WP8 9

ENHANCEMENT OF AIRCRAFT SUBSYSTEM BIRDSTRIKE RESISTANCE*

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ABSTRACT

Aircraft subsystem birdstrike resistance technology is being developed and applied by the USAF Wright Aeronautical Laboratories. Technology development investigations are underway in the transparency and engine subsystems areas. Advanced state-of-the-art transparency system technology is being utilized to develop improved birdstrike resistant windshield systems for several aircraft. Transparency subsystem technology investigations include development of: computer aided procedures for birdstrike structural analysis; birdstrike hazard risk prediction techniques; design procedures for integration of birdstrike protection and high visibility into high temperature transparencies; testing procedures for improved correlation between lab and field performance; criteria, equipment and procedures for insuring availability of suitable optical quality; and a transparency system design guideline document (handbook). Engine subsystem technology investigations include development of: structural design criteria that account for the transient overloads produced by bird and ice impacts on turbine engine first stage fan/compressor blades; development and interfacing of structural response analysis and impact loading model computer programs to provide direct assessment of a blade's impact damage tolerance capability; and improved validation testing techniques to establish reliable foreign object impact design criteria. The design analysis methods, failure criteria and testing methods will be applicable to both advanced composite materials and monolithic materials of construction for current and advanced fan/compressor blading. These technology development and application efforts will be discussed in general terms as will the rationale behind these efforts, the manner in which the technology development and application efforts are interrelated, and some technical voids in designing for, and integration of, birdstrike resistance.

INTRODUCTION

USAF aircraft repeatedly prove that birds and aircraft cannot occupy the same airspace at the same time; 1000 to 1500 birdstrikes per year cause millions of dollars in damage to USAF aircraft. During the past 12 years nine military pilots have been killed and 15 aircraft have been destroyed due to bird impact. By far the majority of these losses are due to windshield and engine impacts. Design guidelines, test technology and hardware are being developed and applied to enhance aircraft bird impact resistance. Windshield systems are being developed to provide improved structural durability for several aircraft. Transparency

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ology investigations are currently being conducted to support these systems ed developments and to provide a technical base for development of transparency ns for new aircraft or for modification of existing aircraft. Engine system ology investigations are being conducted to provide a means of incorporating valuating birdstrike resistance during the early phases of engine design.

The purpose of this report is to present a brief overview of some of these ities. Recent publications are identified for use in obtaining additional led information.

STRIKE TECHNOLOGY DEVELOPMENT

Technology development activities focus on problems encountered in develop- of current systems and on problems anticipated in development of future ems.

strike Hazard Risk Prediction

Figure 1 is illustrative of the birdstrike environment. Establishing the strike resistance level to be incorporated into a system design is obviously tter of tradeoff. Designing for survival against impact of a very heavy l at the aircraft maximum speed may be comforting to the aircrew but the ciated penalties in weight, transparency optics, engine performance, etc. tate acceptance of something less. Figures 2 and 3 are illustrative of the ects of a birdstrike exceeding the designed level of protection. Decision ers need a means of quantifying risks associated with acceptance of reduced dstrike resistance levels. This information is needed both for design of a aircraft system as well as in evaluating the effects of changing mission files, or of changing operating locations for existing aircraft.

As part of an effort to assess the adequacy of windshield system birdstrike tection being incorporated into a new aircraft, an analytical model was developed analyze the potential risk of birdstrike damage. The model has also been ilized to evaluate the change in risk resulting from a change in mission profile d a change in birdstrike resistance level.

The model is based on a premise that the expected number of birdstrikes n be predicted and that damage will result when the kinetic energy from a rdstrike is greater than some critical level. A velocity distribution for the rcraft and a weight distribution for the birds are mathematically combined to tablish a probability distribution for bird impact kinetic energy. By assuming at the ability of any given windshield system to defeat a birdstrike is essentially lated to impact kinetic energy and impact location, the proportion of the wind- ield system which will be damaged can be identified as a function of birdstrike inetic energy level. Mathematically combining the kinetic energy probability istribution with the critical strength level distribution yields the probability f damage due to a single birdstrike. The expected number of damaging birdstrikes an then be determined by combining the expected number of strikes with the prob- bility of damage.

A reasonable correlation was obtained by comparing predicted damaging strikes ith historically recorded damaging strikes on two different high speed aircraft. igure 4 presents the results of one such comparison. Sensitivity of the model o variations of the input parameters has also been evaluated. Results reveal hat the model is sufficiently sensitive to take into account specific variations such as those due to mission characteristics and geographically related bird population characteristics. This sensitivity, however, necessitates caution in acceptance of results for they can be biased towards preconceived or erroneous conclusions.

This model was initially developed by Dr J. Halpin, USAF. Additional development and evaluation was by Dr A. Berens, University of Dayton Research Institute. The model and its applications are further described in References 1, 2, and 3.

Computer Aided Procedures for Structural Analysis

Empirically derived birdstrike resistant systems continue to be the general rule in system development. Lack of analytical procedures to predict birdstrike resistance of alternate designs has resulted in systems of less than optimum strength, weight and performance properties. Turn around time and cost to design, build and evaluate a modified configuration impose such penalties that desired performance is frequently sacrificed for program expediency.

Finite element computer programs developed for linear or nonlinear analysis of complex three dimensional structures are being developed and evaluated for application to the windshield and engine birdstrike problem areas.

Windshields - The program being developed for windshield birdstrike structural analysis is called MAGNA (Material and Geometric Nonlinear Analysis). The program includes preprocessors, nonlinear analysis packages, user-written incremental loading subroutines and post processors including shape plotting and stress and strain contour mapping. Figure 5 illustrates some of the MAGNA features.

Initial results show strong promise for MAGNA use in predicting test results at various conditions once the results are known for one condition, and for predicting test results for modifications to the baseline design. The degree to which the modified design can depart from the baseline tested design, and still yield reasonable predictions, is being evaluated. Figure 6 illustrates a finite element model of a monolithic F-16 canopy. Figure 7 illustrates comparison of predicted and actual deflections on an early monolithic polycarbonate canopy.

The utility of MAGNA in developing an initial design is being evaluated. The program was recently used to compare the stress levels and deflection characteristics of two different thicknesses for an acrylic monolithic canopy for the F-16. Units are being built to birdstrike test for correlation with predicted performance.

The MAGNA computer program and its application to the transparencies problem area is further described in References 4, 5, 22, 25 and 26.

Engines - The finite element computer aided procedure being developed for engine application is called NOSAPM (Nonlinear Structural Analysis Program Modified). The ultimate goal of the program is to develop analytical and test procedures and design criteria needed to establish impact damage tolerant fan/compressor blade designs for future aircraft turbine engine application. Figure 8 illustrates the overall approach which involves a blade transient response model interacting with a foreign object loading model to establish, as a function of time, blade deflection (tangential, axial and spanwise) and velocity resulting from a bird, ice or stone impact. Knowing the blade's shape, material properties, and velocity

the foreign object geometry, density, velocity angle of impact, etc., the
:sures at the various modes of the finite element blade model can be predicted.
resulting blade stress and strains are calculated using the blade transient
)onse model and compared with blade material response model to establish the
ige level, during discrete time steps of the impact event.

The blade structural response and bird loading models have been success-
ly run in the interactive mode. Figure 9 shows close agreement between analytical
dictions and initial calibration test results for the blade of a J79 engine
acted at 70 percent span by a 2 ounce bird. The figure shows blade tangential
placement versus blade span at approximately 1000 micro seconds after the
tial bird impact. In the near future the ability of the interactive structural
ponse/loading model computer program will be examined for predicting the response
composite and monolithic blade constructions impacted by small and large birds,
: slabs and ice balls. If successful, the final step will be to derive and
.idate foreign object impact design criteria for current and future fan/com-
ession blades for aircraft turbine engine applications. It is anticipated that
: validity of this approach for design/test of damage tolerant blades will be
npleted in approximately one year.

References 32 and 33 present additional information on development of this
sign/test approach.

gh Temperature Transparencies

Development programs for high performance aircraft have emphasized the need
r closing the design options technology gap between the capabilities of aircraft
ansparency systems and the performance requirements of the aircraft. Current
ghtweight, large field-of-view, bird impact resistant transparency systems
ing acrylic and polycarbonate transparent materials are temperature limited
) below about 300 degrees Farenheit, which typically corresponds to a flight
ach number below 2.5. Transparency systems which utilize glass to provide
igh temperature capabilities are relatively heavy, have a limited field-of-
iew and can have poor resistance to bird impact.

A program is being conducted to develop design criteria and analysis methods
o permit optimum use of existing materials in maximizing the thermal performance
apabilities of lightweight, birdstrike resistant, large field-of-view trans-
arency systems, Figure 10. Improved design criteria and analysis methods will
optimize the capability of, and reduce the weight and cost penalties associated
vith transparency systems for aircraft operating at speeds up to Mach 3.0.
The shapes and configurations of the transparencies studied in this program
vill not be restricted to any particular type and the program includes: detailed
theoretical and design analyses, development of methodology for prediction of
thermal gradients, design tradeoff studies, and the fabrication and testing of
representative transparencies. Additional information on this program can be
obtained from Reference 8.

Birdstrike Resistant Transparency Testing

Aircraft transparency system field performance continues to be indicative
of less than adequate test and evaluation prior to operational usage. Several
efforts are underway to obtain more meaningful test results at reduced overall
costs. The general approach is to develop screening tests or procedures which
have the ability to predict subsystem or system performance prior to actual
fabrication of that subsystem or system.

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Efforts underway include: development of a standardized test for evaluating the energy absorption characteristics of polycarbonate; examination of various combinations of environmental exposures to determine their long term structural degradation effects on polycarbonate energy absorption characteristics; development of more reliable bird impact testing and data reduction techniques; and evaluation of current full-scale system testing to identify potential areas for modification(s) which would contribute to insuring satisfactory long term system performance.

The impact resistance of a polycarbonate transparency is influenced by many factors during its design, fabrication, and utilization. These factors include such items as processing temperature, thickness, surface finish, adjacent materials, and environmental exposure. Evaluation of the effect which these factors have on eventual system performance requires a reliable test method. Current test methods were examined and a falling weight type test procedure was selected, Figure 11, which offers a good compromise of sensitivity, versatility and economics. The resulting test technique is being reviewed for American Society for Testing and Materials (ASTM) adoption. This test technique is further described in References 9 and 10.

The ability to use a coated polycarbonate transparency offers obvious potential advantages over a laminated acrylic-polycarbonate transparency. Reduced design complexity, reduced fabrication cost and improved optical quality are but three examples. Prior service life experience with coated polycarbonates has not been very favorable and laboratory ability to predict eventual system durability has proven less than adequate. Results from a series of tests using the impact test method described above are being evaluated to determine the change in impact resistance of coated and uncoated polycarbonate specimens. The specimens have been subjected to various combinations of accelerated environmental exposure conditions which are believed representative of actual field service. Additional information on this testing can be obtained from Reference 11.

Current computer programs used to predict and evaluate system performance and to optimize system design require accurate experimental data for input and for verification of predictions, Reference 22. Evaluation of bird impact testing to establish characteristics of the impact force-time pulse for computer usage revealed the importance of bird attitude at impact, References 12 and 27. A gelatin bird is being evaluated for its impact comparability with a real bird in an attempt to further reduce testing variability, Reference 82.

The ability of the MAGNA Computer Program to generate predicted deflection maps during the impact event necessitates availability of a technique for accurately and economically recording actual deflections. State-of-the-art deflection measurement procedures were yielding unacceptable results due to the low level of confidence in measured values. A semi-automatic procedure utilizing a Moire Fringe type interference pattern was evaluated and adopted. This technique is illustrated in Figure 12 and is further described in References 13 and 29.

As one step in assessing the overall adequacy of transparency system testing to reasonably foretell eventual long term system performance, a test facility survey has been conducted. The survey addressed types of facilities and capabilities presently available, types of testing currently being conducted and identification of recognized voids in capabilities and facilities for testing of current and advanced systems. The results of this survey (including number of ilities participating) are categorized into seven areas: Environmental), Birdstrike (10), High Velocity Impact (7), Mechanical Tests (15), sical Properties (17), Optical Properties (12) and Laser/Nuclear Effects). Reference 14 contains the results of this survey.

Subsequent to completing the test facility survey, an effort was initiated assess and improve realism of current testing methods, procedures and prac- :es for use in laboratory prediction of in-service durability. Design require- ıts, laboratory testing and field experience data for the F-15, F-16, and F-111 ansparency systems will be compared for adequacy of testing methodology and aluation criteria. The results will be used for guidance in developing proved methodology and criteria for use in the design, development and pre- oduction testing of transparency systems.

ansparency Optical Quality Enhancement

Inherent in the effort to provide transparency systems of improved dura- .lity and structural capability has been the necessity to improve optical ıality. There is little benefit in designing a transparency that will defeat flight hazard if in the process the optical quality of the design is such ıat the aircrew has difficulty effectively performing their visual tasks. ikewise, it makes little economical sense to arbitrarily establish optical riteria that are not relatable to the aircrew visual tasks. Reference 7 resents the results of acquiring and evaluating aircrew reaction to optical uality of an early version of the F-111 bird impact resistant windshield system.

Efforts to improve optical quality have therefore focused on relating design variables to their effects on aircrew visual task performance, Figure 13. Design variables being investigated include distortion, deviation, binocular vision, rainbowing, haze, multiple images and reflection. The principal aircrew visual tasks being used in evaluating these variables are those related to acquisition and identification of targets (refueling aircraft, runway lights, enemy aircraft, ground target, etc.). Once the relationships are understood it becomes a straight- forward task of setting reasonable limits that are relatable to the aircrew member task. With such information the decision maker will have the ability to assess the cost versus benefit aspects of meeting, exceeding or waiving selected requirements. Developing these relationships includes being able to describe and measure the variable in terms that can be used in establishing a specifica- tion or standard or in performing an economical laboratory evaluation. This overall approach to development of improved optical criteria is typified in References 15, 16, 17, 30, and 35.

Obviously one could not stop development of more structurally durable transparencies while the improved techniques for setting optical standards were being developed. Arbitrary standards were thus used to obtain reasonable optical quality consistant with industry capability. These transparencies, now in field service, may or may not be adversely effecting aircrew task performance. Field portable equipment is being developed to evaluate these installed transparencies in relationship to the current understanding of desired optical quality. Long awaited quantitative criteria upon which to base a decision concerning removal of a transparency from service may now become practical. This field portable equipment is further described in References 18 and 30.

TECHNOLOGY APPLICATION

Technology application activities are focused on utilizing the above-mentioned transparency technology development and demonstration activities to improve the birdstrike protection and durability of current operational systems including the F-111, F-16, and T-38. To facilitate use of transparency system technology, application activities also include development of a handbook-type document.

F-111 Transparency System

The F-111 transparency system, Figure 14, resistance against a four pound birdstrike has been increased from a nominal 150 knots to a nominal 500 knots. System weight penalty associated with the laminated plastic transparency system has decreased with various design modifications until it is presently only about 12 pounds over the weight of the original all-glass system. The system is presently being installed in the aircraft fleet. At least ten aircraft saves from otherwise catastrophic birdstrikes are credited to use of this new transparency system. Efforts involved in development of this transparency system are further described in References 20, 21, 31 and 34.

Current F-111 transparency system related activities include evaluation of system life cycle characteristics for information of benefit to other laminated plastic transparency programs and examination of design modifications for reduction of system weight and cost.

F-16 Transparency System

The F-16 transparency system, Figure 15 is of an abrasion resistant coated monolithic polycarbonate construction. Operational experience with prior attempts to utilize coated polycarbonate forward facing transparencies has resulted in coating degradation prior to an "acceptable" service life. As a backup to the coated canopy, in event similar problems were encountered, three versions of a 350 knot four pound birdstrike resistant laminated plastic canopy were developed. An unplanned benefit of one of the alternate canopy designs is a potential weight savings of about 25 pounds over the current monolithic design.

Based on a recent life cycle cost assessment, production contracts were awarded for two of the three laminated designs to be installed on production aircraft beginning late 1981.

T-38 Transparency System

An alternate transparency system is also being developed for the T-38 aircraft, Figure 16. The transparencies will provide an increase in the four pound birdstrike protection level to 400 knots. This is an increase from a nominal capability of 250 knots for the windshield and 150 knots for the forward canopy. The present system utilizes through-the-canopy ejection as a backup emergency escape procedure. This feature, or a suitable alternative, will be retained while increasing the canopy birdstrike protection level.

Present T-38 transparency system related activities involve development ıd evaluation of candidate designs capable of providing the required increase ı birdstrike protection while retaining the backup crew escape capability. ctivities to date are described in References 23 and 24.

ransparency Design Guide

In the various efforts to develop and utilize technology in improving trans-arency system performance it became apparent that the existing data base is so idely dispersed that one occasionally redevelops data or makes assumptions, sometimes erroneous, in lieu of using available data. An effort to consolidate ransparency system design and performance technology, Figure 17, into an easily ısable design guide format has recently been completed. This handbook-type locument, Reference 6, was developed to provide a single source for design require-nents, performance data, and systems design recommendations. This guide can be ısed by engineering and management personnel to gain cognizance of the many facets of transparency system design. In this design guide, available transparency technology is consolidated and presented in a format which provides for easy iden-tification of existing data and technology voids. Technology voids were identified in such areas as material sensitivity to environmental conditions, appropriateness of current optical quality requirements, and definition of a statistically accept-able bird impact threat. The document is organized into the following chapters: Management of Transparencies and Related Subsystems Design; Transparency/Aircraft Configuration Relationship; Vision and Optical Design; Structural Design and Analysis; Bird Impact; Materials; Environmental Design; Combat Exposure Design; Maintainability; Reliability; and Transparency Design Verification and Quality Assurance Requirements. This compendium of design and test guidelines is further described in Reference 19.

CONCLUSION

Structural enhancement utilizing advanced technology to reduce dependence on empirical system development is an effective way to provide more system per unit of program cost and duration. In addition to its applicability to new systems, this technology also makes it practical to upgrade the structural dura-bility of some current systems thus improving their flight safety and/or cost-of-ownership characteristics, and doing so with little, if any, penalty.

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FIGURES

FIGURE 3.

FIGURE 3. PROPULSION SYSTEM BIRDSTRIKE

FIGURE 5.

BIRDSTRIKE RISK PREDICTION
MODEL ASSESSMENT

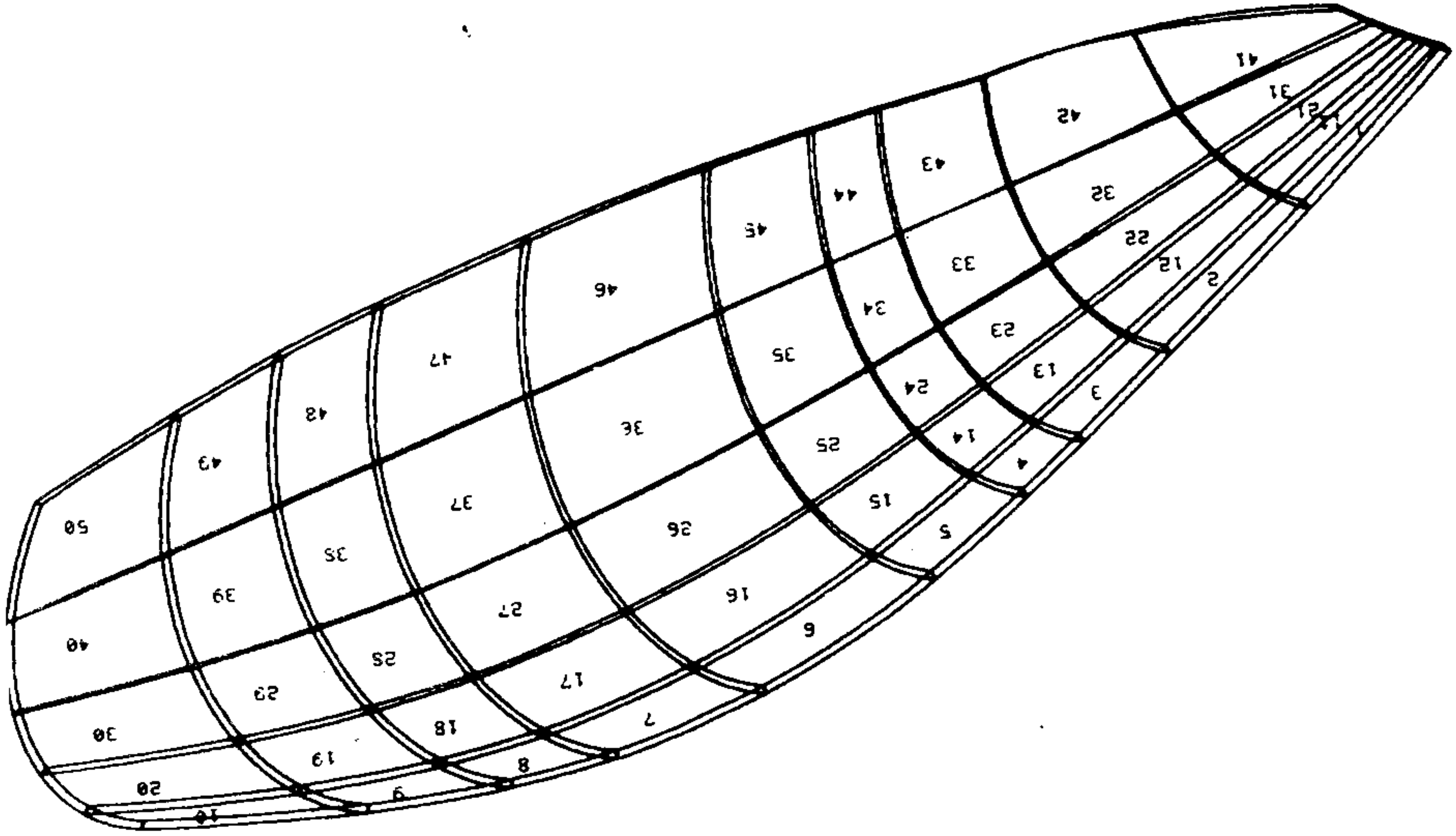
	CANOPY	WINDSHIELD
FLIGHT RECORDS (1968-1978)		
BIRDSTRIKES RECORDED	17	29
SYSTEM 'FAILURES'	6-8	1-2
PROBABILITY OF FAILURE	.35-.47	.035-.068
USE OF PROBABILISTIC PREDICTION MODEL		
PREDICTED PROBABILITY OF FAILURE	.31	.047

MAGNA ANALYSIS CAPABILITY

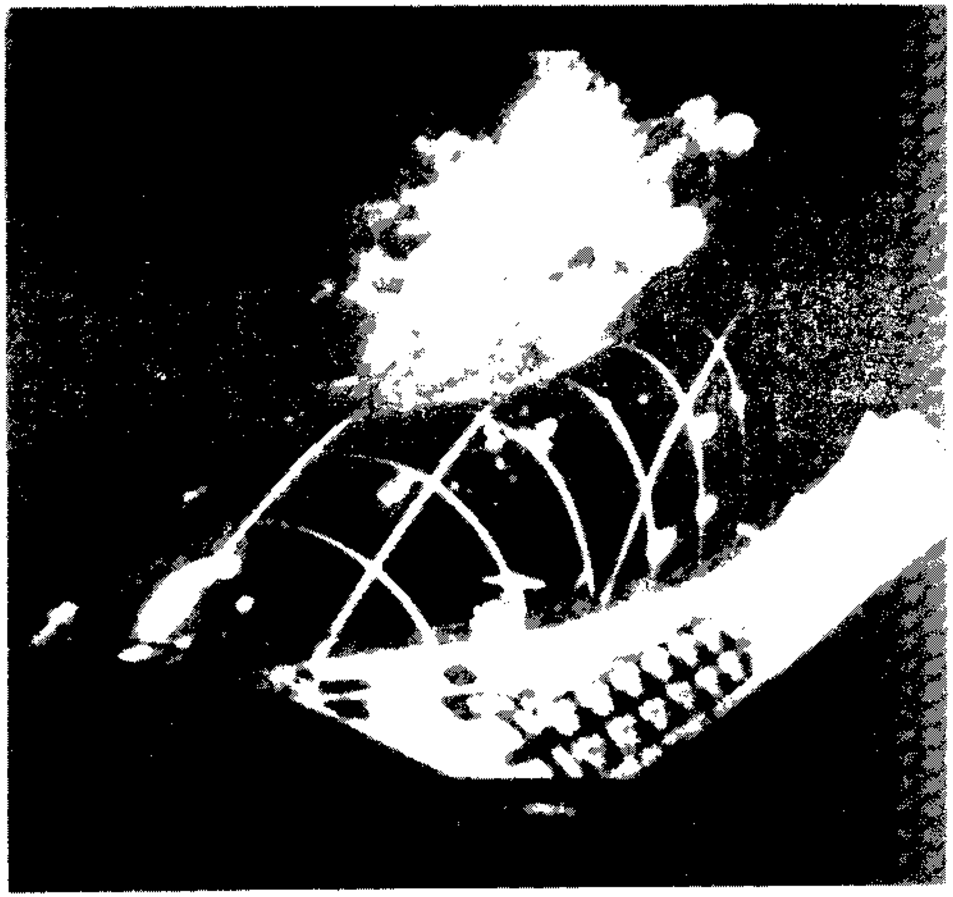
- STRUCTURE TYPES
  - TRUSS
  - MEMBRANE (PLANE STRESS)
  - PLANE STRAIN
  - "SHEAR PANELS"
  - GENERAL SOLIDS
  - THIN PLATES, SHELLS
  - SANDWICH AND LAYERED STRUCTURES
- MODELLING
  - ALL ELEMENTS ARBITRARILY ORIENTED
  - ALL ELEMENT TYPES <u>FULLY</u> <u>COMPATIBLE</u>
  - SKEWED BOUNDARIES
  - RIGID LINKS
  - GENERAL CONSTRAINTS
- STRUCTURAL RESPONSE
  - LINEAR OR NONLINEAR ANALYSIS
  - STATIC OR DYNAMIC RESPONSE
  - ARBITRARY LOADING (TIME-DEPENDENT, NON-PROPORTIONAL)
  - STRUCTURAL DAMPING
  - UNIFORM MASS DAMPING
  - MULTIPLE LOAD CASES
- NONLINEAR CAPABILITIES
  - FULL GEOMETRICAL NONLINEARITIES (LARGE DISPLACEMENTS, STRAINS)
  - ARBITRARILY LARGE ROTATIONS IN THIN SHELL ANALYSIS
  - ELASTIC-PLASTIC BEHAVIOR
  - ISOTROPIC, KINEMATIC, AND COMBINED STRAIN-HARDENING MODELS
- SOLUTION METHODS
  - LAGRANGIAN REFERENCE FRAME
  - AUTOMATIC CORRECTIONS IN NONLINEAR SOLUTIONS
  - IMPLICIT TIME INTEGRATION
- USER CONTROLS
  - FREQUENCY OF STIFFNESS REFORMULATION
  - TIME INTEGRATION PARAMETERS
  - TIME STEP CHANGES
  - ELEMENT INTEGRATION ORDER
- USER SUBROUTINE INTERFACES
  - MESH GENERATION
  - COORDINATE SYSTEM DEFINITION
  - INCREMENTAL LOADING
- CONVENIENCE FEATURES
  - INCREMENTAL NODE GENERATION
  - INCREMENTAL ELEMENT GENERATION
  - BOUNDARY CONDITION GENERATOR
  - GEOMETRY PLOTTING (DEFORMED AND ORIGINAL SHAPES)
  - STRESS PLOTTING (CONTOURS, RELIEF)
- PROGRAM CAPACITY
  - LARGE PROBLEMS - OUT-OF-CORE ELEMENT STORAGE, ASSEMBLY, and SOLUTION
  - CAPACITY DEFINED AT RUN TIME
  - DYNAMIC CORE ALLOCATION
  - STORAGE CONTROLLED INTERNALLY FOR USER CONVENIENCE
  - ORIENTED TOWARD LARGE, THREE-DIMENSIONAL PROBLEMS
- DEVELOPMENT AREAS
  - FREQUENCY AND MODE SOLUTIONS
  - ADAPTIVE SOLUTION METHODS
  - EXPLICIT TIME INTEGRATION
  - FULL RESTART CAPABILITY
  - POSTBUCKLING ANALYSIS

FIGURE 5.

COUPLED LOADS, 5.4 MS



BIRDSTRIKE COMPUTER SIMULATION
FOUR POUND BIRD AT 350 KNOTS



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COUPLED LOADS, 5.4 MS

FIGURE 6. F-16 CANOPY FINITE ELEMENT

BLADE TRANSIENT RESPONSE MODEL AND FOREIGN OBJECT LOADING MODEL INTERACTION

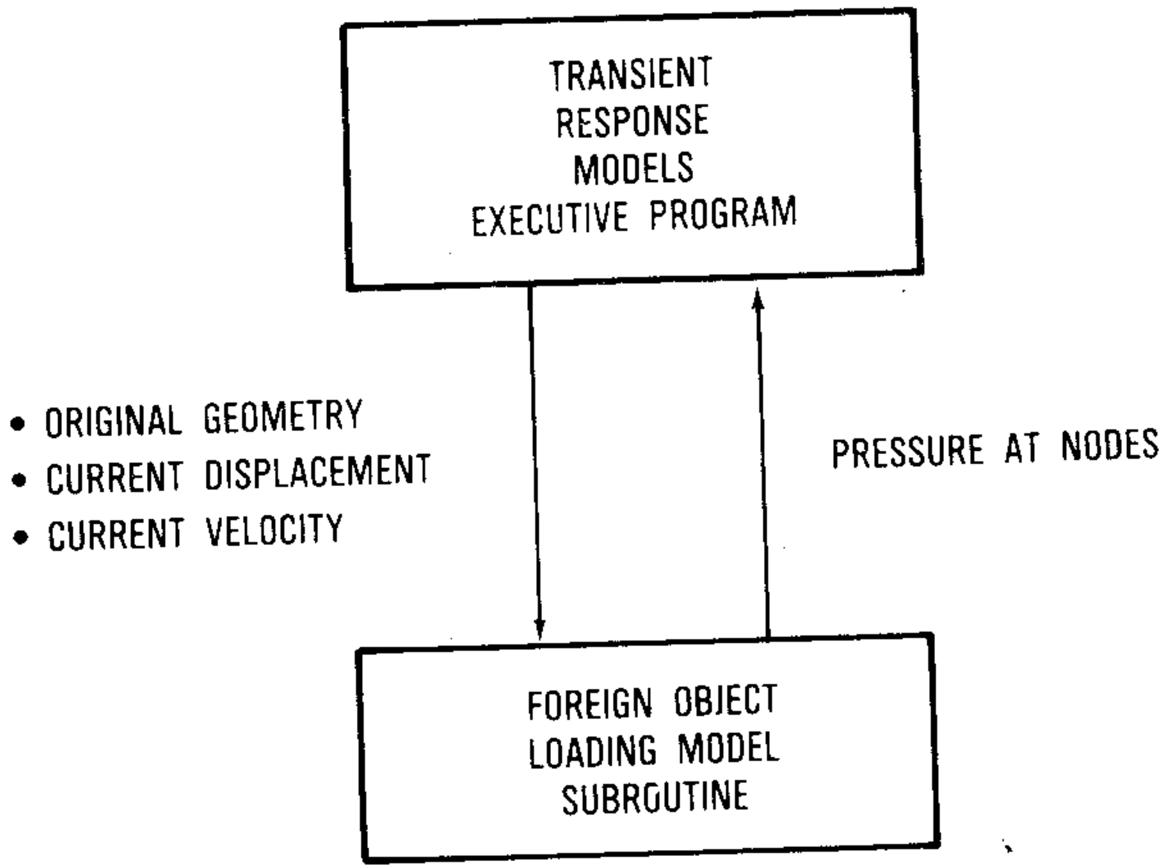


FIGURE 8.

COMPARISON OF PREDICTED AND MEASURED BLADE DISPLACEMENT

J-79 ENGINE BLADE ROTATING
AT 8200 RPM IMPACTED AT
70% SPAN BY 2 OZ. BIRD

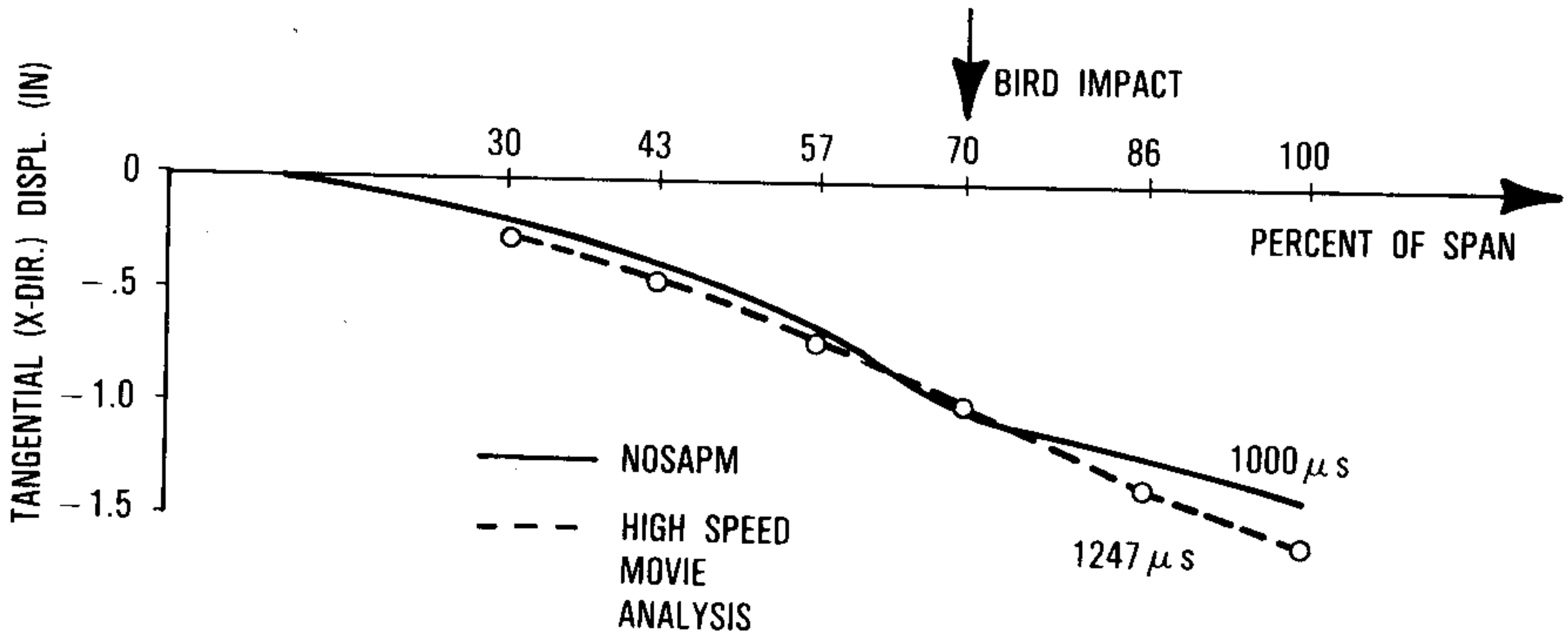


FIGURE 9.

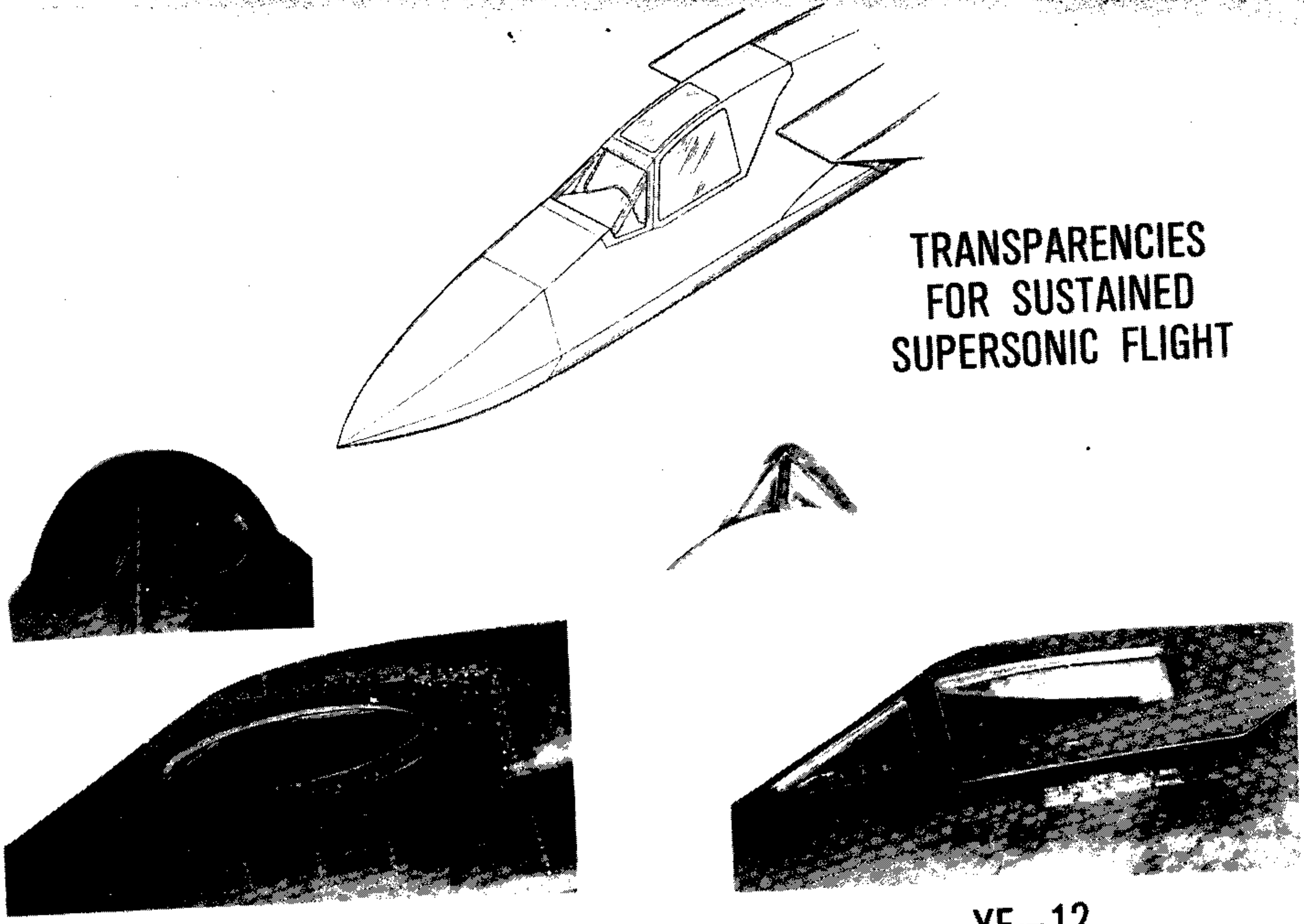


FIGURE 10.

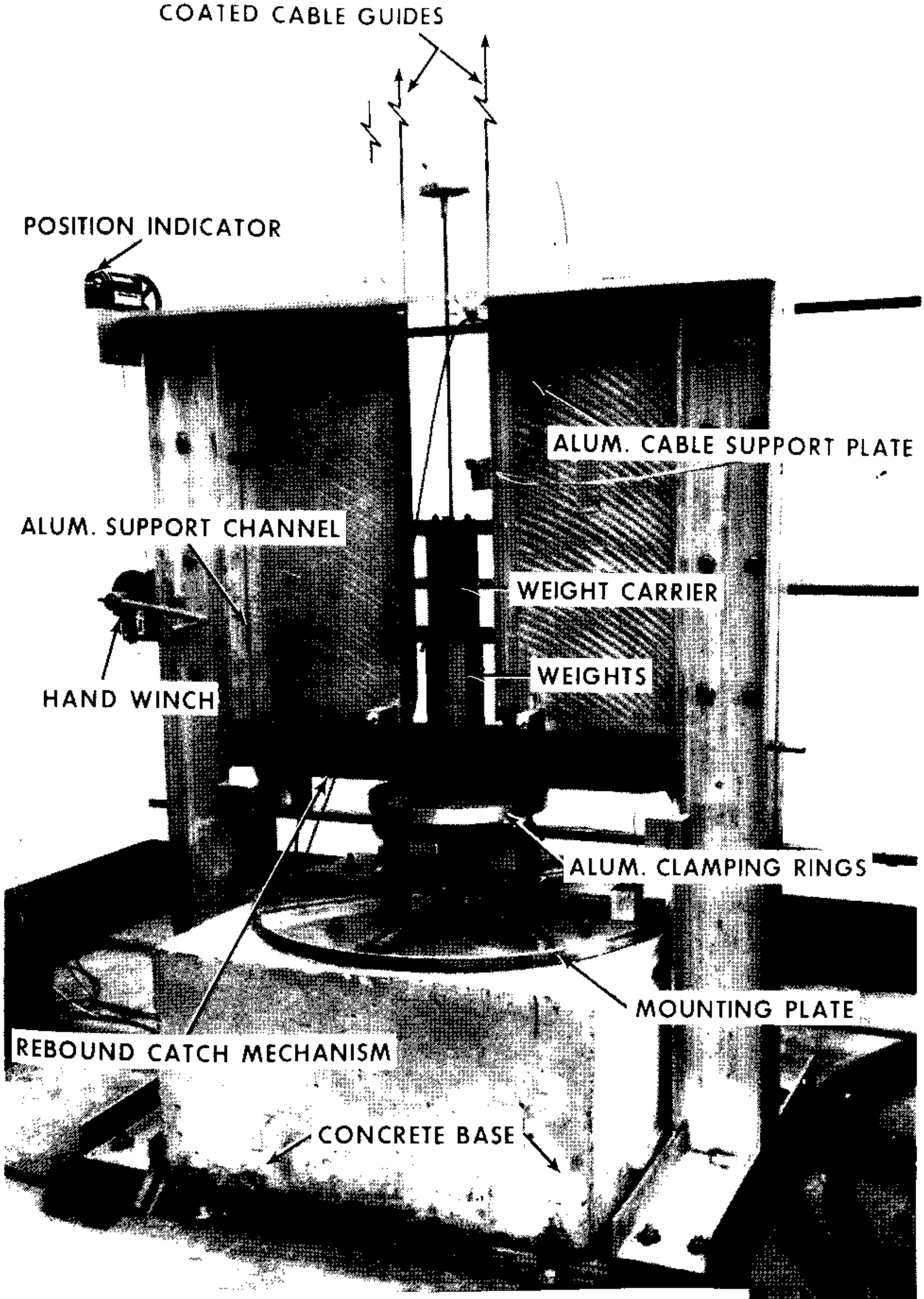
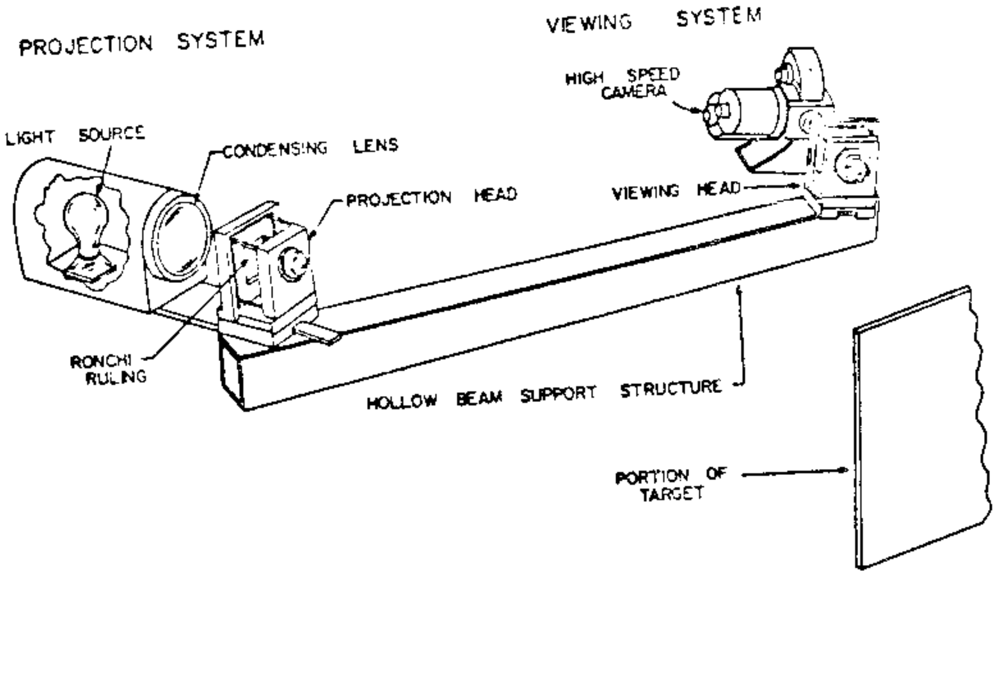
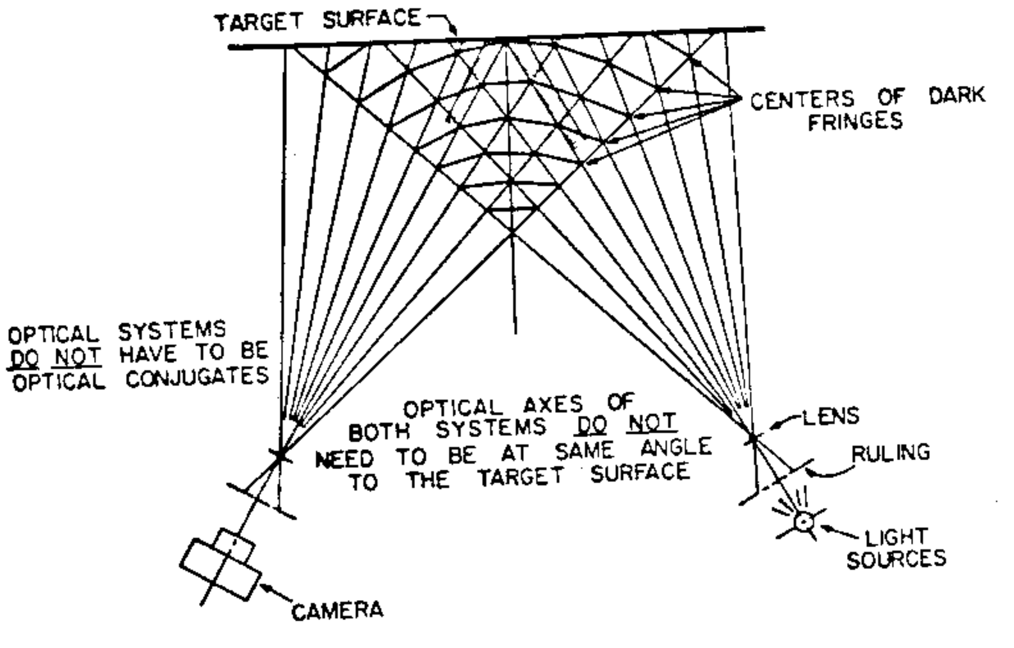
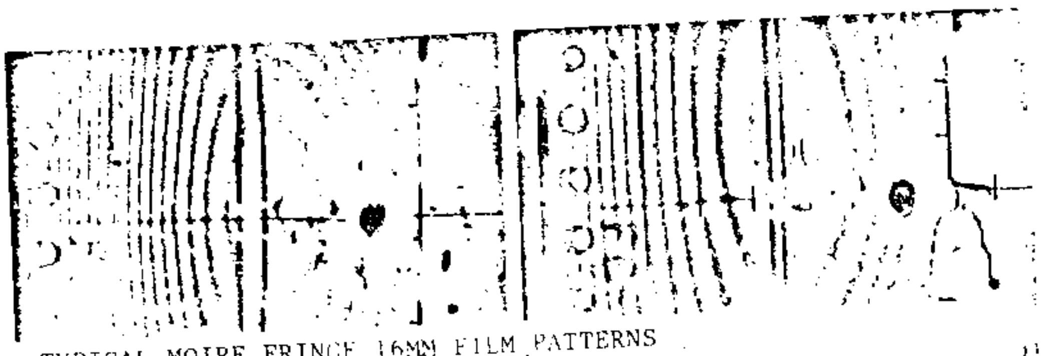


FIGURE 11. FALLING WEIGHT IMPACT TESTER







TYPICAL MOIRE FRINGE 16MM FILM PATTERNS

FIGURE 12. MOIRE FRINGE DEFLECTION MAPPING SYSTEM

VISUAL EFFECTS OF WINDSCREENS (VIEW) PROGRAM

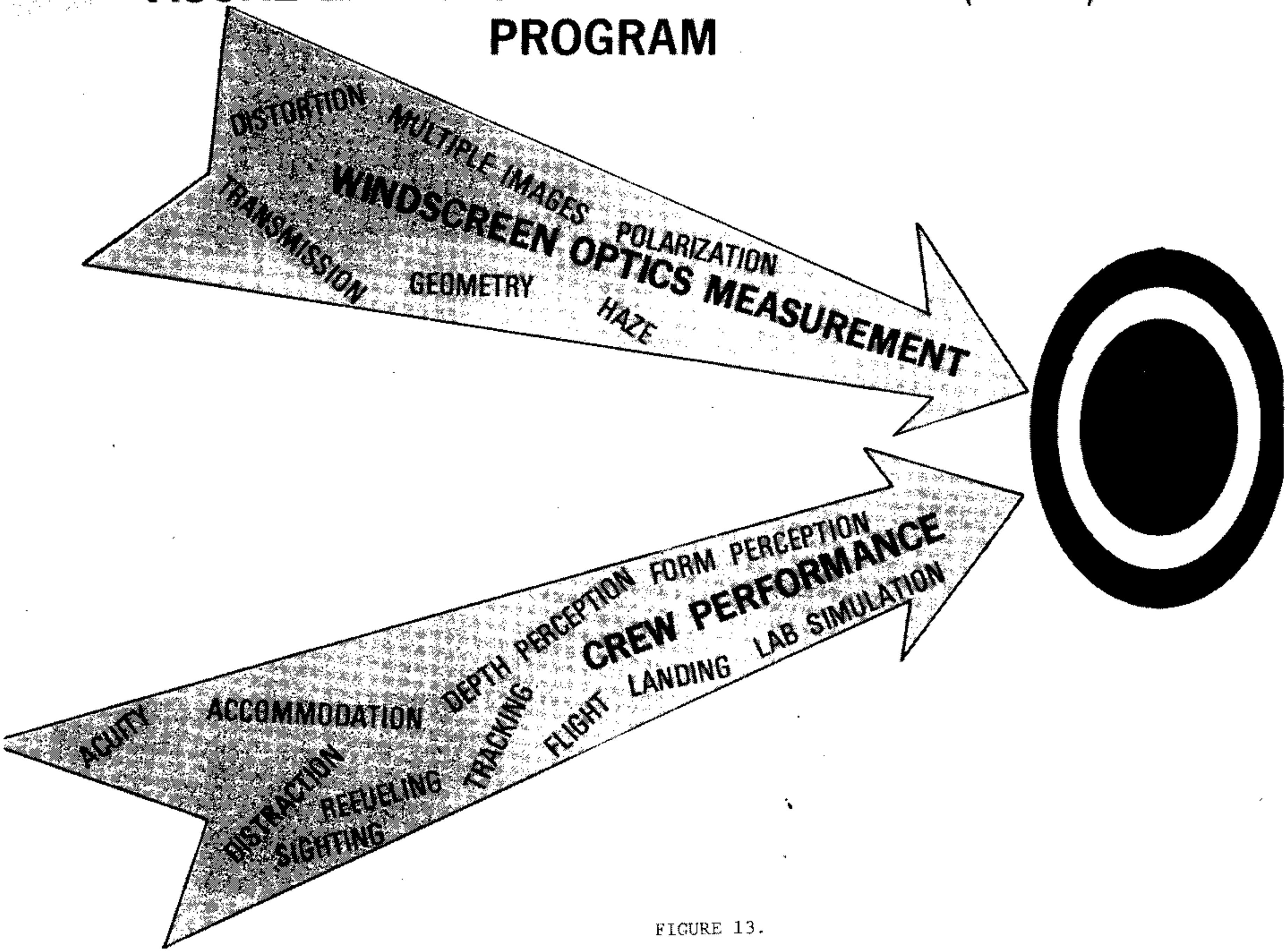
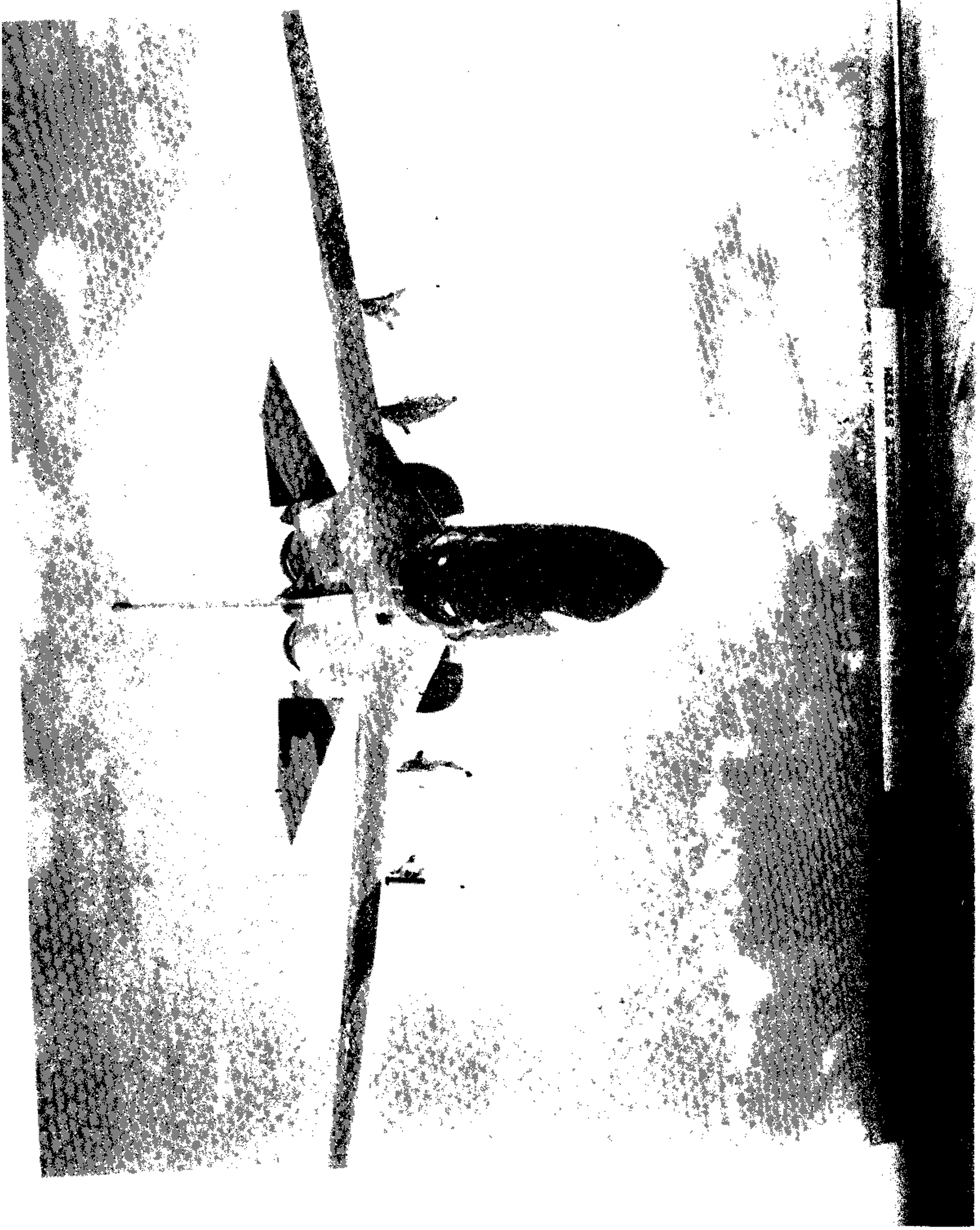


FIGURE 13.



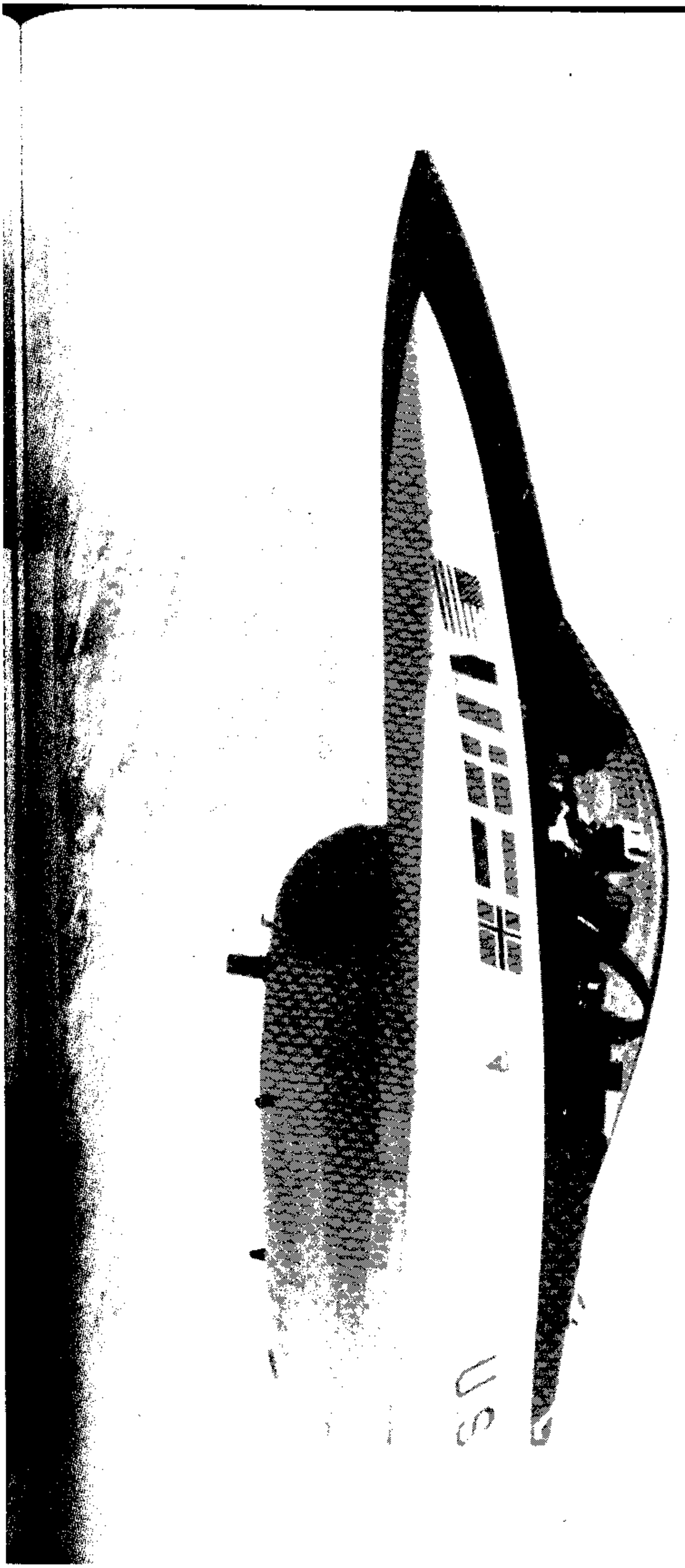

US

FIGURE 17. TRANSPAREN...

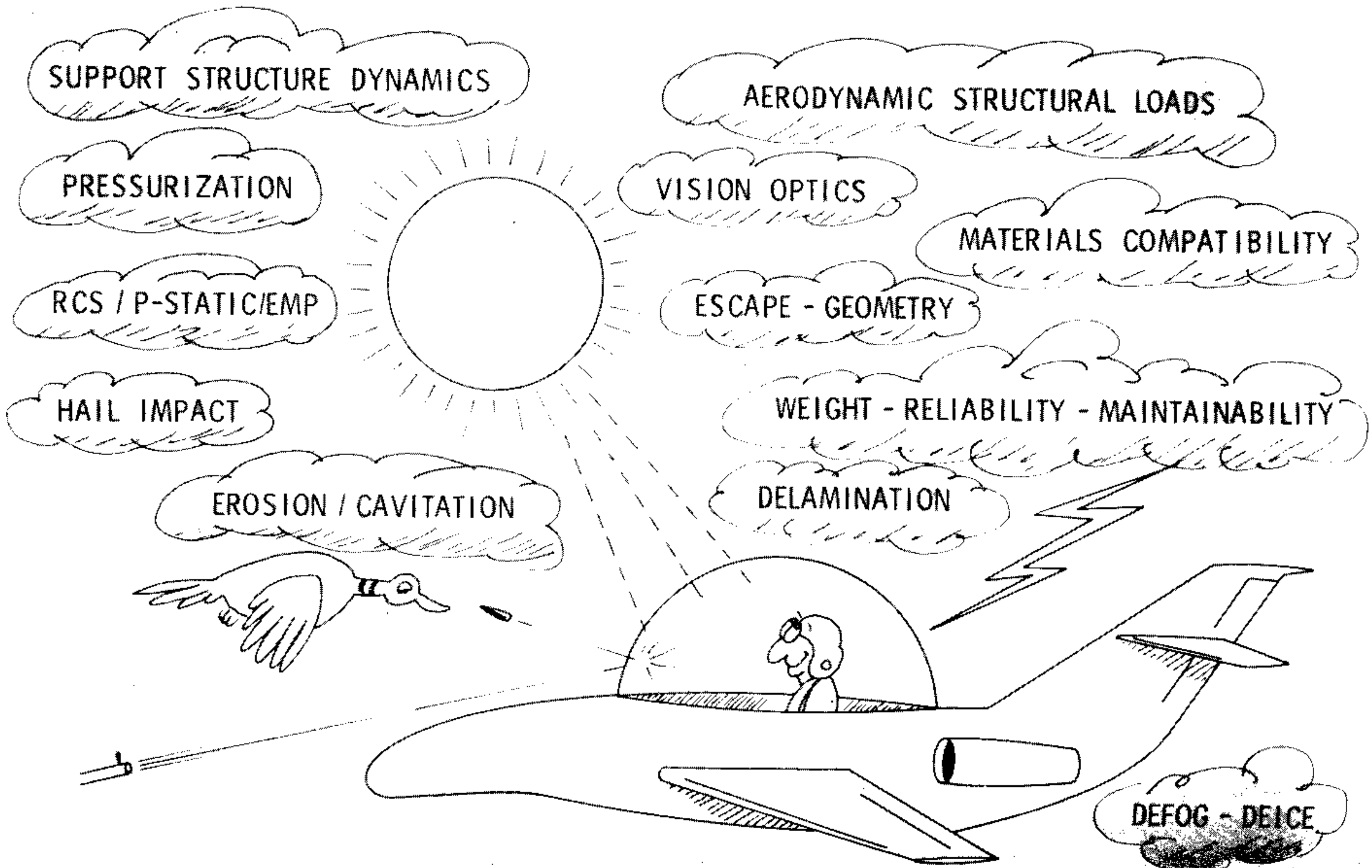


FIGURE 17. TRANSPARENCY DESIGN