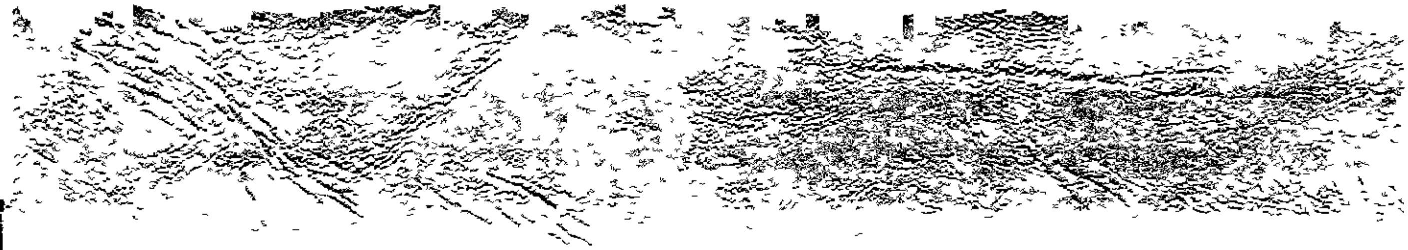

ORNELL AERONAUTICAL LABORATORY, INC.

Report No. JA-1266-S-8

FINAL REPORT ON TASK 8

FLIGHT SIMULATORS FOR USE IN AIR TRAFFIC CONTROL STUDIES

Contract No. FAA/BRD-15

February 15, 1959

B U F F A L O, N E W Y O R K

CORNELL AERONAUTICAL LABORATORY, INC
OF CORNELL UNIVERSITY

BUFFALO, N Y

REPORT NO JA-1266-S-8

FINAL REPORT ON TASK 8

FLIGHT SIMULATORS FOR USE IN AIR TRAFFIC CONTROL STUDIES

Contract No FAA/BRD-15

Prepared for
Systems Analysis Directorate
Bureau of Research and Development
Federal Aviation Agency

February 15, 1959

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ACKNOWLEDGMENTS

The authors wish to express their gratitude to the following companies for their cooperation in supplying specific data as well as general information for the studies reported herein

Aircraft Armaments, Inc
Cockeysville, Md

Curtiss-Wright Corp.
Electronics Division
Carlstadt, N. J.

Erco Division
ACF Industries
Riverdale, Md

Goodyear Aircraft Corp.
Akron, Ohio

Link Aviation, Inc
Binghamton, N Y

Melpar, Inc
Falls Church, Va

RCA
Airborne Systems Laboratory
Burlington, Mass.

Sylvania Electric Products, Inc
Electronic Systems Division
Waltham, Mass.

SUMMARY

An investigation was performed by the Cornell Aeronautical Laboratory, Inc. for the Systems Analysis Directorate, FAA/BRD, to determine the minimum number and kind of fixed-wing-aircraft flight simulators that would be needed to represent the range of aircraft likely to be encountered in air traffic control problems. Airplane characteristics were examined and a number of aircraft representing a cross-section of the current fleet were divided into groups based on performance and pilot/crew workload. A survey of the flight simulator field was made to determine types and characteristics of both commercially available training units and general purpose computer-simulators. The findings of this survey are summarized in the tables on pp. iv-vi

The results of the investigation showed that a) simulators are not available for some aircraft groups, b) in other groups there is considerable duplication in simulator availability, and c) some simulators are not particularly suited for air traffic control problems. Details of simulator design, operation, and cost were acquired and are presented. The following recommendations are made to the Federal Aviation Agency regarding the procurement of simulators for the air traffic control simulation facility now under construction at Atlantic City, New Jersey.

1. Using its present simulators the FAA should investigate further the role and requirements for flight simulators in the experimental facility.

2. An aircraft simulator in the large, civil, jet aircraft category (Boeing 707 or DC-8) should be acquired.

3. The purchase of a general purpose computer-simulator should be delayed until early simulation experiments have shown whether it is needed, and have defined better how it would be used.

4. The psychological difference between simulator and actual flight operation, as affected by human operators, should be investigated.

SUMMARY OF COMMERCIALLY AVAILABLE FLIGHT SIMULATORS

I. AIRCRAFT SIMULATORS*

*For definition, see p. 13

MFR.	SIMULATOR	COST	SIZE, WEIGHT AND LOADINGS	REMARKS
CURTISS-WRIGHT	B-36F B-50D B-52 B,D,F,G C-97A KC-97G C-118A C-119C,G C-121C RC-121D C-124A,C C-130A,B C-131A C-133A,B F2H-1 F4H-1 WV-2 A4D-2N BOEING 377 CV-340 DC-6B DC-7B,C LOCKHEED 1049G LOCKHEED 1649A LOCKHEED ELECTRA DC-8 707	\$500,000 - \$1,000,000	TYPICAL: 49'x21-1/2' x 10-1/2' 29,500 LBS. 250 LBS/SQ. FT. (NO MOTION SYSTEM) 500 LBS/SQ. FT. (WITH MOTION)	
GOODYEAR	F3H-2 F3H-2N P6M	$\$1 0 - 1 5 \times 10^6$ $\$1.0 - 1.5 \times 10^6$ $\$1.5 - 2.0 \times 10^6$	SEE REMARKS	EACH SIMULATOR IS HOUSED IN A 10' x 40' TRAILER. ALL UNITS ARE CLASSIFIED.
MELPAR	F-86 F-101 A4D F-100A,C,D	N A. N.A. N A. N.A.	N.A. N A. SEE REMARKS 33' x 40' x 11' 100 LBS/SQ. FT.	— — TRAILERIZED SIZE, WHEN COUPLED WITH F-151 GUNNERY TRAINER: 40' x 60' x 20'

SUMMARY OF COMMERCIALLY AVAILABLE FLIGHT SIMULATORS

I. AIRCRAFT SIMULATORS (Cont'd)

MFR.	SIMULATOR	COST	SIZE, WEIGHT, AND LOADINGS	REMARKS
ERCO	F9F - 2,5,6	N A	SEE REMARKS	ERCO SIMULATORS ARE PACKAGED TO FIT EITHER A 36 OR 40 FT. TRAILER(S), 12 FT. HIGH AND 8 FT. WIDE. CLASSIFIED UNDER GOVERNMENT SECURITY REGULATIONS.
	F-86D,K	N.A.		
	S2F-1,3	N.A.		
	AD-5N	N.A.		
	P2V-5,7	N.A.		
	P5M - 1	N.A		
	A3D-1	N.A.		
	F4D-1	N A.		
	B-66B	N.A.		
	B-57B	N A		
	F-105D	N.A.		
	KC-135	$500,000	41' x 42' x 14' 250 LBS/SQ. FT.	
LINK	DC-8, 707 CV-880 ELECTRA	$1,000,000	34' x 29' x 13' 48,000 LBS 185 LBS/SQ. FT.	
	F-89D,H	$500,000	24' x 23' x 12' 29,540 LBS. 53 LBS/SQ FT.	
	F-89J	$500,000	25' x 23' X 10' 38,430 LBS. 69 LBS/SQ. FT.	
	B-47B	< $1,000,000	23' x 12' x 10' 15,680 LBS 60 LBS/SQ. FT.	
	B-47E	< $1,000,000	23' x 12' x 10' 18,455 LBS 68 LBS/SQ. FT.	
	F-102	N A.	30' x 27' x 12' 25,000 LBS. 50 LBS/SQ. FT.	
	F-106	N A	N A	THESE UNITS ARE CLASSIFIED
	A3J	N A.	N A.	
	F8U	N A	N A	
	B-58	N A	N A	

SUMMARY OF COMMERCIALLY AVAILABLE FLIGHT SIMULATORS

II. AIRCRAFT-CLASS SIMULATORS*

*For definition, see p. 13

MFR	SIMULATOR	COST	SIZE, WEIGHT, AND LOADINGS	REMARKS
ERCO	ERCO-TWIN (2-F-25)	$200,000 ($300,000 WITH RADIO AIDS)	N A.	PATTERNED AFTER B-25 AND CV-340; INSTRUMENT AND NAVIGATIONAL TRAINER; HAS LANDING AND TAKE-OFF CAPABILITIES.
CURTISS-WRIGHT	P-3A	N A.	N.A.	PATTERNED AFTER B-25, INSTRUMENT TRAINER; NOT DESIGNED TO TAKE-OFF OR LAND.
	GENERAL PURPOSE TRAINER	N.A.	N.A.	CAN BE OPERATED AS JET OR TURBO-PROP, NAVIGATIONAL TRAINER; NO GROUND-HANDLING CAPABILITIES, BUT CAN LAND TO POINT OF TOUCH-DOWN
LINK	E-600	$200,000	17' x 15' - 10,000 LBS.	PATTERNED AFTER CV-340
	AT-100	$100,000	22' x 12' x 12-1/2'	PATTERNED AFTER DC-3 AND CV-340
	C-11	$100,000	18' x 8' x 9' 6840 LBS. 75 LBS/SQ. FT.	PATTERNED AFTER T-33 AND F-80; AC COMPUTATION
	ME-1	$300,000 ($400,000 WITH COCKPIT MOTION)	20' x 18-1/2' x 10' 10,000 LBS. 40 LBS/SQ FT.	PATTERNED AFTER T-37

INTRODUCTION

This report describes an investigation performed by Cornell Aeronautical Laboratory, Inc., under Contract No. FAA/BRD-15, Task Order 8, for the Systems Analysis Directorate of the Federal Aviation Agency, Bureau of Research and Development The purpose of the task was to determine the minimum number and kind of aircraft flight simulators that would be needed to cover the range of aircraft likely to be encountered in the work of the air traffic control simulation facility that is now under construction at the National Aviation Facilities Experimental Center, Atlantic City, New Jersey

The NAFEC simulation facility will be composed of the following basic sections (see Fig. 1)

1. air traffic simulator consisting of analog target generators, radar simulators, and data reduction and communication equipment,
2. air traffic control center, and
3. aircraft flight simulators

The air traffic simulator consists of analog air target generators which are operated by "pilots" who manipulate their "aircraft" in accordance with a prearranged flight plan as altered by controllers' instructions The outputs of the target generators feed radar simulators which transform the target position data into radar form. The video targets from the radar simulators are then fed to the controllers' displays which are a part of the air traffic control center (1)*

Since the usefulness of any evaluation of an air traffic control system through simulation depends upon the verity of simulation, it is imperative that the elements involved be as realistic as possible within the limits of practicability

* Numbers in parentheses refer to References, pg. 55.

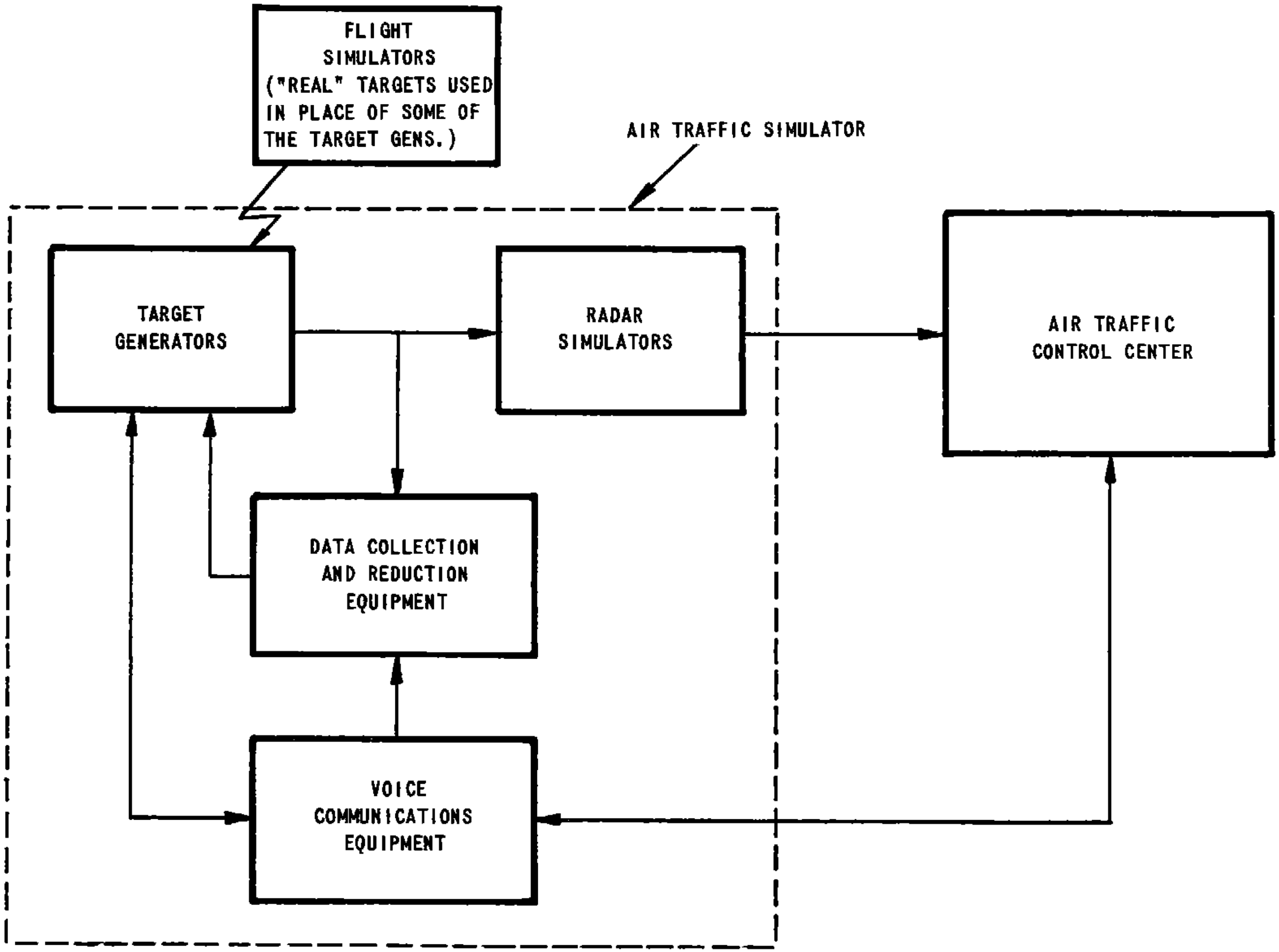

FIG. 1 ATC SIMULATION FACILITY

JA-1266-S-8

The role of the aircraft flight simulators, then, is to provide the system with "real" aircraft which will furnish the desired checks on the validity of system performance with analog target generators. The flight simulators will also be used as research tools in other FAA work. The present concept of their application is as follows

1. Control experiments to determine the accuracy and validity of the target generator - human operator combination in the performance of air traffic control simulation experiments.
2. Pilot reaction and technique studies.
3. Research on cockpit design, navigational problems, etc.
4. Proficiency training for pilots engaged in full-scale flight experiments
5. ATC problems involving aircraft flying under emergency conditions, e.g , minimum fuel, engine out, communications failure, etc.

The specific flight simulators selected should possess the capabilities of handling the above problems and should also represent a cross-section of the current aircraft fleet

This report presents recommendations for the selection of flight simulators which appear to be best suited for the FAA experimental facility These recommendations are based on the results of an investigation of aircraft characteristics and a survey of the flight simulator field

AIRCRAFT GROUPING

One purpose of flight simulators in the air traffic control experimental work is to provide spot checks on the validity of simplifying assumptions made in representing the pilot-aircraft component To do this job effectively, the simulators should be representative of all variations in aircraft complexity and capability to assure that one segment of aircraft will not be unintentionally favored over another. The logical procedure in choosing simulators would be to group all present-day aircraft in such a way that within any one group the factors influencing the traffic control problem would be constant. By then specifying one simulator in each group, complete coverage would be accomplished.

To choose simulators in this way involves, first, deciding what these factors are, second, procuring the needed data on a large number of aircraft, and third, determining some way of reducing the number of factors to essentials so the aircraft can be logically grouped. However, all of these tasks cannot be performed with certainty at this time. The question of importance of various aircraft and pilot factors in air traffic control is in itself the main one to be answered through the use of the simulators. If the answers were known now, modifications could be made to the simplified consoles incorporating those important factors not now included, and experiments could proceed on firm ground

Acknowledging the fact that the important factors are not known for certain, one alternative approach would be to list all characteristics which conceivably could influence the control problem, and group aircraft according to these parameters. A beginning can be made by restricting consideration to those characteristics of the aircraft and pilot which can be detected directly or indirectly by a remote controller and which significantly affect the control task

Also, attention should be focused on those characteristics which are lacking in the simplified representation (console and non-pilot operator) Reference 1 describes the equipment in detail. The console controls a spot moving in space which can have velocity (V), heading (ψ), altitude (h), acceleration or deceleration (V), rate of turn ($\dot{\psi}$), and rate of climb or descent ($\dot{h}$).

1 The spot moves in a straight line except when inputs of $\dot{V}$, $\dot{\psi}$ or h are applied and when wind and wind gradient with altitude are simulated A real aircraft, of course, has continual variations in V, ψ, h, V, $\dot{\psi}$ and h which would be quite important when precise navigation is required.

2 There is a time delay in the simplified situation in achieving V, ψ or $\dot{h}$ in response to the traffic controllers' command due to operator delay and a console delay designed to simulate aircraft's dynamic response But this delay, in a given experiment, is likely to stay relatively constant The real aircraft, due to changes in dynamics with speed, altitude, and configuration and due indirectly to the pilot's many different responsibilities in the cockpit, is much more likely to have widely varying delay times.

3 The console operator can be informed of the basic limitations in performance which must be adhered to such as V_{max}, V_{min}, V_{max}, h_{max}, $\dot{h}_{max}$, and ψ_{max}, but there are many other factors which can influence real aircraft behavior For example,

Fuel consumption (affecting V, $\dot{V}$, h, $\dot{h}$)
Approach procedure (V, $\dot{h}$)
Flap and gear structure (V)
Basic structural design for normal acceleration and gust loads (V, $\dot{\psi}$)
Instrument flight in severe turbulence (bank angle)

Icing (V, h, $\dot{h}$)

Passenger discomfort due to pressure changes, turbulence and acceleration (V, $\dot{V}$, h, $\dot{h}$, $\dot{\psi}$)

Emercencies (V, $\dot{V}$, h, $\dot{h}$, $\dot{\psi}$)

4. The consoles will have push-button radio communications and the operator's navigation task is quite simplified. The pilot many times must contend with more complex communication equipment, and navigating often involves tuning electronic aids, interpreting their information, reading maps and radio facility information, and doing computation.

It can be seen from this discussion that a straightforward attempt to group aircraft according to the above factors, even if the data were available, would be rendered exceedingly difficult by the very number of items to be considered.

This, then, leads to another alternative which was adopted. The aircraft were grouped according to type and number of engines, weight, and performance, similar to the grouping in Task 3 of the FAA/BRD-15 Contract. (See Reference 2.) This grouping covers the range of all aircraft commonly operated in this country, in this respect, it suits the purposes of this present task. But beyond this, it is evident that this grouping will result in categories of aircraft within which the aircraft will have a great deal in common from the viewpoint of traffic control. For example, grouping according to type of power plant at once separates the jet aircraft with their very important fuel consumption problem from propeller driven aircraft which have less critical demands on cruise altitude, holding time, climb and descent procedures, etc. Grouping according to weight, number of engines, and performance tends to provide natural separation according to the nature of the pilot's task in the cockpit. As the aircraft becomes heavier or faster and the number of engines increases, the pilot's task becomes more complex, and the difference between the pilot's task and that of the operator of a target generator is greater. Also, with this grouping, the aircraft in each group will be similar from the standpoint of possible emergency conditions which could exist and procedures to counteract emergencies.

The method of grouping described above was considered satisfactory, and, accordingly, 63 aircraft were divided into seven groups as shown in Table 1. Those performance figures which were readily available were included in Table 1 for comparison purposes. The data for all military aircraft were taken from Refs. 3 and 4 and are applicable to the "basic mission" as defined in those references. The civil aircraft data were taken from Refs 5 and 6 The cruise speed given is approximately the speed for maximum range, the stall speed is that for maximum gross weight and no flap deflection, and the rate of climb is approximately the maximum rate of climb at sea level at maximum take-off weight. An indication of the level flight acceleration characteristics of each aircraft was derived from the maximum and minimum speeds and the maximum rate of climb. The measure of over-all acceleration performance was taken as the acceleration which would occur if maximum power were applied while in level flight at the velocity for best rate of climb. The derivation is as follows

$$a = \frac{T - D}{W} g$$

$$R/C = \frac{V (T - D)}{W}$$

$$(R/C)_{max} = \frac{V_{BC} (T - D)_{BC}}{W}$$

Therefore $$a_{(at\ V_{BC})} = \frac{(R/C)_{max}}{V_{BC}} g$$

where

a	=	acceleration
T	=	thrust
D	=	drag
W	=	weight
V_{BC}	=	velocity for best climb
g	=	acceleration of gravity
R/C	=	rate of climb

From Ref 7, the velocity for best climb was estimated as

$$V_{BC} = V_{stall} + \frac{1}{3} (V_{max} - V_{stall}) \text{ for propeller driven aircraft}$$

$$V_{BC} = \frac{1}{1\ 73} V_{max} \quad \text{for jet aircraft}$$

The acceleration figure resulting for each aircraft was converted to a rating -- low, medium or high -- for maximum utility of the data

TABLE 1

GROUPING OF PRESENT-DAY AIRCRAFT

Key to Acceleration Data

Knots/Sec	Rating
6 to 1 5	Low
1 6 to 2 5	Medium
Greater than 2 6	High

Group 1 -- Small, Single Engine, Propeller Aircraft

	Cruise (Kts)	Stall (Kts)	Climb (FPM)	Acc	Simulator Available
T-34A	120	47	1,100	Med	No
T-28A	149	69	1,520	Med	
Bonanza	155	55	1,000	Med.	
Cessna 172	103	45	660	Med	
Cessna 180	132	49	1,130	High	
Helio H-391-S	139	22	2,000	High	
Piper PA 22	115	43	725	Med.	
Taylorcraft 20 Ranch Wagon	100	40	1,000	High	↓

Group 2 -- Small, Twin Engine, Propeller Aircraft

	Cruise (Kts)	Stall (Kts)	Climb (FPM)	Acc	Simulator Available
Twin Bonanza	143	70	1,620	High	No
C-45H	128	66	1,260	Med.	
Aero Commander 560 E	183	57	1,450	Med	
Beech Super 18	179	75	1,490	Med.	
Beech Travel Air	169	58	1,330	Med	
Cessna 310	168	60	1,700	High	
Piper Apache	148	45	1,350	High	
Twin Navion	148	50	1,400	High	↓

Group 3 -- Small, Piston-Engined Transports*
(Gross Weight less than 80,000 lbs)

	Cruise (Kts)	Stall (Kts)	Climb (FPM)	Acc	Simulator Available
DC-3	141	65	720	Low	No
C-123	145	80	845	Low	No
C-119C	176	95	730	Low	Yes
C-131A (Convair 240)	183	86	1,195	Low	Yes
C-131B (Convair 340)	168	77	1,175	Med	Yes
C-131E (Convair 440)	174	81	960	Low	No
Howard Super Ventura	270	80	2,500	High	No
Learstar Mark II	239	67	2,400	High	No

* Also included in this group, but not listed due to insufficient data Martin 202, Martin 404

TABLE 1 (Cont'd)

Group 4 -- Large, Piston-Engined Transports*
(Gross Weight greater than 80,000 lbs)

	Cruise (Kts)	Stall (Kts)	Climb (FPM)	Acc.	Simulator Available
DC-4	167	88	540	Low	No
C-121A (Constellation 749)	190	84	1,310	Med.	No
C-121C (Constellation 1049A)	225	84	1,100	Low	Yes
DC-6A	229	97	700	Low	
C-124	183	99	500	Low	
C-97A	204	108	555	Low	
DC-7C	238	102	--	--	
Constellation 1649	297	88	1,660	Low	

Group 5 -- Turboprop Transports

	Cruise (Kts)	Stall (Kts)	Climb (FPM)	Acc.	Simulator Available
C-130A	290	94	1,770	Med	Yes
Viscount 700	283	87	1,200	Low	No
Electra	352	93	1,670	Low	Yes
F-27 Friendship	236	70	1,400	Med	No
Vickers Vanguard	365	96	1,800	Med.	
Viscount 840	348	92	1,640	Low	
Britannia 310	300	115	1,430	Low	

Group 6 -- Small Jet Aircraft
(Gross Weight less than 40,000 lbs.)

	Cruise (Kts)	Stall (Kts)	Climb (FPM)	Acc.	Simulator Available
T-33	395	105	3,440	High	Yes
F-86F	460	108	6,000	High	
T-37A	252	72	2,300	Med	
F-89D	406	118	3,400	Med	
F-84G	427	123	5,300	High	No
F-84F	468	131	4,370	Med	
Morane-Saulnier 760 Paris	313	78	2,280	Med.	
F-94B	382	113	3,650	High	
Supersonic Maximum Speed Type 1**	512	138	5,000	Med.	Yes
Supersonic Maximum Speed Type 2	478	169	8,300	High	
Supersonic Maximum Speed Type 3	520	129	7,000	High	
Supersonic Maximum Speed Type 4	514	173	7,100	High	

* Also included in this group, but not listed due to insufficient data DC-6B, DC-7, DC-7B, 1049C, 1049G, 1049H Constellations

** Designation omitted for security reasons

TABLE 1 (Cont'd)

Group 7 -- Large Jet Aircraft*
(Gross Weight greater than 40,000 lbs)

	Cruise (Kts)	Stall (Kts)	Climb (FPM)	Acc	Simulator Available
B-57C	411	109	4,000	High	Yes
B-66B	459	131	3,640	Med.	↓
KC-135	462	128	2,250	Low	↓
707-320	526	99	--	--	↓
DC-8	496	101	2,300	Low	↓
Caravelle	420	91	1,860	Low	No
Comet 4A	425	116	3,000	Med.	No
Convair 880	509	117	--	--	Yes
Bombers Type 1	433	154	2,560	Med	↓
Bombers Type 2	453	141	2,110	Low	↓
Bombers Type 3 (Supersonic)	544	97	--	High	↓

SUMMARY

Group	Cruise (Kts)	Stall (Kts)	Climb (FPM)
1	100-155	22- 69	660- 2,000
2	128-195	45- 75	1,260- 1,700
3	141-270	65- 95	720- 2,500
4	167-238	84-108	500- 1,310
5	236-365	70-115	1,200- 1,800
6	252-520	72-173	2,280- 8,300
7	411-544	91-154	1,860- 4,000

* Also included in this group, but not listed due to insufficient data 707-120, 707-220, 707-420, 707-023, Convair 600, DC-8 Intercontinental

FLIGHT SIMULATORS

GENERAL DESCRIPTION

A flight simulator is basically a cockpit with associated controls and instrumentation linked to an analog computer having the capacity to work in real time. The "airplane" is manually controlled in the cockpit section and the resulting control signals are fed to the analog computer which solves the aircraft equations of motion Outputs from the computer are then fed to flight instruments in the cockpit yielding appropriate instrument readings in accordance with the prevailing "flight conditions".

There are numerous types of simulators and they vary in versatility, capability, performance, and price The following discussions point out some of the aspects in which the units differ

Flight simulators can be divided into two basic categories (1) research tools, and (2) training devices

Research Tools

In the field of research, general purpose computing equipment (both analog and digital) has been used extensively for the purpose of solving problems involving aircraft dynamics While this work has been called "simulation", it has usually included only a computer solution of the aircraft equations of motion, and did not involve manual control inputs from a cockpit section Only recently has there been any development of full-fledged simulators having the flexibility required for research work. Units of this type are discussed in more detail in the section on Aircraft Simulation Using General Purpose Computing Equipment, pg. 46

Training Devices

The Link Trainer, the forerunner of modern flight simulators, was developed in 1929 to assist in the teaching of radio and instrument flying procedures. It was 20 years later, early in 1949, that the first electronic simulator was put into service.[8] Since that time, tremendous advances have been made in the methodology of simulation so that, today, an extremely convincing illusion of flight can be created on the ground with complete safety and relatively low cost

Flight simulators designed as training devices can be divided into the following two groups

1 Aircraft-class simulators -- those which simulate a general airplane type that is typical of an aircraft class.

2. Aircraft simulators -- those which simulate a particular airplane

Aircraft-class simulators, sometimes called trainers or duplicators by the industry, are characterized by the following

a. These simulators are patterned after a particular airplane, but cockpit interior, instrument layout, and flight characteristics are approximated rather than being faithfully duplicated

b Basic emergency situations (engine out, communications failure, etc) can be simulated

c Some units are designed for specialized tasks, such as instrument or navigational training and may not have the capabilities to simulate the aircraft over the complete flight spectrum

d. In general, aircraft-class simulators are much less complex than aircraft simulators and are, therefore, less costly.

Aircraft simulators have the following characteristics

a. These simulators duplicate, as accurately as possible, both flight characteristics and cockpit interior of a particular model of an aircraft

b The cockpit is usually outfitted with a complete set of controls, even those which do not affect the flight of the aircraft, such as cabin lights, air conditioning, etc

c. A large number of malfunctions and failures of practically all equipment can be simulated.

d Because these units are complex and have "custom-built" features, they are much more expensive than aircraft-class simulators

GENERAL CHARACTERISTICS OF FLIGHT SIMULATORS

The following discussions of simulator characteristics pertain, in general, to both aircraft and aircraft-class simulators. Specific characteristics appear in the section on Manufacturers' Data, pg 30.

Initial Cost

The general feeling in the simulator field is "One million dollars will buy one flight simulator" referring, of course, to aircraft (as opposed to aircraft-class) simulators Actually, the price of aircraft simulators was found to vary from $500, 000 for the smaller, less elaborate units to $1, 500, 000 for trailerized versions of the newer, more complex simulators Aircraft-class simulators were found to be much cheaper, costing between $100, 000 and $500, 000.

The relatively high cost of aircraft simulators is due to some extent to the custom-built features which preclude the use of the "mass-production" techniques that can be utilized in the manufacture of aircraft-class simulators This custom-building is necessitated by the airlines' lack of standardization of cockpit interiors, instrument layout, auxiliary equipment, etc. Therefore, an aircraft simulator for one of the airlines must be "tailor-made" to the customer's specifications. Consequently, it is sometimes possible to obtain a reduction in cost of 10-25% by ordering a simulator identical to one of the previous units

For the most part, however, aircraft simulators are more expensive than aircraft-class simulators simply because they provide more complete and more accurate simulation

Operating Costs

A table of operating costs is presented on pg 16 for a typical flight simulator. Although Table 2 pertains to one of Link's jet simulators (Douglas DC-8, Boeing 707, Convair 880, or Lockheed Electra), it can be used as a basis for calculating operating costs for other units Note, however, that in FAA applications, the cost of a qualified pilot to "fly" the simulator may be an additional item

Size and Weight

The floor area and floor loading requirements vary for different simulators, but whenever possible, this information was obtained from the manufacturer and appears in the Manufacturers' Data, pp 30-45

Because the space available for the FAA simulation facility is limited, the floor area required will be a major consideration in the selection of simulators unless means can be found to alleviate the space requirements.

Economy of Operation

The estmated cost of operatng Lmk's jet flight simulators is as follows

Power

Basic Tramer	44 4 KW at 04	$1 78
Lmk Visual System (complete with lights)	26 5 KW at 04	1 03
Motion	7 4 KW at 04	30
	Total per hour	$3 11

Personnel

Mamtenance (2 men, 1 doubles as Radio Aids Operator) 2 at $500/mo or $2 90 per hour	$5 80
Instructor—1 at $650/mo or $3 75 per hour	3 75
Total per hour (excluding shift differential rate)	$9 55

Spare Parts

Based on 8, 16, 20 hrs/day utilization

Total per hour* $3 00

Simulator Cost

Initial Cost	$1,000,000 00
Installation Cost (excluding shipping cost)	
(1) 4 Customer Tech at $93 per day for 30 days	2,790 00
(2) 1 Link Tech for 30 days at no additional cost	–0–
Total	$1,002,790 00

*This amount provides estimated spares support including those required for

(1) each 1,000 hrs. – minor inspection – accomplished during preflight and shutdown periods
(2) each 5,000 hrs – major overhaul

Depreciation

Based on 10-year life and residual value of 20% or $200,000 00

(1) 40 hrs per week or 2080 hrs/yr	$	38 65
(2) 80 hrs per week or 4160 hrs/yr		19 32
(3) 100 hrs per week or 5200 hrs/yr (Considered to be maximum utilization)		15 46

Total Cost per Hour

(including cost of 2% average downtime)

(1) at 40 hrs. per week	$	55 47
(2) at 80 hrs per week		35 76
(3) at 100 hrs per week		31 82

Summary

COST PER HOUR

	Daily Utilization		
	8 hrs	16 hrs	20 hrs
Power	3 11	3 11	3 11
Personnel	9 55	9 55	9 55
Spares	3 00	3 00	3 00
Depreciation	38 65	19 32	15 46
Cost of 2% Downtime	1 16	78	70
Totals	$55 47	$35 76	$31 82

TABLE 2 EXAMPLE OF SIMULATOR OPERATING COSTS

One solution would be the use of trailerized simulators in either of two ways (1) trailer-mounting the entire simulator, or (2) trailer-mounting the computing section and installing the cockpit section in the simulation building In either case, the only requirement would be adequate parking area adjacent to the building housing the simulation facility

The trailers are usually 40 ft. long and 10 ft. wide or 40 ft long and 8 ft wide with expanding sides (expanded width 14 ft.). The major disadvantages of trailerized simulators is the cost, which runs 10-15% higher than that for a floor-mounted simulator. This additional expense is due to the following

1 packaging problems,
2. cost of the special trailer, and
3 cost of associated equipment heating, air conditioning, etc.

Another solution to the limited space problem involves the separation of the simulator computer from the cockpit section -- that is, housing the cockpits in one building and the computers in another The inherent problems of separating electronic components are discussed below

Simulator Computers

The analog computing sections of flight simulators can be divided into two basic categories DC computers and AC computers.

Some of the primary characteristics of DC computers are

1 Variables are represented by the magnitude of positive and negative DC voltages
2. High quality DC amplifiers must be used to minimize drift
3. Integrations are performed simply with a DC amplifier and capacitive feedback yielding accurate integration for both large and small variations
4. Multiplication and function generation are performed by servos

Some of the primary characteristics of AC computers are

1. Variables are represented by the amplitude of AC voltages. Positive signals are distinguished from negative signals by a reversal in phase (180° phase shift) of the AC voltage
2. Because of the inherent capacitance and inductance in the computing circuits, careful lead wire placement and shielding are required in order to maintain zero or 180° phase with respect to some reference signal
3. Integrations are performed by electromechanical integrators of the servo type which function well for large variations, but perform relatively poorly for small variations or rapidly changing quantities However, AC integrators are capable of multiplication and function generation directly without the use of additional servos.

Manufacturers of flight simulators are quick to point out the merits of the particular system they use,* however, it is becoming common practice to employ both AC and DC computing components in a simulator, thereby utilizing the advantages of both systems. It should be emphasized that good simulator reliability and maintenance are primarily functions of good engineering practice and are not greatly dependent upon the type of computing used

Perhaps, the choice of AC or DC may be most influenced by the problems encountered when attempting to separate simulator components by large distances of the order of 300 to 500 ft. The cables connecting the components will be susceptible to stray inputs from external sources and steps must be taken to reduce this "noise" pickup Direct current circuits can be shielded without difficulty and presumably, the only other requirement for separation is an increase in wire size to avoid large voltage drops. Shielding AC lines, however, is not always

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* For both sides of the argument, see Refs 9 and 10

feasible Low impedance circuits present no problem, but the added capacitance of shielding precludes its use for high impedance circuits. In such cases, other means, such as the use of buffer amplifiers, must be found to resolve the "noise" problem

In any event, it is felt by simulator manufacturers that both AC and DC computers can be separated from the cockpit section if proper shielding or "black box" techniques are employed, and the additional cost involved would be less than that required to trailerize the simulator

Accuracy

The inherent accuracy of any flight simulator depends upon the cumulative effect of a number of factors, such as the validity of propulsive and aerodynamic data, the fidelity of representation of this input data, the precision of computing components, etc It is imperative that the errors introduced be kept to a minimum so that the degree of simulation is such that a realistic impression of flight is presented.

Unfortunately, it is very difficult to determine the faithfulness with which a simulator duplicates the behavior of the real airplane without resorting to exhaustive acceptance tests which are equivalent to flight tests of actual aircraft. However, as an indication of simulator accuracy one can consider manufacturers' tolerances.

It is the general practice within the industry to maintain the following tolerances on flight simulators

Performance factors (V_{max}, R/C, V_s, etc) $\pm$ 5-10%

Secondary factors (stick forces, temperatures, etc.) $\pm$ 15-25%

Some detailed tolerance figures for a typical aircraft simulator are presented in Table 3 on pg 21 It is the claim of simulator manufacturers that the finalized units, built to these tolerances, will behave within the production tolerances of the actual aircraft Tolerance curves for a typical aircraft-class simulator (Link E-600) are presented in Figs 2-6 Although the tolerances may be reasonably small, it must be remembered that, in the case of aircraft-class simulators, the performance curves, themselves, are only approximate representations of actual aircraft characteristics

The above discussion of tolerances pertains to steady-state performance In general, the dynamics of the airplane are simulated less accurately in even the best simulators,* however, dynamic characteristics such as stall, short period, phugoid, etc may not play an important part in ATC studies It is recognized, however, that dynamics may be important in any simulation if the aircraft has difficulties in this area By increasing the pilot's attention required for just flying the airplane, it reduces the time available for navigation and radio procedures It also increases difficulty in maintaining the desired flight altitude, heading, and airspeed

It is interesting to note that a simulator, before it is finalized, is always calibrated by a group of pilots with appropriate experience and the simulator characteristics are then adjusted until the pilots are satisfied with the analog [13] The following comments, taken from Ref 14, indicate some of the shortcomings that can be detected by experienced pilots The particular simulator under test was the F-100A coupled with F-151 Gunnery Trainer Steps were taken by the manufacturer to remedy these faults in later versions of the simulator.

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* For a detailed discussion of the accuracy of dynamic simulation, see Refs. 11 and 12

TABLE 3

TYPICAL AIRCRAFT SIMULATOR TOLERANCES
(From Link 707 Spec.)

ITEM	TOLERANCE*
Indicated airspeed	± 5 knots or ± 1%
Rate of climb	± 50 fpm or ± 5%
Altimeter ground reading	± 30 ft.
Time to accelerate on ground	± 2 sec. or ± 5%
Take-off attitude	± 2.0 deg.
Time from TD to complete stop (no brakes)	± 10%
Longitudinal force	± 3% or 1/500 gross weight
Lateral force	± 3% or 1/500 gross weight
Normal force	± 3% or ± 0.1 g
Stall speed	± 5%
Engine RPM time responses	± 20%
Tail-pipe temperature	± 25%
Fuel flow	± 100 lbs./hr. or ± 5%
Elevator control forces	± 3 lbs. or ± 10%
Aileron control forces	± 3 lbs. or ± 10%
Rudder control forces	± 5 lbs. or ± 25%
Turn rate	± 10 deg./min. or ± 10%

* whichever is greater

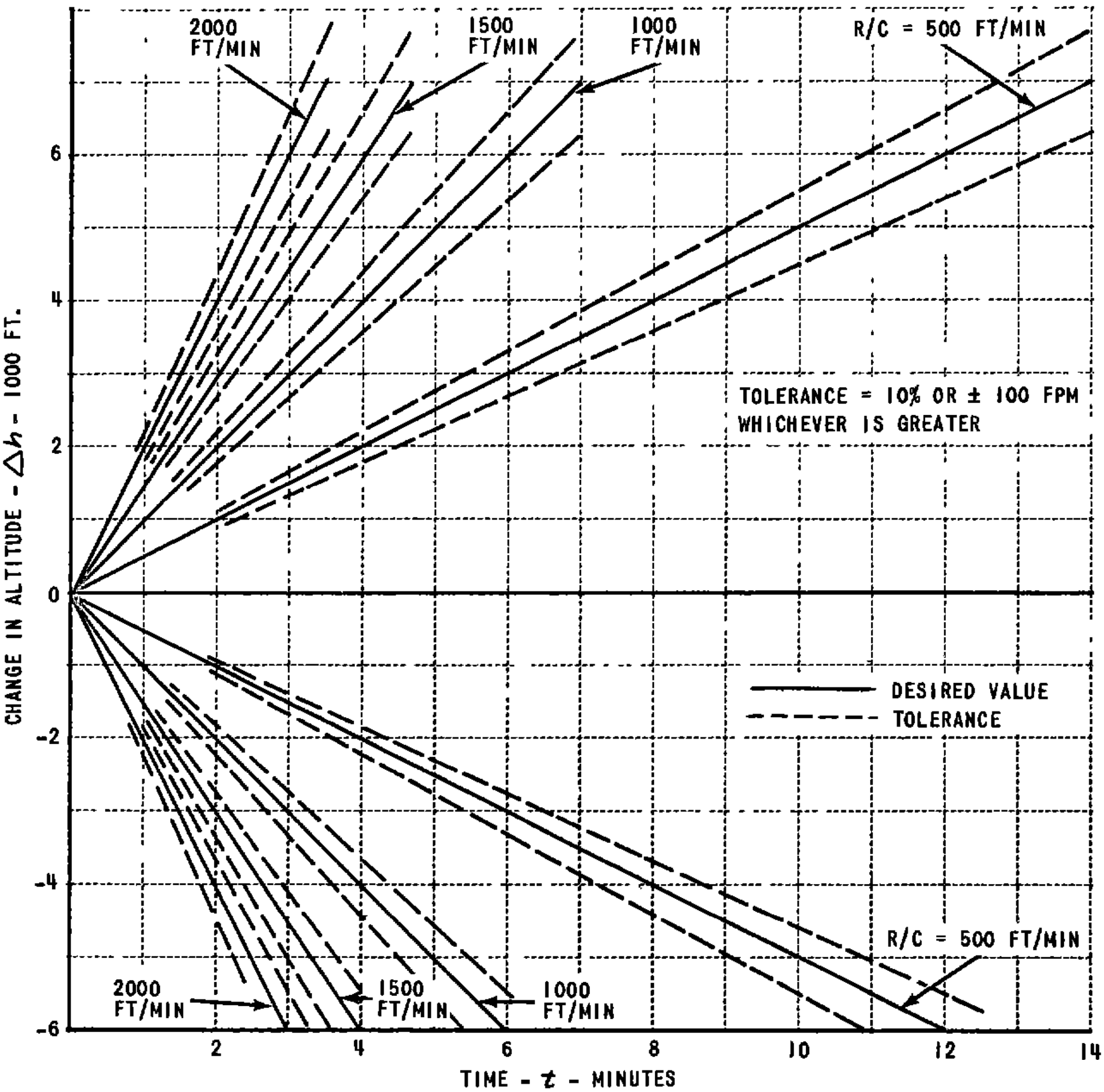


FIG. 2 RATE OF CLIMB TOLERANCE FOR TYPICAL AIRCRAFT-CLASS SIMULATOR

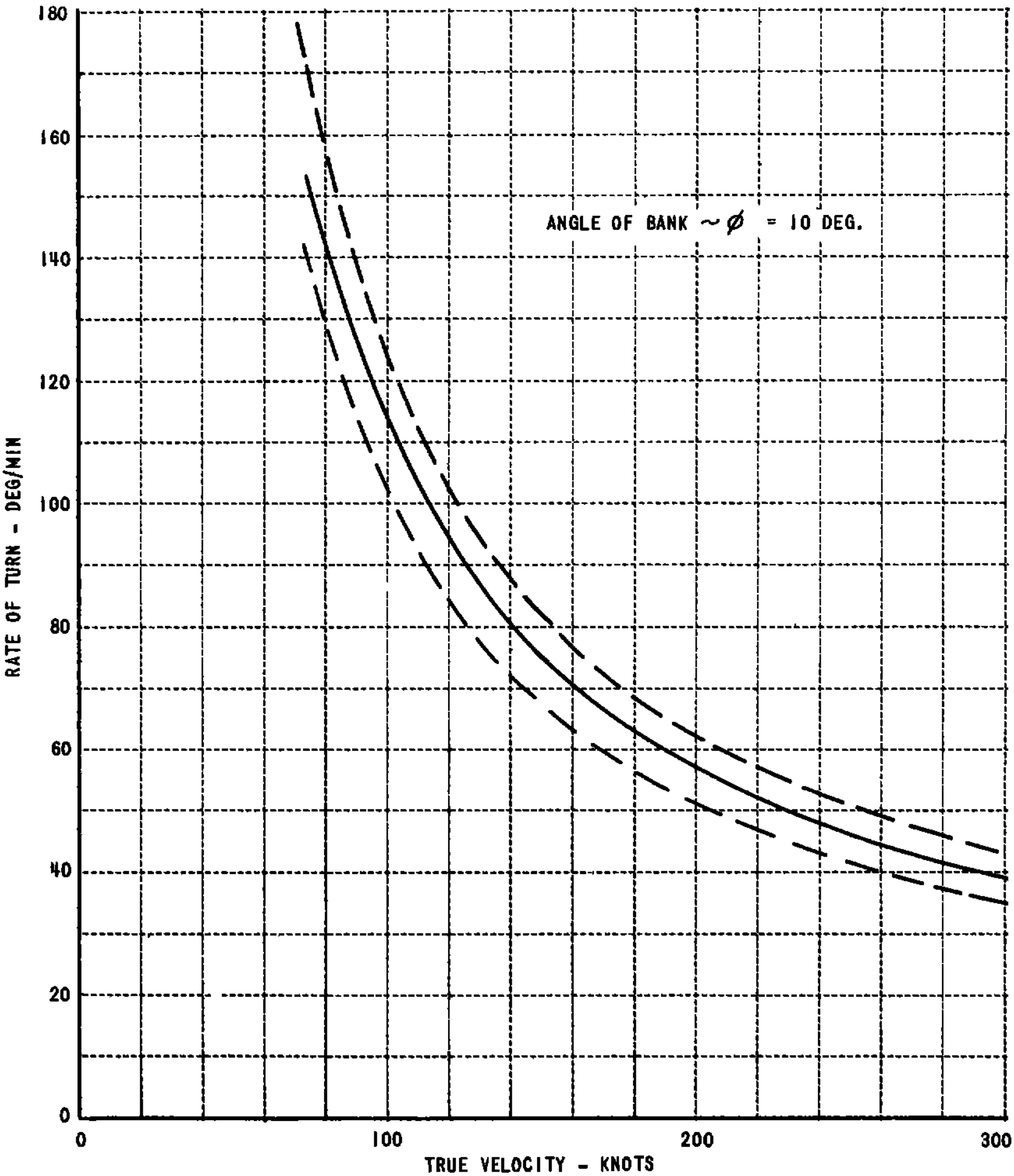


FIG. 3 RATE OF TURN TOLERANCE FOR TYPICAL AIRCRAFT-CLASS SIMULATOR

JA-1266-S-8

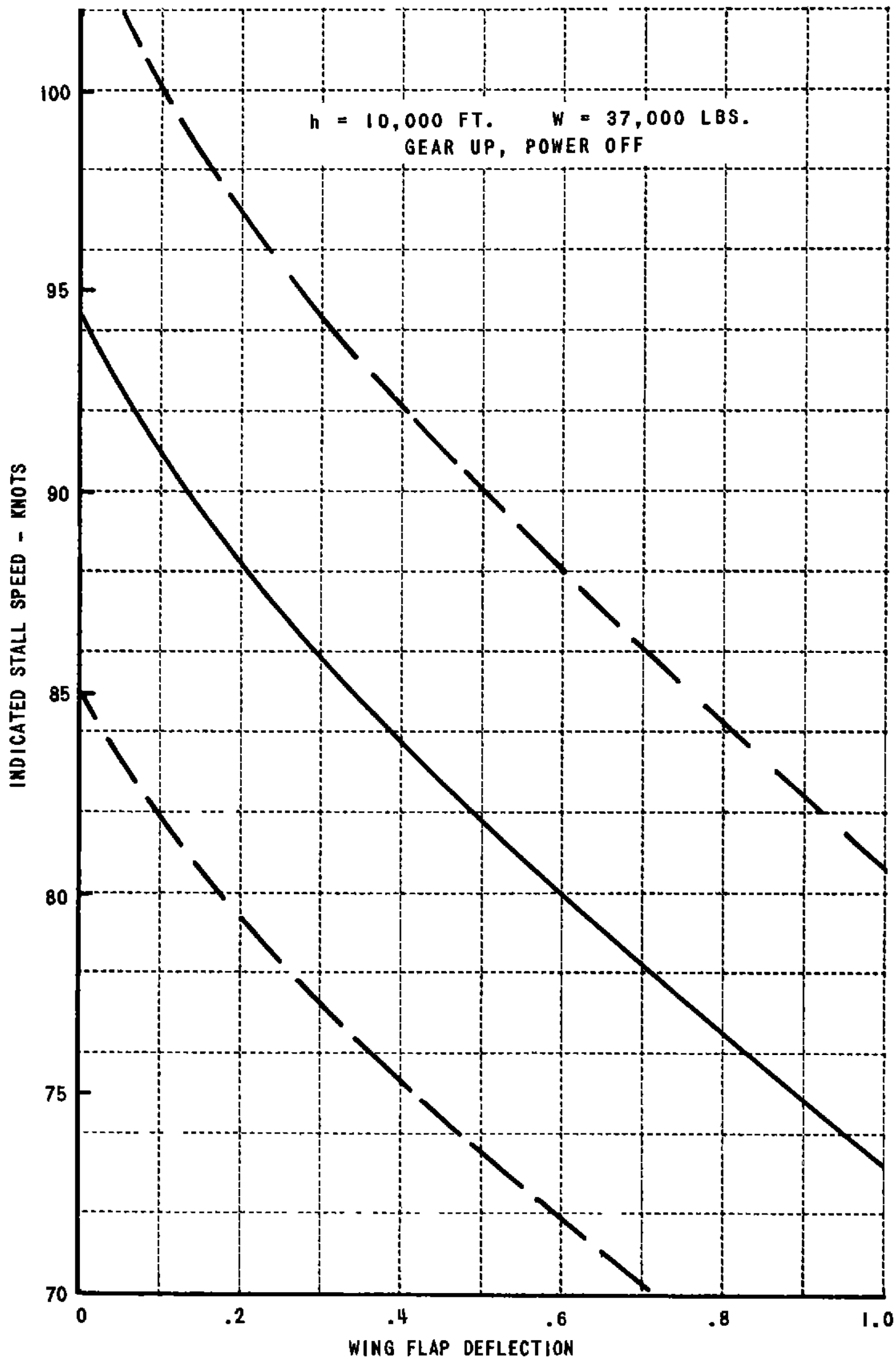


FIG. 4 STALL SPEED TOLERANCE FOR TYPICAL AIRCRAFT-CLASS SIMULATOR

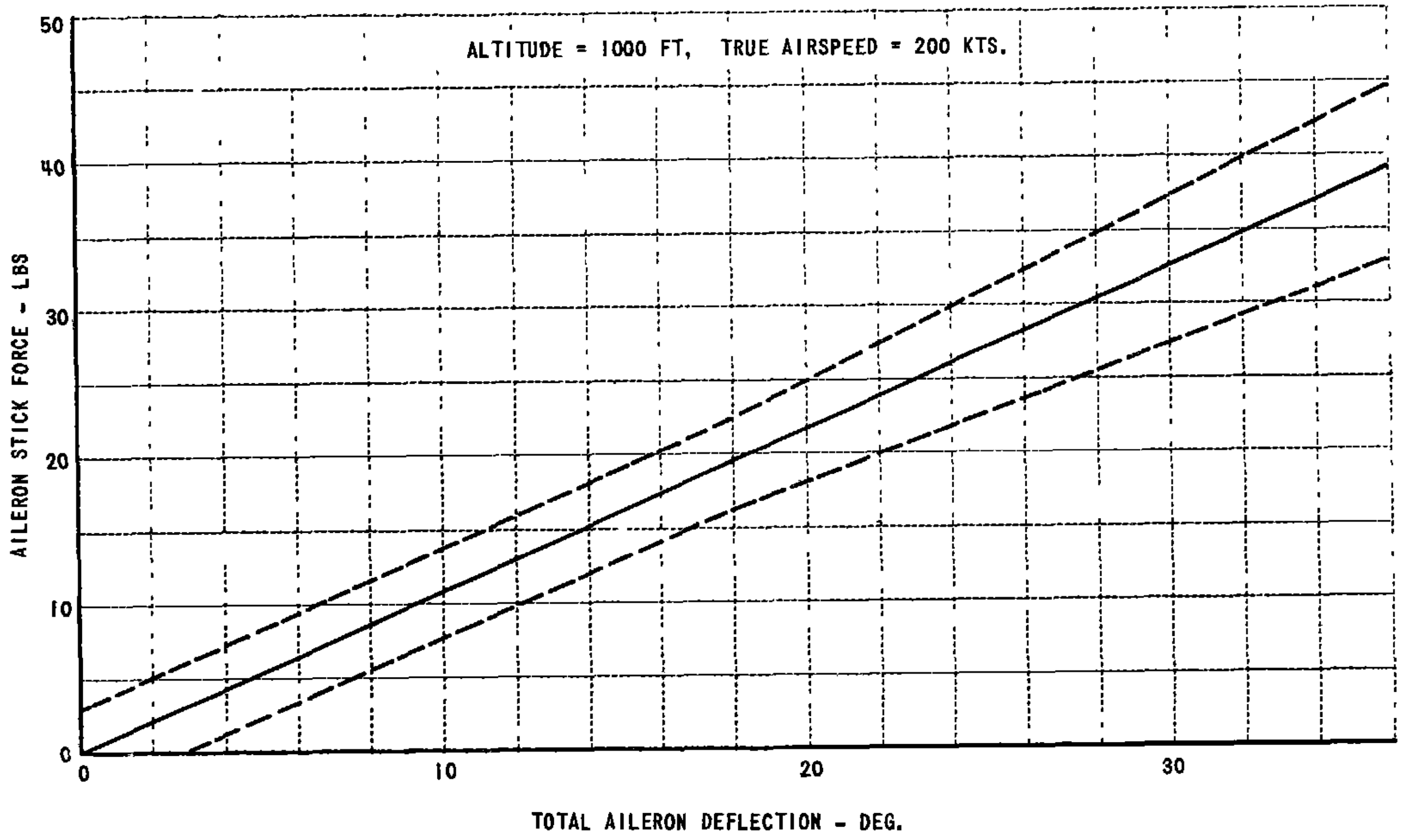


FIG. 5 AILERON STICK FORCE TOLERANCE FOR TYPICAL AIRCRAFT-CLASS SIMULATOR

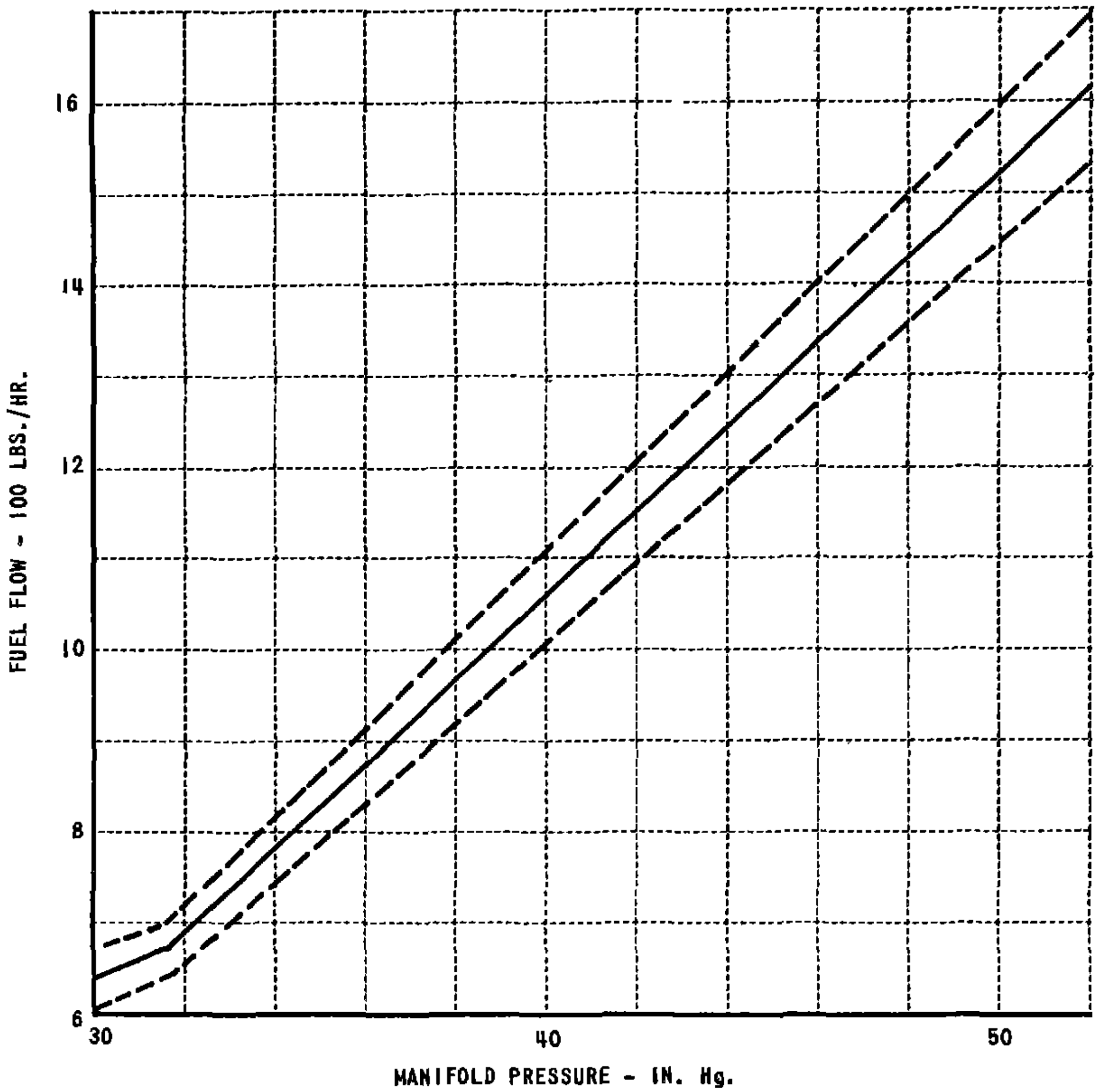


FIG. 6 FUEL FLOW TOLERANCE FOR TYPICAL AIRCRAFT-CLASS SIMULATOR

1 "The forces required to move the control stick were so great that pilots unconsciously used both hands to control the trainer "

2 "Aileron control was extremely sensitive This caused the pilots to set up lateral oscillations in the trainer "

3 "A longitudinal overshoot caused the pilots to over-correct constantly while tracking the target "

4 "Acceleration and deceleration rates are low . this causes an experienced F-100A pilot to use afterburning too often to maintain flight conditions which seem normal."

5 "For a given power setting, the climb rate and the indicated airspeed are low."

6 "The G forces which can be obtained and maintained [on instruments] are unrealistic "

FLIGHT SIMULATOR ACCESSORIES

Simulator manufacturers provide a number of auxiliary devices which are not essential for basic simulator operation, but do help to present a more convincing impression of flight In some cases, these accessories are included as standard equipment, but in others, they are supplied as optional, at extra cost

Noise Simulation

Simulation of engine and airstream noise is standard on practically all flight trainers of both types (aircraft and aircraft-class) The noise generated varies in both frequency and amplitude depending upon the flight conditions In some training units, the noise of auxiliary equipment, such as motors and generators, is also simulated Tire screech, which is almost always simulated, is extremely important since, in the simulator, it is the pilot's only indication that he has touched the ground (In some instances, this is augmented by "landing bounce" from a motion system)

Motion Systems

It is impossible to simulate the correct physical sensations of flight, but means have been devised to provide the pilot with, at least, a partial representation of his orientation and the forces acting on him In the Link Trainer of 1929, angular movements of the cockpit were reproduced quite realistically, but this type of motion system which simulates orientation, but not forces, often presents a misleading impression of flight For example, in a coordinated turn, the cockpit will roll providing the pilot with the correct visual sensation of bank but also the physical sensation of lateral acceleration This presents the impression, not of a coordinated turn, but of a sideslip On the other hand, it is quite impossible to duplicate the actual accelerations felt by the pilot during various maneuvers As a compromise, the motion systems currently in use are hydraulically-actuated to reproduce only the initial build-up of accelerations which are allowed to decay imperceptibly as the aircraft motion reaches steady accelerated states. This allows the actual cockpit movements to be kept within manageable proportions and still give the pilot all the physical warning of the aircraft's responses to his control efforts [13] Motion systems of this type, costing $50, 000-100, 000, not only give a reasonably convincing impression of flight, but they provide the pilot with force cues, thereby alleviating the tendency to "overload" the aircraft

Visual Landing Systems

There are two similar visual systems, both employing a vertically mounted three-dimensional terrain model with a traveling TV camera which is displaced and rotated by signals from the computing section of the simulator

1 Link Visual System Mark IV
   a Model size 10 ft x 70 ft
   b Model represents terrain 3000 ft. wide by 7000 ft long
   c Pilot's viewing angle (horizontal plane) approximately 45°
   d Breakthrough 600 ft or less

e. Night or day landings (additional visibility data unavailable)

f. Cost $200, 000

2 Curtiss-Wright "Visulator"

a Model size 8 ft x 13.5 ft

b Model represents 10 sq miles

c Pilot's viewing angle (horizontal plane) 90°

d Visibility zero to unlimited

e Cost $145, 000

Another notable visual system is the DALTO (Doman-Approach-Landing-Take-Off) manufactured by Doman Helicopters, Inc This unit employs a horizontal moving belt on which are painted fluorescent markings that duplicate runway lights and markings. A TV camera photographs the display and the picture is projected on a screen in front of the cockpit in a manner similar to other visual systems This system permits breakthrough at 300 ft or less and simulates visibility from 300 to 2600 ft

Radio Aids

Most flight trainers of both types provide simulated radio stations (usually from 2 to 6 in number) as standard equipment These stations, using the appropriate call letters and frequency, can be positioned geographically on a radio aids map board and can simulate such facilities as VOR, ILS-GCA, LFRR, DME, etc The inclusion of radio aids increases the cost of a simulator by approximately $100, 000

An eight-station Automatic Radio Aids Unit (AT-500) manufactured by Air Trainers Link Ltd * is available for use with flight trainers having no radio aids simulation

* Air Trainers Link Ltd of England is a subsidiary of Link Aviation, Inc Purchases can be made through Link Aviation, Inc., Binghamton, N Y

SYSTEM COMPATIBILITY

It is important to note that flight simulators are designed as self-contained training units, whereas in FAA applications, they will be one link in a large system Consequently, the simulators must be capable of supplying information to other components in the system.

Any output or input which might be of interest in an analysis of air traffic control problems certainly appears somewhere in the computing section of a flight simulator If the quantity appears as a servo shaft rotation, a potentiometer excited by an external voltage may be connected to the shaft If the quantity appears as a voltage, it can be transformed to another voltage compatible with a computer, radar simulator, recorder, etc In any event, simulator manufacturers are certain that it is feasible to extract data from the simulator and feed it to another component in the system without unreasonable expenditure of time or money

MANUFACTURERS' DATA

The following pages present a summary of information obtained from five major simulator manufacturers Whereas all the companies produce training units for the military, only Curtiss-Wright and Link manufacture simulators for civil aircraft

All figures and data were obtained from either manufacturer's representatives or company publications. Additional information in the form of sales brochures and installation handbooks can be obtained by writing directly to the companies The following reference contains a large quantity of data pertaining to flight simulators used by the Air Force

Standard Aircraft Flight Simulator Characteristics
Air Force Guide No 4 Orange Book

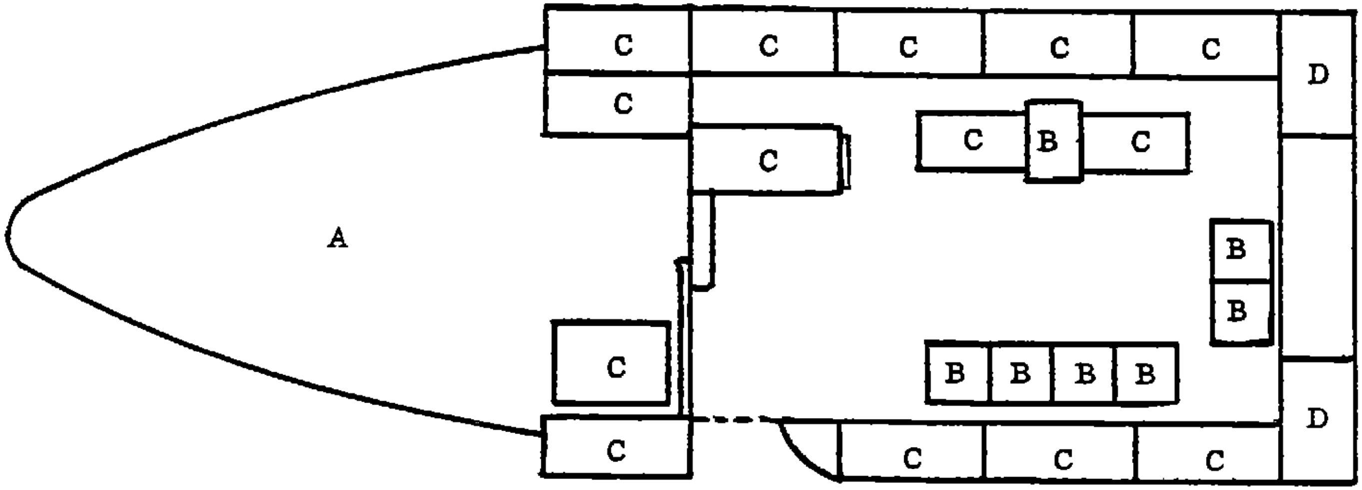
Curtiss-Wright

1 Design Features and Accessories -- Almost all of Curtiss-Wright's simulators have used AC computation up to the latest civil jet and turboprop transport units Non-linear aerodynamic functions are generated with potentiometers which are wound on contoured cards This gives smooth, accurate representation of the function but replacements cannot be made from stock items. A full complement of accessories is available, including a newly developed visual system, cockpit motion (pitch and roll), and cockpit noise (engine, aerodynamic, crash, tire screech)

2. Cost -- Initial cost varies from $500,000 to $1,000,000 depending on the complexity and year of design No specific operating figures were given by Curtiss, but a planning manual (which has been furnished the FAA) included data which could be used to arrive at some costs Maintenance was estimated at 1 62 man-hours per hour utilization based on eight hours per day operating time Data on spare parts needed over a 3000 hour period are also included, and personnel requirements are also discussed

3 Weight -- The typical simulator weighs about 29,500 pounds uncrated with the heaviest single piece weighing 2000 pounds The floor loading of the heaviest piece of 250 pounds per square foot (see Fig 7), although transient loads up to 500 psf can be encountered when cockpit motion is present Most units are mounted on legs which concentrate the load up to 350 psi Steel plates can be used to spread the load if necessary

4 Size and General Layout -- Curtiss uses a layout which places all computing and power equipment behind the cockpit (see Fig 8) The simulator size varies depending on the accessories used Without visual or motion simulation, the simulator is 39 feet long, 13 5 feet wide and 9.5 feet high, 40 x 20 5 x 14 with visual system (does not include visual studio 19 x 8 x 12), 42 x 13 5 x 12 5 with motion, 43 x 20 5 x 18.6 with visual and motion



KEY TO LOADING

A - 100 lb/ft.^{2}

B - 150 lb/ft.^{2}

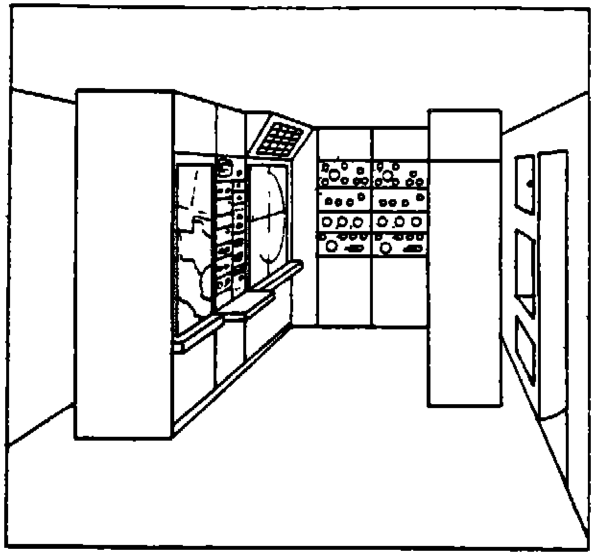
C - 200 lb/ft.^{2}

D - 250 lb/ft.^{2}

Above values are maximum

ESTIMATED TOTAL SIMULATOR WEIGHT - 29,500 lbs.

FIG. 7 FLOOR LOADING ESTIMATE FOR CURTISS-WRIGHT DEHMEL SIMULATOR



INTERIOR OF SIMULATOR

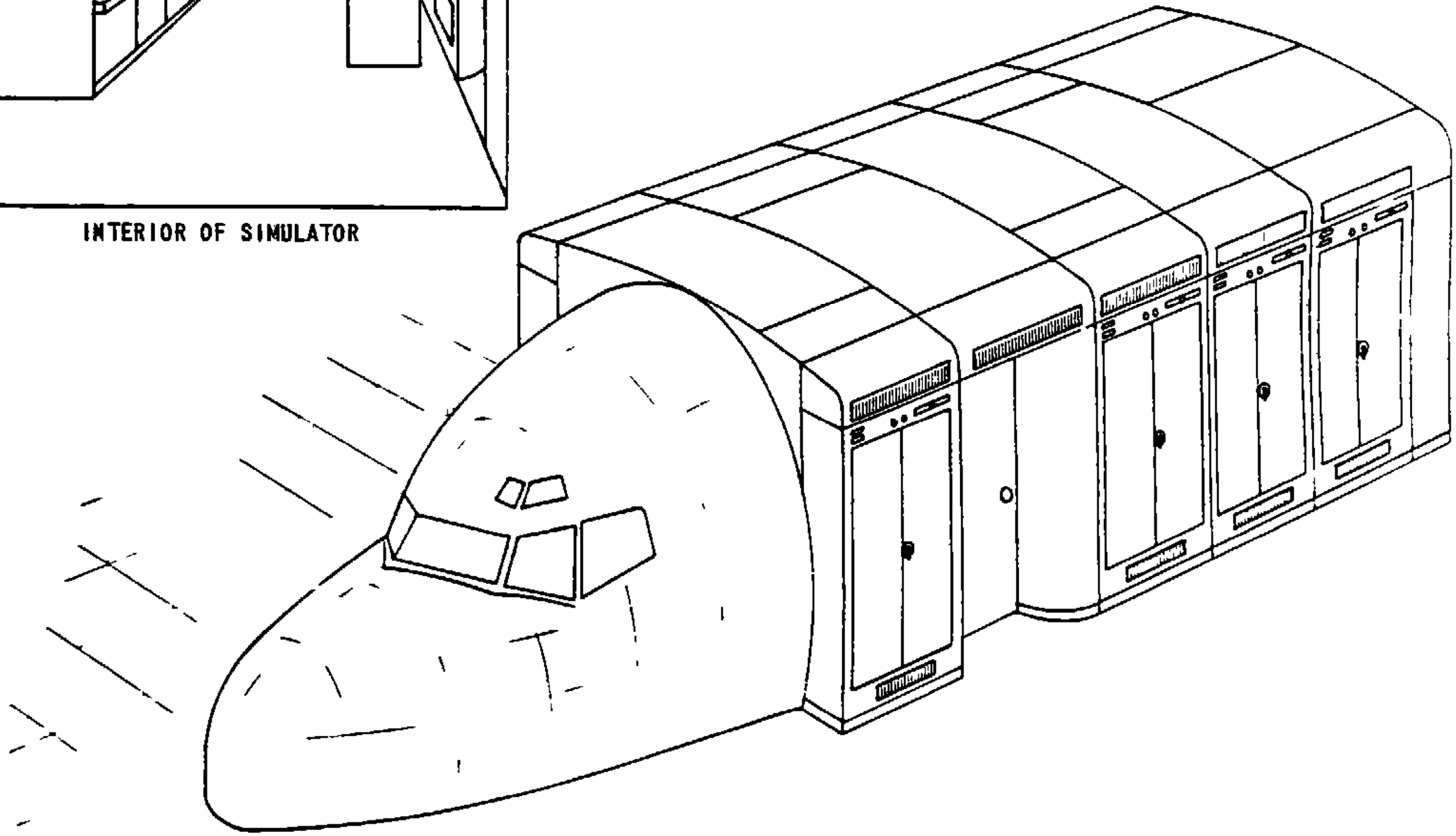


FIG. 8 GENERAL LAYOUT FOR CURTISS-WRIGHT DEHMEL SIMULATOR

5 Power and Air-Conditioning Requirements -- Three phase, Y-connected power is required at 208/120 ± 10 volts and 60 cps. A minimum of 50 kilowatts plus 20 for visual system and 10 for cockpit motion is required The maximum allowable rate of line voltage fluctuation is 10 volts per second, maximum distortion is 6% and maximum unbalance 2% The simulator has an interior five-ton air-conditioner which can absorb 60, 000 BTU per hour Since the total heat liberated is 136, 000 BTU per hour this leaves 76, 000 BTU per hour which enters the simulator room. Curtiss recommends room air-conditioning to control temperature and humidity and remove dust

6 Specific Data -- Curtiss has built simulators of the following aircraft

B-36F	C-121C	F2H-1	DC-7B, C
B-50D	RC-121D	F4H-1	Lockheed 1049-G
B-52B, D, F, G	C-124A, C	WV-2	Lockheed 1649-A
C-97A	C-130A, B	A4D-2N	Lockheed Electra
KC-97G	C-131A	Boeing 377	DC-8
C-118A	C-133A, B	CV-340	707
C-119C, G		DC-6B	

Also available is a general purpose navigation trainer It can be made to represent either a jet or a turboprop aircraft, and can be landed to the point of touchdown. Cockpit motion is included

The P-3A Duplicator which is in use at NAFEC was built during World War II as an instrument trainer patterned generally after the B-25 It has a single-place cockpit and was not designed to land or take-off.

Erco

1 Design Features and Accessories -- All Erco simulators have AC computing sections, except one of their most recent designs, the F-105 simulator, which has DC computers All simulators are built to fit in legal-size trailers even though the customer may not require trailerization Erco has designed a visual landing presentation for their F-105, and, previously, an Erco carrier landing training device had a visual illusion produced by closed circuit television The other standard accessories of cockpit noise and motion are also available

2 Cost -- The cost is highly variable depending on how complex the simulator and its training mission are The KC-135 simulator is roughly $500, 000 and the Navy general instrument trainer (2-F-25) is $200, 000, with $100, 000 additional cost for radio aids

3 Weight -- No general weight data was available, but the KC-135 installation specification calls for a floor capable of carrying 250 pounds per square foot The heaviest single piece of this simulator weighs 3000 pounds

4 Size -- As stated above, all Erco's simulators will fit in trailers These trailers are 12 feet high and 8 feet wide with lengths running from 36 to 40 feet Some simulators require two trailers The KC-135 when installed in a room requires a room 38 x 34 x 14 feet high for sufficient working space around the simulator (see Fig 9)

5 Power and Air-Conditioning -- The KC-135 requires three phase power at 208 volts ± 10% and 60 cps ± 5 cps The load is 33 kilowatts With the cockpit and instructor's and operator's stations air-conditioned by using air from outside the simulator room, the effect on simulator room temperature during operation should be small (approximately 16, 000 BTU/hour gain due to surface conductance and radiation)

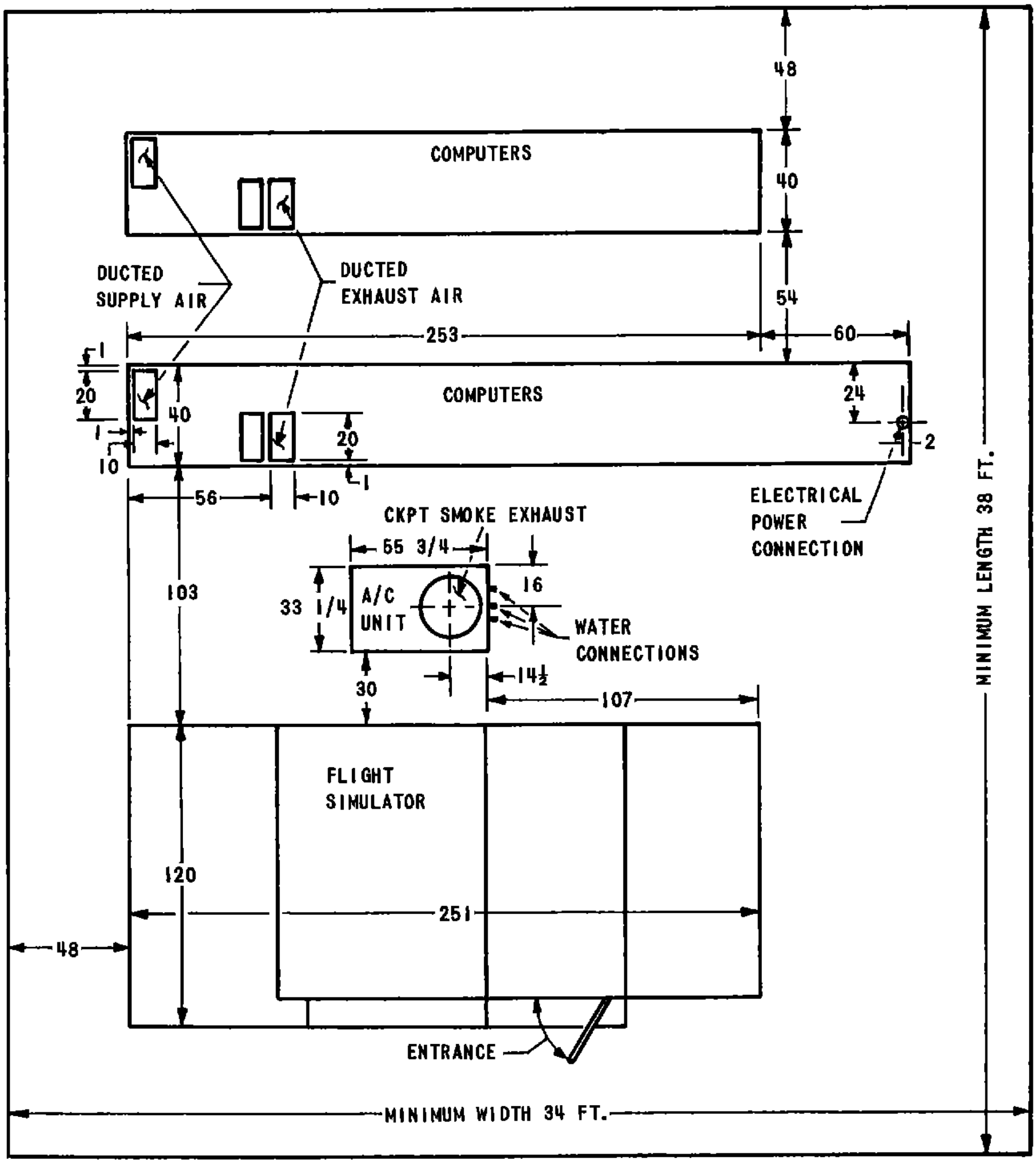


FIG. 9 GENERAL LAYOUT FOR ERCO KC-135A SIMULATOR

6 Specific Data -- Erco has built the following simulators

F9F-2, 5, 6	P5M-1	B-57B
F-86D, K	A3D-1	F-105D
S2F-1, 3	F4D-1	P2V-5, 7
AD-5N	B-66B	KC-135

In the line of aircraft-class simulators, Erco has recently designed the Navy 2-F-25 (Erco Twin) which is a twin engined, reciprocating, instrument and navigation trainer, patterned after the B-25 and Convair 340 This simulator has some of the features of more costly simulators such as take-off and landing capability and cockpit noise simulation

Goodyear

1 Design Features and Accessories -- Goodyear builds the following flight simulators F3H-2, F3H-2N, and the P6M All these units are trailerized, utilize 400 cps AC computation, and are classified under government security regulations

2 Cost -- The F3H-2 and F3H-2N units cost between 1 0 and 1 5 million dollars The P6M costs between 1 5 and 2 0 million

3 Weight -- No data available

4 Size -- All units are mounted in 10' x 40' trailers

5 Power and Air Conditioning -- No data available

6 Specific Data -- In addition to the above simulators, Goodyear produces a general-purpose unit, the Aircraft Flight Synthesizer (AFS), which is discussed in detail in the section on Aircraft Simulation Using General Purpose Equipment, pg 46

Link

1 Design Features and Accessories -- Link uses DC computation in special purpose flight simulators, thereby achieving greater accuracy in dynamic flight conditions Before 1954 Link used AC computation, so that only the more recent Link simulators have this feature Non-linear aerodynamic data is represented by tapped potentiometers These have the advantage of simplicity of manufacture and can be replaced by standard parts, but a small amount of accuracy and smoothness of data representation is sacrificed All the accessories typical of the present state of the art are available, including a visual system operating by closed circuit television, cockpit motion, and noise

2 Cost -- Flight simulators representing all phases of operation and incorporating most of the newest developments in the field cost about $1, 000, 000 The range of variation can be from $500, 000 to $1, 500, 000, depending on the aircraft, the mission simulated, and the accessories used Link also has manufactured several aircraft-class simulators, not simulating any specific aircraft but having the characteristics of a restricted class of aircraft The cost of these ranges from $100, 000 to $300, 000

Operating cost is estimated by Link as $55 47 per hour for jet aircraft simulators operating eight hours a day

3 Weight -- Total weight varies from 15, 500 to 48, 000 pounds for simulators of full complexity and 7, 000 to 10, 000 for aircraft class simulators Floor loadings are 50 to 185 psf and 40 to 70 psf respectively with up to 340 psf generated on the former during transients of cockpit motion Some units are equipped with casters so point loadings are important

4 Size and General Layout -- The length varies from 17 to 34 feet, the width from 8 to 29 feet, and the height from 9 to 13 feet The typical layout preferred by Link is roughly square as in Fig 10

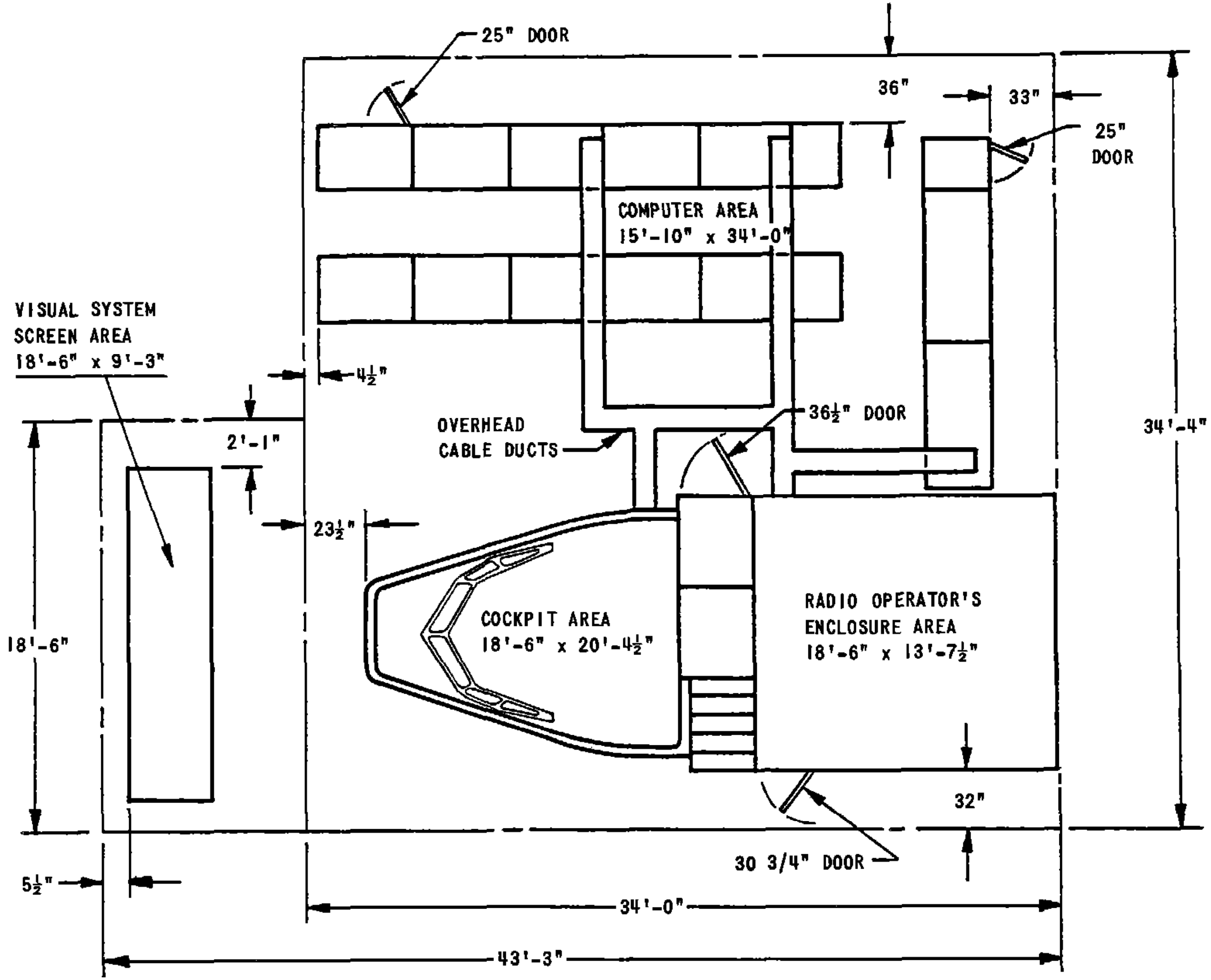


FIG. 10 GENERAL LAYOUT FOR LINK BOEING 707 SIMULATOR

JA-1266-S-8

5 Power and Air-Conditioning Requirements -- Usually three-phase 208/230 volt power is required with ± 10% variation tolerated Frequency is 60 cps ± 5 cps and the kilowatt requirement varies from 6 5 for the simplest trainer to 50 for the most complex Most units are air-conditioned, but the heat exhausted to the room ranges from 8, 000 to 160, 000 BTU per hour

6 Specific Data -- The Boeing 707 simulator and the ME-1 jet instrument trainer are described below as representative of the two different simulator types.

Boeing 707 -- Cost $1, 000, 000

Weight 48, 000 pounds (with motion)

Weight Breakdown

Unit	Max Weight	Max Avg. Floor Load	Max Concentrated Load
Computer Cabinets	22, 500#	160 psf	550 lbs on 7 sq in
Power Cabinets	9, 500#	185 psf	1, 200 lbs on 7 sq in
Radio Operator's Enclosure	4, 000#	50 psf	350 lbs on 7 sq in
Cockpit (Without Motion)	10, 500#	72 psf	3, 500 lbs on 45 sq in
(With Motion)	12, 000#	85 psf	30, 000 lbs max on 96 sq in area for 10 millisecond transient

Size -- (see Fig 10) Maximum height 13' 3" without visual system -- with visual, 16'

Power and Air-Conditioning -- 3 phase, 208 volts, 60 cycle, 4 wire or 3 phase, 230 volts, 60 cycle, 3 wire Voltage regulation ± 8% Frequency regulation ± 3% Load 36 kilowatts Total heat exhausted to room -- 160, 000 BTU/hour

ME-1 -- Cost $300, 000

Weight 10, 000 pounds

Weight Breakdown

Unit	Weight	Floor Loading
Cockpit	3, 500#	57 psf
Radio Aids Cabinet	800#	56 psf
Engine Computer Cabinet	800#	63 psf
Flt Computer Cabinet	1, 000#	79 psf
Hydraulic & Pneumatic Cabinet	1, 500#	118 psf
Power Supply Cabinet	1, 800#	142 psf

Size -- (see Fig 11)

Power and Air-Conditioning -- 3 phase 208/230 volts ± 10% Frequency 60 cps ± 5 cps Load 12 kilowatts (est) Total heat exhausted to room under most severe temperature conditions -- 45, 000 BTU/hour

Link has made a simulator for each of the following aircraft

DC-8*	B-47B, E
Boeing 707*	F-102
Convair 880	F-106
Lockheed Electra	A3J
F-89, D, H	F8U
F-89J	B-58

Also these aircraft-class simulators have been built

E-600	(Convair 340 class)
AT-100	(DC-3 & Convair 340 class made by Air Trainers Link Ltd)
C-11	(F-80 class)
ME-1	(T-37 class)

* These units have the flexibility to simulate any of the various production models

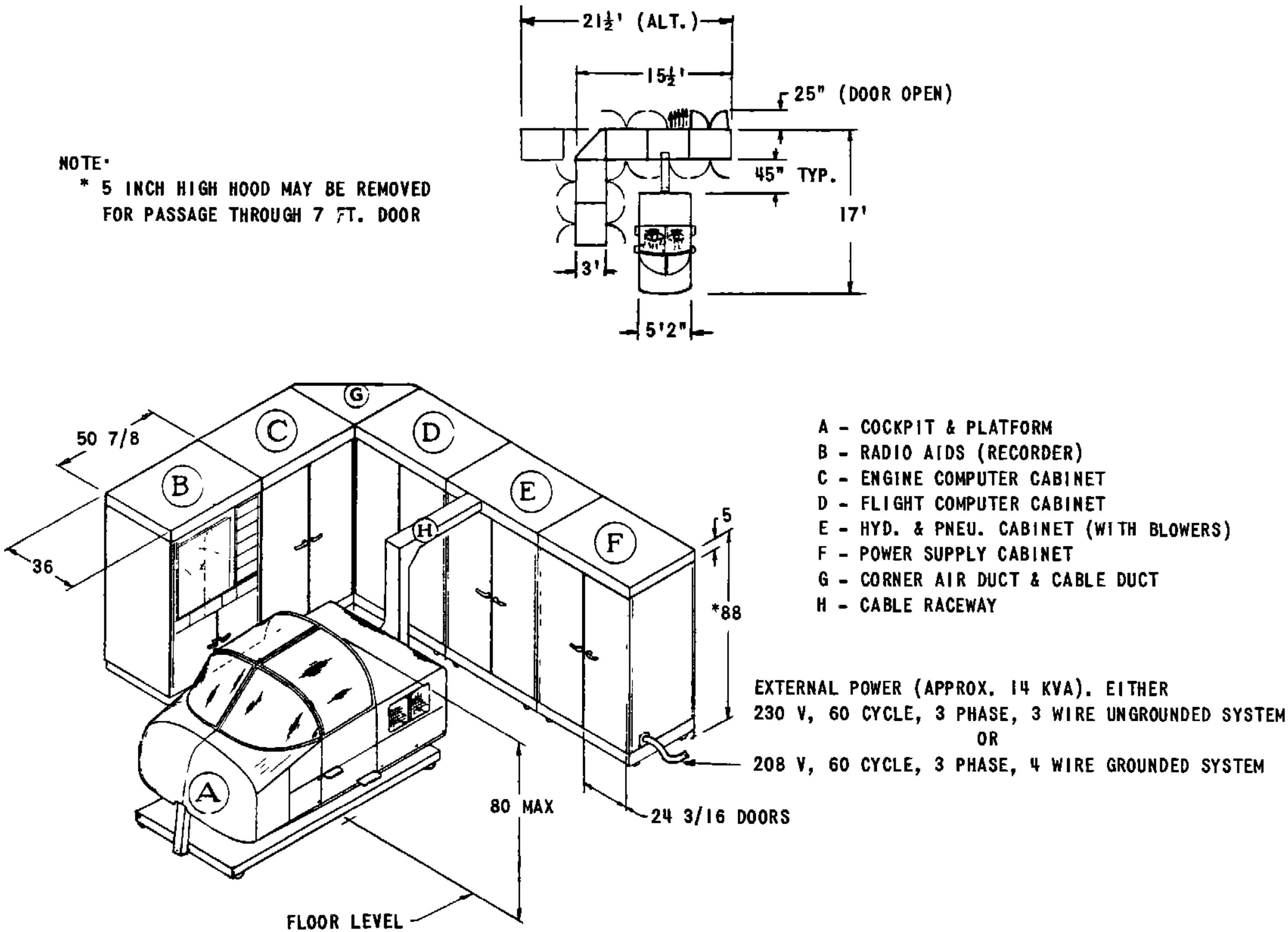


FIG. 11 GENERAL LAYOUT FOR LINK ME-1 TRAINER

Melpar

1 Design Features and Accessories -- Melpar is currently building simulators for the A4D and F-101, previously they produced simulators for the F-86 and F-100 series fighters The A4D simulator is trailerized, but the others are designed for room installation All Melpar units utilize AC computation Noise and radio aids are simulated in all units, and motion is provided in the current production models (A4D and F-101)

2 Cost -- The cost of the F-86 and F-100 simulators is $500, 000 each The A4D and F-101 cost approximately $1, 500, 000

3 Weight -- The F-100A weighs 23, 405 lbs and requires a floor capable of supporting 100 pounds per square foot, no other information was available

4 Size -- The F-100A requires a room size of 33 x 40 x 11 feet high When this simulator is used in conjunction with the Rheem F-151 Aerial Gunnery Trainer, the required room size is 40 x 60 x 20 feet high (see Fig 12)

5 Power and Air Conditioning -- The F-100A requires three phase power at 208 volts ± 8%, 60 cps, and 200 amps A second identical source is required for the F-151 Gunnery Trainer The simulator is cooled by two independent air-conditioning units -- a three-ton unit for the instructor's room and a 1-1/2 ton unit for the cockpit In addition, an exhaust fan capable of exhausting 5, 000 cfm to the outside of the building is recommended

6 Specific Data -- The F-100A simulator was designed to provide instruction in cockpit familiarization, flying technique, emergency procedures, and radio navigation When used in conjunction with the Rheem F-151 Aerial Gunnery Trainer, it also provides gunnery practice under visual flying conditions.

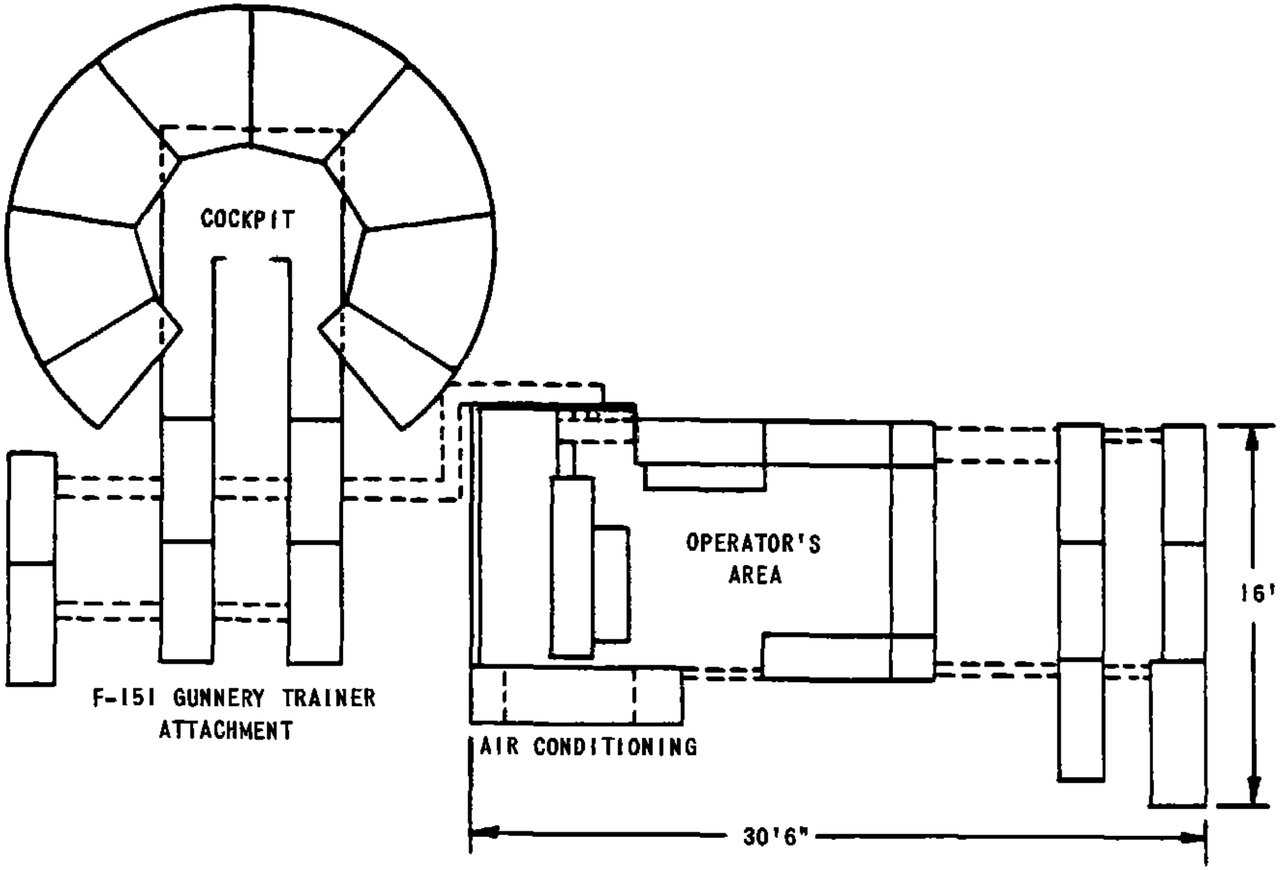


FIG. 12 GENERAL LAYOUT FOR MELPAR F-100A SIMULATOR

This unit has facilities for simulating two radio stations in conjunction with 800 x 800 mile and 60 x 60 mile plotting boards

Turbine whine, exhaust noises, and instrument indications are realistically simulated

AIRCRAFT SIMULATION USING GENERAL PURPOSE COMPUTING EQUIPMENT

The general purpose analog computer and the flight simulator computing section are quite similar The flight simulator, as described previously, is basically an analog computer wired to solve the aircraft equations of motion It solves these equations continually by accepting inputs from the pilot's controls The output motions of the aircraft are obtained at the appropriate points in the circuit and converted to cockpit indications The computer is built, as is a general purpose analog computer, from basic components, each performing an elementary mathematical function In one component, the output may be the integral of the input, in another, it may be just the negative of the input, in another, two inputs may be multiplied together to give the output, in another, the output may be the sum of several inputs, etc

One of the basic differences between the general purpose analog computer and the flight simulator computer section is that, in the latter, these basic building blocks are wired together in a permanent fashion to solve one set of equations, whereas, the general purpose computer can be easily rewired to deal with any computing problem requiring the basic mathematical operations which the computer can perform

It would appear that, in the case where the simulator customer has a requirement for general purpose computing equipment, or has the need to simulate many different aircraft, the use of general purpose equipment instead of conventional flight simulators might be more economical The same equipment could be used for a variety of computing work As new aircraft appear on the scene, the same equipment could be adjusted to simulate their flight characteristics Recording the motions of the aircraft would require no additional manipulation of the signal since general purpose equipment is designed so that all input-output parts of each basic mathematical operation are available for direct recording

The answer to the question of economy rests to a large extent on the scope and fidelity required in the simulation Aircraft manufacturers and research engineers have been using general purpose analog computing equipment for economical simulation of aircraft for many years, but the problems they investigate are rarely of the same order of magnitude as the complete flight simulation problem Much of their work does not require that a cockpit be connected to the computer, and typically, only the dynamic or transient motions are of interest, whereas in air traffic control applications, steady-state flight is usually of greater importance A common assumption made in dynamics work is that the airspeed is constant This assumption greatly simplifies the simulation task since aerodynamic parameters which are a function of Mach number can be kept constant and the number of equations reduces from six to five Such a simplification, of course, is not feasible when a wide range of flight conditions must be simulated, as is the case in air traffic control problems

In a few instances, engineers have used general purpose equipment in a simulation effort approaching that achieved by flight simulator manufacturers But here the gains in versatility of equipment begin to be nullified by the complexity of the problem An example of such an effort is the work of the Airborne Systems Laboratory of RCA in Burlington, Massachusetts In testing pilot reaction to various fire control systems, high-performance, single engine fighters are simulated throughout much of their flight regime Electronic Associates' PACE equipment is used including 300 operational amplifiers, 16 precision resolvers, 20 multiplying servos, 20 function generating servos, and 10 rate resolvers (integrators) Realistic cockpits are used and many, but not all, of the cockpit controls and instruments are simulated. The computation equipment is valued roughly at \$500, 000 and the cockpit and associated servo equipment at \$200, 000 Several technicians are employed to trouble-shoot, repair, and augment the equipment It was stated that roughly twice the amount of equipment would be needed to handle flight at all Mach numbers and altitudes with the fire control equipment, non-linear aerodynamics, and aeroelastic effects included In the opinion of RCA personnel, the system has been less reliable in operation than an inflexible flight simulator. Not mentioned, but still indispensable in this operation, are a number of engineers thoroughly familiar with aircraft simulation and computer techniques The technical know-how required is comparable to that of engineers in the flight simulator design field itself To set up a complete simulation problem requires about six engineering man-weeks

It can be seen from the above discussion that straightforward application of general purpose analog techniques to simulate aircraft must somewhere reach the point of diminishing returns as the complexity of the problem increases Justification for using such equipment for a complex problem hinges on whether or not a flight simulator which could do the job is available, or whether the degree of flexibility desired can be obtained any other way

Another approach to the problem of simulating many different aircraft economically is to start with the permanently wired and programmed flight simulator and provide convenient ways to change the simulator characteristics Recently, the military and the flight simulator industry have realized the need to make their flight simulators more flexible Some ideas have been suggested -- making part of the circuitry flexible by using cards or plug boards, substituting digital computation for part of the problem, or making a flight simulator which uses digital computation exclusively A digital computer has been developed which can solve the aircraft motion equations in real time This is the Sylvania Universal Digital Operational Flight Trainer (UDOFT) computer, designed by the University of Pennsylvania By special techniques, the time required to evaluate all the equations has been reduced to 50 milliseconds, which means that the aircraft position is recomputed 20 times per second. Presently, an experimental version of the computer is being built, and it will be tested using Erco F9F-2 and Melpar F-100A cockpits Results, thus far, have shown that a great deal of flexibility will be achieved, although it will be a minimum of two to three years before the development stage is complete The size, weight, and power requirements of the present computer are quite large and a transistorized version is contemplated as the end product One and a half million dollars is a rough estimate of the procurement cost of the final version

Another development along these lines is the Goodyear Aircraft Flight Synthesizer This unit is similar in concept to the Sylvania UDOFT except that the scope of the simulation is reduced, and its computation is done entirely by analog The AFS was designed as a flexible research tool and is not a device for training pilots. Basically, it is an AC (400 cps) analog computer pre-wired to solve the aircraft equations over the complete flight spectrum, including take-off and landing. Its design includes provision for inputs (DC or 400 cps) representing power setting, control surface deflection, flaps, landing gear, etc These signals can originate from another analog computer or from potentiometers linked to controls in a cockpit mock-up Outputs such as airspeed, altitude, orientation angles, etc , appear as servo shaft positions A potentiometer mounted on each servo shaft provides output signals that can be fed to cockpit instruments, computers, or recorders The aircraft's power plant and aerodynamic characteristic are inserted in the AFS through the use of plug-in printed circuit boards (or potentiometers) and can be changed easily

The size of the computing section is 84 inches long, 28 inches wide, and 78 inches high and its cost including simple cockpit controls is approximately $200, 000 Such items as radio aids, stick forces, and system failure simulation can be added to the basic unit

Theoretically, one AFS can simulate anything from a Piper Cub to a DC-8, however, Goodyear recommends that an AFS specifically designed for each performance class of aircraft will yield greater resolution of output data. The accuracy in duplicating actual aircraft performance, stability, and control as well as such details as high speed buffet, trim changes due to flap settings, gear extension, etc , and changes in stall speed with power is up to the standards of more sophisticated simulators

It is questionable at this time how much additional cost and complexity would be needed to provide an adequate simulation of the pilot's environment and task Also, another factor in the cost would be the procurement of aircraft data and the actual programming of the computer The time required to reprogram the computer to represent a different airplane may be important if changes are contemplated frequently

Undoubtedly, the trend in flight simulation is toward increased flexibility However, a reasonable summary of the state of the simulation art is that, for the time being, flexibility without sacrificing scope or fidelity of simulation is not yet practical for the general user

This does not eliminate general-purpose or flexible special-purpose equipment from consideration where some simplifications would be acceptable in representing the aircraft Most off-the-shelf simulators have been designed for pilot and crew training and therefore include many features which would be unnecessary in the ordinary navigation and instrument flying tasks These features include such things as aircraft subsystems failures, military mission simulation, and high Mach number and inertia coupling stability problems. A significant simplification could be made for those aircraft which have supersonic top speed capability but cruise subsonically, since speeds higher than normal cruise might be unnecessary in cross-country flying, and certainly all flying within terminal areas will involve subsonic speeds By restricting the problem to subsonic Mach numbers, the large variations in aerodynamic parameters could be avoided

Thus, it is possible that the use of flexible computation equipment may prove advantageous in the FAA in traffic control simulation problems

The following is a short list of papers and reports dealing with the use of general-purpose computing equipment in flight simulation

UDOFT, Presentation at U S Naval Training Device Center, Electronic Systems Division, Sylvania Electric Products, Inc , January 1958

Melpar F-100A Operational Flight Trainer - Simulation of a Supersonic Fighter Using a Digital Computer, University of Pennsylvania Moore School, Report 55-20

Blanton, H E , Use of Flight Simulators in the Design of Aircraft Control Systems, Aeronautical Engineering Review, February 1954

Eakin, G , A Mechanically Implemented Normal Acceleration Limiting System, Cornell Aeronautical Laboratory, Inc Report No TB-986-F-1, 1956

Connelly, Mark E , Simulation of Aircraft, Servomechanisms Laboratory, Massachusetts Institute of Technology Report 7591-R-1, Feb 15, 1958

The Proceedings of the First Flight Simulation Symposium, White Sands Proving Ground Special Report No 9, November 1956

- Rubinoff, M , Some Recent Developments in Real-Time Digital Simulation and Control
- Murry, F J , Combined Use of Digital and Analog Simulation
- Leger, R M , Requirements for Simulation of Complex Control Systems
- Hamer, H , An Automatic Digital Input-Output System for Analog Computers
- Nosker, P , Dynamic Systems Synthesizers
- Bauer, L , Karen, A , and Lovemen, B , Solution of Large Problems at Project Cyclone
- Steinhoff, E A , and Green, M C , Real-Time Flight Performance Analysis
- Warshawsky, M., WADC's New Large Analog Computer

CONCLUSIONS AND RECOMMENDATIONS

In selecting flight simulators, the objective of the FAA is to provide the ATC simulation system with "real airplanes" which are representative of all variations of aircraft complexity and capability Referring to pp 9-11 , it appears that specifying at least one simulator for each group of aircraft would provide complete coverage of the current aircraft fleet Such an approach, however, is not only unfeasible from the standpoint of economy, but is quite impossible since simulators are not available for all aircraft groups.

In order to effect a more practical solution to the problem, the following conclusions and recommendations are presented

1. The NAFEC has already acquired the following flight trainers

   Curtiss-Wright P-3A
   Link C-11
   Melpar F-100A

   Although the over-all suitability of these simulators may be questionable, they certainly possess the basic capabilities for performing preliminary experiments to further investigate the role and the requirements for flight simulators in the experimental facility. The results of these preliminary experiments will help to establish a firmer basis for the selection of additional flight trainers and appropriate action can then be taken

2. There appears to be a definite need for ~~a simulator for~~ an aircraft simulator in the large civil jet aircraft category (Douglas DC-8, Boeing 707, etc) and it is recommended that such a simulator be acquired. This recommendation is based on the fact that high performance airplanes of this type will, when mixing frequently with heavy piston-engine traffic at civil airports present new problems which the FAA will be particularly concerned in investigating. In particular, such factors as fuel consumption and noise will probably require a revision in the current methods of terminal control. Additionally, the pilot/crew workload involved in the operation of large jet aircraft approaches a maximum from the standpoint of physical capacity.

3. Whenever possible, the acquisition of a civil flight trainer should be favored over that of a military version. Any security classification, if it exists, will obviously limit the usefulness of the entire simulation facility Further, the instruments, radio, and navigational equipment in military aircraft often differ from that found in civil aviation. Finally, some of the military aircraft may not include various control devices, such as speed brakes, whose absence may prevent thorough examination of traffic control system operations.

4 The acquisition of a general purpose computer-simulator would offer many advantages. A unit such as this could be used to simulate aircraft for which no commercial flight trainers exist and also any future aircraft Designed basically as a research tool, the unit could readily investigate the effect on air traffic control of varying performance parameters of any aircraft. Unfortunately, simulators of this type require sources of accurate aerodynamic and propulsive input data, as well as a highly-qualified complement of engineers and technicians to program, maintain, and operate the unit. In addition, a cockpit configuration must be purchased or built for each type of

aircraft simulated. It is apparent, therefore, that the advantages and disadvantages must be considered in great detail before any decision is made regarding a unit of this type.

It is recommended, at this time, that the purchase of general purpose computer-simulator be delayed until early simulation experiments have shown whether it is needed, and have defined better how it would be used.

5 Although it is beyond the scope of this task, it appears that investigation is warranted in the field of human factors Specifically, the psychological differences between simulator and actual flight operation should be investigated to determine how these differences affect the pilot's control actions, and ultimately the performance of the simulation system

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