LEAN PREMIXED-PREVAPORIZED COMBUSTOR DESIGN STUDY

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Phase I of the Lean Premixed-Prevaporized Combustor Design Study is a nine month analytical study effort with no experimental or testing activities included. The objective of this Program is to design and analyze advanced combustor concepts with features for fuel premixing and prevaporization upstream of the combustion zone for use in future subsonic aircraft engines. All of the designs also embody some form of variable geometry for combustor flow modulation. The primary criterion for these designs is low oxides of nitrogen (NO_x) emissions at stratospheric cruise conditions. The specific goal for these designs is an emissions index for NO_x of less than or equal to three grams per kilogram at the cruise condition. Additional criteria include meeting the ground level EPA emissions standards and all combustor performance requirements typical of advanced turbofan engines plus practicality of implementation.

In this study, four combustor concepts are being designed for the NASA/GE Energy Efficient Engine (E^3) envelope and cycle. The E^3 has a cycle pressure ratio of approximately thirty to one and a combustor exit temperature in excess of 1600K at sea level takeoff conditions. Table I shows combustor parameters at various operating conditions for the E^3. The combustor designs evolved are to be applicable to other high pressure ratio subsonic aircraft engines and one of the designs will also be designed and sized for the CF6 engine cycle and envelope.

Current status of the program is that the four concepts sized for the E^3 have been designed and are currently undergoing analysis and evaluation.

The four concepts are illustrated in Figures 2 thru 5. Table II presents design parameters. Concept 1 (Figure 2) features premixing-prevaporizing tubes with variable area primary swirlers. At cruise conditions approximately 53% of the combustor air flow is admitted through the swirlers so that the primary zone fuel air ratios are lean for low emissions of oxides of nitrogen. The equivalence ratio is approximately 0.55 at the exit of the secondary swirler. The combustor pressure drop at high power conditions is five percent. In order to obtain good low power combustion performance including low idle emissions, the primary swirler flow areas are reduced to admit approximately fifteen percent of the air flow. The equivalence ratio at the swirler exit was set at a little over 1.0 for idle. After addition of primary zone dilution and cooling air, the equivalence ratio is approximately 0.6 for good CO consumption. At idle conditions the combustor pressure drop is approximately 10 percent (versus 5 at hi power)because of the reduced dome flow. It has been shown in other experimental programs that idle emissions can be improved considerably by minimizing build up of film cooling air in the primary zone. Therefore, impingement cooling of the entire primary zone including the dome has been used to minimize the quantity of cooling required. Also the dome cooling air has been admitted in a manner to promote mixing with the primary zone gases as shown in Figure 6.

LEAN PREMIXED-PREVAPORIZED COMBUSTOR DESIGN STUDY (cont.)

Two potential problem areas with this concept are high pressure drop at low power conditions and the possibility of flash back or auto-ignition in the premix tubes. Cycle studies have indicated that at steady state conditions (i.e. idle) there is adequate compressor stall margin for the selected pressure drop. During transient conditions (i.e. acceleration from idle) where stall margin is diminished by increased combustor temperature rise, it is anticipated that the primary swirler flows would be increased to counterbalance this effect. The premix duct residence times are set to avoid autoignition time and discontinuities are avoided to the max extent possible. At high power conditions the residence time in the duct is 1.4ms. This is believed to provide approximately a two to one safety margin for auto-ignition assuming reasonably uniform flow and no discontinuities.

Some features of this design are (1) only one stage of fuel injectors is employed, and (2) primary swirlers are continuously modulating for setting optimum local operating conditions at all times including transient operation.

Concept 2 shown in Figure 3 features a multiple annular duct main stage with variable inlet vanes and conventional swirlers in the pilot stage. At cruise conditions, the duct inlet vanes are full open for lean, low NO_x operation. The main stage has low pressure drop injectors for introduction of fuel into the annular passages. Each of the injectors spray fuel into both the upper and lower passages and from both sides of the injector. Uniform fuel distribution at the entrance to the dome is the main objective. The flow from the main stage enters the dome region through ports located between the pilot stage swirlers The main stage air stream is injected into the dome at an angle to the axial centerline and in a direction opposite to that of the pilot swirlers for good mixing. The dome is illustrated in Figure 7. At low power conditions, the primary zone air flow is reduced by closing the inlet vanes and all of the fuel is introduced through conventional pressure atomizing nozzles and fixed area swirlers.

Of prime importance in the design of this concept is achieving uniform fuel distribution in the main stage. A feature of this design is that the main stage may be operated at ultra lean fuel air ratios, because of the excellent piloting of the primary stage with the arrangement selected.

At idle, the inlet vanes will be closed so that the pressure drop will be 10 percent. During transients, the vanes may be modulated for reduced pressure drop, however, main stage fuel is not admitted until the vanes are opened. The high power pressure drop is five percent.

Concept 3 (Figure 4) is a series staged system with a fluidic flow control diffuser. This fluidic diffuser achieves variable flow split without the need for moveable geometry in the combustion cavity. At cruise conditions, a large portion of the flow is directed into the main stage for lean, low NO_x operation. The main stage is fueled with low pressure drop injectors and has a series of "V" shaped flame holders which permit flow of pilot zone gases to intermingle and mix with the main stage flow. Continuous ignition of the main stage is thereby provided by the pilot stage. The pilot has conventional pressure atomizing injectors and fixed area counterrotating swirlers. This concept has the advantage that the pressure loss coefficient is comparable at all operating conditions. Fuel would not be admitted to the main stage until the flow is completely switched to the mode with high mainstage flow.

Concept 4 shown in Figure 5 is a parallel staged system with variable geometry and premixing. This system draws heavily from experience gained in the NASA/GE Experimental Clean Combustor Program, but has the advantage of variable geometry to meet the emission requirements over the required operating range. The main stage employs variable inlet vanes, sixty low pressure main stage injectors and a perforated plate main stage flame holder. Because the main stage operates only at high power conditions the perforated plate type flame holder has adequate stability. Further the low power stability of the main stage is extended by the piloting action of the pilot stage.

The pilot stage configuration and operation is similar to that of concepts 2 and 3. This configuration has the potential for the use of catalysts in the main stage flame holder.

These four designs have been established and are currently undergoing detailed analysis and performance prediction including both steady state and transient operation. The four designs will then be compared in detail for the purpose of ranking the designs and selecting the configuration that has the greatest potential for actual application. The selected design will also be designed for the CF6 cycle and envelope to demonstrate translation of the design concept to another engine.

Table I Reference Engine Cycle Parameters

Combustor Pressure Drop = 5%

Cycle Point	4% Idle	6% Idle	30% Approach	85% Climb	100% Takeoff	Hot Day Takeoff	Very Hot Day Takeoff	Max. Cruise	Normal Cruise	Min. Cruise
Ambient Conditions	Std Day	Std Day	Std Day	Std Day	Std Day	+27° F	+63° F	+18° F	+18° F	+18° F
h_o, Flight Altitude, k ft	0	0	0	0	0	0	0	35.0	35.0	35.0
M_o, Flight Mach No.	0	0	0	0	0	0	0	0.80	0.80	0.80
F_N, Installed Net Thrust, lb	1460	2190	10,948	31,032	36,501	36,506	30,864	8423	6740	3369
W_3 Compressor Exit Airflow, pps	19.1	23.6	63.4	121.7	136.0	132.4	114.0	59.5	52.8	39.1
W_{36}, Combustor Airflow, pps	17.0	21.0	56.4	108.3	121.1	117.9	101.5	53.0	47.0	34.8
P_{T3}, Compressor Exit Total Pressure, psia	46.5	58.2	171.5	380.9	438.0	436.1	375.5	189.4	162.6	112.2
T_{T3}, Compressor Exit Total Temperature, ° F	346	413	679	947	1005	1072	1096	948	881	759
T_{T4}, Combustor Exit Total Temperature, ° F	1154	1233	1584	2292	2452	2588	2585	2411	2219	1861
W_f, Fuel Flow, pph	711	902	2814	8689	10,634	11,006	9327	4672	3714	2177
f_{36}, Combustor Fuel-Air Ratio	0.0116	0.0119	0.0139	0.0223	0.0243	0.0259	0.0255	0.0245	0.0220	0.0174
M_3, Compressor Exit Mach No.(1)	0.273	0.281	0.296	0.286	0.283	0.282	0.285	0.281	0.282	0.289

(1) Assumes A_{e3} = 48.7 in.^{2}

TABLE II

COMBUSTOR DESIGN PARAMETERS

	CONCEPT 1	CONCEPT 2	CONCEPT 3	CONCEPT 4
COMBUSTOR OVERALL LENGTH, INCHES	14.5	14.5	14.5	14.5
COMBUSTION LENGTH	6.5	7.3	8.8	9.0
DOME HEIGHT	2.8	3.2	3.0	2.6
LENGTH/DOME HEIGHT	2.3	2.3	2.9	3.5
NUMBER OF INJECTORS (MAIN/PILOT)	28	60/30	60/30	60/30
NUMBER OF FUEL STAGES	1	2	2	2
VARIABLE GEOMETRY TYPE	CONTINUOUSLY VARIABLE VANES	VANES (OPEN/CLOSED)	FLUIDIC	VANES (OPEN/CLOSED)
PRESSURE LOSS, % (CRUISE/IDLE)	5/10	5/10	5/5	5/9
REFERENCE VELOCITY, FT/SEC.	78	69	60	67
DOME FLOW/COMBUSTOR FLOW, CRUISE	0.63	0.67	0.18	0.16
DOME FLOW/COMBUSTOR FLOW, IDLE	0.25	0.28	0.26	0.27
SPACE RATE, BTU/HR.-FT^3. ATM. (HI POWER)	9.0×10^6	7.0	6.1	5.7
PREMIX SWELL TIME - MS	1.4	1.2	2.0	1.9

LEAN PREMIXED-PREVAPORIZED (LPP) COMBUSTOR CONCEPTUAL DESIGN STUDY

OBJECTIVE:

- DESIGN AND ANALYZE LEAN PREMIXED-PREVAPORIZED COMBUSTORS FOR ADVANCED SUBSONIC AIRCRAFT ENGINES.
- DESIGNS INCLUDE VARIABLE GEOMETRY FOR FLOW CONTROL.
- A PRIMARY GOAL IS LOW OXIDES OF NITROGEN AT SUBSONIC CRUISE $\leq$3G/KG)

PHASE I

ELEMENT

1.0 COMBUSTOR DESIGN
2.0 DESIGN ANALYSIS
3.0 DESIGN RANKING
4.0 REPORTS & RECORDS

TIMING

9 MONTHS (EXCLUSIVE OF REPORTS)

COMPLETE 4/79

FIGURE I

CONCEPT 1-SWIRL TUBE LPP COMBUSTOR WITH VARIABLE SWIRL VANES

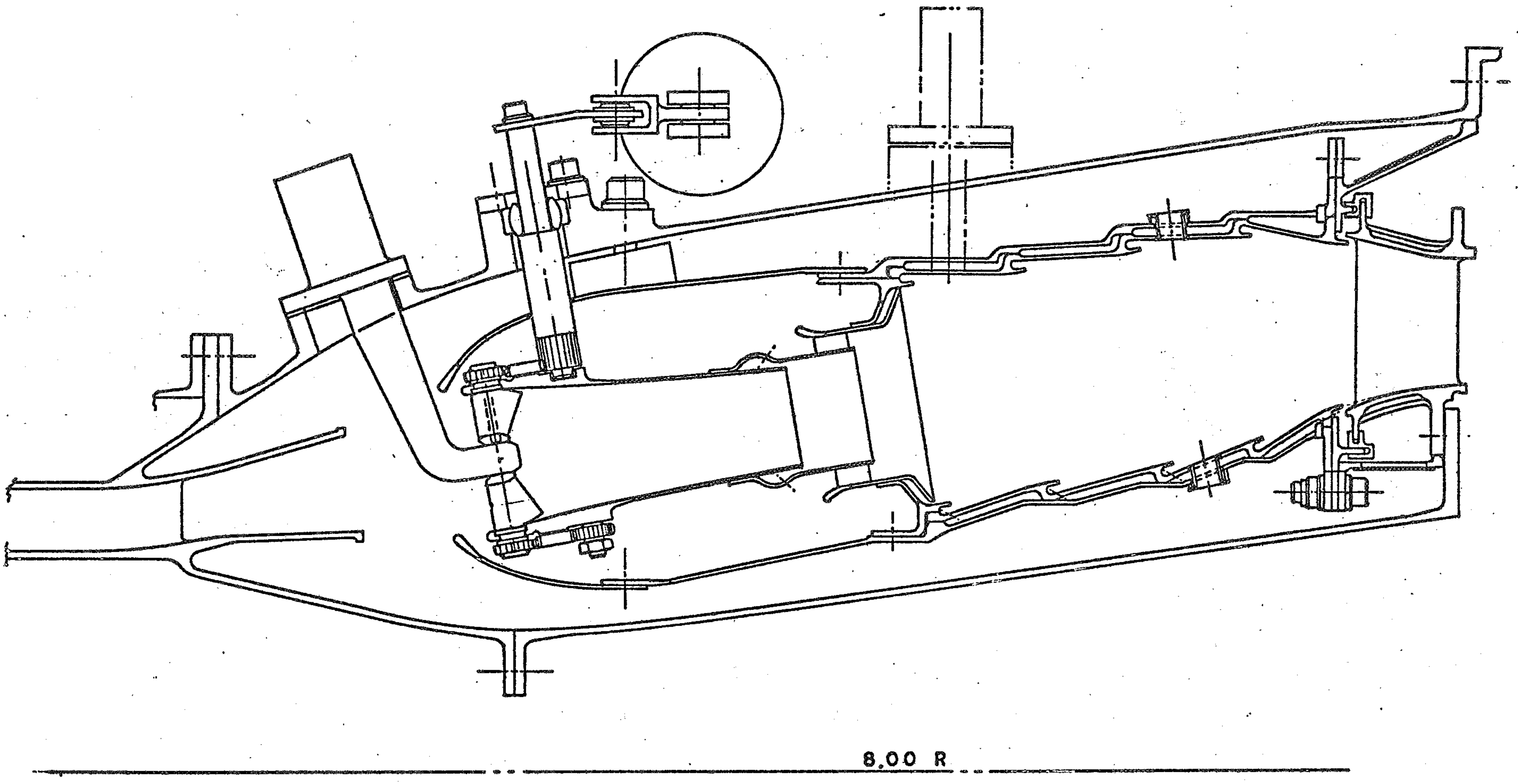

FIGURE 2

CONCEPT 2-MULTIPLE DUCT LPP COMBUSTOR WITH VARIABLE VANE ANNULAR PREMIXER

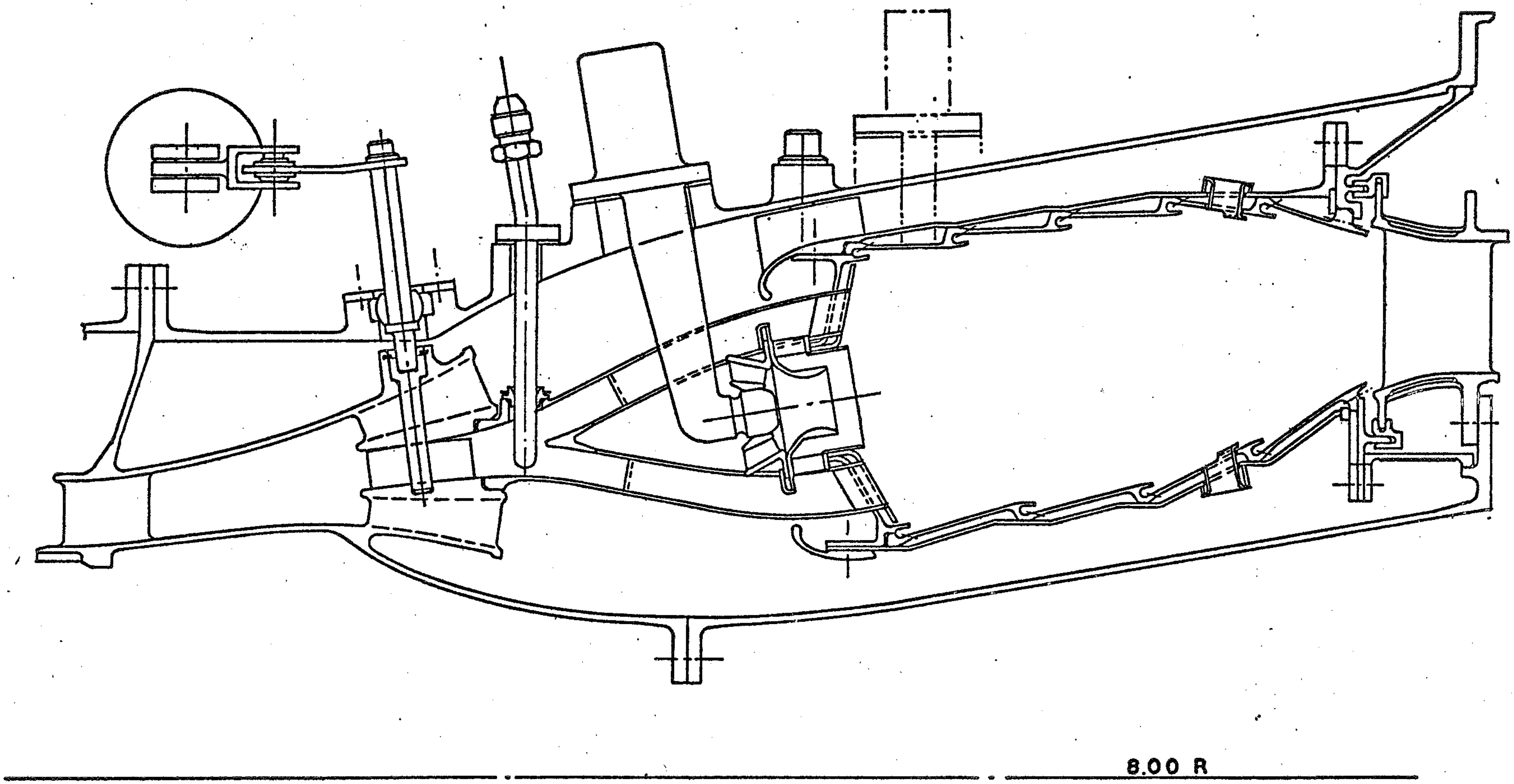

FIGURE 3

CONCEPT 3 - SERIES STAGED LPP COMBUSTOR WITH FLUIDIC FLOW CONTROL

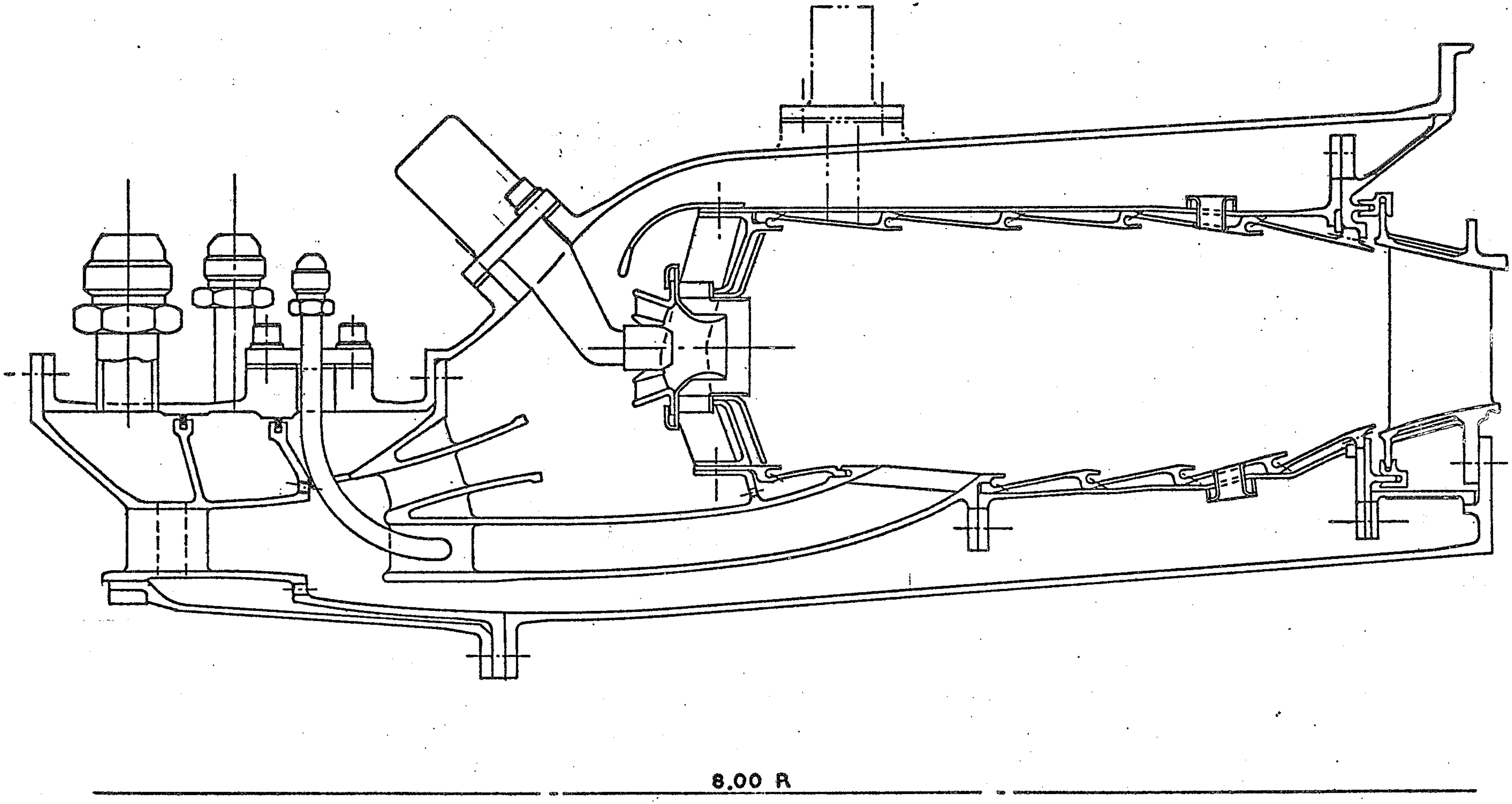

FIGURE 4