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PART 1
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DYNAMIC SYSTEM STUDIES: CONCLUSIONS AND RECOMMENDATIONS

ADVISORY BOARD ON SIMULATION

UNIVERSITY OF CHICAGO

SEPTEMBER 1956

AERONAUTICAL RESEARCH LABORATORY
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PROJECT 7060

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

The Advisory Board on Simulation has concluded a three-year research program in air weapon system dynamics sponsored by Wright Air Development Center, with P. W. Nosker/WCRR as project engineer. This volume is one of the following 16 comprising the final report, WADC TR 54-250, entitled Dynamic System Studies:

Part No.	Subtitle	Editing Agency
1	Conclusions and Recommendations	University of Chicago
2	The Design of a Facility	University of Chicago
3	The Mission of a Facility **(Confidential)**	" " "
4	Technical Staff Requirements	" " "
5	Analog Computation	Naval Ordnance Lab.
6	Operation & Maintenance Procedures for Analog Computers	University of Chicago
7	Digital Computers	" " "
8	Recorders	" " "
9	Flight Tables (Confidential)	" " "
10	Performance Requirements for Flight Tables	Mass.Inst. of Tech
11	Load Simulators (Confidential)	Cook Research Lab.
12	Guidance Simulation **(Secret)**	Naval Ordnance Lab.
13	Error Studies	University of Chicago
14	Error Analysis for Differential Analyzers (written by F. J. Murray, Columbia U., and K. S. Miller, N.Y.U.)	" " "
15	Air Vehicle Characteristics (Secret)	" " "
16	Aerodynamic Studies (written by M.Z.Krzywoblocki, U. of Ill.)	" " "

All reports may be obtained through the project engineer.

This report represents the culmination of the assignment to determine the proper mission, equipmentation, operating procedures, and personnel for an engineering facility in the field of air weapon systems dynamics. The subdivisions of the report correspond to these four basic objectives and the subsidiary work in their support, and reflect the role of simulation as a dominant technique. The functions of each part and the relations among them are indicated in the technical summary, Part 2.

The following organizations have participated directly in the program:

Organization	Contract No.	Time of Performance
University of Chicago	AF33(038)-15068 Supplements 2 and 11	1 Feb. '51-31 Aug. '54
J. B. Rea Company	AF33(038)-15068 Subcontract 2	1 Feb. '51-31 Oct. '52
Cook Research Laboratories	AF33(038)-15068 Subcontracts 3 and 9	1 Feb. '51-31 May '54
RCA Laboratories	AF33(038)-15068 Subcontract 4	1 Feb. '51-1 Mar. '53
Armour Res. Foundation of Ill.Inst. of Technology	AF33(038)-15068 Subcontract 5	1 Feb. '52-30 Nov. '52
Northwestern University Aerial Meas. Lab.	AF33(038)-15068 Subcontract 8	17 July '52-22 Aug. '52
Mass. Inst. of Technology, Flight Control Lab.	AF33(038)-15068 Purchase Order A2086	20 Apr. '54-31 Aug. '54
Mass. Inst. of Technology, Dynamic Analysis & Control Laboratory	AF33(038)-15068 Purchase Order A23883	22 July '53-30 Nov. '53
Mass. Inst. of Technology, D.A.C.L.	AF33(616)-2263 Task Statement 2	1 Dec. '53-30 Sept. '54
Nat. Bur. of Standards Corona, which became	AF33(038)-51-4345-E	25 Feb. '51-Sept. '53
Naval Ordnance Lab., Corona	MIPR(33-616)54-154	20 Nov. '53-31 Dec. '55

This is a record of formal participation only; the program was aided immeasurably by the splendid cooperation of all governmental, industrial and educational organizations (particularly the simulation laboratories) contacted. Although it is impractical to mention them all here, the extent of their assistance is evident throughout the reports and is hereby gratefully acknowledged. Details of these affiliations, including statements of work, may be found throughout the 21 Bimonthly Progress Reports issued by the University of Chicago during the course of the work. (All formal participation in the program is recorded above;

missing supplement and subcontract numbers do not pertain to this project.)

The University of Chicago was assigned prime responsibility for integration of the program. This has been effected by a full time staff at the University, andby aperiodicmeetings of the following advisory committee, selected by the Air Force;

Dean Walter Bartky, Chairman	University of Chicago	1 Feb. '51-31 Aug. '54
Prof. C. S. Draper	Mass.Inst. of Tech.	1 Feb. '51-28 Feb. '53
Mr. Donald McDonald	Cook Research Lab.	1 Feb. '51-31 Aug. '54
Prof. F. J. Murray	Columbia University	1 Apr. '52-31 Aug. '54
Dr. J. B. Rea	J. B. Rea Company	1 Feb. '51-28 Feb. '53
Prof. R. C. Seamans, Jr.	Mass.Inst. of Tech.	1 Sept. '53-31 Aug. '54
Mr. R. J. Shank	Hughes Aircraft Co.	1 July '51-31 Aug. '54
Dr. H. K. Skramstad	NBS-NOLC	1 Feb. '51-31 Aug. '54
Mr. A. W. Vance	RCA Laboratories	1 Feb. '51-31 Aug. '54
ex officio:		
Mr. P.W. Nosker, Project Eng.	WADC	1 Feb. '51-31 Aug. '54
Dr. B.E. Howard, Secretary	University of Chicago	1 Feb. '51-31 Aug. '54

The meetings have been recorded in the Bimonthly Progress Reports previously mentioned. Except for Dr. Skramstad, who has participated through direct arrangement between NBS-NOLC and WADC, members of the advisory committee who are not connected directly with the University have participated in the program through consulting agreements with the University of Chicago. In addition, similar consulting agreements with the University have provided for the participation of:

Dr. R. R. Bennett	Hughes Aircraft Co.	1 Jan. '52-31 Jan. '54
Mr. J. P. Corbett	Libertyville, Ill. (formerly with the University)	11 May '54-31 Aug. '54
Mr. G. L. Landsman	Motorola, Inc.	1 May '54-31 Aug. '54
Dr. Thornton Page	Johns Hopkins Univ. (formerly with the University, and Secretary to the Board until 1 Aug. '51)	7 Aug. '51-1 Mar. '53

Prof. M. Z. Krzywoblocki	Univ. of Illinois	15 Jan. '52-31 Aug. '54
Prof. K. S. Miller	New York Univ.	2 Nov. '53-31 Aug. '54
Dr. J. Winson	Riverside, N. Y. (formerly consultant to Project Cyclone)	1 Mar. '53-30 June '54

Many others have contributed significantly to the progress of the work. Among those from other organizations in regular attendance at most of the meetings of the committee have been Mr. Charles F West, Air Force Missile Test Center; Prof. L. L. Rauch, University of Michigan, representing Arnold Engineering Development Center; Col. A. I. Lingard, WADC; and Dr. F. W. Bubb, WADC.

Coordination of the program and administration of the prime contract at the University of Chicago has been under the charge of Dr. Walter Bartky, Dean of the Division of Physical Sciences and Director of the Institute for Air Weapons Research; Dr. B. E. Howard, Assistant to the Director; and Messrs. William R. Allen and William J. Riordan, Group Leaders. The work at the cooperating institutions has been directed by the appropriate member of the advisory committee and his assistants: Dr. H. K. Skramstad and Mr. Gerald L. Landsman at the National Bureau of Standards-Naval Ordnance Laboratory, Corona; Messrs. Donald McDonald and Jay Warshawsky at Cook Research Laboratories; Messrs. A. W. Vance, J. Lehman, and Dr. E. C. Hutter at RCA Laboratories; Dr. J. B. Rea at J. B. Rea Company; Prof. R. C. Seamans at the Flight Control Laboratory and Dr. W. W. Seifert and Mr. H. E. Blanton at the Dynamic Analysis and Control Laboratory, Mass. Inst. of Technology. V. H. Disney, S. Hori, and G. F. Warnke at Armour Research Foundation and J. C. MacAnulty and George Goelz at Northwestern University, Aerial Measurements Lab. have directed the contributory studies at their respective organizations. More explicit credit is found in appropriate places throughout the reports; biographical sketches are in Chapter 3 of this part. Space does not allow full credit that is due to all the workers on the combined project, but special mention is certainly due the project engineer for his conception of the project and for his cooperation during its execution.

Authorship of Part 1 is attributable to the members of the advisory committee, listed on page iii, from whose statements and writings at the formal board meetings the information has been derived. The conclusions and recommendations which follow stem from their composite authority and concurrence, but specific responsibility for the wording and arrangement of this part has been the responsibility of E. R. Spangler, editor for the Advisory Board on Simulation, who has also written the history of the project and compiled the biographies and the bibliography which is herein contained. Special acknowledgement is due Dr. B. E. Howard, as well, for suggestions and assistance in the preparation of the volume.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or the conclusions contained therein. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER:

Aldro Lingard
ALDRO LINGARD
Colonel, USAF
Chief, Aeronautical Research Laboratory
Directorate of Research

TABLE OF CONTENTS

1. CONCLUSIONS AND RECOMMENDATIONS

This volume, Part 1 of the Advisory Board on Simulation's final report, sets forth the fundamental conclusions and recommendations reached or agreed upon by the members of the Board's advisory committee, listed on page iii of the Foreword. These conclusions and recommendations have resulted from the three-year study program centering at the University of Chicago to investigate and evaluate the tools and techniques of dynamic systems engineering, and are here stated in brief to assist in the conception of system dynamics laboratories. Expositions of the technical bases for these recommendations are summarized in Part 2 and given in detail in the other 14 parts of this report.

1.1 Simulation Facilities

It is agreed, first of all, that simulation is an essential tool in the economical design and development of aerial weapons, that a system dynamics laboratory is a valuable tool in the field of aerial weapon research and conserves scientific manpower, and that therefore such a laboratory is a necessity for any organization concerned with air weapon systems.

1.2 Mission

The mission of a system dynamics laboratory is to maintain technical cognizance of air weapons systems dynamics, solving problems in this field as required. A dynamic system consists of an input, a system operator, and an output; the problems involve determining one of these quantities, given the other two. Examples of the technical problems which arise are: (a) determining the stability of the system in rejecting extraneous information, (b) analyzing the ability of the system to respond to a given command, (c) predicting and/or analyzing the trajectory of a vehicle under a given set of initial conditions, (d) determining the values of angles of attack, altitude, and the like for which satisfactory system operation is realized. A facility must be capable of solving the technical problems which arise concerning the dynamic behavior of the weapon systems at any stage in their design, development, and evaluation; it must maintain continuity among the problems; and it must be an authority and a research center in the field.

Manuscript released by the author in October 1954 for publication as a WADC Technical Report.

The mission of a facility should not be conceived in terms of specific technical problems, for new classes of problems are always arising; nor should it be conceived in terms of procedures, for these should be subject to flexibility and modification. Rather the mission should be conceived in terms of an objective and an area of activity, as in the previous paragraph.

1.3 Personnel

Obviously a system dynamics laboratory requires, in broad terms, five distinct classes of specialists: engineers capable of translating tactical requirements into aerial weapons systems requirements and aerial weapons system specifications into component requirements; components experts familiar with the types of components, in order to determine whether given specifications are attainable; aerodynamicists capable of determining the best form of the aerodynamic equations for each air vehicle to simulate the airframe on a computer; mathematicians and statisticians to design simulation runs, determine solution accuracy, and interpret results; and physicists and electronic engineers thoroughly familiar with the specialized equipment of a facility.

This technical staff can be organized effectively into three branches, one to formulate and perform studies in the field of air weapon system dynamics, one to operate, maintain, and design the equipment used in these studies, and one to furnish information and advice on such subjects as component response, aerodynamics, thermodynamics, structures, military requirements, statistical evaluation of data, programming of digital check problems, and the like.

1.4 Equipment

To simulate complex systems adequately requires specialized equipment; since the application of such equipment is confined to simulation, its efficient use necessitates its location on the premises of a laboratory. In addition, however, general purpose equipment is required. Some of this equipment, by virtue of its constant use, should also be located at a facility; but some will be called for only occasionally and thus need not be on the premises.

Although in a simulated system it is convenient to replace the airframe subsystem by an aerodynamic section and a kinematic section, an aerial weapon system consists essentially of but two major subdivisions: the airframe subsystem and the guidance and control subsystem. Between these, a system dynamics laboratory is more interested in guidance and control; as a consequence a laboratory will not in general require wind tunnels or actual flight test facilities, relying rather on airframe behavior data from those organizations with those facilities.

It is recommended, therefore, that the simulation equipment of a laboratory cover the following major categories: (1) a dynamic systems synthesizer, (2) computers, (3) flight tables, (4) load simulators, (5) guidance simulators, (6) pilot simulation equipment, and (7) recorders and similar auxiliary equipment.

1.4.1 Dynamic Systems Synthesizer. A large scale device for solving the full six degrees of freedom problem of the motion of an aerial weapon in real time in essential. Such equipment can be used for the mathematical simulation of aerial weapons or with a flight table and other equipment for physical simulation employing real components. Consequently early in 1951 it was recommended that a dynamic systems synthesizer, sometimes referred to as a general analog flight simulator, be acquired for the purposes of a dynamic systems laboratory.

1.4.2 Analog Computers. A system dynamics laboratory should also possess general purpose analog computers for smaller problems not requiring the full capacity of the dynamic systems synthesizer. Since anticipated work load indicates that the synthesizer can be used constantly on problems requiring its full capacity, other equipment is needed for the smaller problems; applications of such general purpose analog computers are sufficiently extensive to warrant their being located at the site of the facility. This analog equipment should take the form of operational amplifier type computers, but the possibility of using fast time analog computers for simple problems requiring many solutions for a wide range of parameters should not be ignored.

1.4.3 Digital Computers. As a part of normal procedures in checking and operating analog equipment, a system dynamics laboratory needs the services of a digital computer to handle problems requiring high accuracy solutions and to check the operation of the other simulation equipment. For the purposes of such a laboratory, magnetic drum memories appear now to be a good compromise in cost, speed, and size between electrostatic tubes and mercury delay lines on the one hand and magnetic and punched tape and punched cards on the other. Developments in computers using magnetic core memory units should be carefully followed, since magnetic cores appear to be fast and relatively inexpensive, if they can be made operative. Because of the rapid development of digital computers and their use in missile guidance and control systems, the possibility of real time digital simulation cannot be ruled out. Demands placed on digital computers in the course of dynamic systems engineering do not require their presence in the laboratory, if their availability is reasonably assured for the laboratory's needs.

1.4.4 Flight Tables. It is essential that flight tables be available in the laboratory to duplicate the environment of angular attitude sensing elements. These devices can be used in the laboratory for closed loop studies of both control and guidance systems, but not under usual circumstances should they be used for computation; instead computing equipment should be constructed as a permanent part of the tables At the present time hydraulic motors controlled by servo valves provide the best form of gimbal drive in these tables. At least two flight tables are necessary to handle the complete range of problems of the dynamic systems synthesizer, one heavy and powerful, the other swift and light.

Delivery time for a high performance three-axis table probably will range from two to three years, so that long term planning for flight table procurement is necessary. It is desirable, therefore, that procurement of flight tables begin immediately Since it is not feasible to procure tables to handle every situation conceivable, it seems logical to begin by ordering one or two three-axis tables which can handle the broadest possible class of problems.

More than three gimbals in a flight table are not required for a dynamic systems laboratory; the extra gimbal is used too infrequently to merit its extra cost. Moreover, the avoidance of gimbal lock, for which the fourth gimbal is frequently used, can be handled in other ways.

1.4.5 Load Simulators. The control actuators of air weapon systems are tested dynamically with the guidance system by a device which can load the actuator with forces or torques matching the aerodynamics of the airframe and control surfaces. Such a device, called a load simulator, falls into two general classes:

mechanical and servo controlled Passive simulators (mechanical weights and springs) may be used for problems not requiring variable spring constants for loads up to 1500 foot pounds. For all problems involving torques beyond 1500 foot pounds and for problems involving variable spring constants, servo loaders (torque transducers) must be used.

1.4.6 Guidance Simulators. To test the complete guidance system, including the sensing elements, it is necessary to have a device in the laboratory to produce in the sensing elements the same signals as are produced by a target. Because guidance may prove to be a limiting factor in future weapon system performance, it is important that this element be taken into account in system analysis. However, present knowledge is insufficient to enable a description of the guidance in mathematical representation alone. As a result, simulation must to some extent incorporate laboratory reproduction of either sensing or target elements.

At the present time there does not seem to exist any commercially available guidance simulation equipment capable of adaptation to the general purpose specifications of a system dynamics laboratory. It is recommended therefore that guidance simulation equipment be individually designed for the tasks of a laboratory and that provision be made for developing the guidance simulation equipment concurrently with the guidance system itself.

1.4.7 Pilot Simulation Equipment. Although the scope of a system dynamics laboratory must include piloted aircraft, not enough is known presently to enable incorporation of equations based on the transfer characteristics of the human operator into the simulator itself. It is essential, however, that means be available for recognizing in the laboratory that important component which is the pilot in the system. Two approaches offer themselves for the solution of this problem: the literal inclusion of a pilot in a simulated flight environment, similar to the procedure of placing an autopilot on a flight table; and the mathematical representation of the pilot in the simulation process. The former approach presents major difficulties in the achievement of a sufficiently high degree of verisimilitude in the environment, and the latter encounters major difficulties in the complexity and number of inputs needed to simulate a pilot mathematically.

It is recommended that the work in this field of Goodyear Aircraft Corporation and the Franklin Institute be followed closely, with a view toward rapidly procuring adequate equipment and mastering successful techniques for including the pilot in the test loop.

1.4.8 Recorders. Four types of recording will be called for in a system dynamics laboratory. For the first type the facility should possess recorders of the kind produced by Brush Development or Midcentury Instruments; at least two six-channel units and several one- or two-channel units are needed. The second type of recording requires an oscillograph of the kind manufactured by Consolidated Engineering Corporation or Heiland Research Corporation, modified in such a way that impedance adjustments are made in order that voltage ranges from -100 to +100 can be recorded. For the third type such equipment as an Electronics Associates Plotting Board is needed. For the fourth, a proper recorder needs to be developed, probably along the lines of the binary quantizer developed by K. H. Barney.*

1.4.9 Instrumentation. The size and complexity of the dynamic systems synthesizer makes ordinary plug board programming too tedious and too susceptible to error. For use with the simulation equipment, therefore, a laboratory must have data processing equipment which can convert data into machine language, and which can convert data from computers to a form more readily treated by the dynamic systems engineers. There is furthermore a definite need for a method or design for rapid problem setup and convenient problem storage. A facility must also have access to an analog-to-digital output device to convert data into a form suitable for statistical analysis.

1.5 Procedures

Procedures at a system dynamics laboratory must be established and maintained from two operating points of view. They must exist in conformance with the overall long-range working philosophy of the laboratory to attain its single, defining goal. And they must exist to achieve the solution of the day-to-day problems which a laboratory encounters.

From the latter point of view, it is recommended that procedures be determined simultaneously from two points of view, that of the best method of

*See Part 8, Appendix 3.

applying a given piece of equipment to the varying types of problems which come to it and that of the best set of steps in the laboratory for handling a given problem. An example of the first type of procedure is the methodology which must be established in solving a particular problem on a flight table. Outside of the more obvious procedural questions such as the relationship of the specific set of parameters involved to the possible or practicable velocities and accelerations of the table, the likelihood of gimbal lock in the table must be anticipated with respect to the table's handling of this specific problem, and the setup and approach selected such that gimbal lock is circumvented. With respect to the second type of procedure, the arrangement and selection of the procedural steps occurring in a given problem must take into consideration the optimal combination of approximations, solutions, and checks, and must arrive at this combination with a view toward the efficient arrangement of specialists into operating units concerned with individual phases of the work. An example of this class of procedures is the eight-step process for the design and development of an aerial weapon as given in Volume I of the Advisory Board on Simulation's Summary Progress Report.

1.6 Theoretical Studies

In order that a system dynamics laboratory operate in the fullest possible framework of scientific knowledge, it is recommended that the theoretical foundations of the areas of knowledge in which it works be kept under constant scrutiny and the scope of knowledge continually extended and deepened. A laboratory must keep tab on the literature of applicable fields, and undertake special theoretical studies bearing centrally on the facility's work. Specifically these studies must incorporate at least five categories: simulation, automatic computation, air vehicle characteristics, aerodynamics, and error theory.

Principally in the early stages of a laboratory's existence but continuing after the facility has been established, information must be obtained from extensive surveys of (1) the operation of other, related facilities, (2) all forms and applications of computation, and (3) the characteristics of proven and experimental aircraft. Such data is invaluable for establishing realistic boundaries or for recognizing potentialities in a facility's operation, and for anticipating by extrapolation the future demands in performance characteristics and the like that a laboratory must meet.

To determine the behavior of an air vehicle, it is necessary to understand the aerodynamic forces acting upon it. Practical answers to the following questions must be sought and constantly reevaluated: What are the most general and most reliable expressions for the aerodynamic forces on an air vehicle? What are the fundamental hypotheses behind these expressions and the inherent limitations in them? What are the boundaries of accuracy for forces calculated by various methods? In what area and in what direction can significant advances in understanding of the aerodynamic forces be expected? Where and why are the aerodynamic problems so profound that significant advances cannot be expected in the foreseeable future?

In order to understand the nature and accuracy of machine solutions of differential equations it is imperative that the foundations of the theory of ordinary differential equations be understood. Stemming from these foundations, error theory can solve the problems of stability and linearization, which are of major importance in evaluating machine solutions. Present error theory can determine the modal behavior of machine solutions; the principal need today is for information on the effect of nonlinear components on stability.

2. HISTORY OF THE PROJECT

During and following World War II the extraordinary demands placed on aircraft performance and the consequent phenomenal growth in their capacities were necessarily matched by intensification in the theoretical and technical sciences concerned. As these sciences expanded, boundaries and definitions in the conventional methods of meeting problems of designing and engineering tended to become fluid; distinctions between aerodynamics and ballistics tended to break down, for example, as the speeds of aircraft increased.

In all of this growth the common denominators were enormous expansion in complexity and increasing reliance on automatic control. In order to design and evaluate the complex component systems and total systems involved, it became apparent that a new concept in the approach to the problems was required. Consumption of time and money involved in the previous methods' dependence on trial and error and on tentative experimental models made the need demonstrably essential, if the U. S. wished to keep its air arm proficiency. By the autumn of 1950 the Air Force had conceived the possibility of single facilities or laboratories which could focus the formerly separate disciplines whose planned cooperation was now essential for the design and development of air weapon systems.

For about five years an organization at Wright Air Development Center had operated the means by which single components and certain types and ranges of automatic control systems could be tested on a small scale. In January 1951 WADC assigned the University of Chicago the task of investigating the feasibility of such an establishment on a full scale and, as worded in the prime contract with the University, of examining "in detail various possible approaches to the problem of laboratory experimental dynamic analysis of flight control systems, to determine what approach or combination of approaches offers the maximum useful return per unit of cost, and to formulate definite requirements for equipment, operational practices, and appropriate personnel complement for conducting such analysis."

For the purposes of this study the Air Force selected an advisory committee representative of the sciences which would be brought to bear on the problems anticipated. Professor Walter Bartky of the University of Chicago, who had directed the Air Force's Project Chore during the war and the Institute for Air Weapons Research after the war, both at the University of Chicago, was named chairman of this committee, and under his supervision a full-time staff was established on the Chicago campus to coordinate the study. For the first few months under the direction of Dr. Thornton Page and for the major portion of the time under Dr. Bernard E. Howard, this staff sought throughout the 42 months of the program to define the problems encountered, to recognize the probable direction their solutions would take, to achieve liaison among contributors to the program, and to organize and articulate the conclusions reached.

The need for a facility as had been conceived was established immediately; consequently the program has centered its attention consistently on the practical problems of its design. As the studies got under way, it became clear that these problems classified themselves into five categories, not, however, mutually exclusive or completely independent: (1) mission, (2) equipment, (3) procedures, (4) personnel, and (5) theoretical foundations. During the course of the work it became expedient to subdivide the five categories further, roughly into the parts of which this final report is constituted. Recognition was soon made, as well, that to be realistic the approach to the goals of the program had to enlarge in scope beyond aircraft simulation conceived narrowly in terms of physically analogous mockups, equations describing the forces on an aircraft, or flight tables and load simulators to duplicate aircraft reactions. Rather, the program had to embrace entirely the skill and knowledge involved in the modern science of dynamic systems engineering.

As a continuing source of advice throughout the progress of this study, members of the advisory committee, together with other interested persons, have met for a total of 16 formal sessions. These meetings, necessarily more frequent in the early months of the program as plans were being crystallized, have been as follows:

8-9 February 1951, University of Chicago
5-6 April 1951, University of Chicago
24-25 May 1951, University of Chicago
5-6 July 1951, R.C.A. Laboratories, Princeton, N.J.

30-31 August 1951, J. B. Rea Co., Los Angeles, Calif.

14 September 1951, University of Chicago

25-26 October 1951, University of Chicago

13-14 December 1951, M.I.T., Cambridge, Mass.

24-25 January 1952, University of Chicago

21-22 February 1952, University of Chicago

21 March 1952, W.A.D.C., Wright-Patterson AF Base, Ohio

24-25 April 1952, National Bureau of Standards, Corona, Calif.

18-19 September 1952, Hughes Aircraft Co., Culver City, Calif.

13-14 November 1952, M.I.T., Cambridge, Mass.

20-21 February 1953, University of Chicago

10-11 December 1953, University of Chicago

From time to time working committees have also met in quasi-formal sessions to discuss facets of the program, to exchange results and resolve conflicts. Following are the highlights of these conferences:

25 July - 1 August 1951, conference on simulation facilities University of Chicago

17-18 September 1951, second conference on simulation facilities University of Chicago

10 March 1952, briefing on the year's work, W.A.D.C.

22-23 May 1952, flight table subcommittee, University of Chicago

2 June 1952, torque transducers conference, University of Chicago

24-25 September 1953, physical simulation conference, University of Chicago

19-20 October 1953, mathematical simulation conference, University of Chicago

17-19 November 1953, flight table design conference, University of Chicago

19-21 November 1953, conference on error studies, Naval Ordnance Laboratory, Corona, Calif.

14 December 1953, conference on analog computation and guidance simulation, University of Chicago

Frequently the assistance of other organizations and individuals has been enlisted for particular phases of the program. During the first year the J. B. Rea Company undertook studies to determine under what conditions simulation is necessary or desirable in control and guidance systems and to investigate the relative applications of digital and analog computations; in the process of this work a study of autopilot control systems was made. Also, beginning in the first year, Cook Research Laboratories brought its facilities to bear on problems involving the accuracy of flight tables and servo loaders. R.C.A. Laboratories in 1951 accepted the investigation of real time simulation using actual missile and guidance components to ascertain the degree of realism required for validity and usefulness, and in the course of its studies branched into the related problem of determining the best method for slaving a flight table to a computer such as Typhoon. An examination of high speed precision recorders was also part of R.C.A.'s contribution.

Armour Research Foundation's previous experience in the construction of flight tables was helpful from the outset of the program, and in 1952 it undertook to investigate specifically for this program the roll axis system and the hydraulic transfer valve associated with its flight table, operating at high speed under heavy loads. The Massachusetts Institute of Technology also was helpful in calling upon prior experience in building flight tables, and during 1954 the Dynamic Analysis and Control Laboratory of M.I.T. tackled specifically the problem of performance requirements for flight tables, and assisted in the staff studies. The Flight Control Laboratory at M.I.T. also participated directly in the program, with studies in high speed analog computation. The National Bureau of Standards at Corona, Calif., which in 1953 became the Naval Ordnance Laboratory at Corona, cooperated in the program by examining methods used in closed loop simulation and open loop testing of guidance equipment, and by analyzing a portion of the error problem.

To help organize the theoretical foundations for the work of a dynamic systems facility, studies in aerodynamics were initiated late in 1951. The first of the series of discussions of problems in aerodynamics, and reviews of the current literature on those problems, was completed in December by Prof. M. Z. Krzywoblocki. Periodically up to the close of the program Prof. Krzywoblocki's reviews were issued, for a total of nine, which in sum constitute an examination of the problems of aerodynamics which a dynamic systems laboratory must confront and of their current theoretical and experimental treatments.

During the course of the program specific aircraft have been brought under scrutiny in order that accurate estimates of the needs in guidance simulation could be made and in order that specific parameters could be applied in determining flight table requirements. A thorough and continuing survey of the control systems and aerodynamic characteristics of both piloted and guided aircraft was made to achieve these ends.

In the process of recognizing the problems to be tackled by the various participants, it was first necessary to assess the general nationwide technical requirements for flight control simulation in aircraft design and development. By August 1951 a survey of simulation facilities and of Air Force projects requiring simulation had been completed. During this same period attention was also directed to automatic computation as a necessary adjunct of aircraft design and testing, and detailed studies were made of computer capacities from the points of view of both actual operating computers and planned or theoretically possible machines. World-wide surveys of existent computers and recorders were completed, the former in 1953, the latter in 1954, to provide the basis for realistic appraisal of computer applications and potentialities.

During the program's second year it became clear that a rigorous analysis of the problems of errors in machine computation was necessary. Centering its attention on the possibilities apparent in the theoretical work of Drs. F. J. Murray, K. S. Miller, and J. Winson, the program tested the application of the theories and brought error description and evaluation toward the point where meaningful mathematical analysis of machine errors could be made. The assistance of the Aerial Measurements Laboratory of Northwestern University was enlisted in this phase of the program in order that its analog computer could be utilized by the Chicago staff to determine the type and quantity of errors introduced by the presence of a flight table in closed loop analysis. In addition, a digital check problem was coded for the OARAC at WADC to assess the procedures of such a check, and a study was made of the REAC solution of a homogeneous system of linear differential equations with constant coefficients.

Interpreting and relating the information achieved by the program's individual studies have been continuing jobs, resulting in the three-volume Interim Report in 1952 and the six-volume Summary Progress Report in 1953. But the final months of the program have been devoted exclusively to this task of sifting, organizing, evaluating, and making articulate the hugh amount of information accumulated in the three years. This work, then, has culminated in the present 16-volume Dynamic Systems Studies.

3. PARTICIPATING PERSONNEL

In very brief outline biographical descriptions are given here of the men who have served as members of the advisory committee during the program. Following these, the other individuals who have contributed to the program are listed. Where applicable, reference is made in this list to the Bimonthly Progress Report in which further details concerning the individual can be found. Members of the Secretariat are in that capacity affiliated with the University of Chicago, and members of the advisory committee are in that capacity consultants to the University of Chicago.

1. Dr. Walter Bartky, Chairman
   Director of the Advisory Board on Simulation and of the Institute for Air Weapons Research (formerly the Air Weapons Research Center, Chicago Ordnance Research 1)
   Dean, Division of the Physical Sciences, University of Chicago
   Professor of Applied Mathematics, University of Chicago
   Ph.D. (mathematical astronomy), University of Chicago, 1926

2. Dr. C. Stark Draper,
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   First Lieutenant, U. S. Army Corps, 1926-1942
   Sc.D. (aeronautical engineering), Massachusetts Institute of Technology, 1938

3. Dr. Francis J. Murray,
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   Chairman, Committee on Applied Mathematics, Columbia University
   Civilian with the Office of Scientific Research and Development, U.S.N.
   OAC Editor, Mathematical Tables and Other Aids to Computation
   Assistant Editor, Duke Mathematical Journal
   National Research Fellow, Princeton University, 1934-1936
   Ph.D. (mathematics), Columbia University, 1935

4. Mr. Donald McDonald,
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   Former Supervisor, Controls and Instrumentation Group, Aeronautical Research Center, University of Michigan
   Former Project Engineer, Doelcam Corporation, Newton, Massachusetts; and Submarine Signal Company, Boston, Massachusetts
   M.S. (electrical engineering), Massachusetts Institute of Technology, 1942

5. Dr. James B. Rea,
   President, J. B. Rea Company, Inc., Los Angeles, California
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   Former research engineer and test pilot in charge of "Systems Analysis Group," Douglas Aircraft Company, 1942-1951
   Flight Captain and Cruise Control Engineer, Pan-American Airways, 1941-1944
   Sc.D. (aeronautical engineering), Massachusetts Institute of Technology, 1947

6. Dr. R. C. Seamans, Jr.
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   Chief Engineer, Project Meteor, Massachusetts Institute of Technology, 1950-1954
   B.S., Harvard, 1939; M.S., Massachusetts Institute of Technology, 1942; Sc.D., Massachusetts Institute of Technology, 1951

7. Mr. Robert J. Shank
   Vice-President, Hughes Aircraft Co., Culver City, Calif.
   Former member, technical staff, Bell Telephone Labs., New York, N.Y.
   B.S. (electrical engineering), Purdue, 1937
   A.B. (physics), Goshen, 1935

8. Dr. Harold K. Skramstad
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   Ph.D. (physics), University of Washington, 1935

9. Mr. Arthur W. Vance
   Research Section Head, R.C.A. Laboratories, Princeton, N.J.
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   Technical observer for U. S. War Department in Europe, 1945
   B.S. (electrical engineering), Kansas State College, 1928

10. Mr. W. R. Allen
    Group Leader, Secretariat, 1 Feb. 1951 - 31 Aug. 1954
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11. Mr. George Backus
    Secretariat, 13 Sept. 1951 - 28 Feb. 1953
    See Bimonthly Progress Report 4

12. Mr. F. A. Barnes
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13. Dr. R. R. Bennett
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    Former member, technical staff, Hughes Aircraft Co.
    Consultant, 1 Jan. 1952 - 31 Jan. 1954

14. Mr. Roy Berg
    Secretariat, 21 April 1952 - 5 Jan. 1953
    See Bimonthly Progress Reports 8, 11

15. Mr. H. E. Blanton
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16. Mr. F. W. Bratten
    National Bureau of Standards/Naval Ordnance Laboratory, Corona, Calif.

17. Mr. J. A. Catrambone
    Secretariat, 2 Feb. 1953 - 31 Aug. 1954
    See Bimonthly Progress Report 13

18. Dr. Mary Dean Clement
    Secretariat, 1 Oct. 1953 - 31 Aug. 1954
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19. Mr. P. J. Cohen
    Secretariat, 14 Jan. 1953 - 30 Sept. 1953
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20. Mr. S. E. Cooper
    National Bureau of Standards/Naval Ordnance Laboratory, Corona, Calif.

21. Mr. J. B. Corbett
    Secretariat, 5 Sept. 1953 - 19 Feb. 1954
    Consultant, 11 May 1954 - 31 Aug. 1954
    See Bimonthly Progress Report 16

22. Dr. D. O. Ellis
    Secretariat, 1 June 1952 - 1 Sept. 1952
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23. Mr. George Ellowitz
    technical publications branch
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24. Mr. R. A. Farrell
    Secretariat, 1 July 1952 - 29 June 1954
    See Bimonthly Progress Report 9

25. Mr. D. J. Gimpel
    Armour Research Foundation

26. Mr. E. A. Goldberg
    R.C.A. Laboratories

27. Mr. Paul Gutt
    Secretariat, 23 June 1952 - 31 May 1953
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28. Mr. E. Hoffer
    National Bureau of Standards/Naval Ordnance Laboratory, Corona, Calif.

29. Mr. S. J. Horowitz
    Aerial Measurements Laboratory, Northwestern University

30. Dr. B. E. Howard
    Secretariat, 1 Feb. 1951 - 7 Aug. 1951
    Director, Secretariat, 7 Aug. 1951 - 31 Aug. 1954
    See Bimonthly Progress Report 1-2

31. Dr. E. C. Hutter
    R.C.A. Laboratories
    See Bimonthly Progress Report 1-2

32. Mr. L. J. Killian
    Technical Editor, Cook Research Laboratories

33. Mr. E. J. Knight, Jr.
    J. B. Rea Company
    See Bimonthly Progress Report 1-2

34. Dr. M. Z. Krzywoblocki
    Professor of gasdynamics, University of Illinois
    Consultant, 1 Dec. 1951 - 31 Aug. 1954
    See Bimonthly Progress Report 6

35. Mr. C. D. LaBudde
Secretariat, 1 Feb. 1951 - 31 Aug. 1954
See Bimonthly Progress Report 1-2, 18

36. Mr. G. L. Landsman
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Consultant, 1 May 1954 - 31 Aug. 1954
See Bimonthly Progress Report 1-2

37. Dr. Harry Lass
Mathematician, National Bureau of Standards/Naval Ordnance Laboratory, Corona, Calif.

38. Mr. J. Lehmann
R.C.A. Laboratories

39. Mr. L. P. Meissner
National Bureau of Standards/Naval Ordnance Laboratory, Corona, Calif.

40. Dr. H. P. Messinger
Secretariat, 16 June 1952 - 13 July 1953
See Bimonthly Progress Report 9

41. Dr. K. S. Miller
Professor of Mathematics, New York University
Consultant, 2 Nov. 1953 - 31 Aug. 1954

42. Mrs. Dorothea Minden
Secretariat, 1 Oct. 1953 - 31 Aug. 1954
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43. Dr. Thornton Page
deputy director, Operations Research Office, Johns Hopkins University
Director, Secretariat, 1 Feb. 1951 - 7 Aug. 1951
Consultant, 7 Aug. 1951 - 1 March 1953

44. Miss Margaret Pratt
National Bureau of Standards/Naval Ordnance Laboratory, Corona, Calif.

45. Mr. J. E. Quinn
Cook Research Laboratories

46. Dr. L. L. Rauch
Associate Professor of Instrumentation, University of Michigan

47. Mr. W. J. Riordan
    Group Leader, Secretariat, 11 June 1951 - 31 Aug. 1954
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48. Mr. Maido Saarlas
    Secretariat, 8 June 1954 - 31 Aug. 1954
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49. Dr. J. B. Salzer
    Hughes Aircraft Company

50. Mr. M. Schreiber
    Secretariat, 1 Feb. 1951 - 31 Aug. 1954
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51. Mr. H. W. Schultz
    Electrical Engineer, Aerial Measurements Laboratory, Northwestern University

52. Dr. W. W. Seifert
    Assistant Director, Dynamic Analysis and Control Laboratory, Massachusetts Institute of Technology

53. Mr. E. R. Spangler
    Secretariat, 18 June 1952 - 31 Aug. 1954
    See Bimonthly Progress Report 9

54. Mr. G. F. Warnke
    Supervisor, Control Systems, Armour Research Foundation

55. Mr. J. Warshawsky
    Research Engineer, Cook Research Laboratories

56. Mr. G. L. Weiss
    Secretariat, 23 June 1952 - 30 Sept. 1953
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57. Mrs. M. C. Weiss
    Secretariat, 8 Oct. 1953 - 31 Aug. 1954
    See Bimonthly Progress Report 17

58. Mr. C. F. West
    Chief, Computer Engineering Branch, Air Force Missile Test Center

59. Dr. Jonathan Winson
    Riverside, N.Y.
    Consultant, 1 March 1953 - 30 June 1954
    See Bimonthly Progress Report 13

60. Dr. F. B. Wright, Jr.
Secretariat, 1 June 1953 - 31 Aug. 1954
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61. Mr. J. P. Zemlin
J. B. Rea Company
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