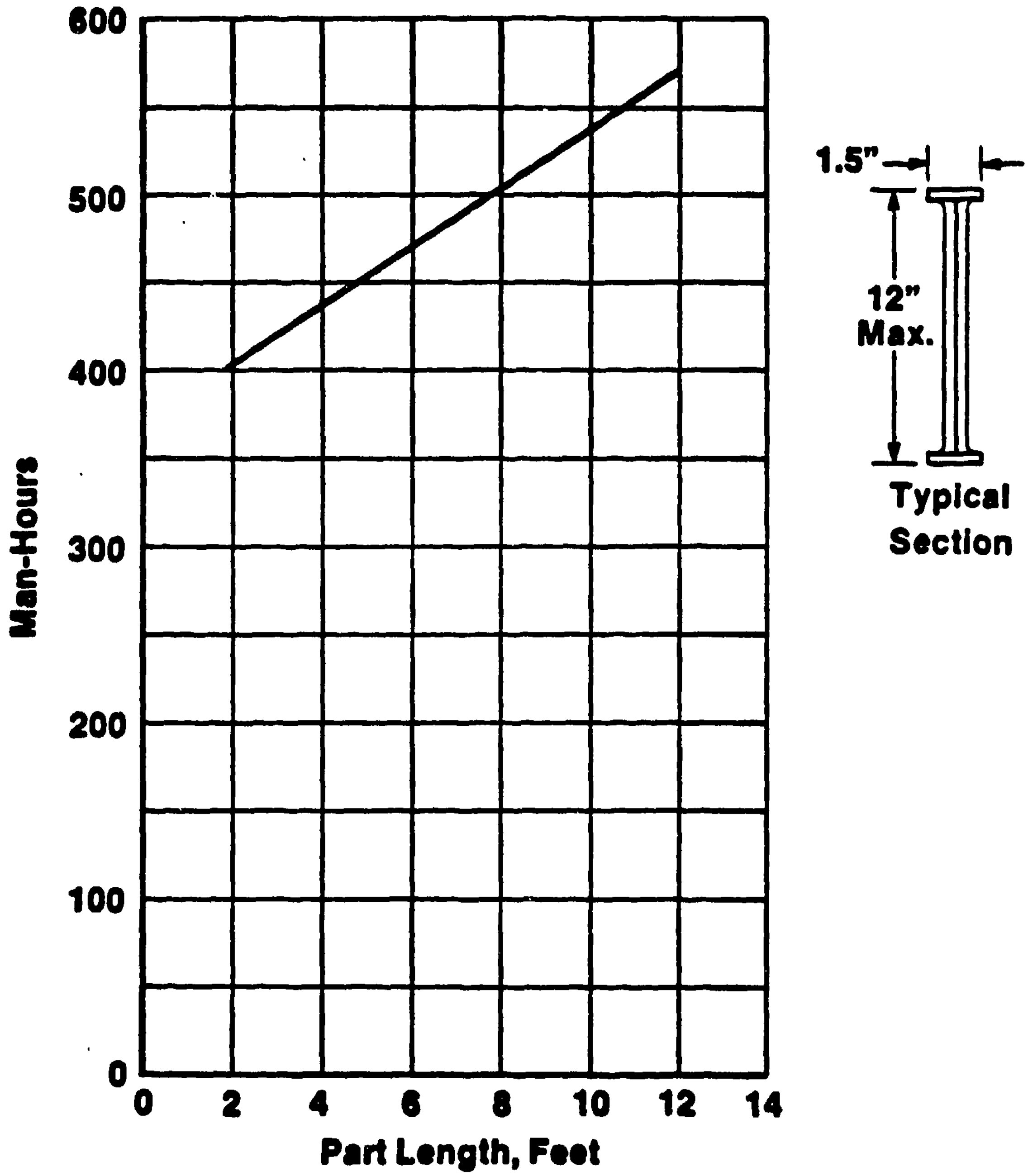
CED-TI&E-MFA-3

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



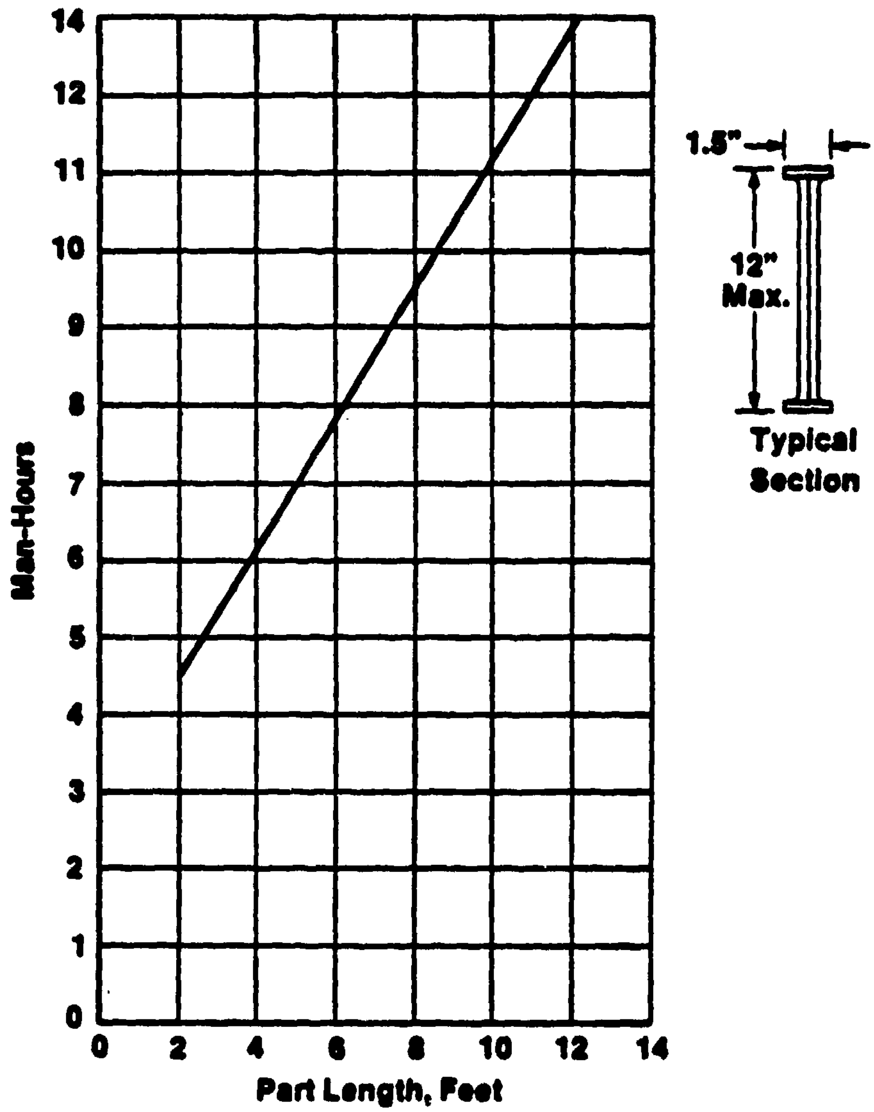
CDE-TI&E-G/E-V

TEST, INSPECTION AND EVALUATION (TI&E) COMPOSITE SINE-WAVE SPAR NONRECURRING COST/PART



CED-TI&E-G/E-10

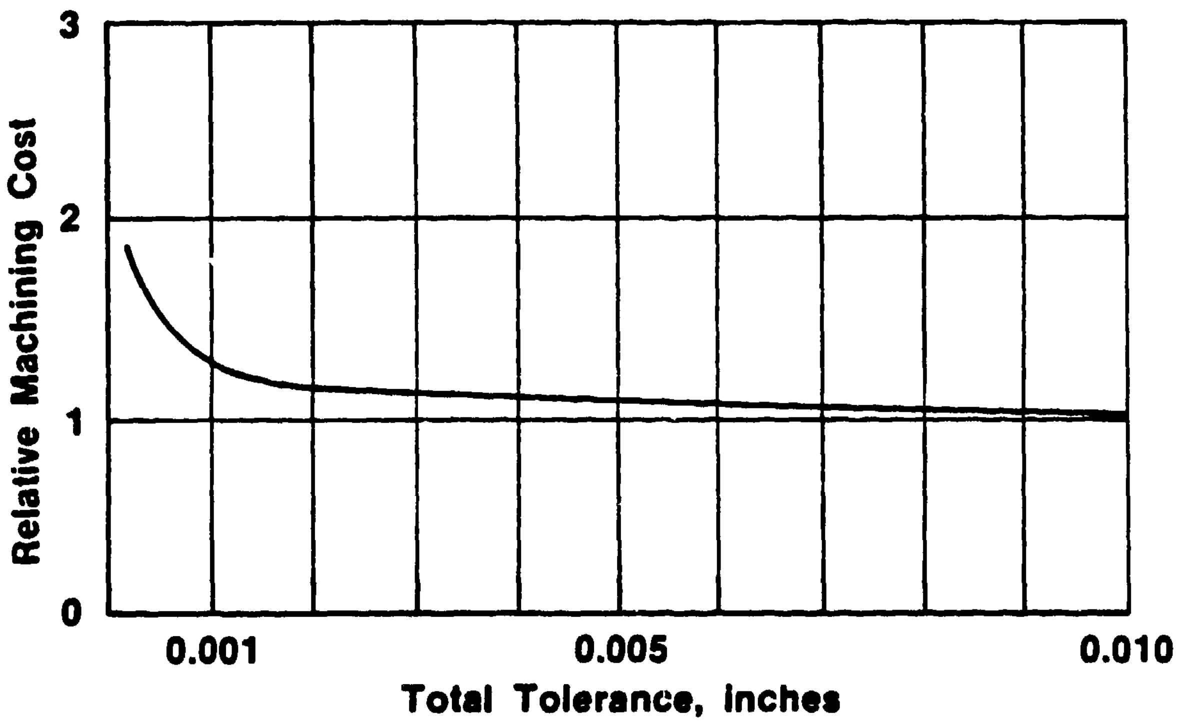
TEST, INSPECTION AND EVALUATION (TI&E) COMPOSITE SINE-WAVE SPAR RECURRING COST/PART



• Applies to laminates up to 24 plies.

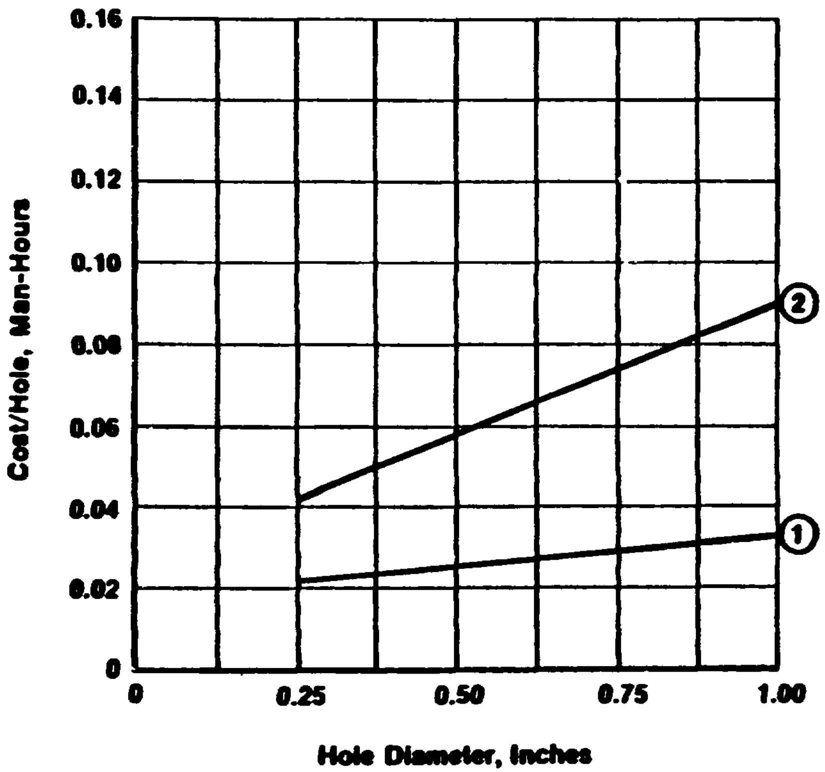
CED-TI&E-G/E-9

MACHINING OF FORGINGS—DIMENSIONAL TOLERANCES COST-DRIVER EFFECT



CDE-FM-II

MACHINING OF FORGINGS
DRILL AND SPOTFACE HOLES



Nonrecurring Tool Cost

NRTC = (32 + 2N) Man-Hours

Where N is the number of holes in the pattern.

① Aluminum

② Titanium, Steel, CRES

Cost/Part = (Cost/Hole • N) Man-Hours

Cost data is valid for hole depths up to twice the hole diameter.

CED-FM-2

EXAMPLES OF UTILIZATION OF MC/DG IN DESIGN PROCESS

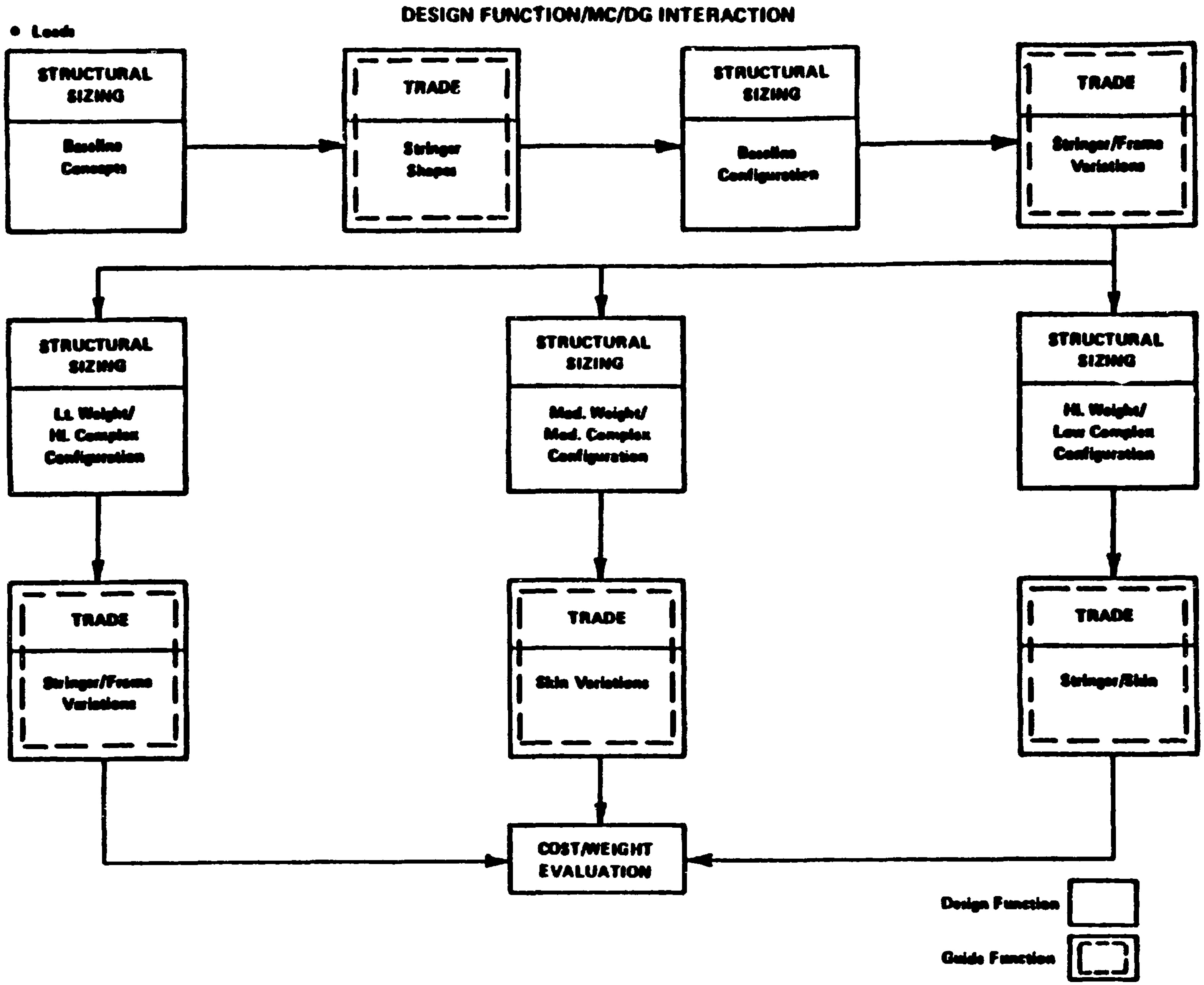
- COMPOSITE STRUCTURES FOR FUSELAGES

"MANUFACTURING COST/DESIGN GUIDE (MC/DG)"

MC/DG TRADE-STUDY

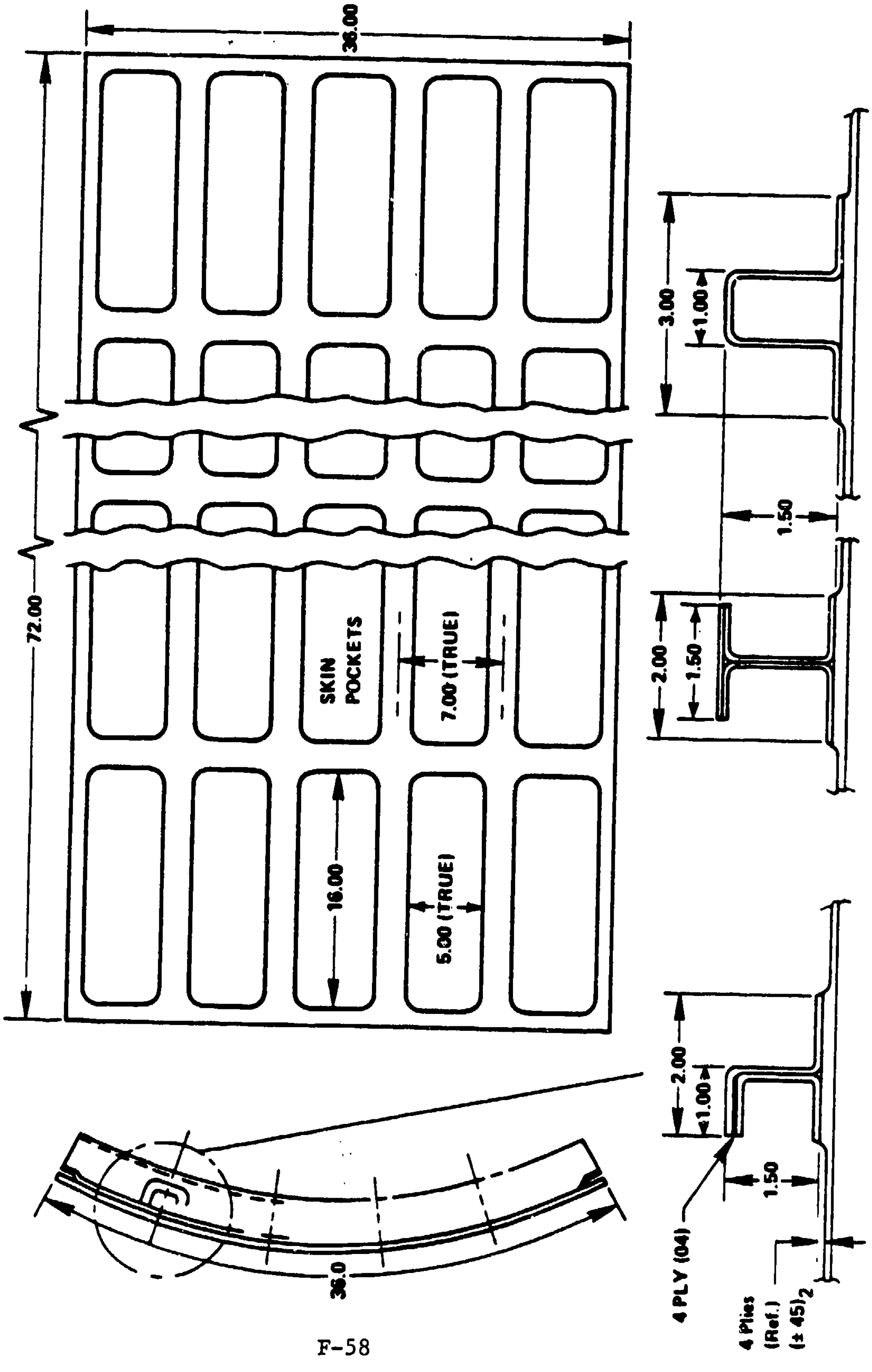
- DESIGN FUNCTION/DESIGN GUIDE INTERACTION
- DEFINE GROUND RULES
- BASELINE CONFIGURATION
- ALTERNATE CONFIGURATIONS
- COST/WEIGHT TRADE EXAMPLE
- TRADE SUMMARY

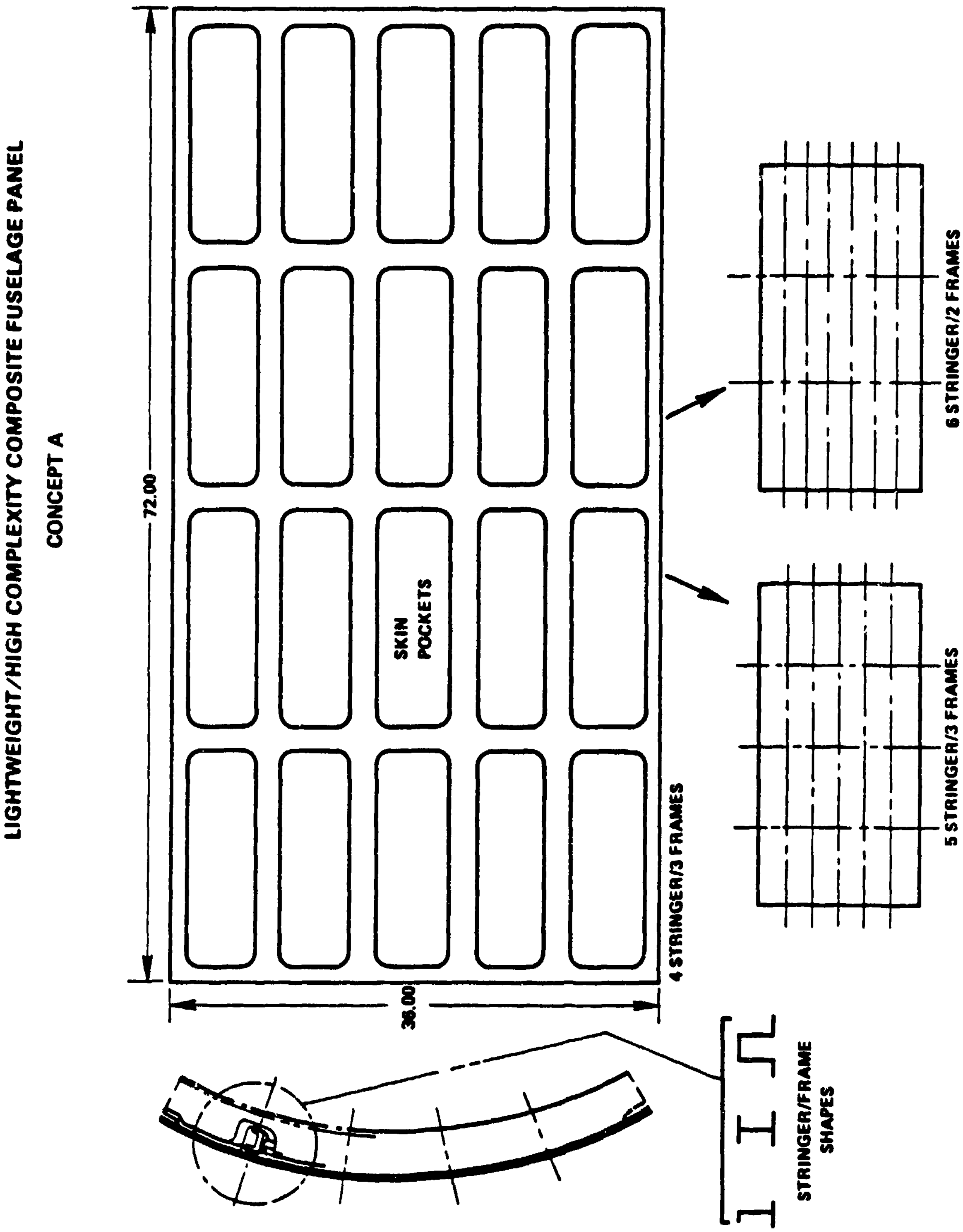
DESIGN FUNCTION/MC/DG INTERACTION



DETAILS OF BASELINE FUSELAGE PANEL IN ADVANCED COMPOSITE TRADE-STUDY

CONCEPT A – BASELINE

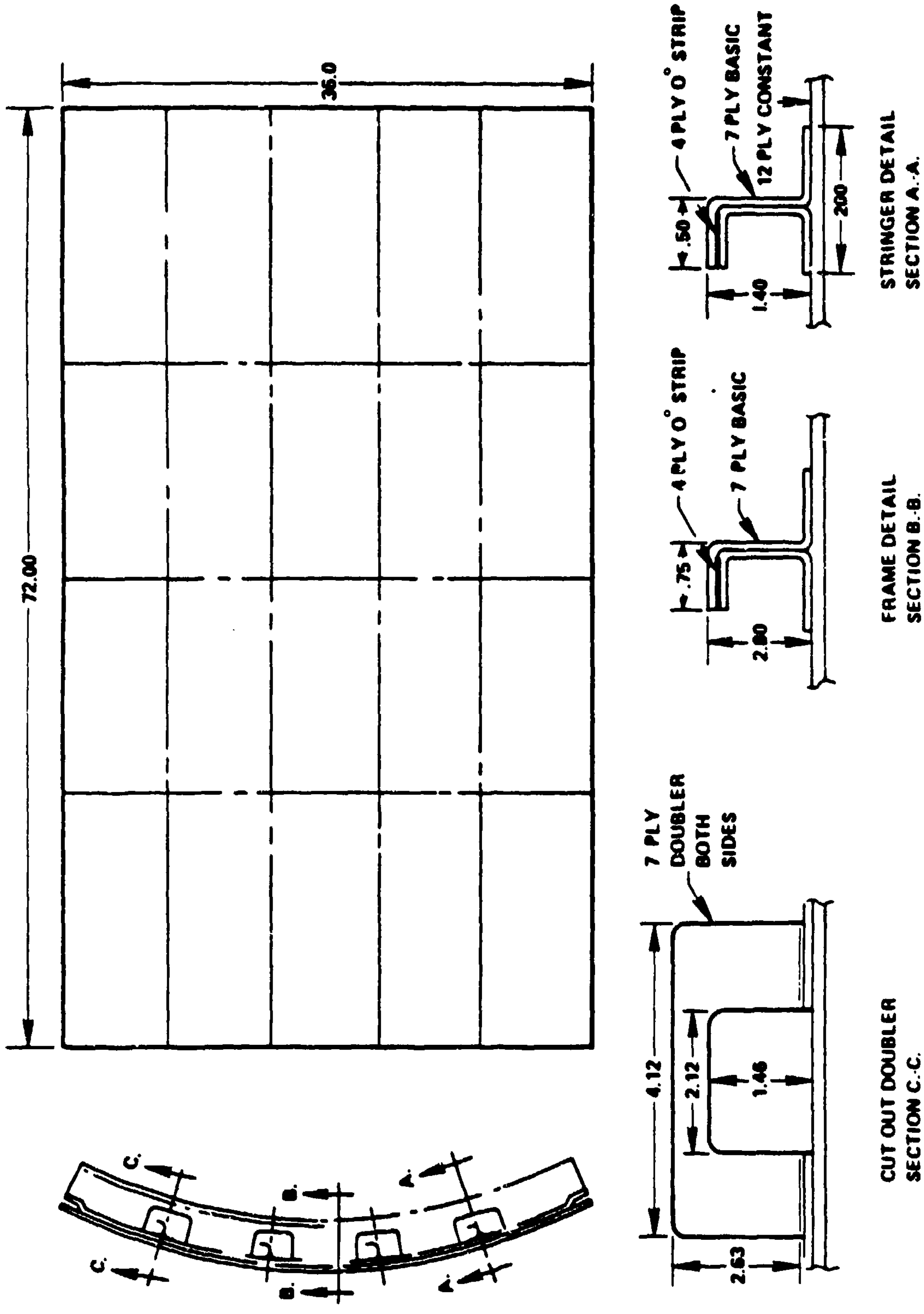



LIGHTWEIGHT/HIGH COMPLEXITY COMPOSITE FUSELAGE PANEL
CONCEPT A
72.00
36.00
SKIN
POCKETS
4 STRINGER/3 FRAMES
6 STRINGER/2 FRAMES
5 STRINGER/3 FRAMES
STRINGER/FRAME
SHAPES

MODERATE WEIGHT/MODERATE COMPLEXITY COMPOSITE FUSELAGE PANEL

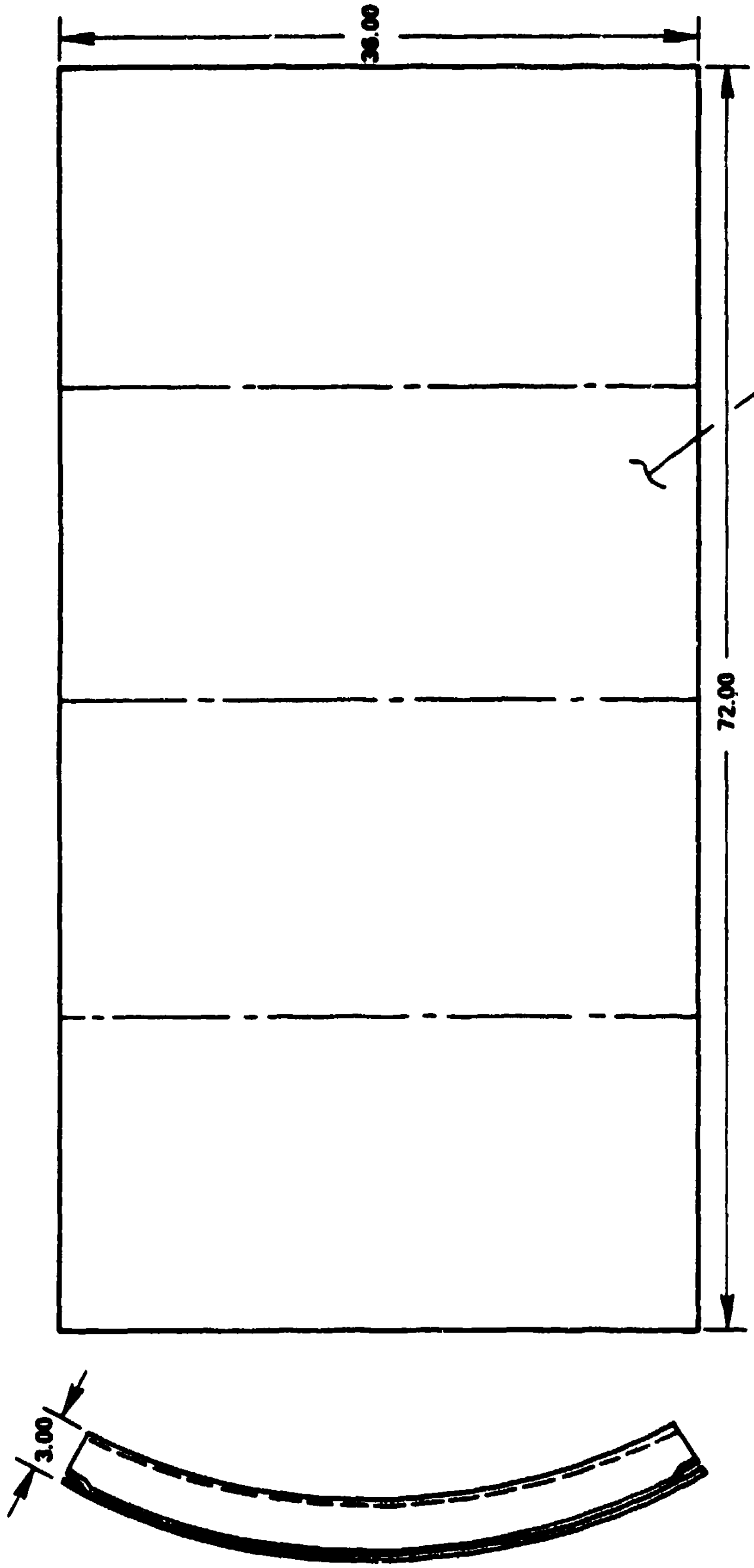
CONCEPT B AND C

B: 4 STRINGERS AND 3 FRAMES
C: 3 STRINGERS AND 3 FRAMES



MINIMUM PART COUNT COMPOSITE FUSELAGE PANEL (PLATE SKIN/3 FRAMES)

CONCEPT D

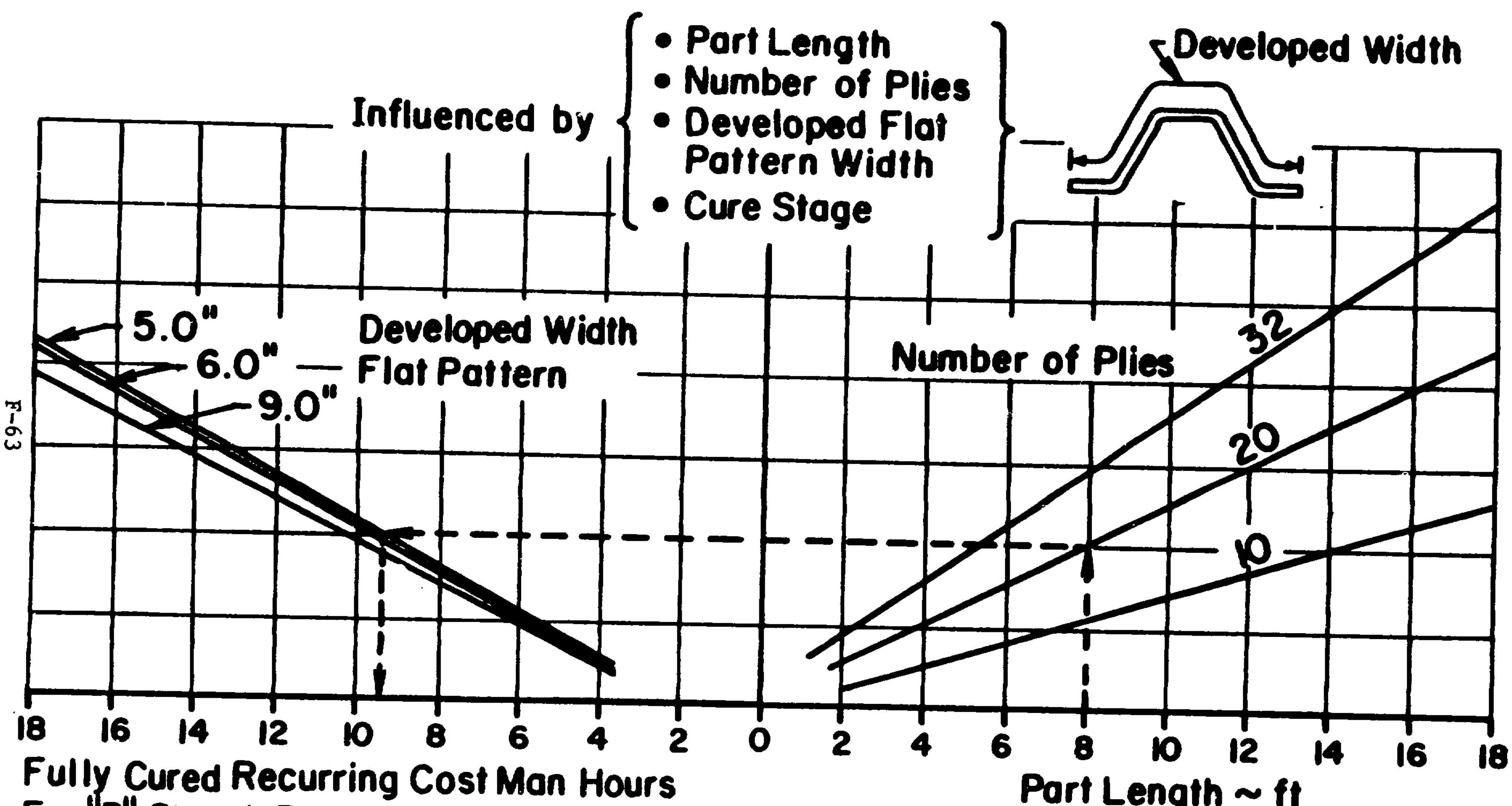


ADVANCED COMPOSITES TRADE STUDY

Formats Utilized for Integrated Example

Concept	Cost Item	Format Number
Lightweight/High	Skin	CED-G/E-7 and CED-G/E-8
Complexity	Hat Stringers	CED-G/E-1 and CED-G/E-2
Mechanically-Fastened	"J" Frames	CED-G/E-3 and CED-G/E-4
	Strip Plies	DICE-G/E-1
(Configuration A-I	Cut-outs	DICE-G/E-2
and A-II)	Cut-out Doublers	DICE-G/E-4
	Assembly (Mechanical)	CED-MFA-2 and CED-MFA-3
Lightweight/High	Skin	CED-G/E-7 and CED-G/E-8
Complexity Cocured	"J" Stringers	CED-G/E-3 and CED-G/E-4
	"J" Frames	CED-G/E-3 and CED-G/E-4
(Baseline -	Strip Plies	DICE-G/E-1
Configuration A-III)	Cut-outs	DICE-G/E-2
	Cut-out Doublers	DICE-G/E-4
	Assembly (Cocured)	CED-G/E-10
Moderate Weight/	Skin	CED-G/E-7 and CED-G/E-8
Moderate Complexity	"J" Stringers	CED-G/E-3 and CED-G/E-4
4 Stringers/3 Frames	"J" Frames	CED-G/E-3 and CED-G/E-4
	Strip Plies	DICE-G/E-1
(Configuration B)	Cut-outs	DICE-G/E-2
	Cut-out Doublers	DICE-G/E-4
	Assembly (Cocured)	CED-G/E-10
Moderate Weight/	Skin	CED-G/E-7 and CED-G/E-8
Moderate Complexity	"J" Stringers	CED-G/E-3 and CED-G/E-4
3 Stringers/3 Frames	"J" Frames	CED-G/E-3 and CED-G/E-4
	Strip Plies	DICE-G/E-1
(Configuration C)	Cut-outs	DICE-G/E-2
	Cut-out Doublers	DICE-G/E-4
	Assembly (Cocured)	CED-G/E-10
Minimum Part Count	Skin	CED-G/E-7 and CED-G/E-8
	"J" Frames	CED-G/E-3 and CED-G/E-4
(Configuration D)	Strip Plies	DICE-G/E-1
	Assembly	CED-G/E-10

COMPOSITE HAT SECTION RECURRING COST/PART



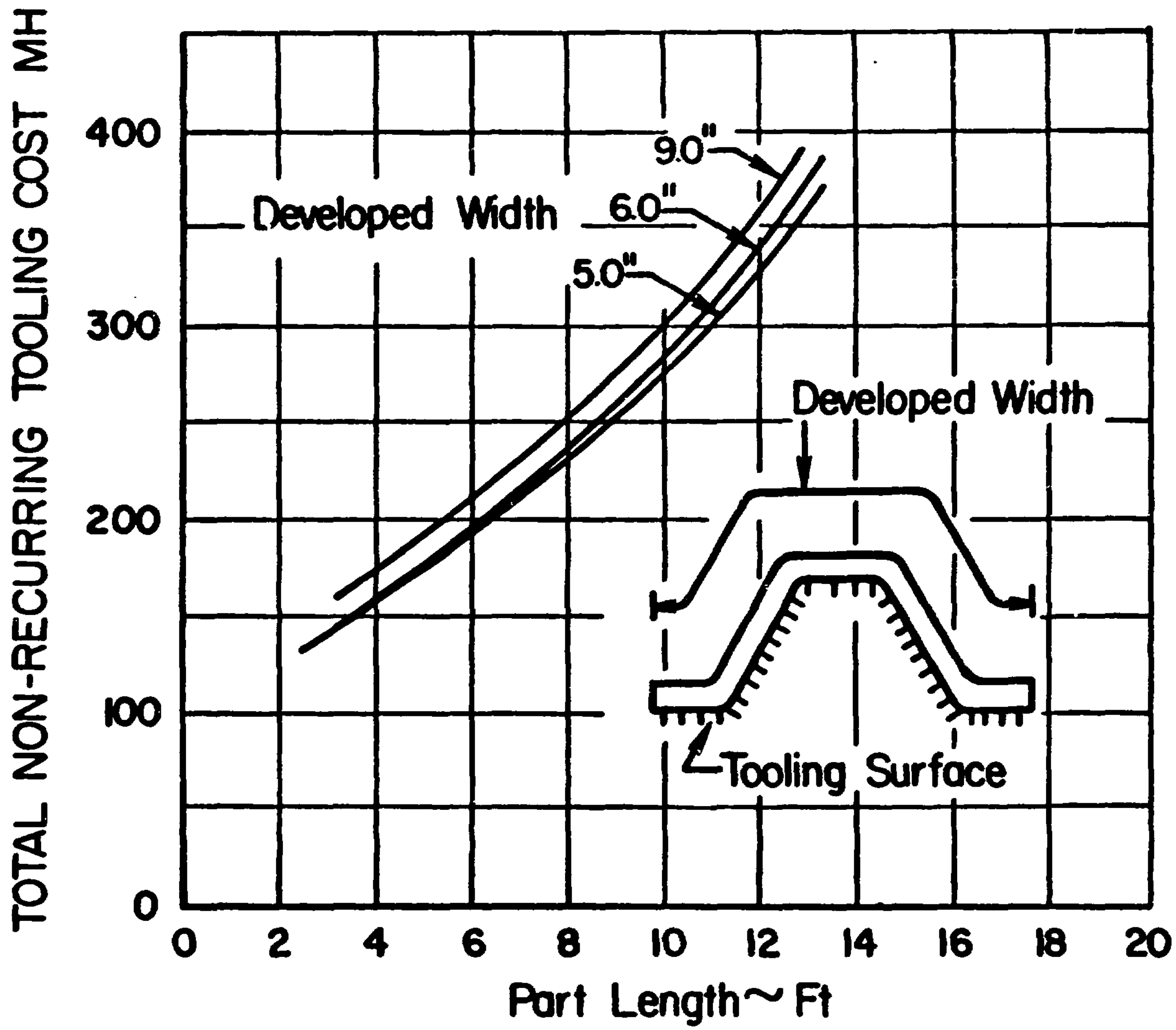
For "B" Staged Recurring Cost, Multiply by 0.84

See Ground Rules for Limitations and Considerations

CED-G/E-1

COMPOSITE HAT SECTION TOTAL NON-RECURRING TOOLING COST/PART

Influenced By {•Part Length •Developed Width}

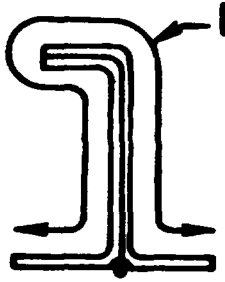


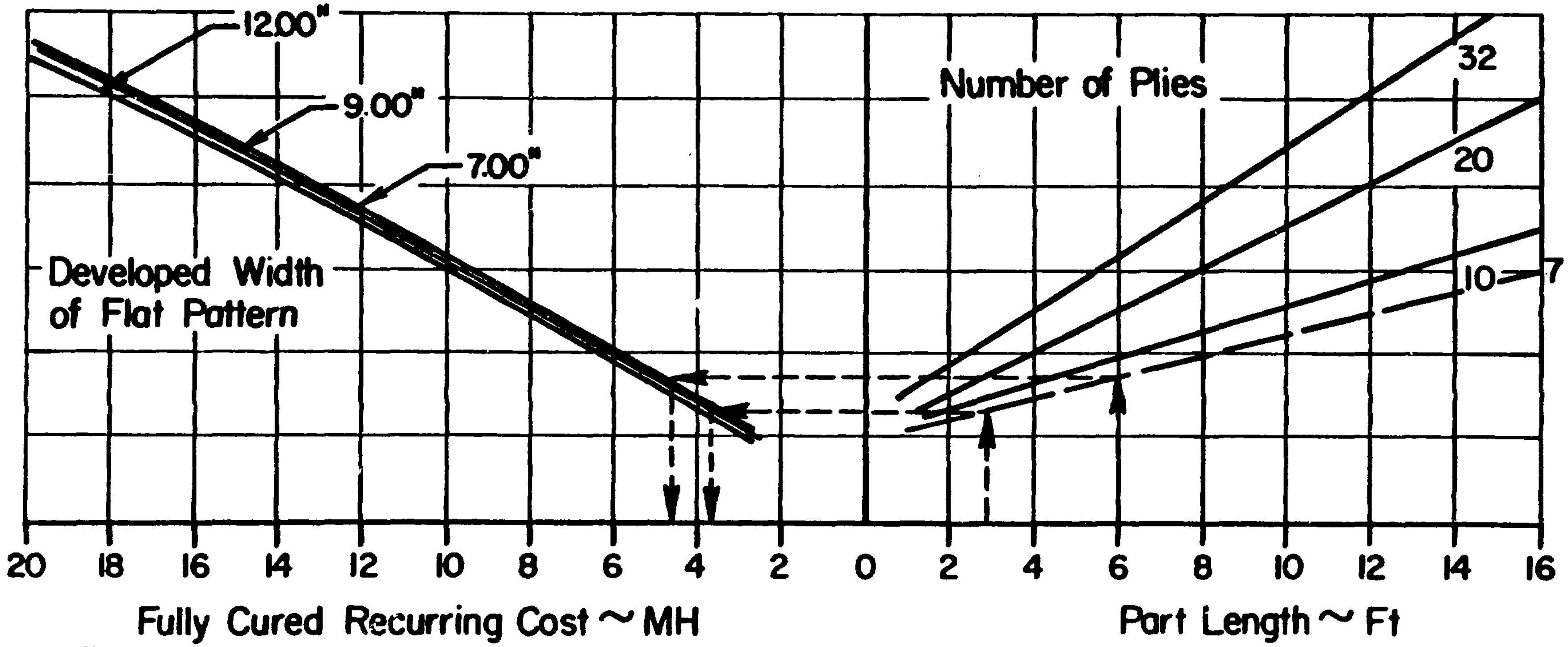
See Ground Rules for Limitations and Considerations

CED-G/E-2

COMPOSITE J SECTION RECURRING COST/PART

Influenced By
- Part Length
- Number of Plies
- Developed Flat Pattern Width
- Cure Stage



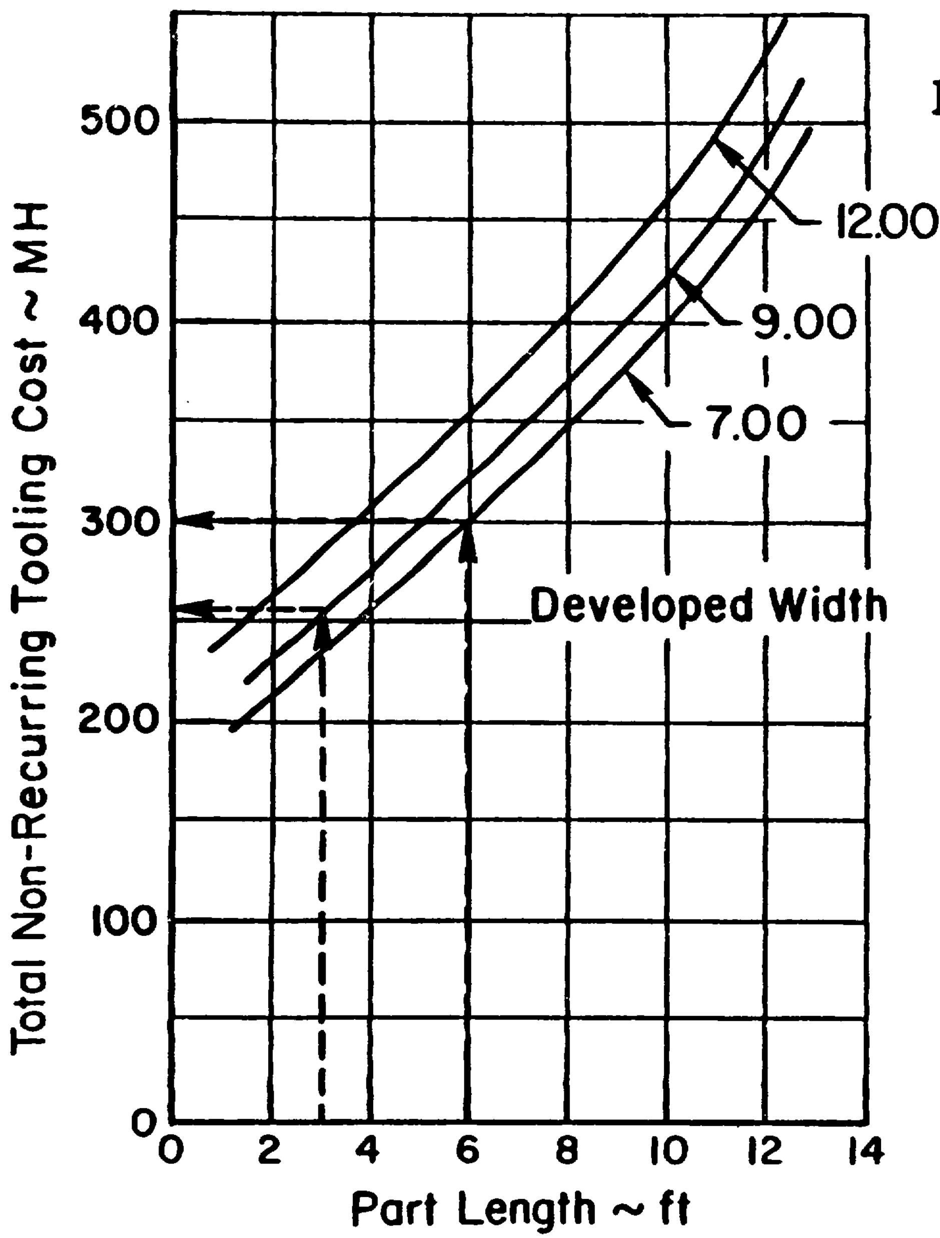


For "B" Stage Recurring Cost, Multiply by 0.84

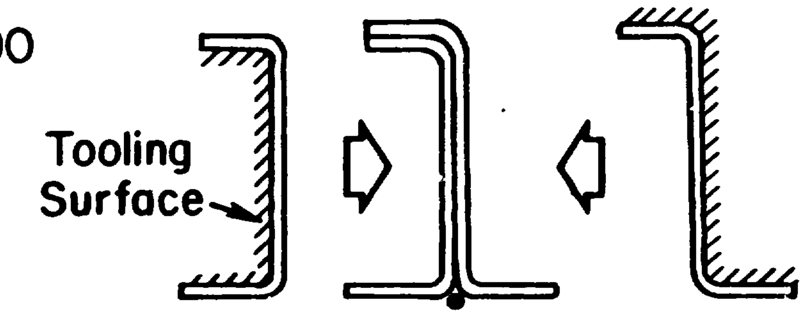
See Ground Rules for Limitations and Considerations

CED-G/E-3

COMPOSITE J SECTION TOTAL NON-RECURRING TOOLING COST/PART



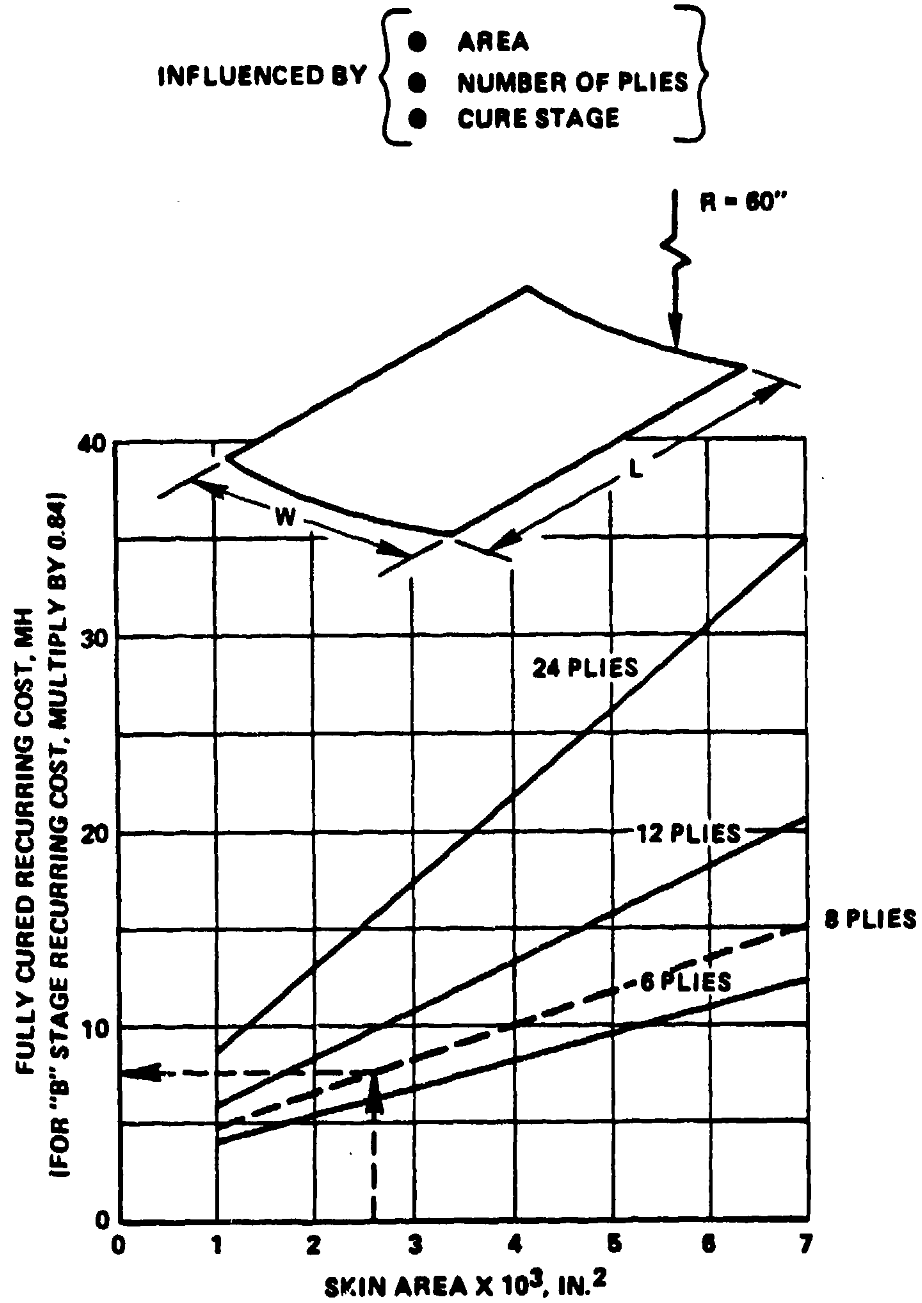
Influenced by { • Part Length • Developed Width }



See Ground Rules for Limitations and Considerations

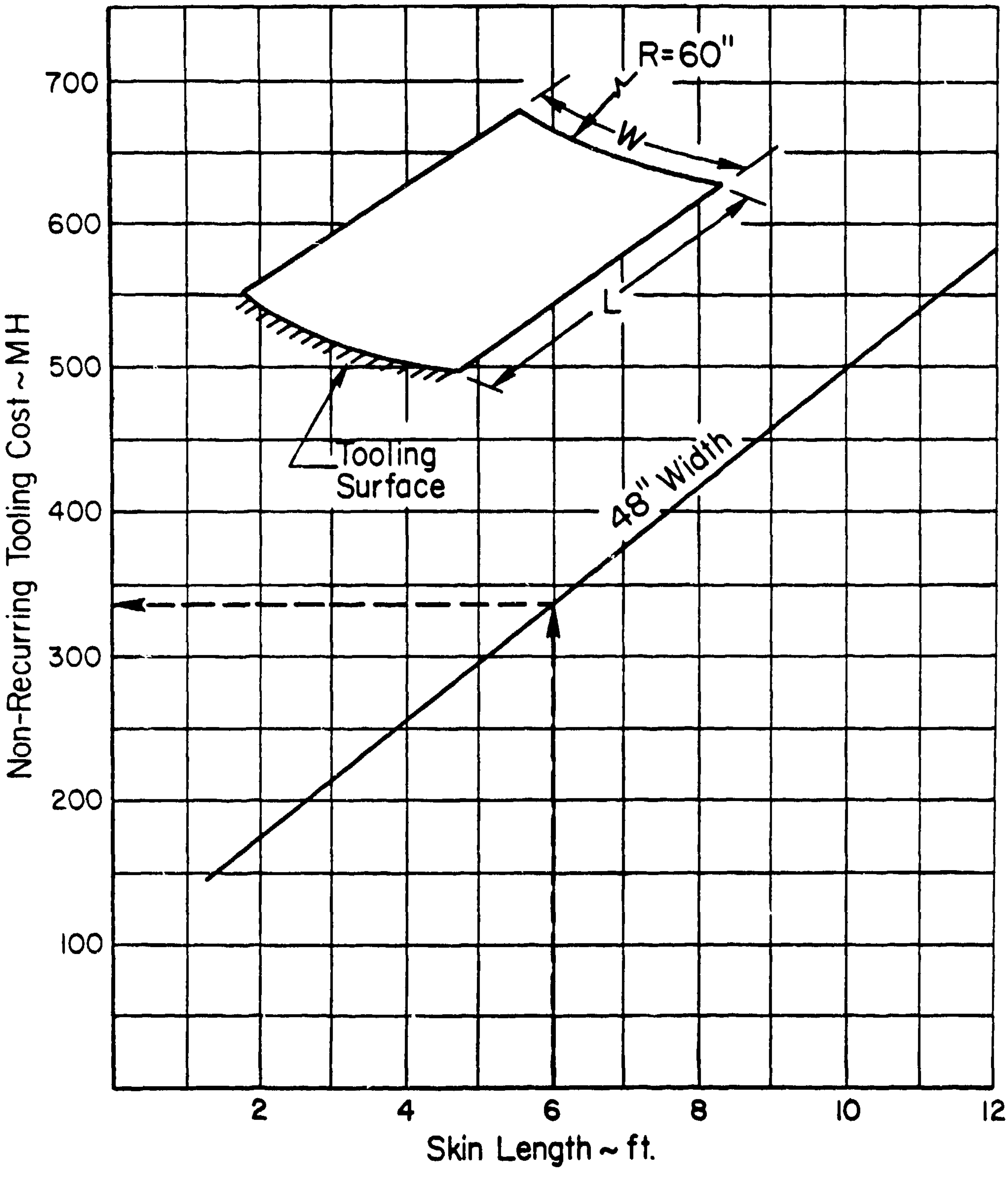
CED-G/E-4

SINGLE CURVATURE SKIN RECURRING COST/PART

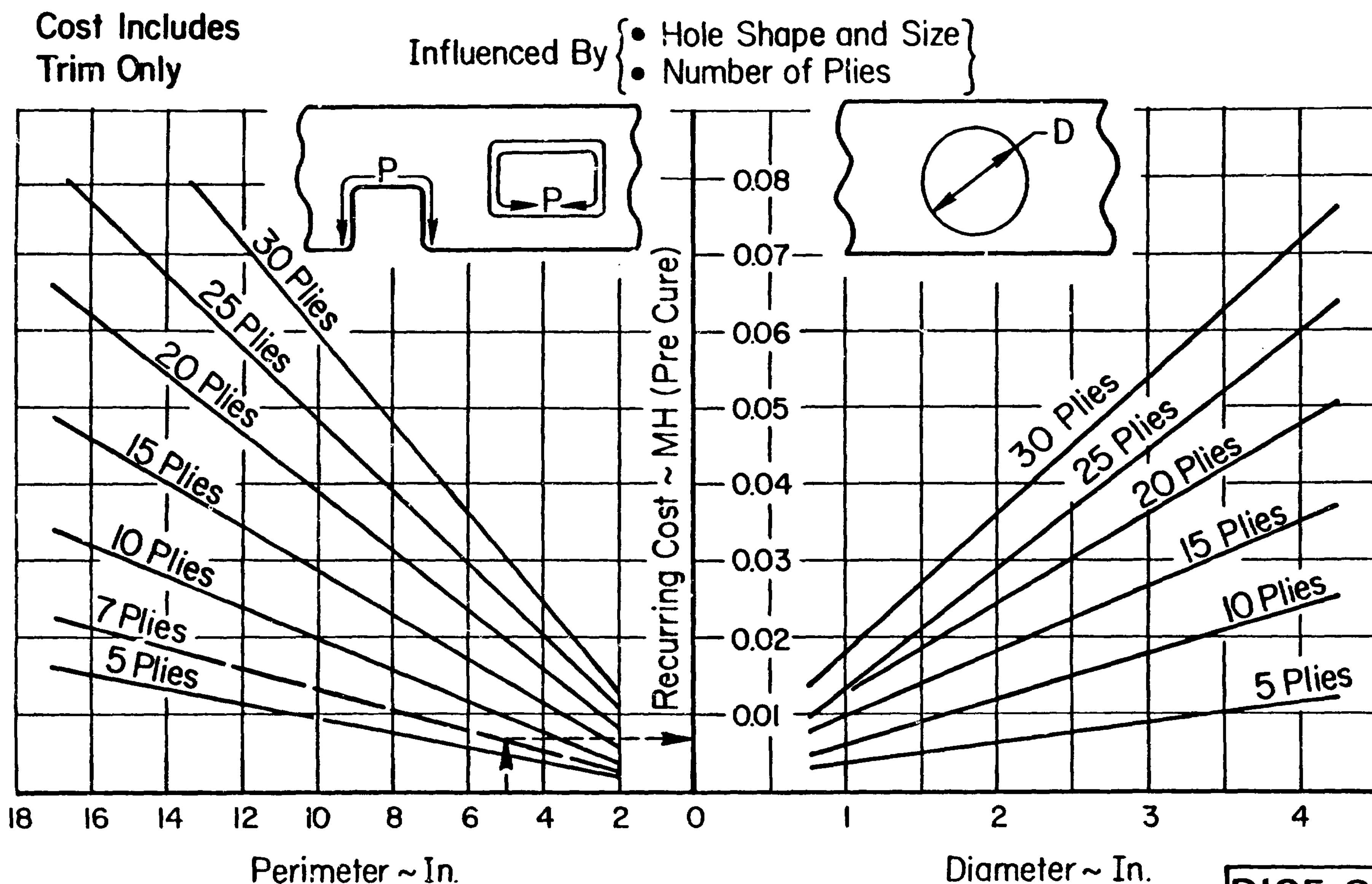


CED-G/E-7

SINGLE CURVATURE SKIN NON-RECURRING TOOLING COST/PART



CUTOUT-HOLE RECURRING COST/DETAIL



See Ground Rules for Limitations and Considerations

DICE-G/E-2

MC/DG COST WORKSHEET

CONCEPT NO.: LIGHTWEIGHT / HIGH COMPLEXITY COCURED

PAGE 1 of 2

DESIGN CONCEPT		RECURRING COST (RC)									NON-RECURRING COST (NRC)			PROGRAM COST		
		L . LC . LR = LS + MS = RC . P/AC . DQ = PRC									NRC . LR = PNRC			9 + 12 ÷ DQ = COST/AC		
PART NO.	DESCRIPTION	LABOR MC/DG MH/PT (1)	LC FACTOR (2)	LABOR RATE $/MH (3)	LABOR RC $/PT (4)	MAT'L $/PT (5)	REC. COST/ PT. $ (6)	PARTS PER AC (7)	DES. QTY. (8)	PROG. RC $ (9)	NRC MC/DG MH (10)	LABOR RATE $/MH (11)	PROG. NRC $ (12)	PROG. COST $ (13)	DES. QTY. (14)	COST/ AC $ (15)
1	SKIN	9.13	1.30	25	296.73	256.96	553.69	1	200	110738	340	25	8500			
2	STRINGERS	4.83	1.30	25	156.98	39.60	196.58	4	200	157264	300	25	7500			
3	FRAMES	4.89	1.30	25	158.93	26.33	185.26	3	200	111156	255	25	6375			
	ASSEMBLY	3.31	1.66	25	137.40	—	137.40	1	200	27480	—	—	—			
	TOTALS									406638			22375	429013	200	2145

COST WORKSHEET – SUPPORTING DATA

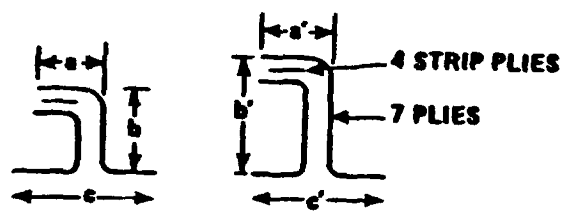
CONCEPT NO. : LIGHTWEIGHT/HIGH COMPLEXITY COCURED

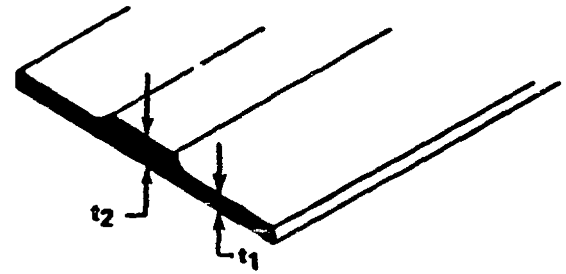
PAGE 2 OF 2

PART: SKIN CED-G/E-7 & CED-G/E-8 8 PLY BASE 7.3 MH/PART × 0.84 FOR B STAGE = 6.13 TOOL 340 MH 6 LAYER STRIPPLIES-DICE-G/E-1 4-2" × 72" 1.44 3-2" × 36" 0.84 2-1" × 72" 0.40 2-1" × 36" 0.32 9.13 MAN-HOURS/PART	MATERIAL: BASE (36×72×8×0.0052) = 107.83 4(2×72×4×0.0052) = 11.98 3(2×36×4×0.0052) = 4.49 2(1×72×4×0.0052) = 3.00 2(1×36×4×0.0052) = 1.50 128.80 CU. IN. 128.80 CU.IN. × 0.057 LB/CU.IN. × 35 $/LB = $256.96
PART: STRINGERS CED-G/E-3 & CED-G/E-4 7 IN. DEV. WIDTH 4.80 TOOL 300 MH 7 PLY BASE .84 - B STAGE 4.03 MAN-HOURS/PART 4 STRIPPLIES 1" WIDE 0.80 (4×0.20 EACH STRIP PLY) (DICE-G/E-1) 4.83 MAN-HOURS/PART	MATERIAL: 7" × 72" × 7 × 0.0052 = 18.35 1 × 72 × 4 × 0.0052 = 1.50 19.85 19.85 CU.IN. × 0.057 LB/CU.IN. × 35 $/LB. = $39.60
PART: FRAMES CED-G/E-3 & CED-G/E-4 7 PLY BASE PART 3.70 MAN-HOURS/PART × 0.84 FOR B STAGE = 3.11 TOOL 255 MH 4 PLY STRIP 1" WIDE (DICE-G/E-1) 0.48 (4×0.12 EACH STRIPPLY) CUTOUTS (4) (DICE-G/E-2) 0.26 (4×0.065) DOUBLERS (DICE-G/E-4) 1.04 (4×2×.013) 4.89 MAN-HOURS/PART	MATERIAL: 9.5 × 36 × 7 × 0.0052 = 12.45 1 × 36 × 4 × 0.0052 = 0.75 13.20 13.20 CU.IN. × 0.057 LB/CU.IN. × 35 $/LB. = $26.33
ASSEMBLY: COCURING CED-G/E-10 HANDLING, ETC. 0.67 BAGGING, ETC. 2.64 3.31 MAN-HOURS/ASSEMBLY	ASSEMBLY:

SUMMARY OF MANUFACTURING COST (MAN-HOURS) AND WEIGHT OF COMPOSITE CONFIGURATIONS

DIMENSIONS IN INCHES

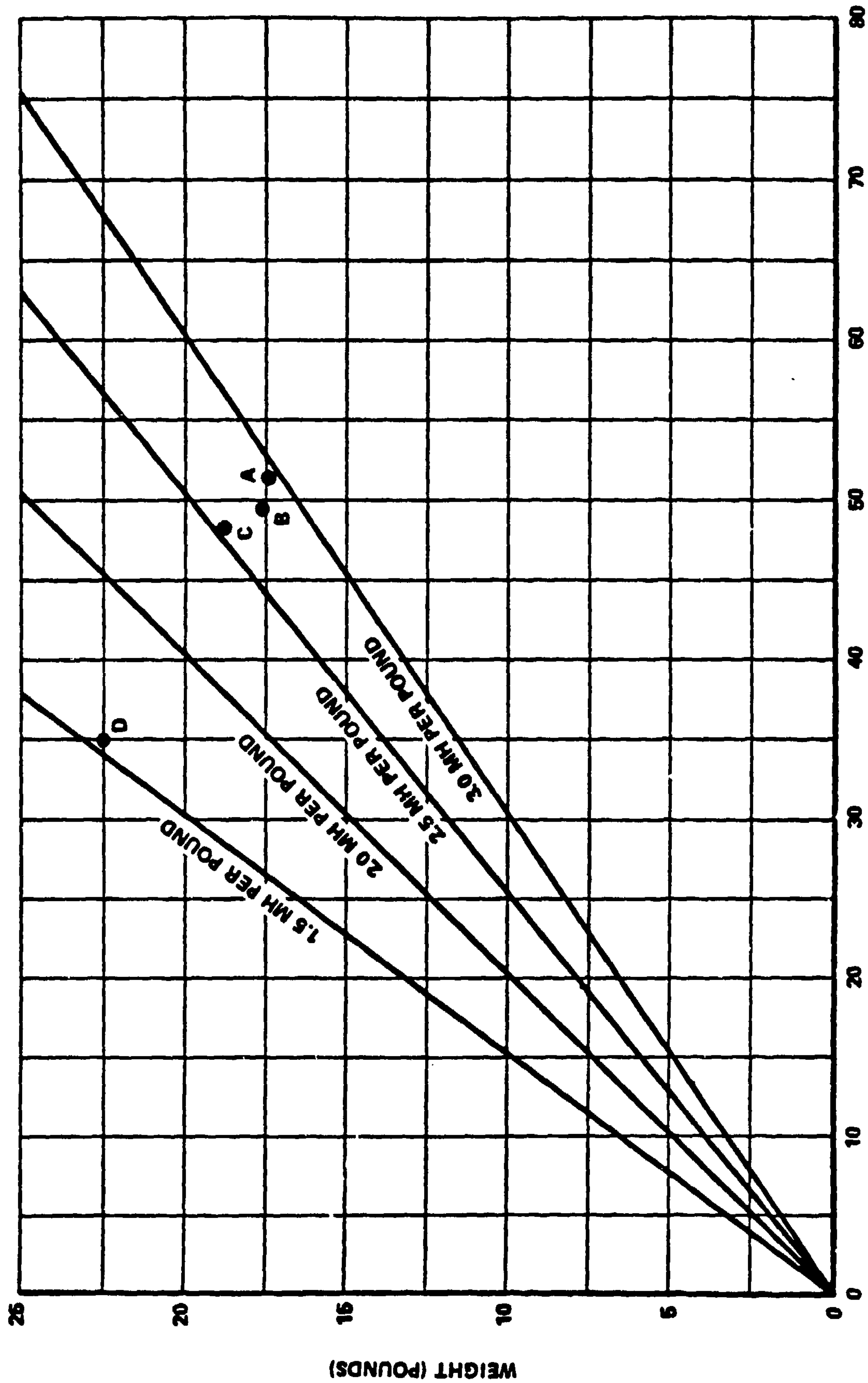




CONFIG-URATION		STRINGERS				FRAMES				SKIN		*MAN-HOURS	WEIGHT, LB
		NUMBER	a	b	c	NUMBER	a'	b'	c'	t_1	t_2		
A	BASELINE- LIGHT WEIGHT/ HIGH COMPLEXITY COCURED	4	1.00	1.50	2.00	3	.75	3.00	2.00	8 PLY	12 PLY	51.10	17.45
B	MODERATE WEIGHT/ MODERATE COMPLEXITY	4	.50	1.40	2.00	3	.75	2.80	2.00	12 PLY	12 PLY	49.20	17.65
C	MODERATE WEIGHT/ MODERATE COMPLEXITY	3	1.00	1.80	2.00	3	.75	3.20	2.00	12 PLY	12 PLY	48.04	18.80
D	LOW COMPLEXITY	0	0	0	0	3	.75	3.00	2.00	24 PLY	24 PLY	34.79	22.50

$$*\text{RECURRING} + \frac{\text{NON-RECURRING}}{200}$$

SUMMARY OF RESULTS IN ADVANCED COMPOSITE FUSELAGE
SHEAR-PANEL TRADE—STUDY



"MANUFACTURING COST/DESIGN GUIDE (MC/DG)"

ADVANCED COMPOSITE FUSELAGE SHEAR-PANEL TRADE-STUDY

CONCLUSIONS

- THE TRADE-STUDY SUCCESSFULLY DEMONSTRATED USE OF MC/DG
- MANUFACTURING COST TRADE-OFFS WERE PERFORMED BY THE DESIGN DISCIPLINE
- THE MC/DG FORMATS WERE UTILIZED
  - — BY INTERPOLATION
  - — WITH EASE

INDUSTRY APPLICATION

MC/DG FOR AIRFRAMES & ELECTRONICS

MC/DG ROLE IN CAM ENVIRONMENT

- PROVIDES LINK BETWEEN CAD AND CAM
  - DESIGN/MANUFACTURING INTERACTION
- HIGHLIGHTS LOWEST COST PRCCESS FLOW
- ALLOWS DESIGN TRADES WITH KNOWN MANUFACTURING COST IMPACTS
- DEMONSTRATES IMMEDIATE COST IMPACT OF DOCUMENTATION CHANGE NOTICE

MC/DG FOR AIRFRAMES

SUMMARY

- USE OF THE MC/DG DEMONSTRATED
- INDEPENDENT TRADE-STUDIES CONDUCTED FOR FUSELAGE PANEL IN THREE DIFFERENT MATERIALS
- THROUGH USE OF MC/DG, DESIGNER ABLE TO EVALUATE LARGE NUMBER OF CONCEPTS (8 TO 10) WITHIN AN 8-HOUR PERIOD
- DESIGNER ABLE TO READILY DEVELOP RECURRING COSTS AND NON-RECURRING TOOLING COSTS FOR EACH PANEL CONFIGURATION (TWO CALCULATIONS REQUIRED; 15-40 OTHERWISE NECESSARY)
- COST/WEIGHT RELATIONSHIPS FOR EACH PANEL DESIGNED IDENTIFIED
- MOST COST/WEIGHT EFFECTIVE DESIGN SELECTED FOR PRODUCTION DEVELOPMENT AND RELEASE TO MANUFACTURING
- OBJECTIVES ESTABLISHED BY THE MATERIALS LABORATORY, AFWAL, FOR MC/DG TO FUNCTION AS A DESIGNER'S TOOL, WERE SATISFIED

"MANUFACTURING COST/DESIGN GUIDE (MC/DG)"

CONCLUSIONS

- VIABLE MC/DG METHODOLOGY BASE ESTABLISHED
- UTILIZATION OF COST DATA BY DESIGNER INVOLVES SIMPLE CALCULATIONS
- GUIDE IS FOR DESIGNERS—NOT COST-ESTIMATING MANUAL
- MC/DG IS A USEFUL TOOL FOR DESIGNERS IN PERFORMING TRADE-STUDIES AND CONTROLLING COSTS
- MC/DG DEMONSTRATED AS EFFECTIVE DESIGN/MANUFACTURING COST TRADE TOOL
- USE OF COMPUTER WILL EXPAND AND ACCELERATE DEGREE AND NUMBER OF TRADE-OFFS THAT CAN BE PERFORMED BY BOTH PRELIMINARY AND PRODUCTION DESIGN DESIGNERS

MC/DG FOR AIRFRAMES AND ELECTRONICS

ICAM MC/DG—POSITIVE EFFECT IN SYSTEMS ACQUISITION

- SERVE AS AN INSTRUMENT DEMONSTRATING THAT COST HAS BECOME A DYNAMIC DRIVING FACTOR IN PROCUREMENT OF DEFENSE SYSTEMS
- CONTRIBUTES TO CREATING A COST-CONSCIOUS ENVIRONMENT IN MANAGEMENT, DESIGN, AND MANUFACTURING COMMUNITIES
- MOTIVATES CONTRACTORS TO BALANCE COST AS AN EQUAL PARAMETER WITH FUNCTION, RELIABILITY, WEIGHT, AND SCHEDULE
- CONVINCES THAT COST IS AN ACTIVE, POSITIVE FORCE IN DEPARTMENT OF DEFENSE PROCUREMENT AND NOT A PASSIVE, SECONDARY CONSIDERATION

MC/DG PAYOFF IN TODAY'S AEROSPACE ENVIRONMENT

- USE OF THE MC/DG DURING DESIGN DEVELOPMENT WILL SAVE AN ESTIMATED 2 TO 5 PERCENT OF AIRFRAME ACQUISITION COSTS
- EXAMPLE OF EXTENT OF PAYOFF:
  - F14—$14,000,000 (FROM MEDIA)
  - ESTIMATE AIRFRAME COSTS TO BE APPROXIMATELY 30 PERCENT OF TOTAL COST
    - AIRFRAME COST:

14,000,000 x 0.30 = $4,200,000

@ 2 PERCENT—SAVINGS WILL BE $84,000/AIRCRAFT
@ 5 PERCENT—SAVINGS WILL BE $210,000/AIRCRAFT

PROGRAM SAVINGS @ ESTIMATED 2 PERCENT	PROGRAM SAVINGS @ ESTIMATED 5 PERCENT
100—$8,400,000 (2 AIRFRAMES)	100—$21,000,000 (5 AIRFRAMES)
300—$25,200,000 (6 AIRFRAMES)	300—$63,000,000 (15 AIRFRAMES)
500—$42,000,000 (10 AIRFRAMES)	500—$105,000,000 (25 AIRFRAMES)

*U.S.Government Printing Office: 1984 — 559-065/20573