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LOW SPEED INDUCERS FOR

CRYOGENIC UPPER STAGES

MILESTONE REPORT

NAS8-29189

Prepared for

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FOREWORD

This document is submitted in fulfillment of the requirement for a Phase I Milestone Report, covering the Conceptual Design Review held at NASA MSFC on 4 January 1973.

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INTRODUCTION

Studies of cryogenic upper stage engine systems such as the Space TUG have shown low net positive suction pressures to trade favorably with vehicle payload. In fact, operation on saturated propellants in the tanks is highly desirable because it would eliminate stage prepressurization and reduce venting requirements. Low-speed inducers appear capable of operating on saturated hydrogen and oxygen over a wide operating range and deserve further investigation as prime candidate approaches to achieving an efficient and lightweight vehicle.

The purpose of this program is to design and construct low speed hydrogen and oxygen inducers and their drive systems applicable to the TUG engine. The inducers will be tested in saturated hydrogen and oxygen to demonstrate that the design technology to operate this hardware is available. The mechanical integrity of the inducers and their drive systems will also be demonstrated. Upon satisfactory completion of the test program, the hardware will be refurbished and delivered to MSFC along with two sets of final drawings.

Phase I of this program is for the design and analysis of the inducers and their drive system.

The contractual statement of work requires the oxygen and hydrogen inducers to provide a head rise of 95 and 300 feet, respectively, at a design flow point compatible with a 15,000 pound thrust engine at a mixture ratio of 6.

Each inducer must be capable of two phase operation in line mounted installations. The drive method for the inducers was to be studied in Phase I using the results from a concurrent NASA contract, NAS3-16751, "Advanced Space Engine Preliminary Design", as the primary input data.

Two additional engines were to be studied during Phase I to determine their compatibility of operation with the inducer designs. These were a 20,000 pound thrust engine of advanced design and an RL-10 engine designated as "CAT III".

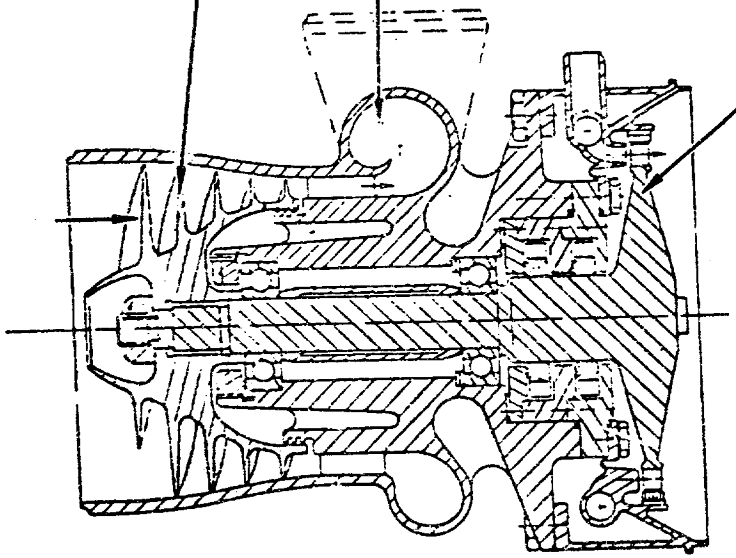
The results and recommendations of the Phase I study were given in an oral presentation at MSFC on 4 January at the Phase I Conceptual Design Review. At that review the program was redirected to satisfy only the 15K and the RL-10 requirements. This was done and the final result was electric-motor-driven inducers for both the two-phase hydrogen and oxygen pumps.

This report contains the briefing charts used in the oral presentation given at MSFC on 4 January. Opposite each chart is a brief statement on the salient feature and/or "point" of the chart.

Following the original charts is a supplement that describes the analysis and design effort relative to the electric motor driven configurations.

LOW SPEED INDUCERS FOR CRYOGENIC UPPER-STAGE ENGINES

NASA/MARSHALL



- DESIGN, CONSTRUCT, TEST AND DELIVER TWO-PHASE HYDROGEN AND OXYGEN INDUCERS FOR SPACE TUG-TYPE ENGINE OF 15 TO 20 K.
- 14 MONTH PROGRAM
  - DYNAMIC ANALYSIS OF TWO-PHASE PROPERTIES DURING START TRANSIENT
  - INERTIA OF LONG LINES FROM DISTANT TANKS
  - STEADY-STATE AND TRANSIENT TESTS IN SATURATED HYDROGEN AND OXYGEN
- SYSTEM TEST CONFIGURATIONS
  - TWO NEW TURBOPUMPS DRIVEN BY A SUPPLY OF WARM HYDROGEN GAS

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PUMPING TWO-PHASE HYDROGEN AND OXYGEN

OBJECTIVES

- PUMP PROPELLANTS TANKED AT ZERO NPSH
- GENERATE HEAD SUFFICIENT FOR SATISFACTORY MAIN PUMP OPERATION
- MAXIMUM INDUCER VAPOR PUMPING CAPABILITY
- HIGH-VELOCITY FLOW TO MINIMIZE LINE AND INDUCER INLET SIZE

PROGRAM SCHEDULE

LOW-SPEED INDUCERS FOR
CRYOGENIC UPPER STAGES

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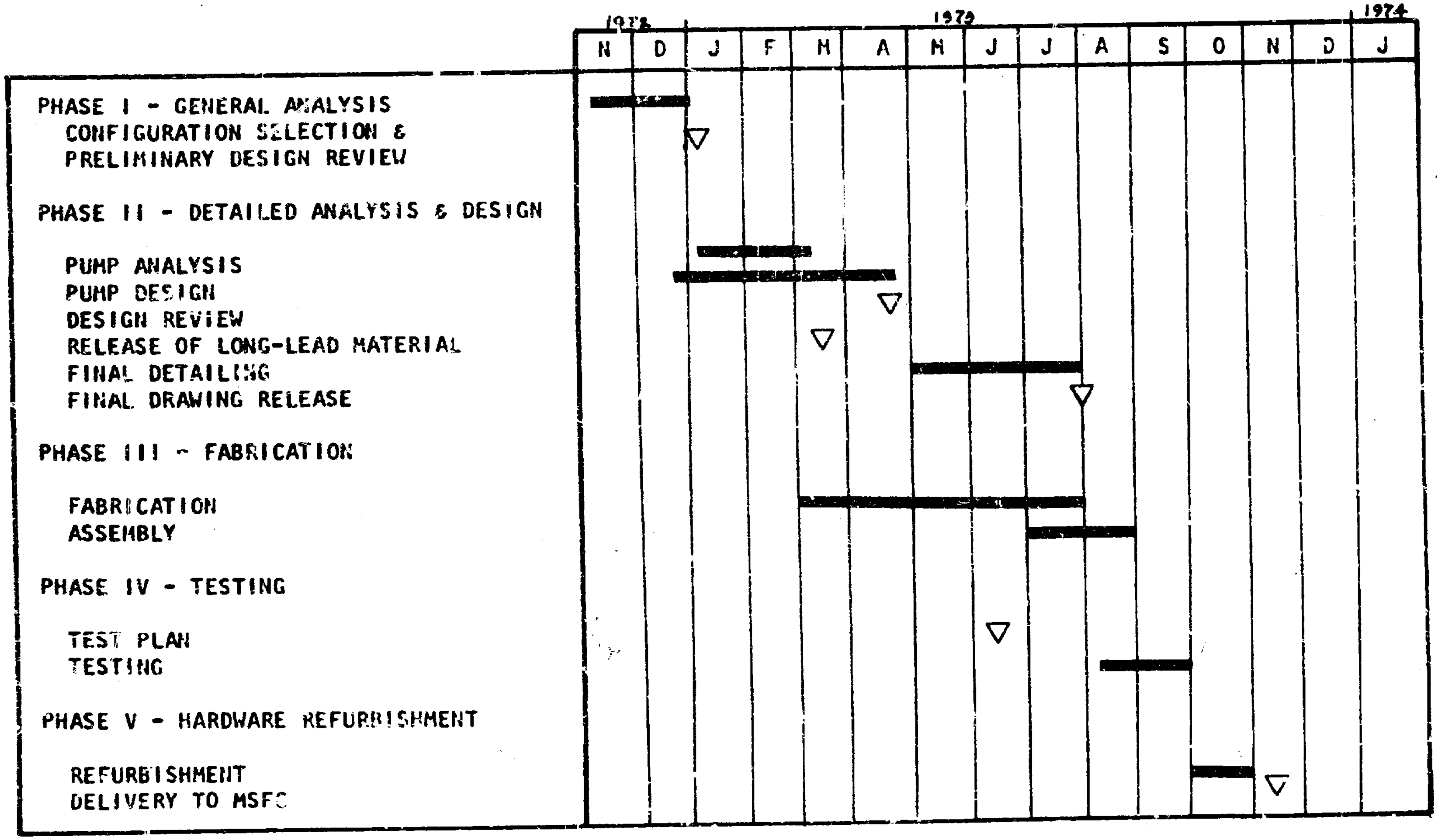


LOW SPEED INDUCER REQUIREMENTS
15K ADVANCED TUG ENGINE

- FLOWRATE

FUEL	4.6 LB/SEC
OXIDIZER	27.4 LB/SEC

- TANK CONDITION

  SATURATED PROPELLANT AT 14.7 TO 30 PSIA

- THROTTLING 5:1
- MINIMUM HEAD RISE

FUEL	300 FEET
OXIDIZER	95 FEET

- OPERABLE IN 20K ADVANCED ENGINE OR IN ADVANCED RL-10

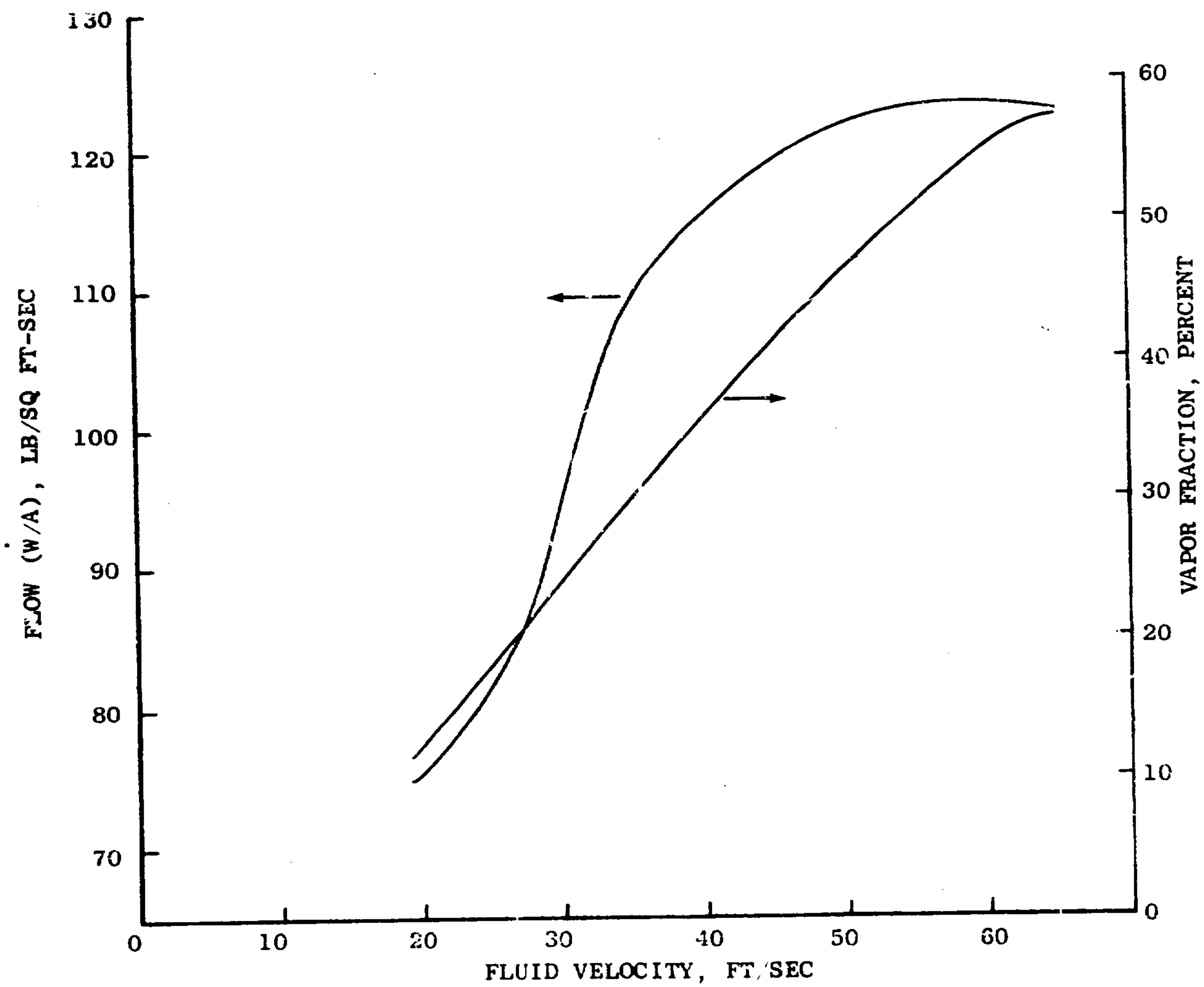
WHEN HYDROGEN IS PUMPED FROM A TANK OF SATURATED LIQUID, THE INDUCED VELOCITY RESULTS IN A DROP IN STATIC PRESSURE AND THE GENERATION OF VAPOR. AS THE VAPOR INCREASES, THE DENSITY DECREASES AND AS

$$\dot{W} = \rho A V$$

THE WEIGHT FLOW REACHES A PEAK VALUE AT THE POINT WHERE THE DENSITY IS FALLING MORE RAPIDLY THAN THE VELOCITY IS RISING.

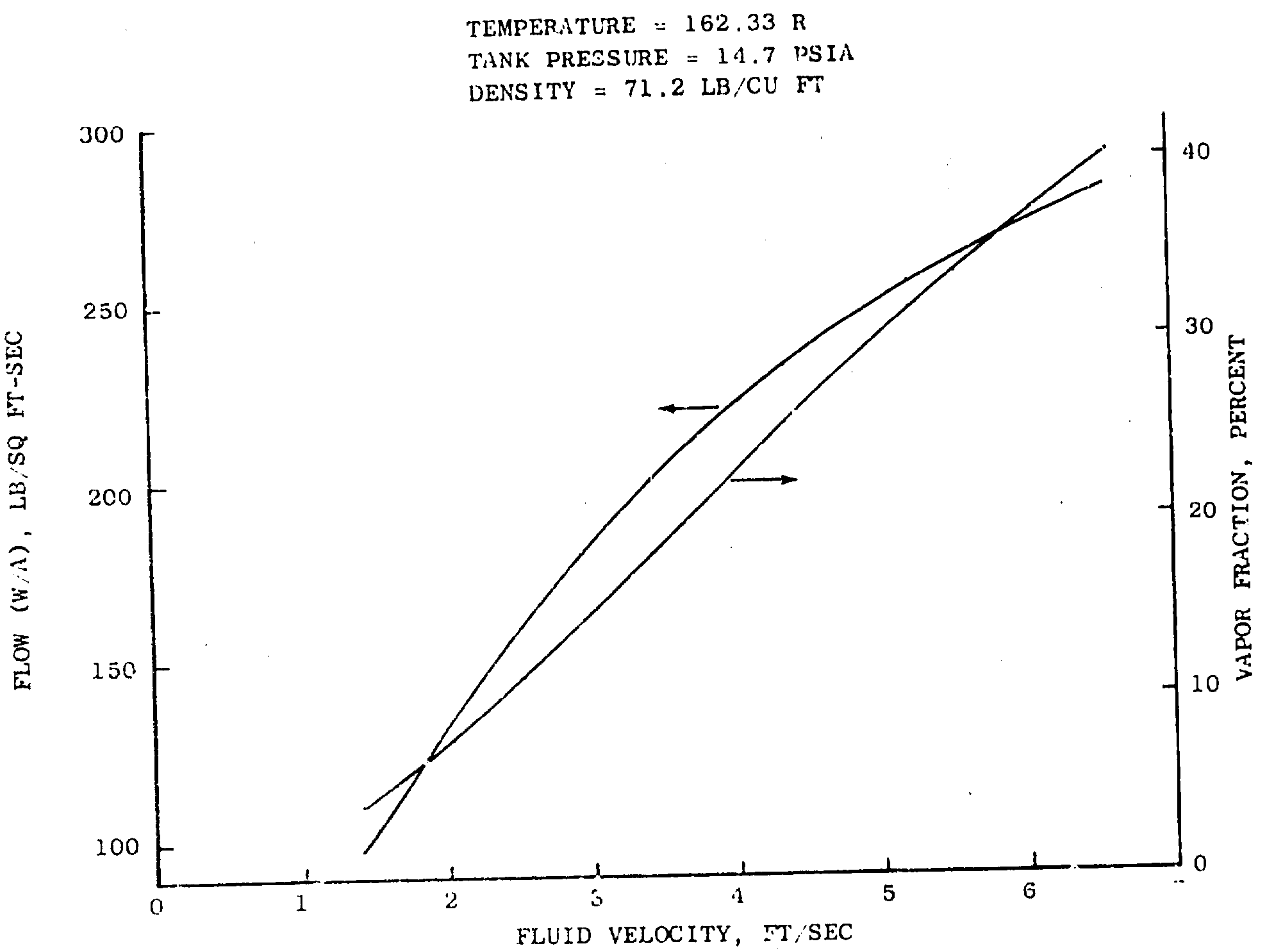
TWO-PHASE HYDROGEN PUMPING

TEMPERATURE = 36.48 R
TANK PRESSURE = 14.7 PSIA
DENSITY = 4.42 LB/CU FT



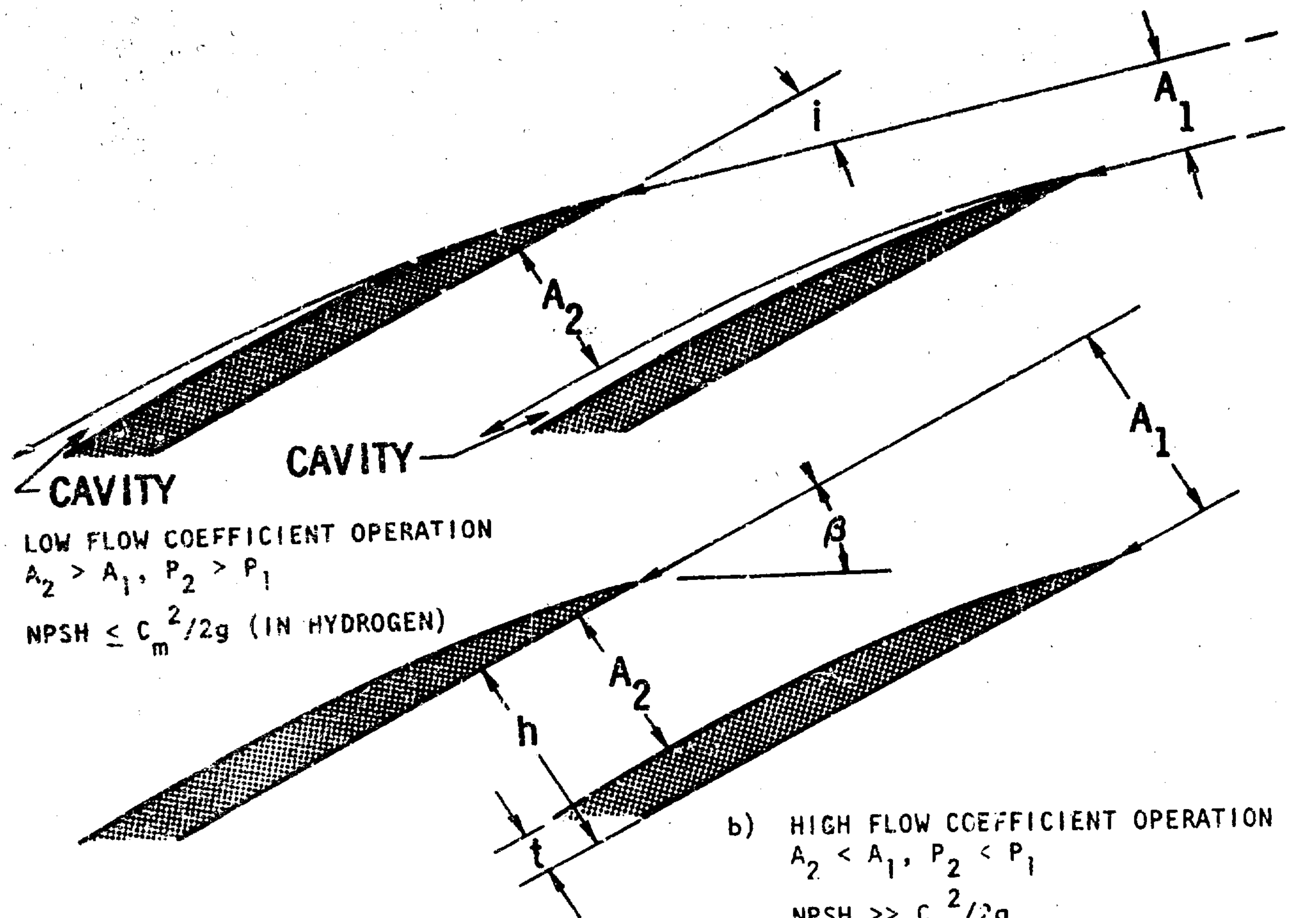
NOTE THAT IN SATURATED OXYGEN, THE VELOCITIES REQUIRED TO GENERATE A CERTAIN VAPOR FRACTION (PERCENT BY VOLUME) ARE MUCH LOWER THAN THEY ARE IN HYDROGEN. THIS NECESSITATES THE USE OF LARGER INDUCERS RUNNING AT RELATIVELY LOW SPEEDS.

TWO-PHASE OXYGEN PUMPING



FOR THE SUCCESSFUL PUMPING OF TWO-PHASE FLUIDS, A_2 MUST BE GREATER THAN A_1. THE RATIO A_1/A_2 CAN BE APPROXIMATED BY THE RATIO i/β.

EFFECT OF FLOW COEFFICIENT ON FLOW GEOMETRY AT INDUCER INLET



a) LOW FLOW COEFFICIENT OPERATION
$A_2 > A_1$, $P_2 > P_1$
$NPSH \leq C_m^2/2g$ (IN HYDROGEN)

b) HIGH FLOW COEFFICIENT OPERATION
$A_2 < A_1$, $P_2 < P_1$
$NPSH >> C_m^2/2g$

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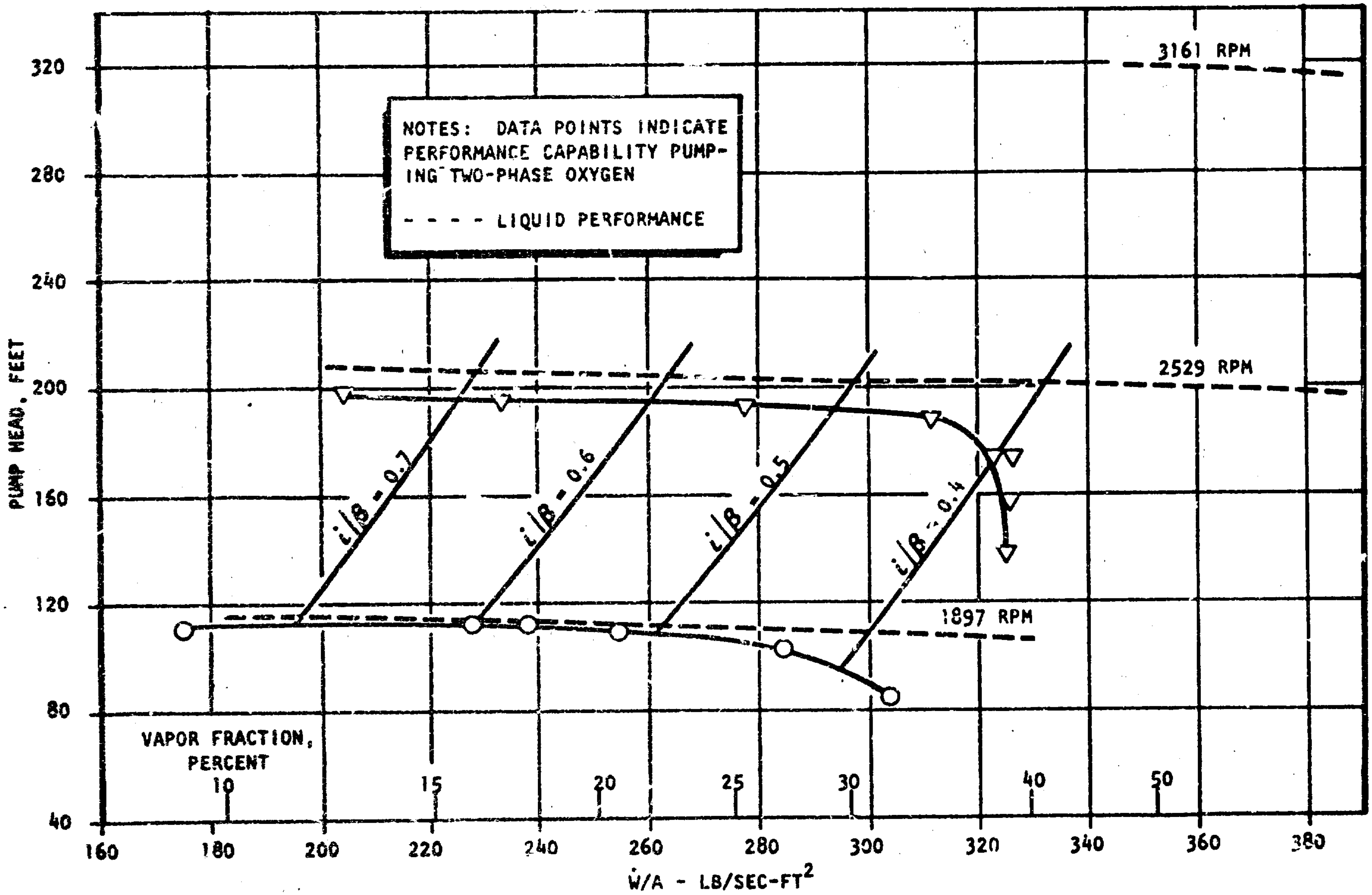
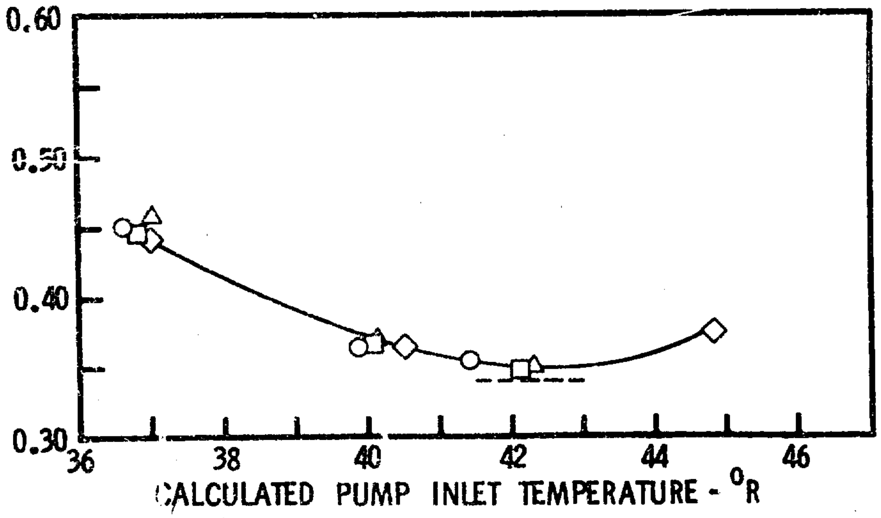
THE MINIMUM VALUE OF i/β AT THE INDUCER TIP FOR TWO-PHASE OXYGEN WAS 0.45 WHICH IS AT THE POINT WHERE THE BREAK OCCURS IN THE PERFORMANCE CURVE.

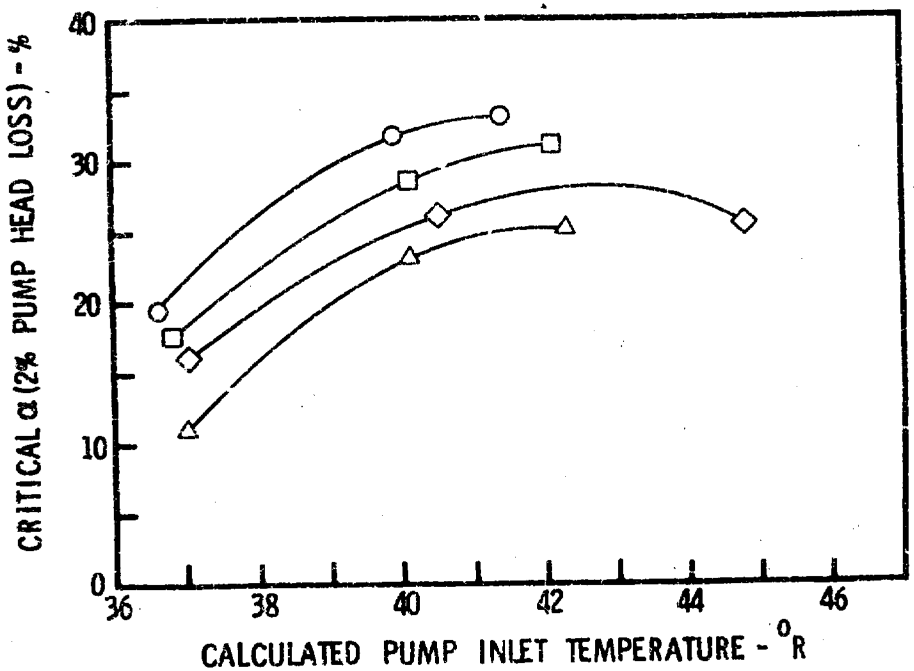


Performance Map of Pump Tested in Two-Phase Oxygen

THE CRITICAL VALUE OF i/β AT THE TIP OF THE INDUCER FOR "COLD" HYDROGEN WAS ALSO 0.45.

PERFORMANCE SUMMARY OF TWO-PHASE FLOW INDUCER (P/N XEOR 936071) N=28,000 RPM





	ϕ_L	% Q/N
○	.0539	93.0
□	.0558	96.5
◇	.0576	100.0
△	.0600	103.5

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RESULTS

- BASELINE VAPOR FRACTION ESTABLISHED
  - HYDROGEN $\leq$ 35 PERCENT
  - OXYGEN $\leq$ 35 PERCENT
- INCIDENCE TO BLADE ANGLE RATIO LIMITS DEFINED
  - $i/\beta \geq .45$

FOR A START TRANSIENT, THE STATIONARY FLUID IN THE LINES MUST BE ACCELERATED UP TO DESIGN SPEED. THE INERTIA OF THE FLUID CAN CAUSE EXCESS VAPOR AT THE PUMP INLET BECAUSE A RAPIDLY ACCELERATING PUMP CAN "PULL A HOLE" IN THE FLUID. OXYGEN, BECAUSE IT HAS A MUCH HIGHER INERTIA THAN HYDROGEN, PRESENTS THE GREATEST ACCELERATION PROBLEM.

INLET LINE DYNAMICS

EFFECT OF TANK PLACEMENT ON TRANSIENT RESPONSE

- EVALUATE WORST CASE CONDITION; I. E., OXIDIZER TANK FORWARD
- EVALUATE OXIDIZER TANK AFT
- VERIFY ADEQUACY OF FUEL TANK FORWARD

ROCKETDYNE HAS COMPUTER PROGRAM THAT CALCULATES THE TRANSIENT PERFORMANCE OF VARIOUS SYSTEMS. A BRIEF DESCRIPTION OF THE PROGRAM IS GIVEN IN THE WORK CHART.

LINE DYNAMIC MODELING

- CALCULATED USING MULTI-ELEMENT - LUMPED PARAMETER METHOD
- CONSIDERS THE EFFECTS OF
  - PROPELLANT DENSITY AS A FUNCTION OF STORED WEIGHT
  - VARIABLE EFFECTIVE RESISTANCE - PROPORTIONAL TO 1/DENSITY
  - FLUID INERTIA EQUAL TO LINE ELEMENT LENGTH/(LINE AREA x g)
- BASIC FLOW EQUATION IS:

$$\Delta P = R/\rho \, \dot{W}^2 + L \, d\dot{W}/dt$$

where

ΔP	LINE PRESSURE DROP
R	RESISTANCE
ρ	DENSITY
$\dot{W}$	FLOWRATE
L	INERTIA

THESE WERE THE DESIGN CONDITIONS OF THE OXYGEN SYSTEM WITH A LONG INLET LINE THAT WERE USED IN THE COMPUTER PROGRAM.

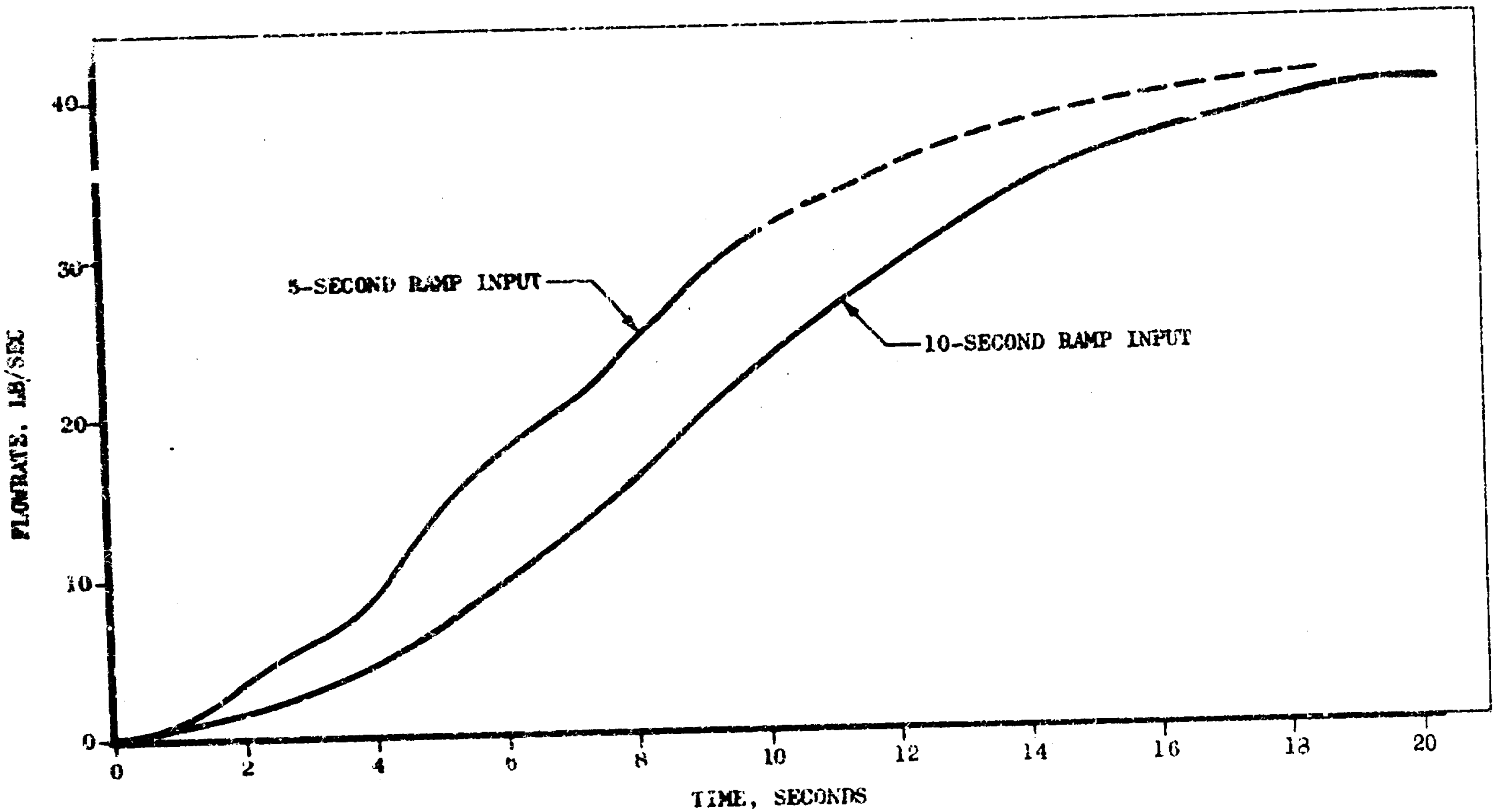
OXIDIZER TANK FORWARD

OXIDIZER SUCTION DUCT LENGTH	368 INCHES
SATURATED EXPANSION	
PRESSURE	14.7 PSIA
ENTRANCE LOSS	0.04 VELOCITY HEAD
VALVE LOSS	0.36 VELOCITY HEAD
LINE LOSS	1.23 VELOCITY HEAD
VAPOR FRACTION	25.99 PERCENT
$\dot{W}/A$	201.19 LB/SEC/SQ FT
C_m	3.810 FT/SEC

WITH EITHER A 5 OR A 10 SECOND RAMP (SPEED IS INCREASED LINEARLY FROM 0 TO DESIGN SPEED) THE WEIGHT FLOW DID NOT REACH ITS MAXIMUM VALUE UNTIL ABOUT 19 SECONDS. THEREFORE, A RAPID START WITH A LONG LINE IS NOT POSSIBLE IN SATURATED OXYGEN. VEHICLE ACCELERATION FORCES WERE NOT CONSIDERED AND WOULD MAKE A DIFFERENCE.

OXYGEN FLOW

LINE LENGTH = 368 INCHES



THESE WERE THE DESIGN CONDITIONS OF THE OXYGEN SYSTEM WITH A SHORT INLET LINE THAT WERE USED IN THE COMPUTER PROGRAM.

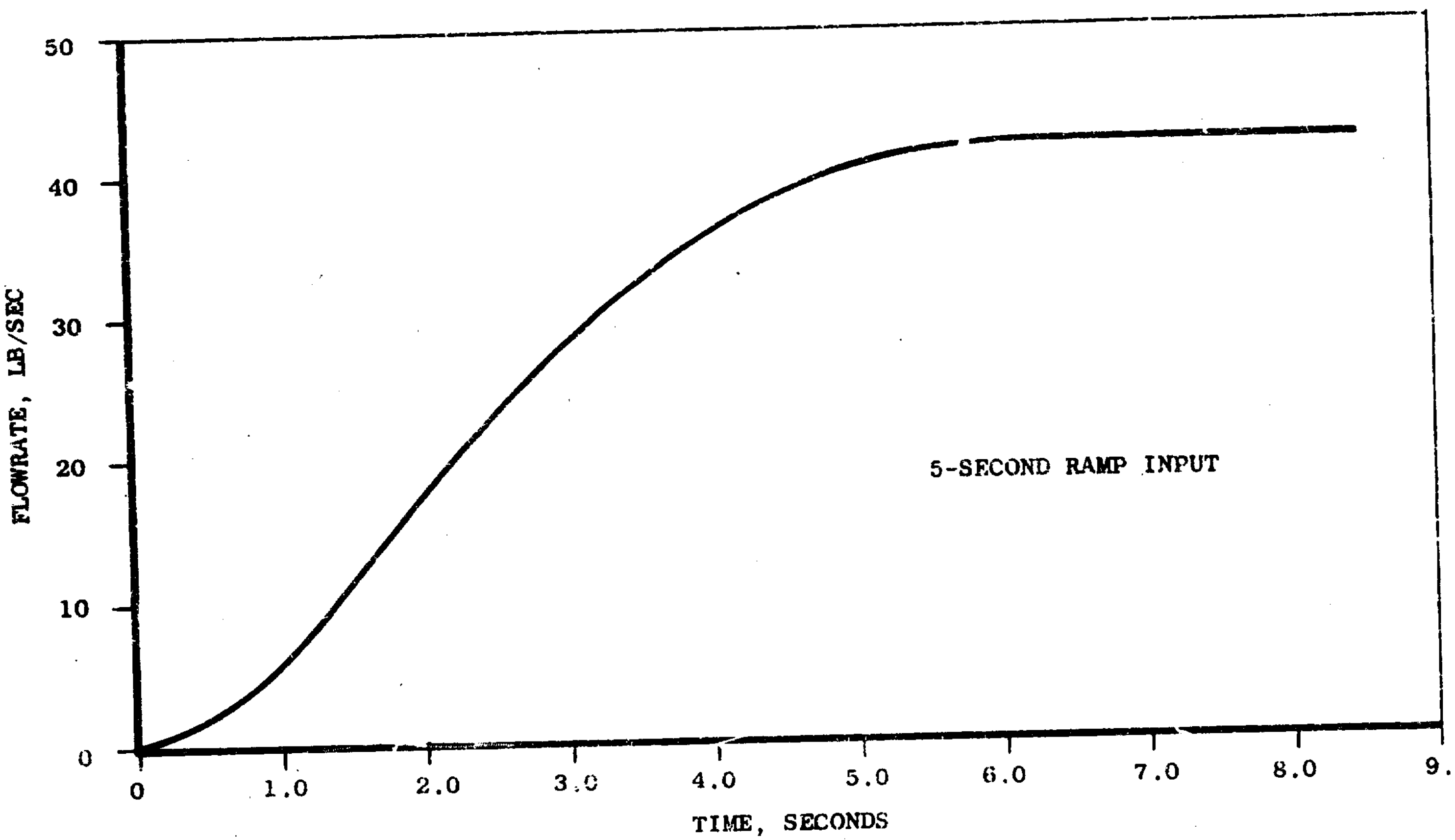
OXIDIZER TANK AFT

OXIDIZER SUCTION DUCT LENGTH	36 INCHES
SATURATED EXPANSION	
PRESSURE	14.7 PSIA
ENTRANCE LOSS	0.04 VELOCITY HEAD
VALVE LOSS	0.36 VELOCITY HEAD
LINE LOSS	0.12 VELOCITY HEAD
VAPOR FRACTION	25.20 PERCENT
$\dot{W}/A$	232.51 LB/SEC/SQ FT
C_m	4.356 FT/SEC

WITH A SHORT LINE AND A 5-SECOND RAMP, THE WEIGHT FLOW REACHED ITS MAXIMUM VALUE IN ALMOST 5 SECONDS.

OXYGEN FLOWRATE

LINE LENGTH = 36 INCHES



THESE WERE THE DESIGN CONDITIONS OF THE HYDROGEN SYSTEM WITH A LONG INLET LINE THAT WERE USED IN THE COMPUTER PROGRAM.

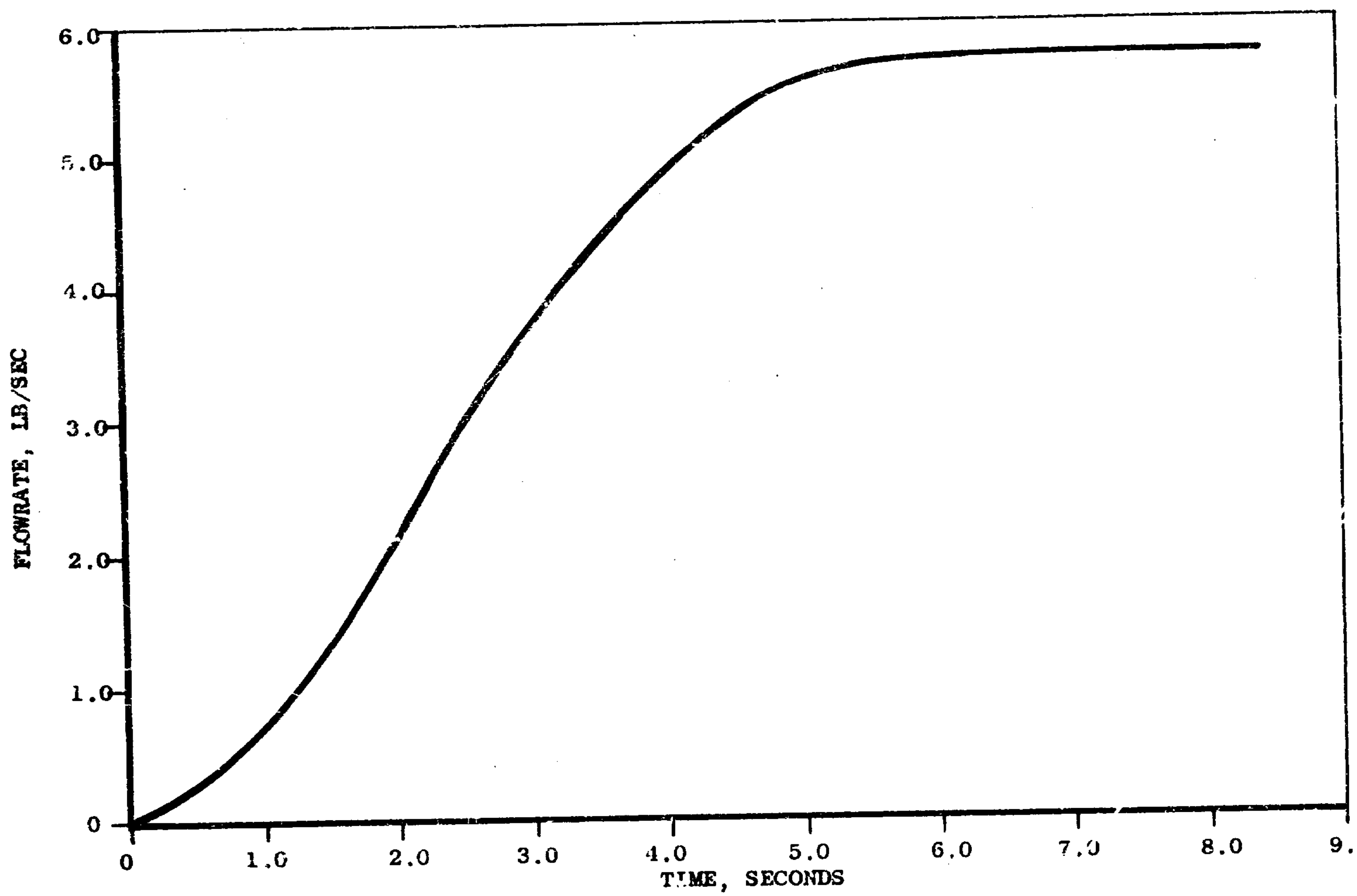
FUEL TANK FORWARD

FUEL SUCTION DUCT LENGTH	278 INCHES
SATURATED EXPANSION	
PRESSURE	14.7 PSIA
ENTRANCE LOSS	0.04 VELOCITY HEAD
VALVE LOSS	0.36 VELOCITY HEAD
LINE LOSS	1.71 VELOCITY HEADS
VAPOR FRACTION	21.04 PERCENT
$\dot{W}/A$	96.23 LB/SEC/SQ FT
C_m	27.34 FT/SEC

THE LONG LINE HAS LITTLE EFFECT ON THE HYDROGEN FLOW RATE. ON A 5-SECOND RAMP, THE MAXIMUM FLOW WAS REACHED IN ONLY A FRACTION OVER 5 SECONDS.

HYDROGEN FLOWRATE

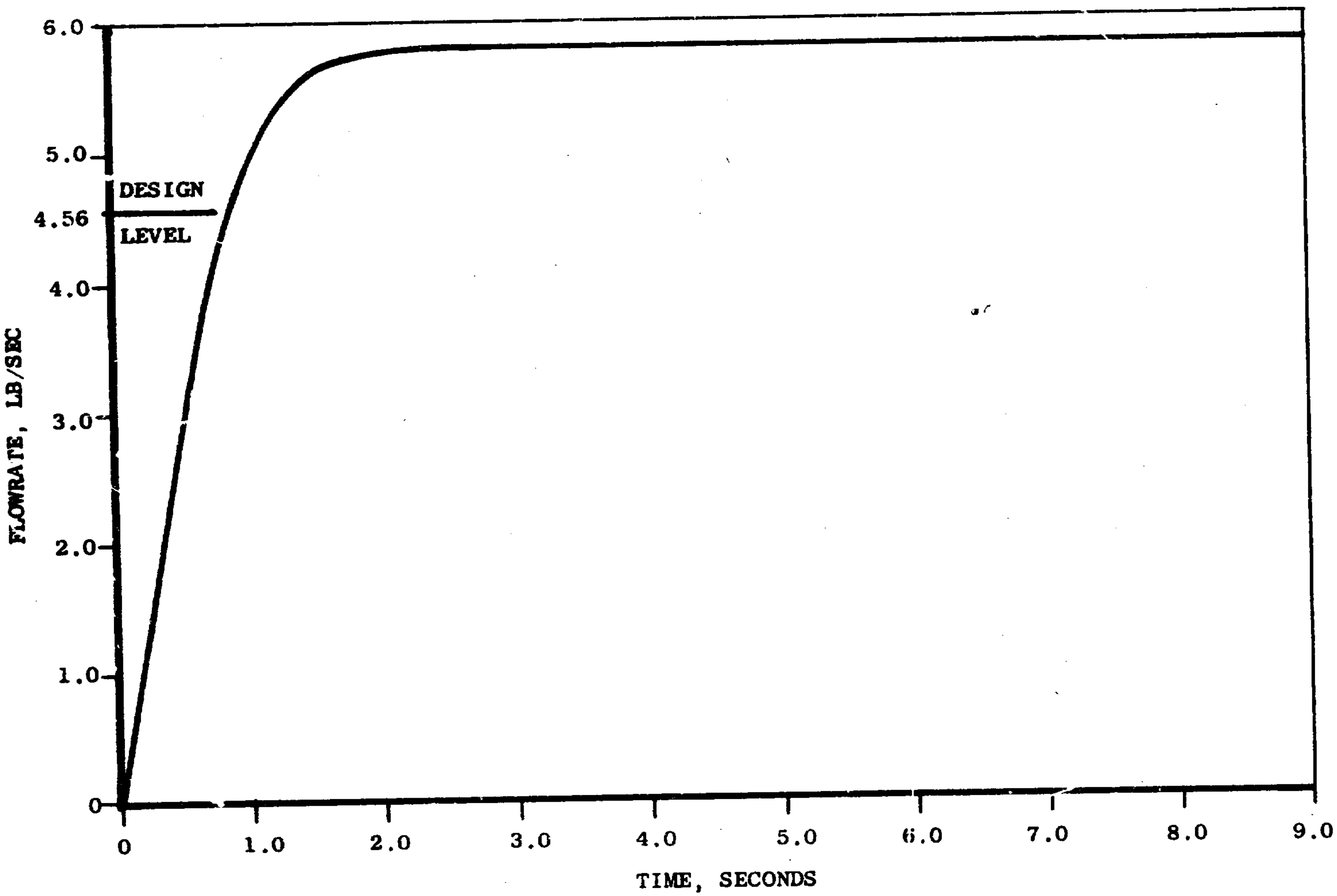
LINE LENGTH = 278 INCHES
5-SECOND RAMP INPUT



WHEN THE STATIC PRESSURE AT THE PUMP INLET IS DROPPED TO IS DESIGN VALUE INSTANTANEOUSLY, THE MAXIMUM HYDROGEN FLOW IN THE LONG LINE IS REACHED IN ABOUT 2 SECONDS.

HYDROGEN FLOWRATE

LINE LENGTH = 278 INCHES
STEP INPUT



THE RESULTS OF THE COMPUTER PROGRAM LED TO THE FOLLOWING CONCLUSIONS.

RESULTS

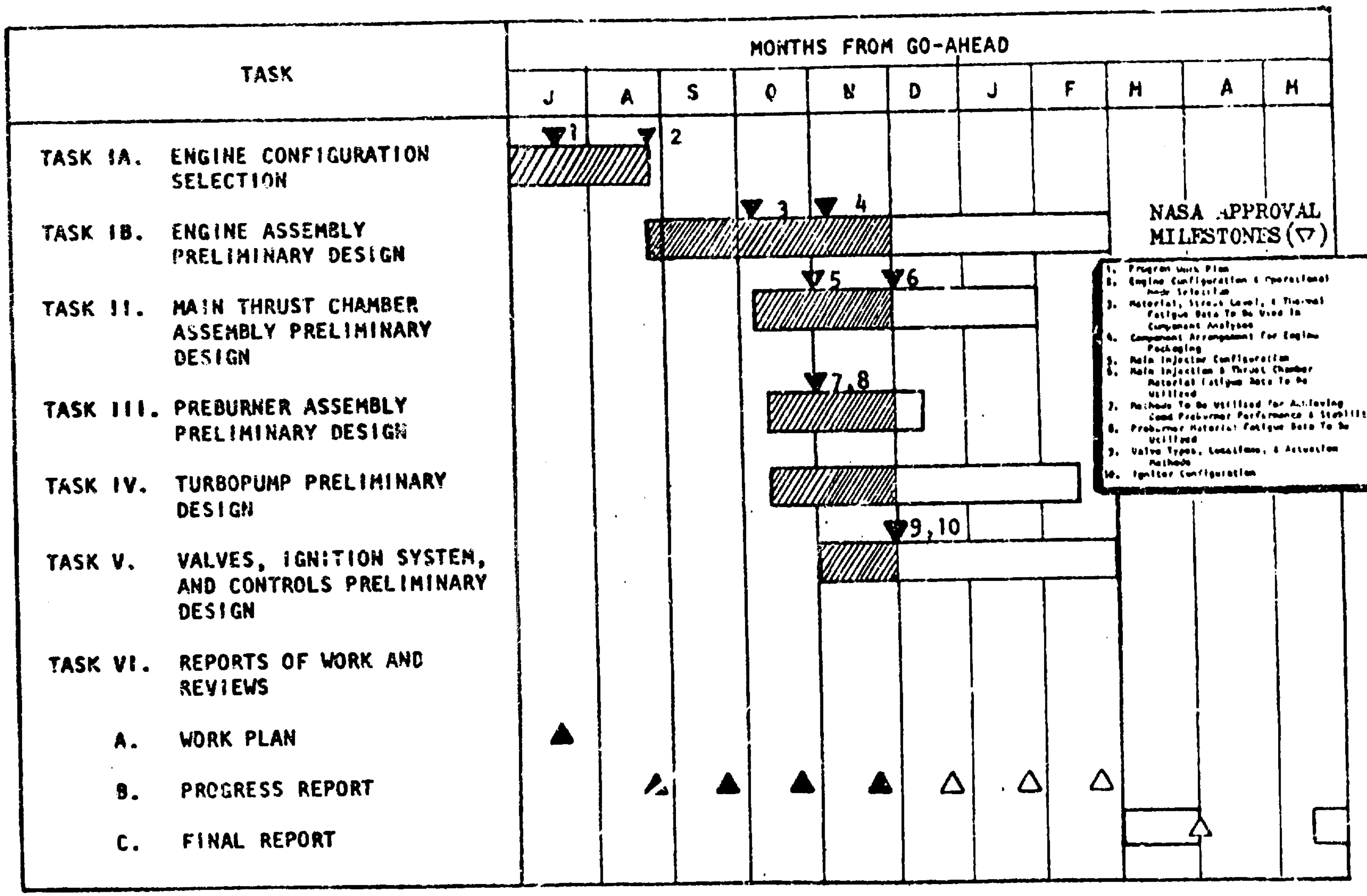
- OXIDIZER TANK FORWARD SLOWS SYSTEM START (19 SEC)
- ENGINE START IN APPROXIMATELY FIVE SECONDS OBTAINED WITH OXIDIZER TANK AFT, FUEL TANK FORWARD
- BASELINE SYSTEM ESTABLISHED WITH OXIDIZER TANK AFT, FUEL TANK FORWARD

LOW SPEED INDUCER

DRIVE SELECTION

A STUDY WAS MADE ON THE METHOD OF DRIVING THE LOW-SPEED INDUCERS ON THE 20K ADVANCED SPACE ENGINE PROGRAM. THE PROGRAM SCHEDULE, THE ENGINE CONFIGURATION AND THE LOGIC THAT WENT INTO THE DRIVE SELECTION ARE PRESENTED IN THE NEXT FEW PAGES.

ADVANCED SPACE ENGINE PRELIMINARY DESIGN
PROGRAM SCHEDULE



THE 20K ADVANCED SPACE ENGINE STUDY WAS BASED ON THIS CONFIGURATION.

ADVANCED SPACE ENGINE CONFIGURATION

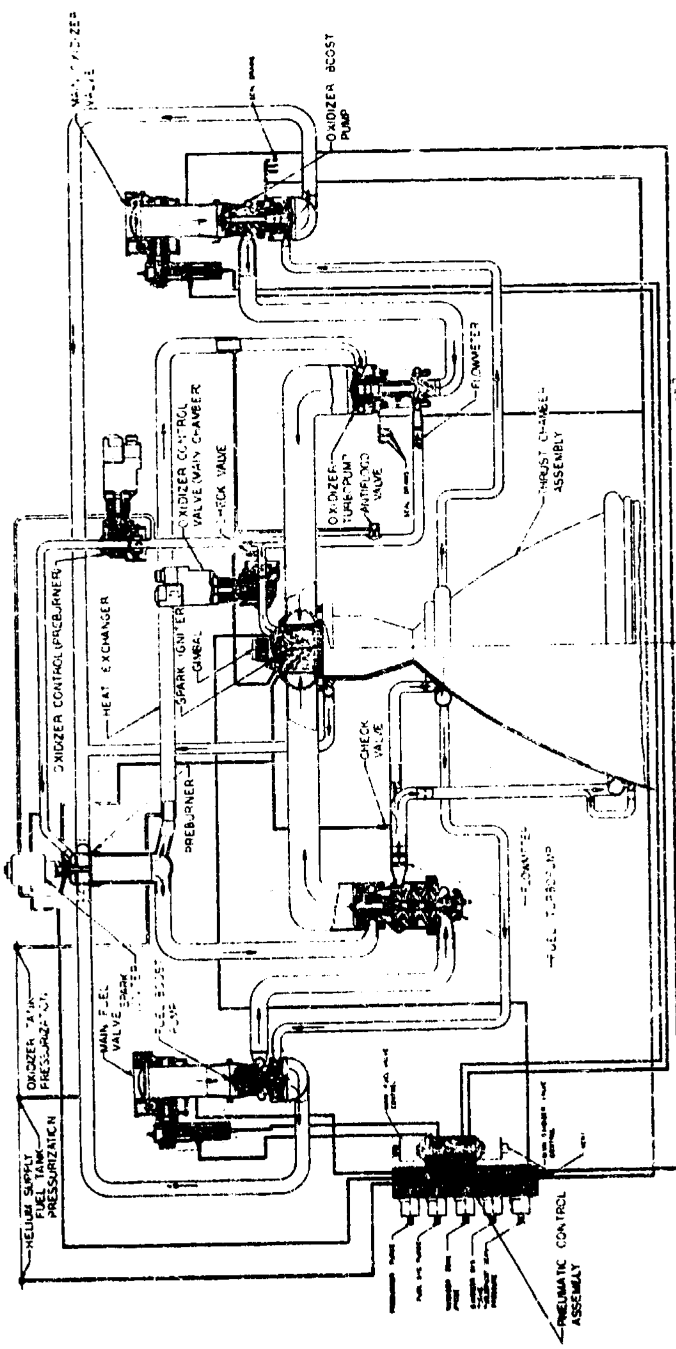
- STAGED COMBUSTION CYCLE
- BELL THRUST CHAMBER NOZZLE
- SINGLE PREBURNER
- GH_2 DRIVEN BOOST PUMPS
- 400:1 AREA RATIO, 90 PERCENT LENGTH NOZZLE

THIS IS THE CALCULATED PERFORMANCE OF THE ADVANCED SPACE ENGINE.

ADVANCED SPACE ENGINE PERFORMANCE

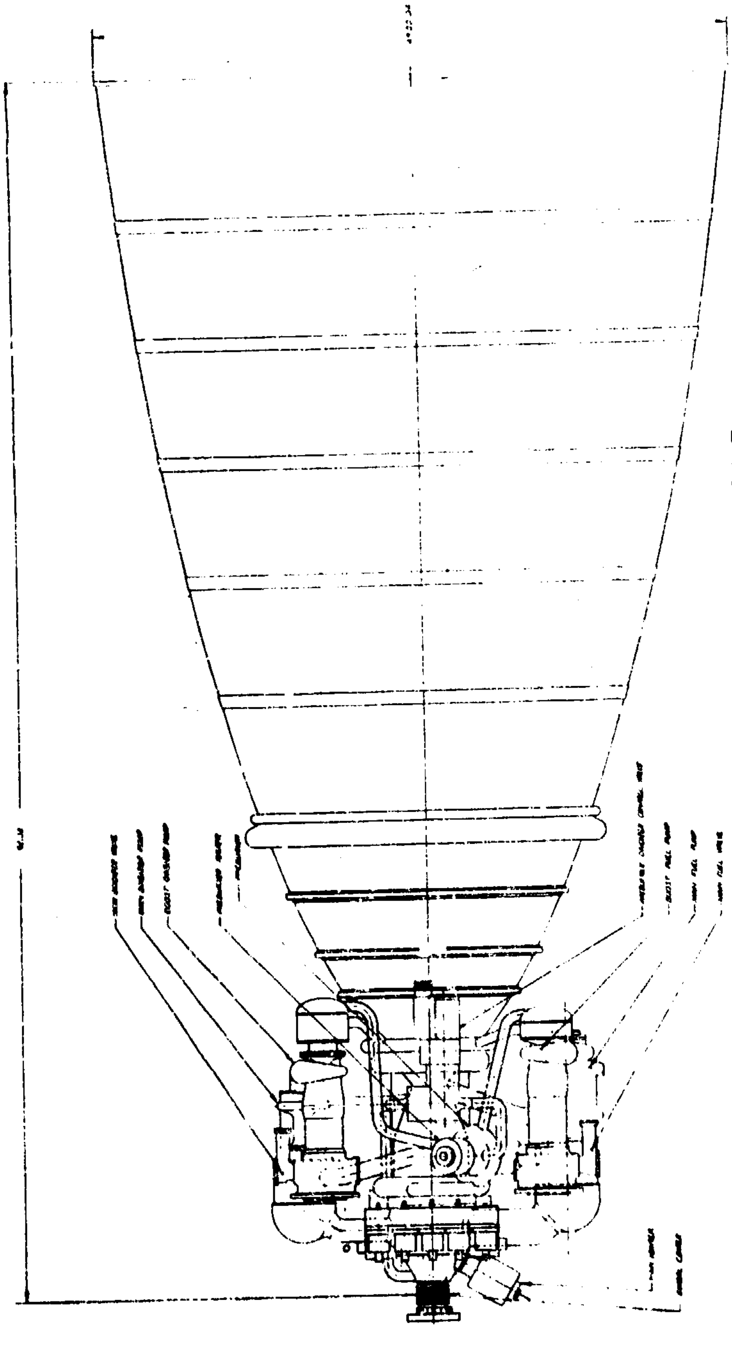
- 20,000 POUNDS THRUST
- 2200 PSIA CHAMBER PRESSURE (NOZZLE STAGNATION)
- SPECIFIC IMPULSE OF 473.4 SECONDS
- WEIGHT OF 337 POUNDS

THIS LAYOUT IS A SCHEMATIC OF THE DIFFERENT COMPONENTS USED IN THE ADVANCED SPACE ENGINE.



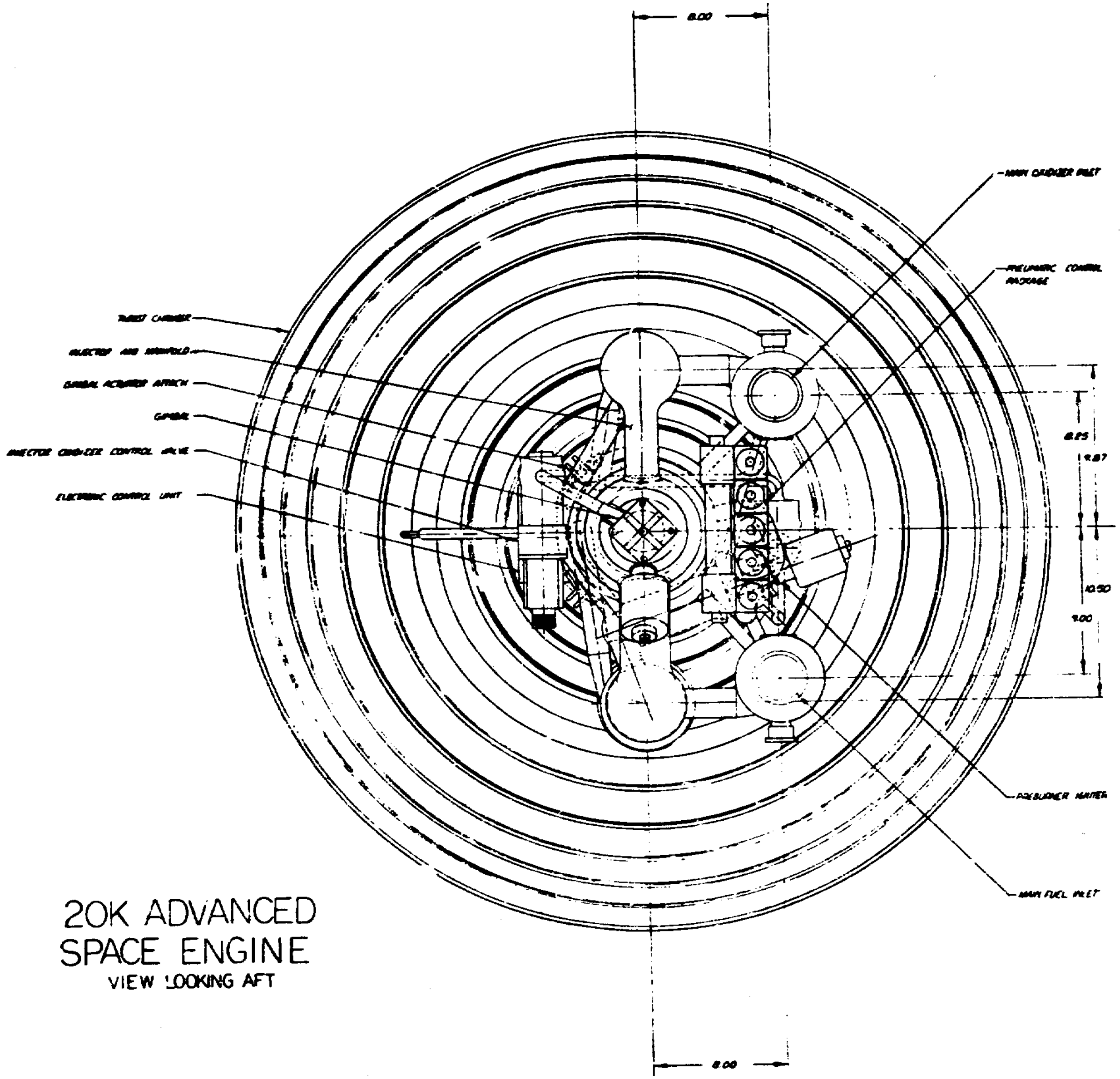
SCHEMATIC-20K ADVANCED SPACE ENGINE

THE LAYOUT SHOWS THE SIZE AND PACKAGING OF THE ADVANCED SPACE ENGINE.



20K ADVANCED SPACE ENGINE

A VIEW FROM THE TOP OF THE PACKAGING OF VARIOUS COMPONENTS.



20K ADVANCED
SPACE ENGINE
VIEW LOOKING AFT

THE DESIGN ALTERNATIVES CONSIDERED IN THE ADVANCED SPACE ENGINE ARE LISTED. TO BE DISCUSSED HERE ARE THE BOOST PUMP DRIVE METHODS.

DESIGN ALTERNATIVES

- DESIGN CONFIGURATION
  - BOOST PUMP DRIVE METHODS
    - GEARS
    - HYDRAULIC TURBINE
    - HYDROGEN GAS TURBINES
  - REGENERATIVE COOLING SCHEME
    - PASS AND A HALF
    - SPLIT
  - PREBURNER CONFIGURATION
    - SINGLE PREBURNER
    - DUAL PREBURNER SEPARATELY SUPPLYING COMBUSTION PRODUCTS TO EACH TURBINE

- OPERATIONAL MODE
  - THROTTLING REQUIREMENTS
    - NO THROTTLING
    - 6:1 THROTTLING*
  - DESIGN POINT NET POSITIVE SUCTION HEAD (FEET)
    - LO_2: 0** 2 16
    - LH_2: 0** 15 60
  - START MODE
    - NORMAL
    - PRESSURIZED-IDLE
    - TANK-HEAD-IDLE

* Perturbation of Baseline Design Only
** -Tank Head Idle Mode Start Only

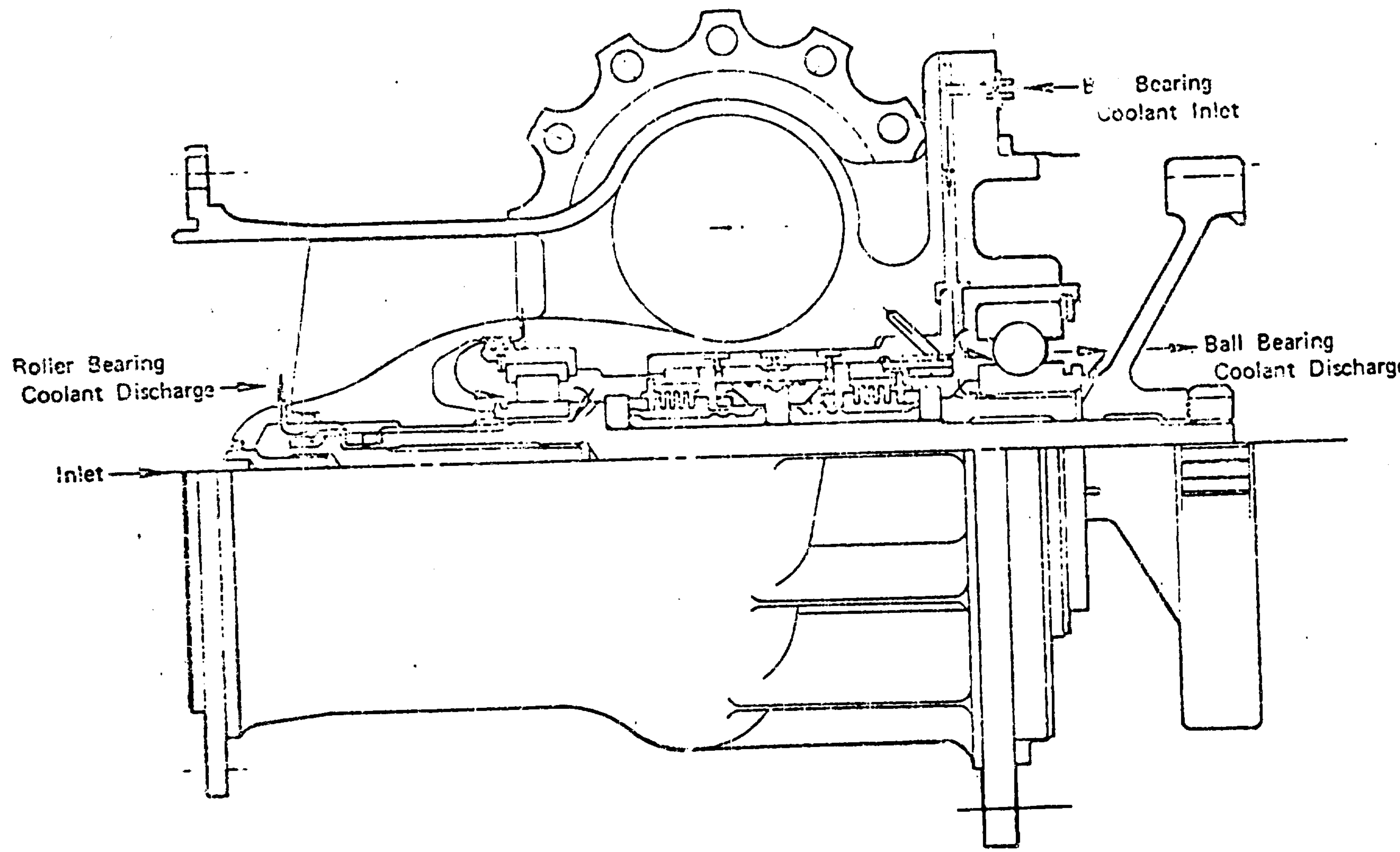
BOOST TURBOPUMP DESIREABLE FEATURES AND REQUIREMENTS

- PROVIDE SYSTEM CHILLDOWN BENEFIT AND TRANSIENT CONTROL DURING START
- MAINTAIN NPSH FOR MAIN PUMP
  - START
  - MAINSTAGE
  - OFF DESIGN
- LIFE (300 STARTS AND 10 HOURS MINIMUM)
- MINIMIZE NONPROPULSIVE PROPELLANT LOSSES
- PRACTICAL MECHANICAL DESIGN
- MINIMIZE IMPACT ON POWER CYCLE

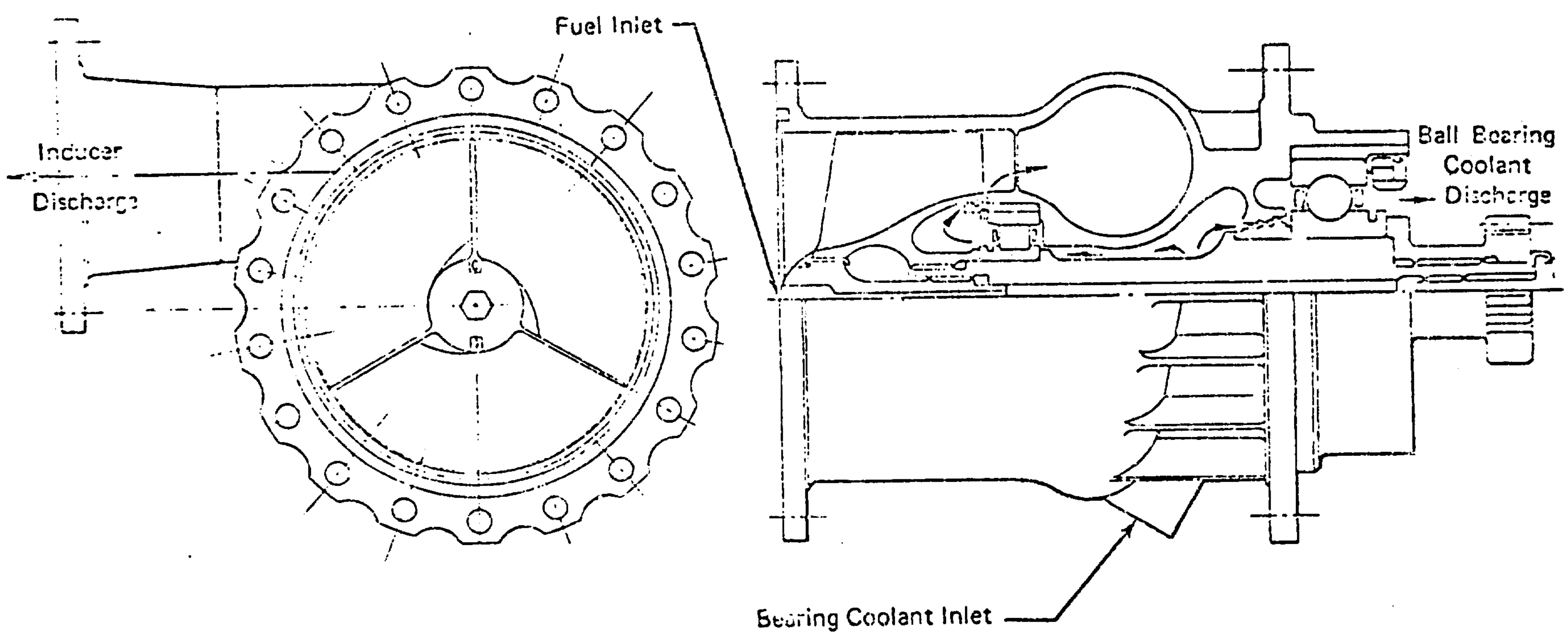
BOOST PUMP DRIVE METHODS

THE BOOST PUMP DRIVE METHODS CONSIDERED DURING THE TRADEOFF WERE GEAR, HYDRAULIC (BOTH FULL FLOW AND PARTIAL FLOW), AND GASEOUS HYDROGEN (GH_2) DRIVES. AS SHOWN, THE GEAR DRIVE METHOD IS DIRECTLY COUPLED TO THE MAIN LO_2 PUMP SHAFT. THE GEARS ARE DRY-FILM LUBRICATED AND HYDROGEN COOLED. THIS ARRANGEMENT NECESSITATES A DYNAMIC SEAL PACKAGE IN THE LO_2 BOOST PUMP.

GEAR DRIVEN LO_2 BOOST PUMP DESIGN



GEAR DRIVEN LH_2 BOOST PUMP DESIGN



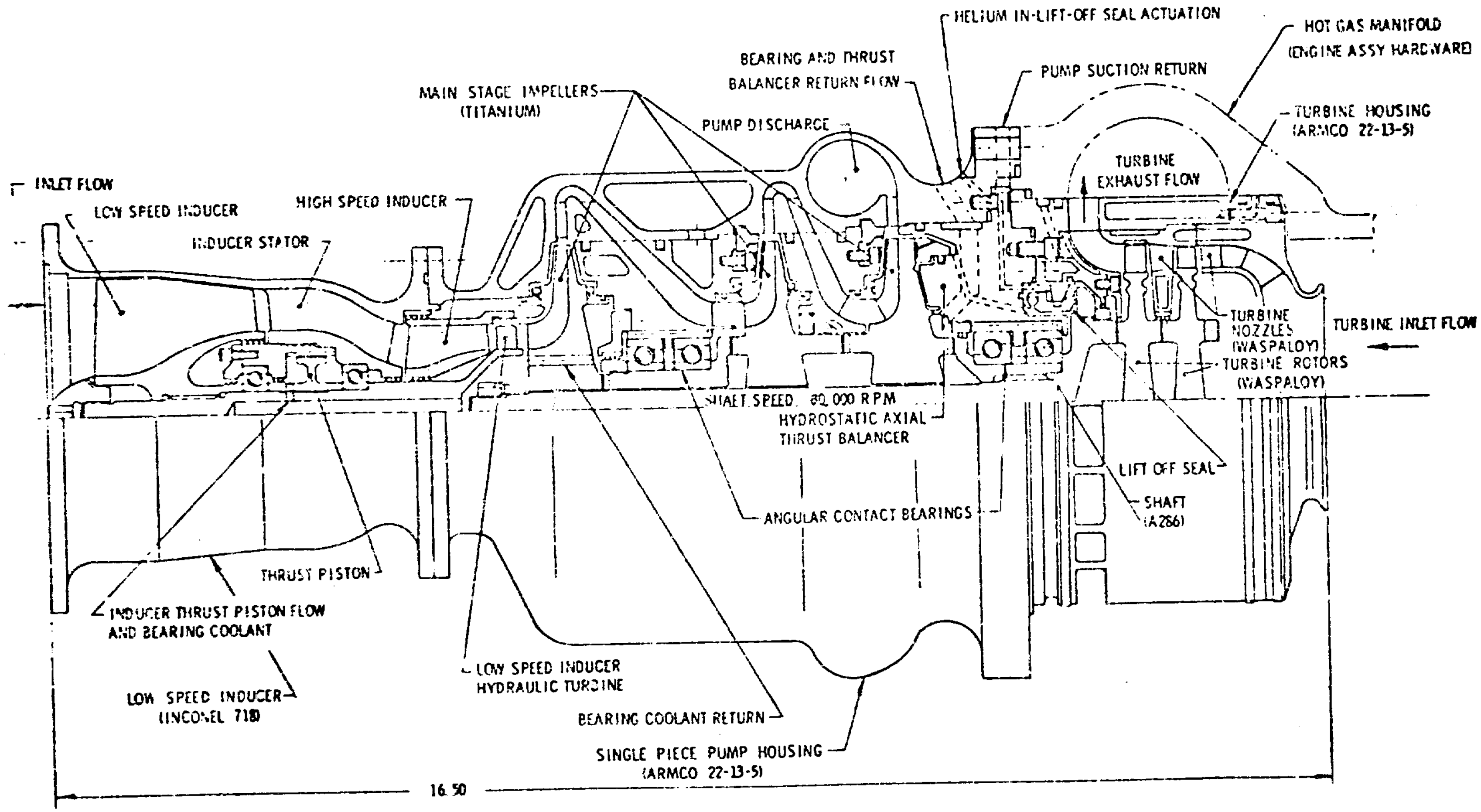
THESE ARE THE ADVANTAGES AND DISADVANTAGES OF GEAR DRIVEN BOOST PUMPS.

GEAR-DRIVEN BOOST PUMPS

- ADVANTAGES
  - POSITIVE BOOST PUMP DRIVE
  - SIMPLICITY OF BOOST PUMP DESIGN
- DISADVANTAGES
  - MAXIMUM LIFE DEMONSTRATED IS 5.56 HOURS AT 16,000 FPM PITCH LINE VELOCITY (GEARS BADLY WORN) - NEED A MINIMUM OF 25,000 FPM PITCH LINE VELOCITY (80,000 RPM)
  - SIMULTANEOUS BOOST PUMP/MAIN PUMP STARTUP WOULD PREVENT USING BOOST PUMP FOR SYSTEM CHILLDOWN
  - BOOST PUMP/MAIN PUMP MECHANICAL COUPLING WOULD LIMIT FLEXIBILITY IN PACKAGING.
  - REQUIRES GEAR BOX COOLANT
  - LO_2 BOOST PUMP REQUIRES PURGED SEAL PACKAGE

THE FULL-FLOW HYDRAULIC BOOST PUMP IS LOCATED DIRECTLY IN LINE WITH ITS RESPECTIVE MAIN PUMP AND THE BOOST PUMP TURBINE IS LOCATED BETWEEN THE MAIN PUMP INDUCER AND FIRST IMPELLER. THE TURBINE DERIVES ITS POWER FROM THE DISCHARGE OF THE MAIN PUMP INDUCER.

FUEL TURBOPUMP CONCEPT
(FULL FLOW HYDRAULIC BOOST PUMP DRIVE)



THESE ARE THE ADVANTAGES AND DISADVANTAGES OF A FULL-FLOW HYDRAULIC DRIVE FOR A HYDROGEN BOOST PUMP.

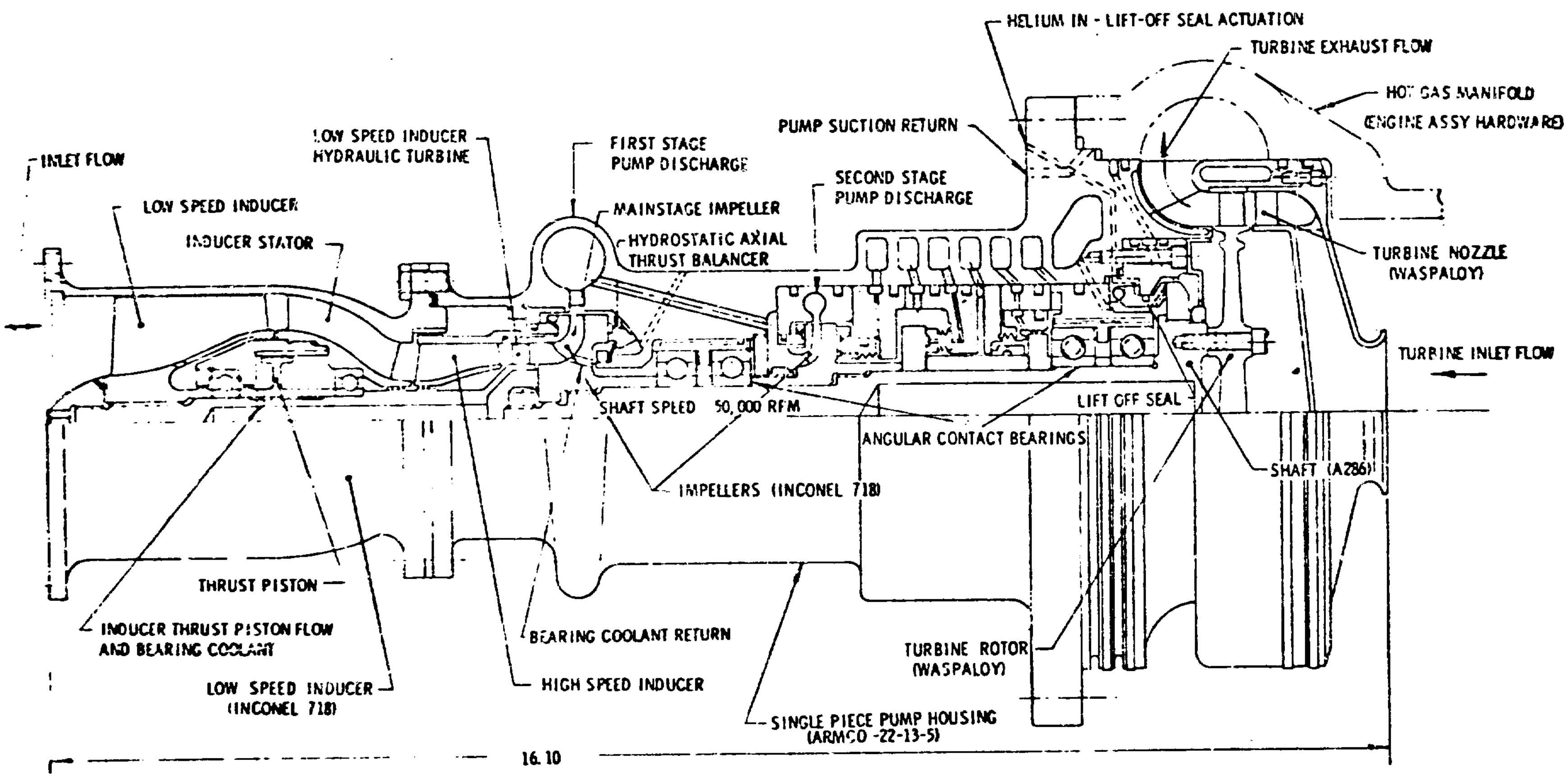
FULL FLOW HYDRAULIC DRIVE FOR LH_2 BOOST PUMP

- ADVANTAGES
  - INTEGRATED PACKAGING
  - NO NONPROPULSIVE PROPELLANT LOSS
  - GOOD LIFE CAPABILITY
- DISADVANTAGES
  - STARTS WITH MAIN PUMP (NO CHILLDOWN BENEFIT)
  - TANDEM DESIGN WITH MAIN PUMP LIMITS PACKAGING
  - LACKS FLEXIBILITY FOR OVERCOMING PROBLEMS
  - POWER REQUIREMENT DIRECTLY IMPOSED ON MAIN FUEL TURBINE
  - LOW NPSH AND FIXED TURBINE DIAMETER (MAIN PUMP INDUCER DIAMETER) LIMITS BOOST PUMP HP AND MAIN PUMP SPEED

THIS IS A LAYOUT OF A FULL-FLOW HYDRAULIC

BOOST PUMP FOR THE OXYGEN SYSTEM.

OXIDIZER TURBOPUMP CONCEPT
(FULL FLOW HYDRAULIC BOOST PUMP DRIVE)



THESE ARE THE ADVANTAGES AND DISADVANTAGES OF A FULL-FLOW HYDRAULIC DRIVE FOR THE OXYGEN BOOST PUMP.

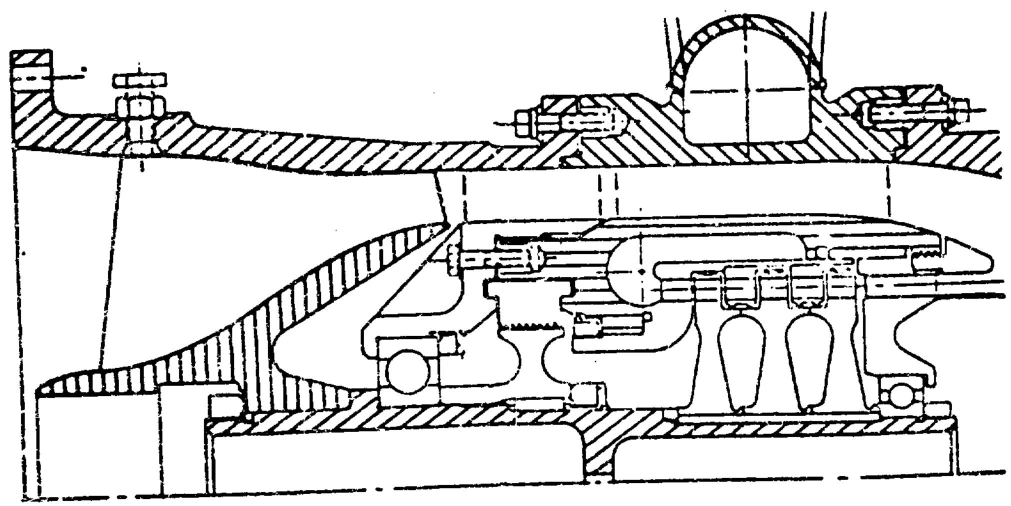
FULL FLOW HYDRAULIC DRIVE FOR LO_2 BOOST PUMP

- ADVANTAGES
  - INTEGRATED PACKAGING
  - NO NONPROPULSIVE PROPELLANT LOSS
  - GOOD LIFE CAPABILITY

- DISADVANTAGES
  - STARTS WITH MAIN PUMP (NO CHILLDOWN BENEFIT)
  - LOW NPSH AND FIXED TURBINE DIAMETER (MAIN PUMP INDUCER DIAMETER) LIMITS BOOST PUMP TURBINE HORSEPOWER
  - LIMITED BOOST PUMP TURBINE HORSEPOWER REDUCES BOOST PUMP ΔP BY 70 PERCENT
  - TO BALANCE MAIN PUMP INLET PRESSURE TO BOOST PUMP DISCHARGE, MAIN PUMP SPEED WOULD BE ~ 20,000 RPM
  - ADDITIONAL BOOST PUMP HORSEPOWER COULD BE OBTAINED BY ADDING TURBINE STAGES BUT WOULD FURTHER INCREASE SIGNIFICANT MECHANICAL COMPLEXITY
  - TANDEM DESIGN LIMITS PACKAGING FLEXIBILITY

THE PARTIAL-FLOW HYDRAULIC APPROACH UTILIZES A SMALL PORTION OF THE MAIN PUMP DISCHARGE FLOW TO DRIVE THE BOOST PUMP TURBINE AFTER WHICH THIS FLOW IS RETURNED TO THE INLET OF THE MAIN PUMP.

PARTIAL FLOW HYDRAULIC BOOST PUMP DRIVE



PARTIAL-FLOW HYDRAULIC DRIVES WERE STUDIED FOR BOTH HYDROGEN AND OXYGEN DRIVES. THE NEXT TWO CHARTS GIVE THE ADVANTAGES AND DISADVANTAGES OF EACH.

PARTIAL FLOW HYDRAULIC DRIVE FOR LH_2 BOOST PUMP

- ADVANTAGES
  - NO NONPROPULSIVE PROPELLANT LOSS
  - FLEXIBLE PACKAGING
  - GOOD LIFE CAPABILITY

- DISADVANTAGES
  - START LAGS MAIN PUMP (NO CHILLDOWN BENEFIT)
  - UTILIZATION OF MAIN PUMP DISCHARGE FOR TURBINE DRIVE (MINIMIZE RECIRCULATION FLOW) COULD RESULT IN LARGE VAPOR FRACTION
  - LARGE VAPOR FRACTION (UP TO 60 PERCENT BY VOLUME FOR DESIGNS STUDIES) MAKES TURBINE DESIGN DIFFICULT
  - POWER REQUIREMENT DIRECTLY IMPOSED ON MAIN FUEL TURBINE

PARTIAL FLOW HYDRAULIC DRIVE FOR LO_2 BOOST PUMP

- **ADVANTAGES**
  - NO NONPROPULSIVE PROPELLANT LOSS
  - FLEXIBLE PACKAGING
  - GOOD LIFE CAPABILITY
- **DISADVANTAGES**
  - START LAGS MAIN PUMP (NO CHILLDOWN BENEFIT)
  - POWER REQUIREMENT DIRECTLY IMPOSED ON MAIN OXIDIZER TURBINE

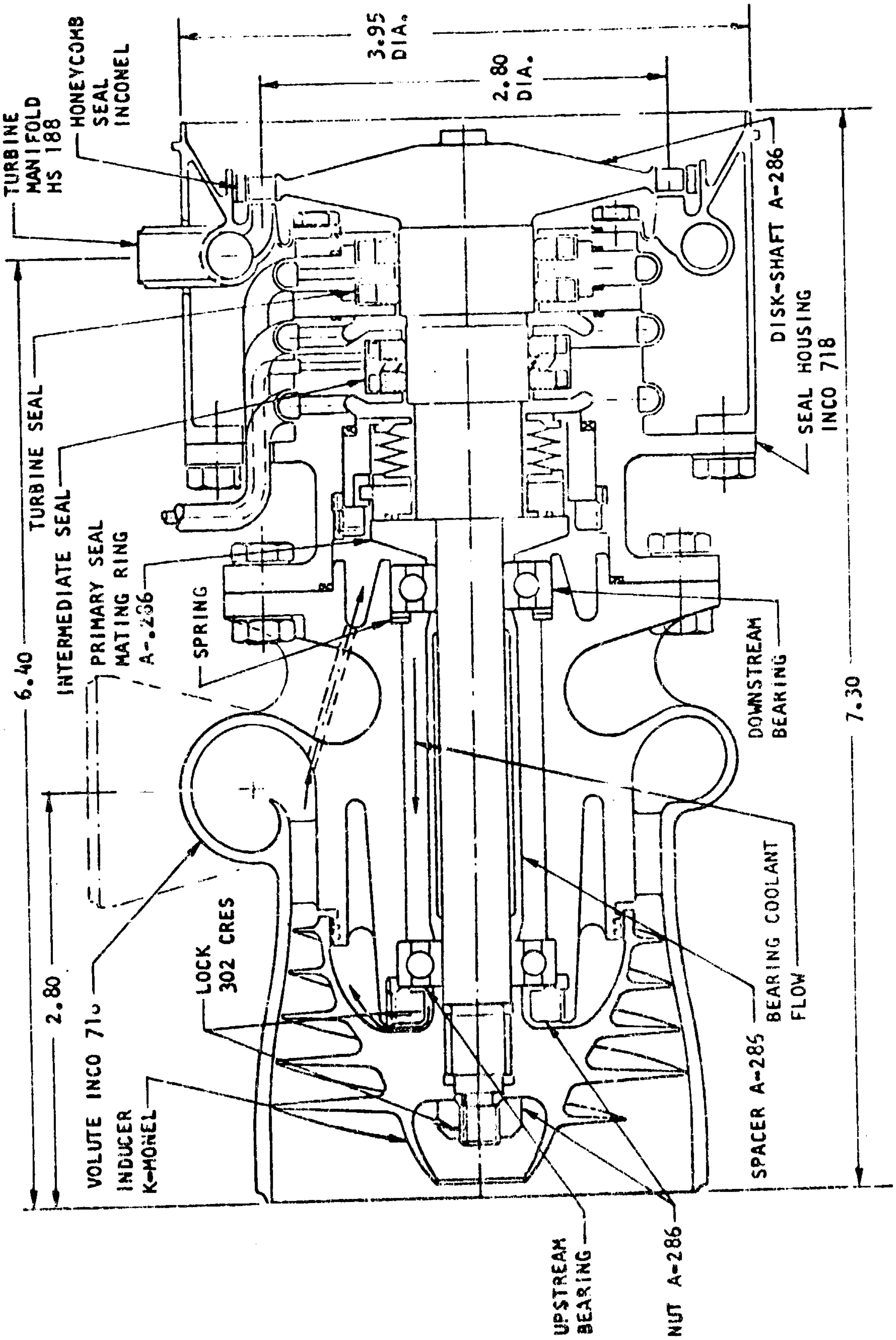
MAJOR DISADVANTAGES OF OXYGEN HYDRAULIC DRIVE IN ADVANCED SPACE ENGINE SYSTEM

- ENGINE STARTS DRY (LO_2 SYSTEM NOT PRIMED)
- LO_2 BOOST PUMP START LAGS LO_2 MAIN PUMP
- LO_2 BOOST PUMP WOULD NOT AID CHILLDOWN, START, IDLEMODE

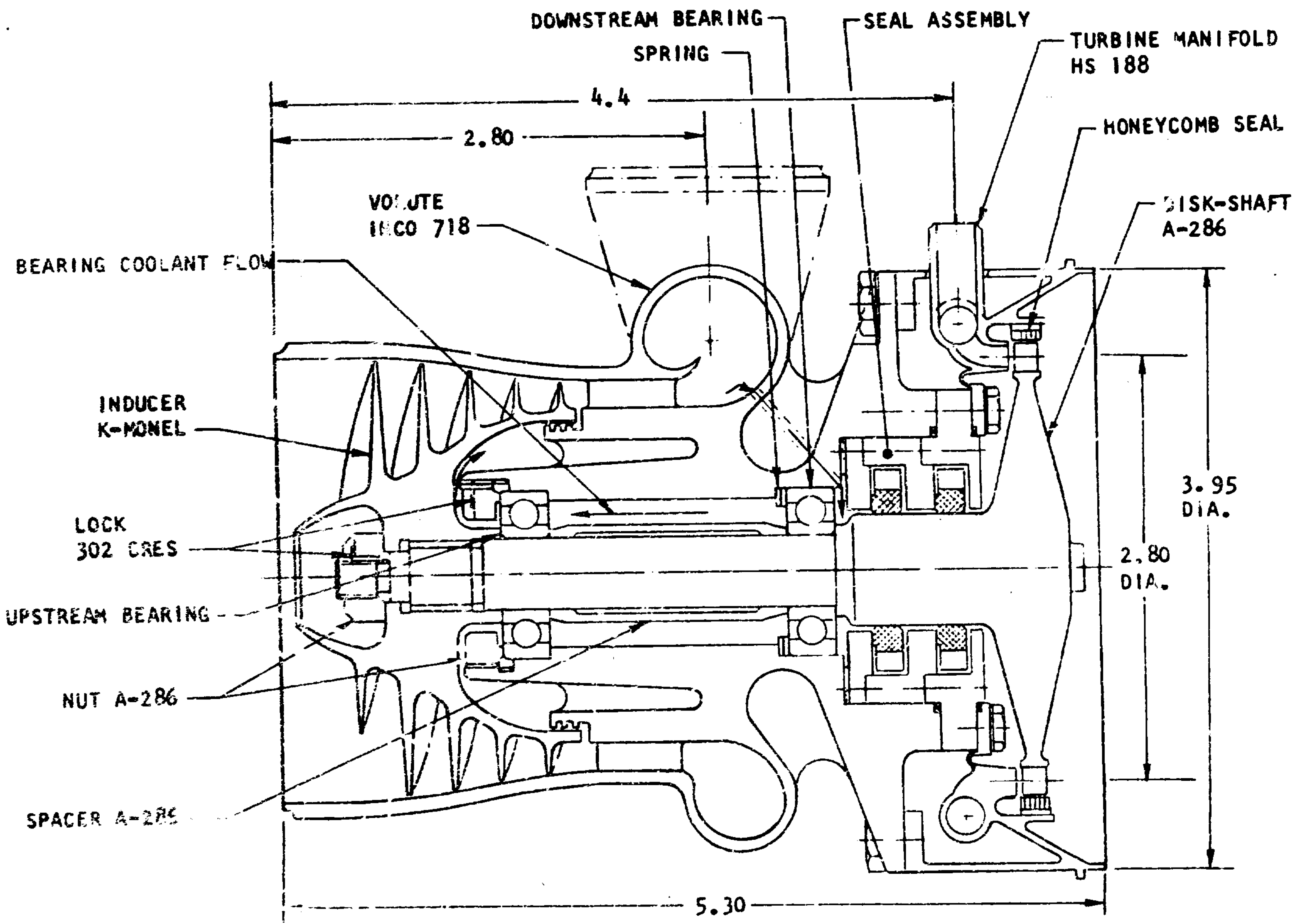
THE GH_2 DRIVE METHOD CONSISTS OF A GAS TURBINE DRIVEN BY GASEOUS HYDROGEN HEATED IN THE THRUST CHAMBER COOLING JACKET. A SMALL PORTION OF THE COOLING JACKET FLOW IS DIVERTED TO DRIVE THE BOOST PUMPS PRIOR TO BEING ROUTED TO THE PREBURNER. THE BOOST PUMP TURBINE INLET PRESSURE AND TEMPERATURE ARE APPROXIMATELY 4000 PSI AND 400 R, RESPECTIVELY.

LO_2 BOOST PUMP

(GH_2 TURBINE DRIVE)



LH_2 BOOST PUMP
(GH_2 TURBINE DRIVE)



THESE ARE THE ADVANTAGES AND DISADVANTAGES OF GH_2 TURBINE DRIVEN BOOST PUMPS.

GH_2 TURBINE DRIVEN BOOST PUMPS

- ADVANTAGES
  - PROVIDES MORE CONTROL OVER START TRANSIENT AND AIDS CHILLDOWN
  - ALLOWS FOR FLEXIBILITY IN PACKAGING
  - FLEXIBLE FOR OFF-DESIGN OPERATION
  - GOOD LIFE CAPABILITY

- DISADVANTAGES
  - HIGH AXIAL SHAFT LOAD
  - GH_2 LEAKAGE INTO LH_2 BOOST PUMP (~ 0.3 PERCENT OF MAINSTAGE MASS FLOW)
  - LO_2 BOOST PUMP REQUIRES PURGED SEAL PACKAGE
  - REQUIRES HIGH PRESSURE GH_2 LINES

THE TRADEOFF CONSIDERED OPERATION DURING START, MAINTENANCE OF MAIN PUMP NPSH (START, MAINSTAGE, AND OFF DESIGN), LIFE, NON-PROPULSIVE PROPELLANT LOSSES, MECHANICAL DESIGN, AND IMPACT ON THE POWER CYCLE. IT WAS CONCLUDED THAT DUE TO THE EARLY BENEFIT TO THE ENGINE START PROCESS, PACKAGING FLEXIBILITY, FLEXIBILITY FOR OFF-DESIGN OPERATION, AND GOOD LIFE POTENTIAL, THE GH_2 DRIVE

(CONTINUED)

BOOST PUMP DRIVE TRADEOFF

Drive	Provide Start Control	Provide NPSH Start	Provide NPSH Mainstage	Provide NPSH OffDesign	Long Life	No Losses	Packaging Flexibility	Mech Design	Low Potential Eng. Cycle Impact	Order of Preference LH_2	Order of Preference LO_2
Gear	No	Yes	Yes	?(LH_2 Pump	No	No	No	?(Life)	No	4	4
LH_2 Hyd Full	No	Yes	Yes	Yes	Yes	Yes	No	?(Turbine)	No	3	
Partial	No	?(Start Lag)	Yes	Yes	Yes	Yes	Yes	Yes	No	2	
LO_2 Hyd Full	No	Yes	Yes	Yes	Yes	Yes	No	?(Turbine)	No		3
Partial	No	?(Start Lag)	Yes	Yes	Yes	Yes	Yes	Yes	No		2
GH_2 Turb. LO_2	Yes	Yes	Yes	Yes	Yes	No	Yes	?	Yes		1
LH_2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	?	Yes	1	

METHOD WAS THE MOST DESIRABLE EVEN THOUGH SEAL LEAKAGE (LO_2 BOOST PUMP) AND POTENTIAL HIGH AXIAL LOAD PROBLEMS ARE DESIGN DRAWBACKS. THE GEAR-DRIVEN BOOST PUMP METHOD WAS CONCLUDED TO BE LIFE-LIMITED UNLESS A SIGNIFICANT REDUCTION IN MAIN PUMP SPEED IS IMPLEMENTED TO LIMIT THE PITCH LINE VELOCITY TO WITHIN TOLERABLE LIMITS. THE LOWER MAIN PUMP SPEED WOULD COMPROMISE THE SYSTEM CYCLE EFFICIENCY. IN ADDITION, THE LACK OF PACKAGING FLEXIBILITY AND LATE START DURING THE START SEQUENCE FURTHER LIMITED ITS APPLICABILITY. THE FULL-FLOW HYDRAULIC DRIVE MECHANICAL COMPLEXITY, DELAYED STARTUP, AND LIMITED BOOST PUMP HORSEPOWER (LOW NPSH AND LIMITED TURBINE DIAMETER) MADE IT LESS DESIRABLE THAN THE GH_2 BOOST PUMP DRIVE METHOD. THE PARTIAL-FLOW HYDRAULIC DRIVE METHOD FOR THE FUEL BOOST PUMP WAS REJECTED BECAUSE THE HIGH PROBABILITY OF TWO-PHASE FLOW WOULD MAKE THE TURBINE DESIGN DIFFICULT.

BOOST PUMP DRIVE SELECTION

- LH_2

  GH_2 TURBINE DRIVE

- LO_2

  GH_2 TURBINE DRIVE

BOOST PUMP DESIGN APPROACH
FOR SPACE TUG ENGINE

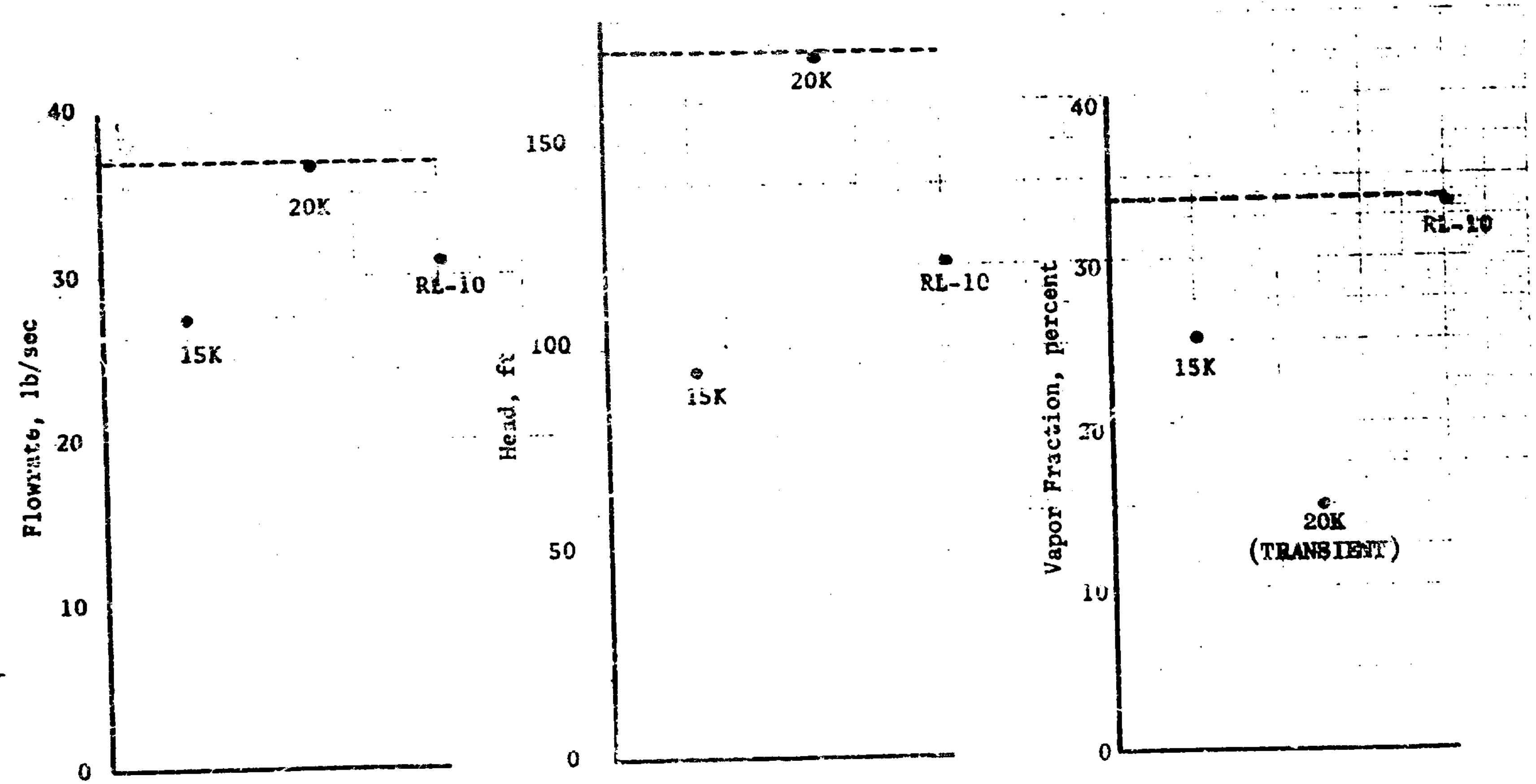
APPLICATIONS

- 15K THRUST (NAS8-29189)
- 20K THRUST (NAS3-16751)
- ADVANCED RL-10 (15K-20K)

IT WAS ASSUMED THAT THE SAME INDUCER COULD BE USED ON THE 15K, THE 20K, AND THE ADVANCED RL-10 ENGINES. THE CHANGE IN FLOW FOR THE DIFFERENT ENGINES COULD BE ATTAINED BY A PROPORTIONAL CHANGE IN SPEED. THE HEAD WAS DICTATED BY THE 20K REQUIREMENT.

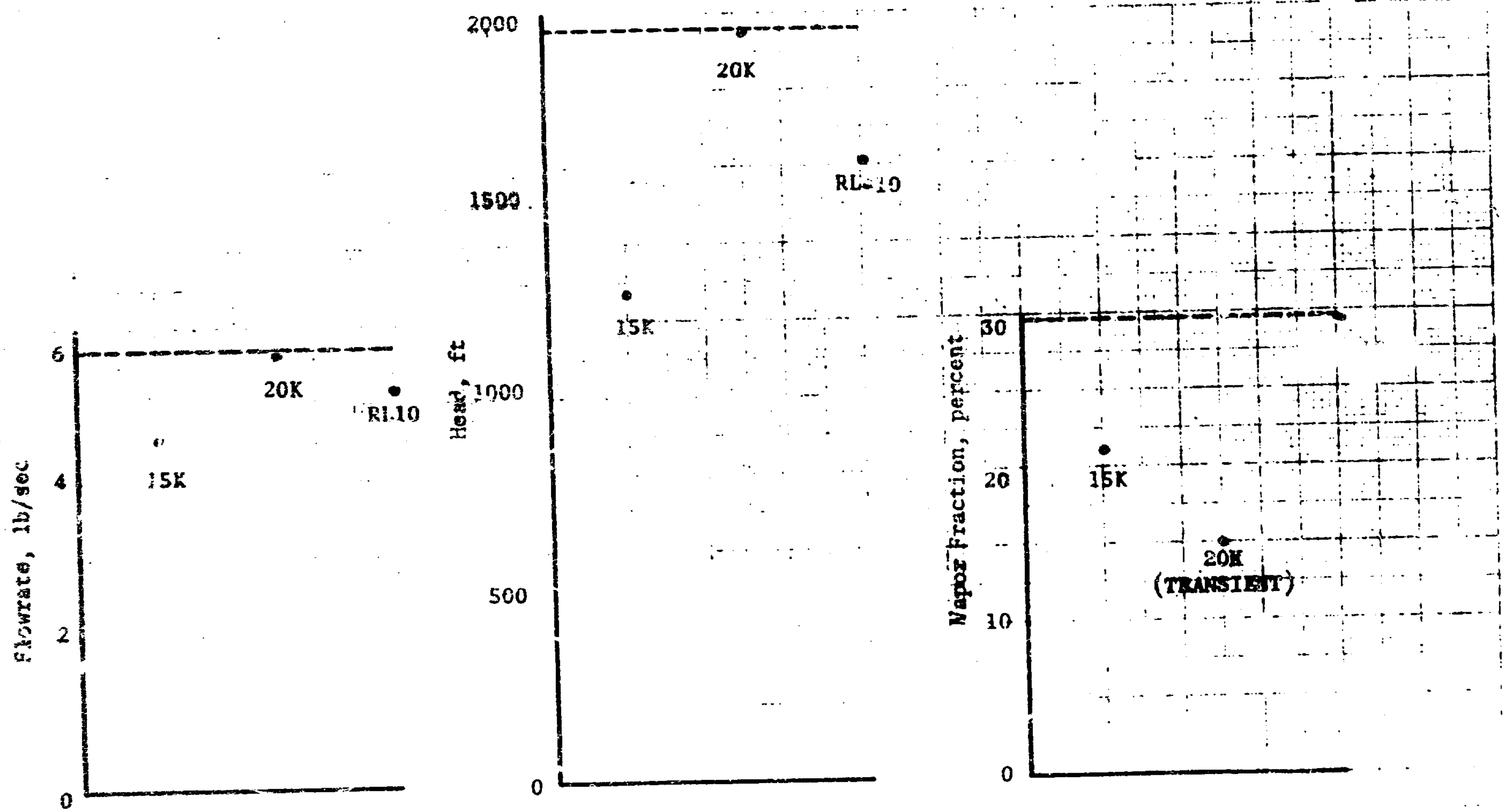
DESIGN REQUIREMENTS

LOW SPEED OXYGEN INDUCER



DESIGN REQUIREMENTS

LOW SPEED HYDROGEN INDUCER



LOW SPEED INDUCER DESIGN

- INDUCER DESIGN
  - FUEL
  - OXIDIZER
- TURBINE DESIGN
- MECHANICAL DESIGN
  - FUEL
  - OXIDIZER

THE THREE DESIGN POINTS ARE LOCATED ON AN "AFFINITY LAW" CURVE WHERE HEAD $\sim$ (FLOW)^2. THE RL-10 AND THE 15K ARE AT SATURATED TANK CONDITIONS. THE 20K, AFTER A LOW-SPEED IDLE MODE, RUNS WITH PRESSURIZED TANKS.

H_2 - LOW SPEED INDUCER DESIGN

D_t = 3.09 inch

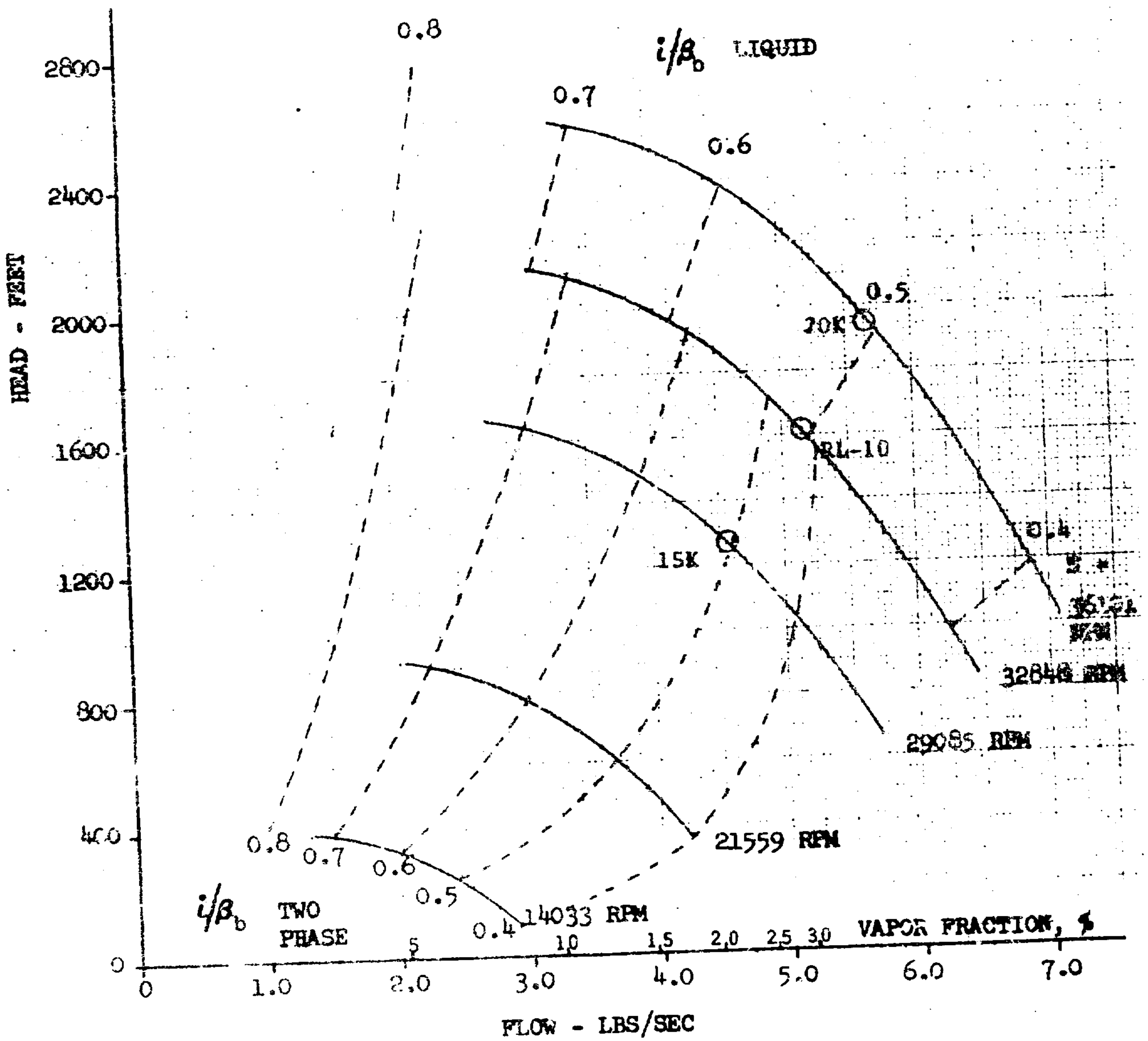
D_i = 3.09 inch

[illegible] = 0.0[illegible]0

[illegible] = [illegible].263

[illegible] = [illegible].450

β_b = 8.[illegible]



THE NEXT TWO CHARTS SHOW THE OPERATING POINTS
AND VARIOUS PARAMETERS OF THE HYDROGEN INDUCER.

H_2 - LOW SPEED INDUCER OPERATING POINTS

	15K	20K	ADV RL-10
$\dot{W}$, LB/SEC	4.56	5.66	5.15
Q, GPM	463	574	523
ΔH, FT	300	1955	53.6
HP	15.0	28.7	21.7
N, RPM	29,085	36,101	32,848
α, %	21.0	-	29.5

H_2 - LOW SPEED INDUCER HYDRODYNAMIC PARAMETERS

	15K	20K	ADV RL-10
C_m, ft/sec	27.3	27.0	34.4
$(U_t)_{ind}$, ft/sec	390	485	441
$(U_t)_{imp}$, ft/sec			
ϕ	0.070	0.0657	0.078
β_f, deg	4.0	3.2	4.5
β_b, deg	8.11	8.11	8.11
i, deg	4.11	4.92	3.65
i/β	0.507	0.607	0.450

AGAIN THE THREE DESIGN POINTS ARE LOCATED ON AN "AFFINITY CURVE" FOR THE OXYGEN INDUCER.

O_2 - LOW SPEED INDUCER DESIGN

D_t = 6.42 inch

D_i = 4.87 inch

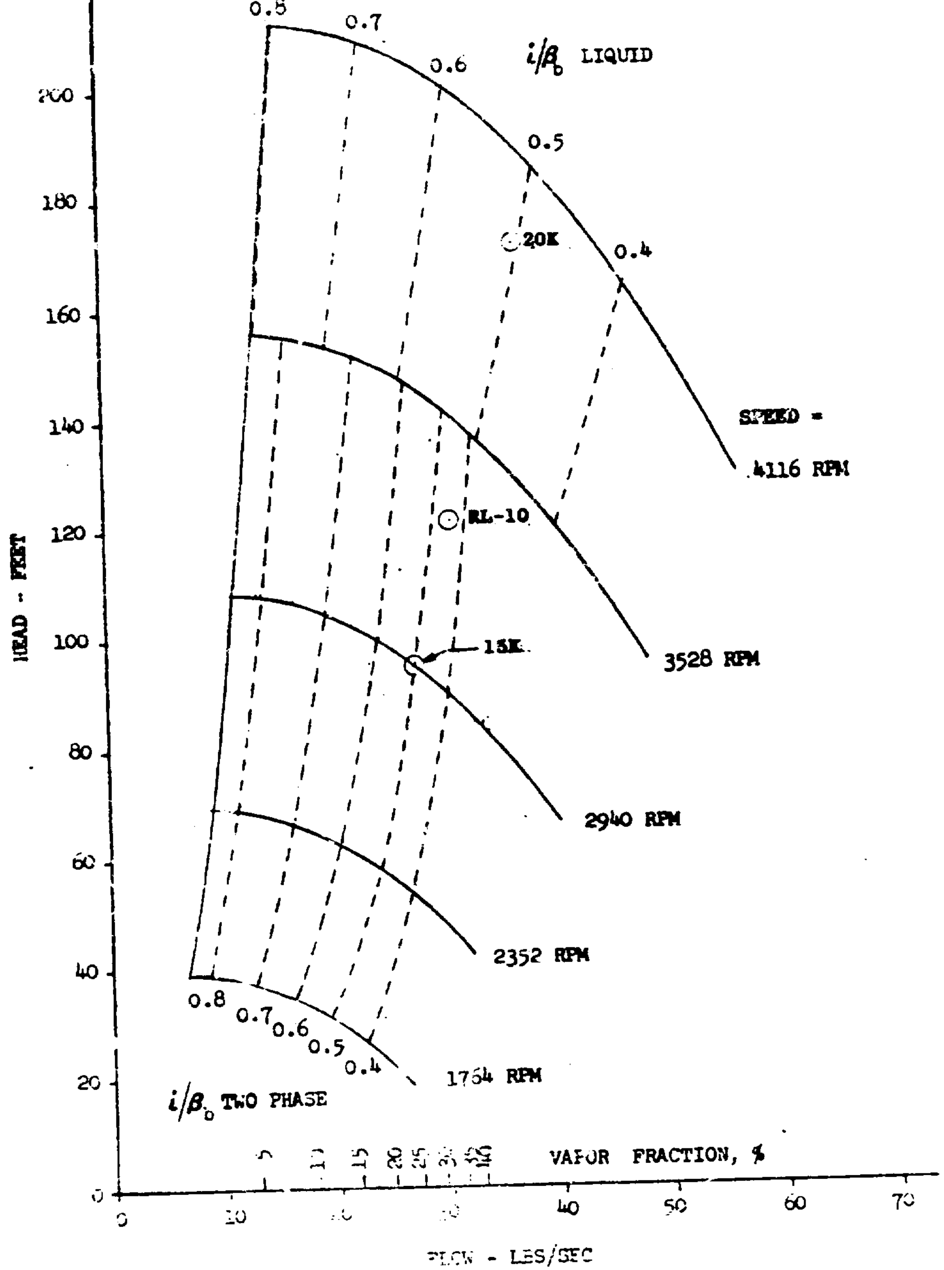
ϕ = 0.070

X = 0.045

i/β = 0 450

β_b = 8.17

PERFORMANCE CHARACTERISTICS
FOR OXYGEN INDUCER



THE NEXT TWO CHARTS GIVE THE OPERATING POINTS AND PARAMETERS FOR THE OXYGEN INDUCER.

O_2 - LOW SPEED INDUCER OPERATING POINTS

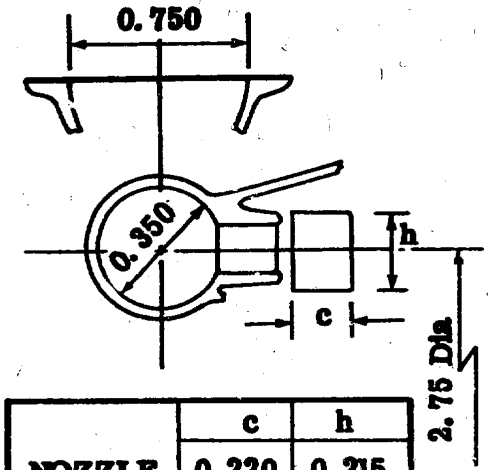
	15K	20K	ADV RL-10
$\dot{W}$, lb/sec	27.4	36.8	30.9
Q, gpm	173	232	195
ΔH, ft	95	162	9.5
HP	6.14	14.9	8.84
N, rpm	2941	3955	3322
α, %	25.2	-	33.5

O_2 - LOW SPEED INDUCER HYDRODYNAMIC PARAMETERS

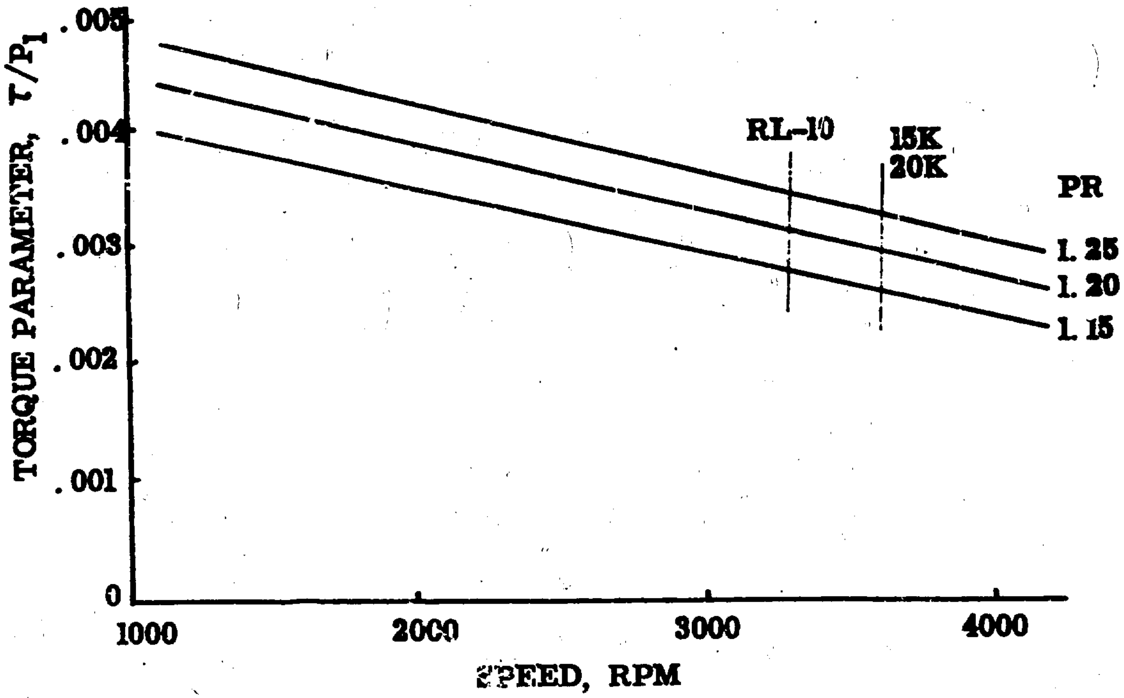
	15K	20K	ADV RL-10
C_m, ft/sec	4.36	4.39	5.52
$(U_t)_{ind}$, ft/sec	62.2	83.7	70.3
$(U_t)_{imp}$, ft/sec	82.4	110.8	93.1
ϕ	0.070	0.052	0.079
β_f, deg	4.0	3.0	4.5
β_b, deg	8.17	8.17	8.17
i, deg	4.17	5.17	3.68
i/β	0.510	0.632	0.450

THE SAME TURBINE IS USED FOR THE 15K, THE 20K, AND THE ADVANCED RL-10. THE VARIOUS RUNNING CONDITIONS CAN BE ACHIEVED BY VARYING THE AMOUNT OF ADMISSION.

FUEL BOOST PUMP TURBINE



	c	h
NOZZLE	0.220	0.215
ROTOR	0.200	0.230



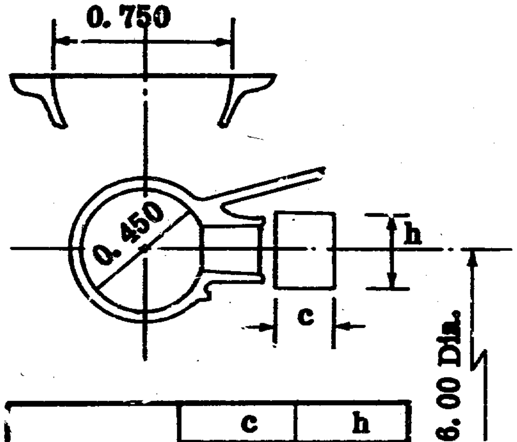
THE CHART SHOWS THE VARIOUS TURBINE PARAMETERS
FOR THE TURBINE THAT DRIVES THE HYDROGEN INDUCER.

HYDROGEN LOW-SPEED INDUCER TURBINE OPERATING POINT

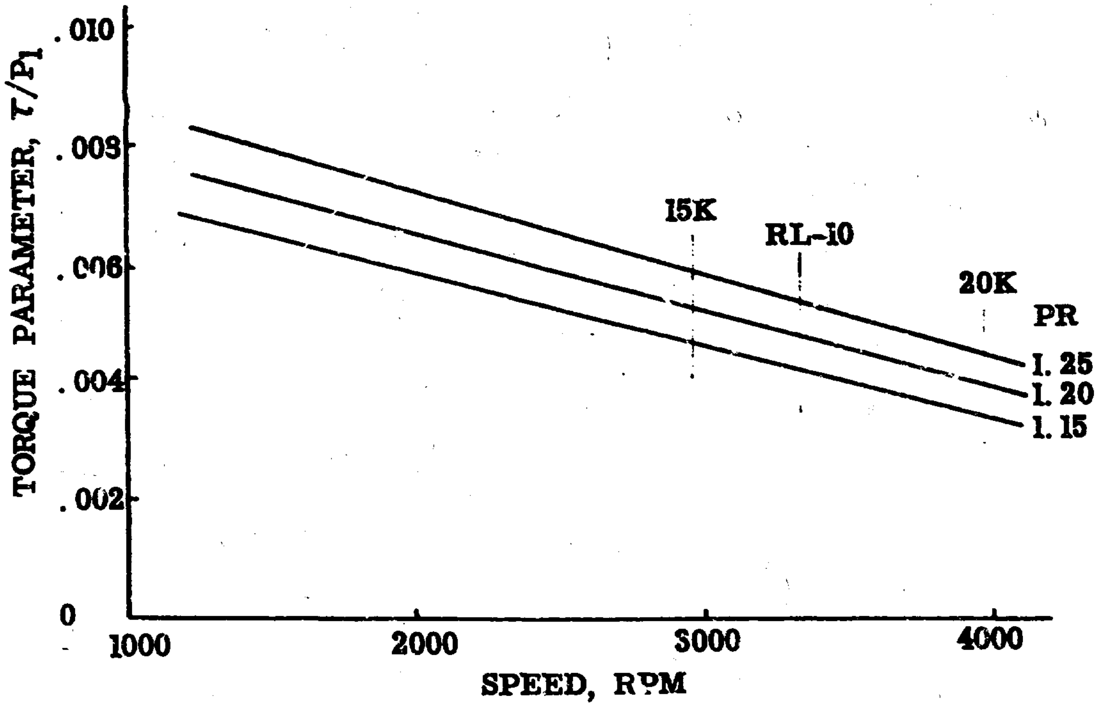
	15K	20K	RL-10
P_t, PSIA	2000	4355	1400
T_t, R	520	550	500
PR	1.15	1.15	1.15
$\dot{W}$, LB/SEC	0.650	0.670	0.572
ϵ, PERCENT	20	8.5	22.5
HP	16.44	21.43	23.68
U_m, FT/SEC	434	434	395
U/C_o	0.229	0.223	0.213
η, PERCENT	48.3	44.0	42.5

THE SAME TURBINE CAN BE USED FOR THE 15K, THE 20K, AND THE ADVANCED RL-10 BY VARYING THE AMOUNT OF ADMISSION.

OXIDIZER BOOST PUMP TURBINE



	c	h
NOZZLE	0.320	0.369
ROTOR	0.300	0.370



THE CHART SHOWS THE VARIOUS TURBINE PARAMETERS
FOR THE TURBINE THAT DRIVES THE OXYGEN INDUCER.

OXYGEN LOW-SPEED INDUCER TURBINE OPERATING POINTS

	15K	20K	RL-10
P_t, PSIA	2000	4355	1400
T_t, R	520	550	500
PR	1.15	1.15	1.15
$\dot{W}$, LB/SEC	0.48	0.90	0.646
ϵ, PERCENT	3.9	3.22	7.25
HP	6.14	14.92	8.84
U_m, FT/SEC	77.2	103.5	87.2
U/C_o	0.041	0.054	0.047
η, PERCENT	12.7	15.5	14.0

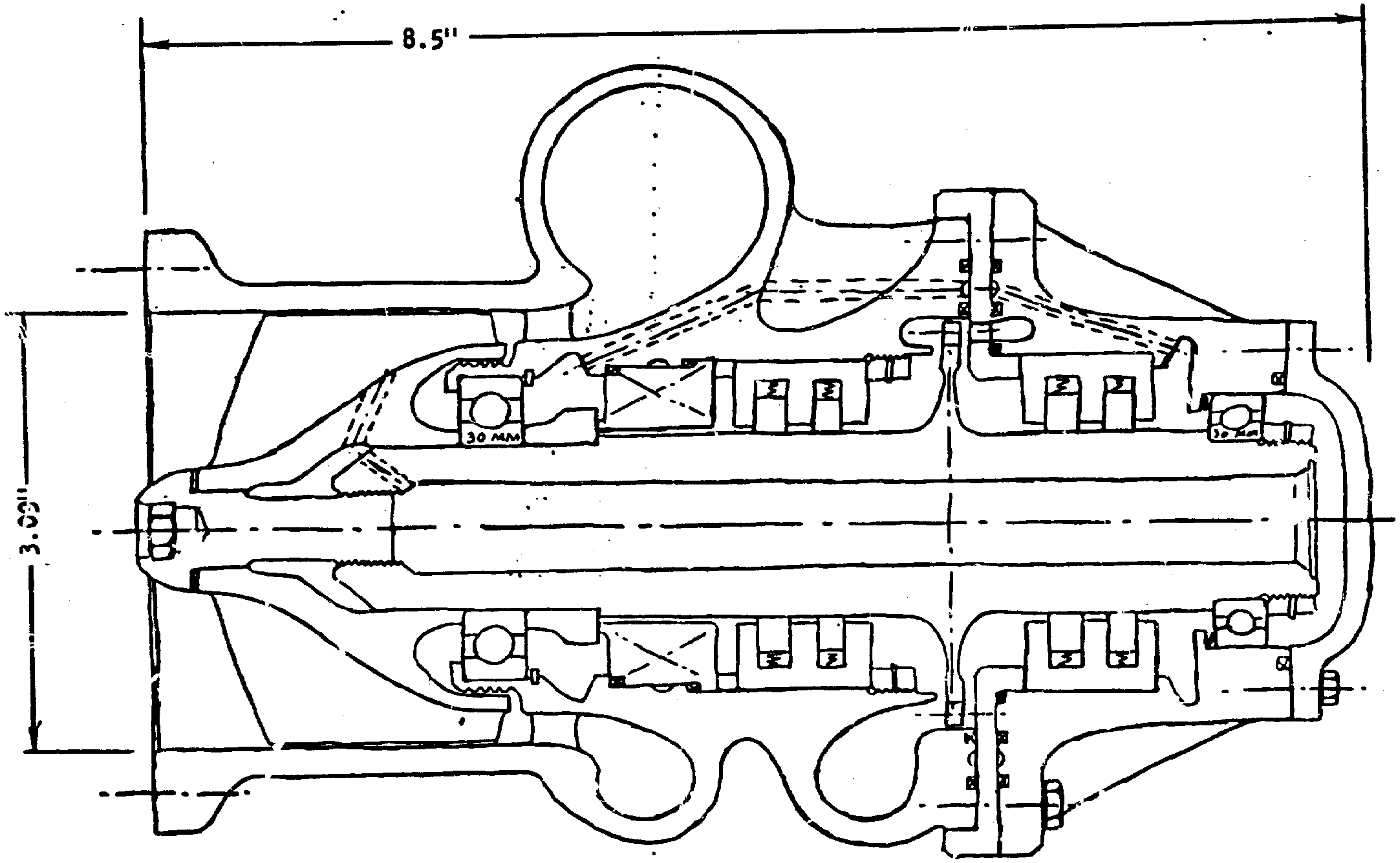
CONFIGURATION 1 ENDED UP WITH TOO MUCH GAS BEING RETURNED TO THE INDUCER AND WAS REJECTED. THE SYMMETRICAL ARRANGEMENT WAS USED TO BALANCE THE END THRUST WHICH COULD AMOUNT TO 4000 LB PUSHING ON THE END OF THE SHAFT

$$A \sim 1 \text{ SQ. IN.}$$

$$P \sim 4000 \text{ PSI}$$

LO-PRESSURE FUEL TURBOPUMP

CONFIGURATION NO. 1

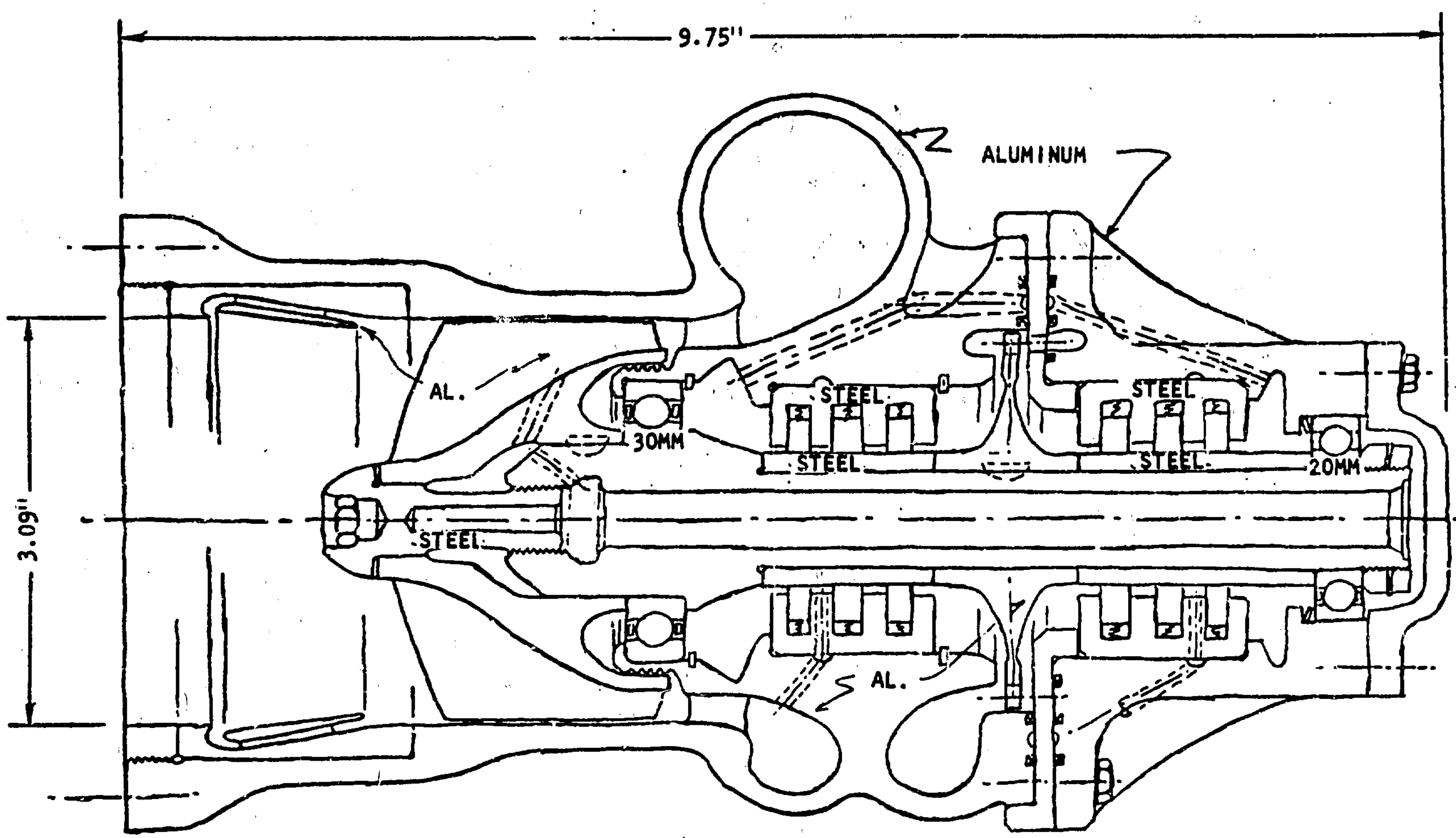


CONFIGURATION 2 WITH THREE SEALS ON EACH SIDE OF THE TURBINE IS RECOMMENDED. THE GAS BLEED BETWEEN SEALS IS VENTED INTO THE INDUCER MANIFOLD, THE LIQUID COOLING THE BEARING COMES BACK INTO THE INDUCER THROUGH THE SHAFT.

NOTE THE SEPARATE PIECE THAT CONTAINS THE PARTIAL ADMISSION NOZZLE FOR THE TURBINE.

LO-PRESSURE FUEL TURBOPUMP

CONFIGURATION NO. 2



THE CHART LISTS THE SEAL TYPES AND THE ADVANTAGES FOR THE LOW-SPEED HYDROGEN INDUCER.

H_2 - LOW SPEED INDUCER SEAL DESIGN

- FLOATING RING SEALS TO WITHSTAND HIGH SPEED AND PRESSURE
- CLEARANCE BETWEEN RINGS AND SHAFT ENSURES 10 HOUR LIFE
- THREE RING DESIGN WITH DRAIN TO PUMP DISCHARGE
  - ELIMINATES EXTERNAL LEAKAGE LOSSES
  - MINIMIZES LEAKAGE CONSISTENT WITH PRESSURE-SPEED-LIFE REQUIREMENTS
  - MINIMUM EFFECT ON NPSH
  - SEPARATES SEAL LEAKAGE FROM BEARING COOLANT
- SEAL SIZE MINIMIZED TO REDUCE LEAKAGE

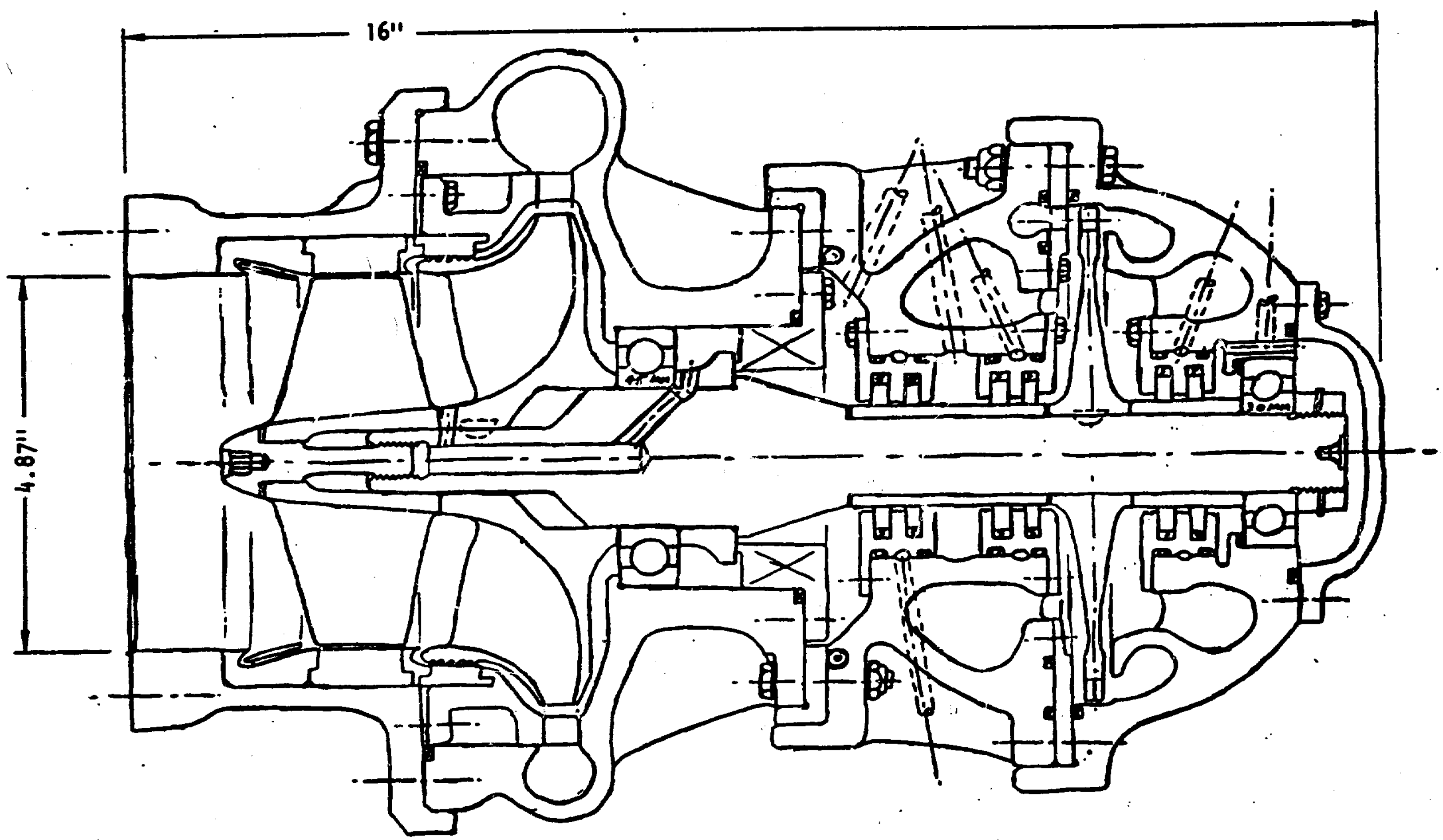
THIS TABLE LISTS THE DESIGN FEATURES OF THE HYDROGEN TURBOINDUCER.

SELECTED H_2 LOW-SPEED INDUCER DESIGN FEATURES

FEATURE	REASON
• BACKFLOW DEFLECTOR	ASSURES HIGH SUCTION CAPABILITY OVER WIDE FLOW RANGE
• OUTBOARD TURBINE BEARING AND SEAL	PROVIDES SYMMETRY, BALANCES TURBINE AXIAL THRUST
• CONTROLLED GAP SEALS	THREE RING TYPE TO SEPARATE TURBINE LEAKAGE GAS FROM BEARING COOLANT FLOW
• LOW AXIAL THRUST	TURBINE/SEAL SYMMETRY ALLOWS AXIAL THRUST CONTROL WITH BEARING ONLY
• POSITIVE BEARING COOLANT FLOW	FROM INDUCER DISCHARGE TO INLET THROUGH HOLLOW SHAFT
• HOUSING	MATERIAL: ALUMINUM TENS 50 (FOR LIGHT WEIGHT AND LOW COST)
• SHAFT	MATERIAL: A286 (MINIMIZES SHAFT DIAMETER FOR MINIMUM SEAL LEAKAGE)

CONFIGURATION 1 FOR THE O_2 TURBOPUMP HAD A 30mm BEARING AFT THE TURBINE THAT WAS EITHER GREASE-PACKED OR LUBRICATED WITH GH_2. THE SYMMETRICAL SEAL PACKAGE WAS AGAIN NECESSARY BECAUSE OF THE HIGH AXIAL THRUST.

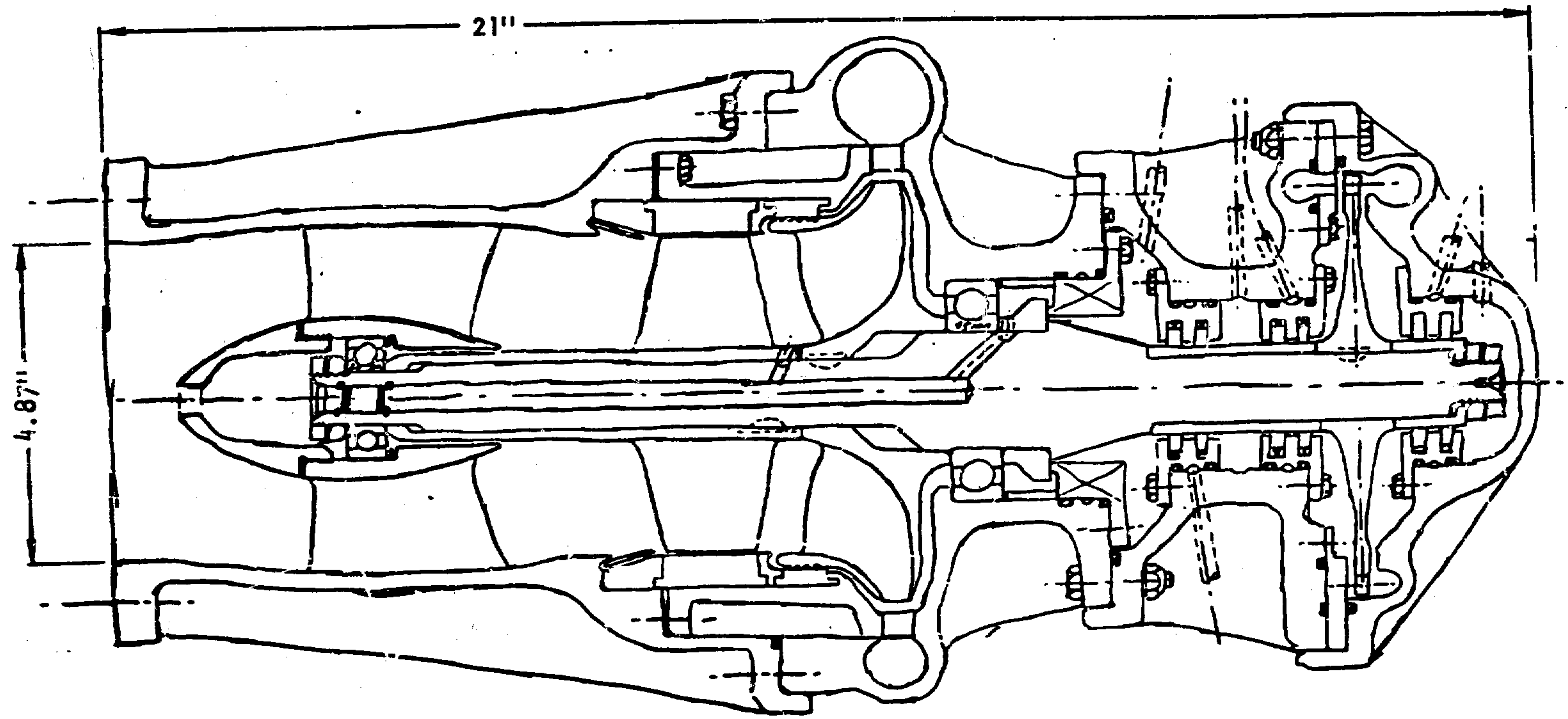
LO-PRESSURE OXIDIZER TURBOPUMP
CONFIGURATION NO. 1



IN THE SECOND OXIDIZER TURBOPUMP CONFIGURATION, THE BEARING WAS PUT IN FRONT OF THE PUMP AND THE TURBINE WAS OVERHUNG. THE EFFECTS OF THE FRONT BEARING HOUSING, THE STRUTS AND THE FRONT BEARING COOLING FLOW ON THE TWO-PHASE PUMPING CAPABILITY OF THE INDUCER WERE THE MAJOR OBJECTIONS.

LO-PRESSURE OXIDIZER TURBOPUMP FWD BEARING

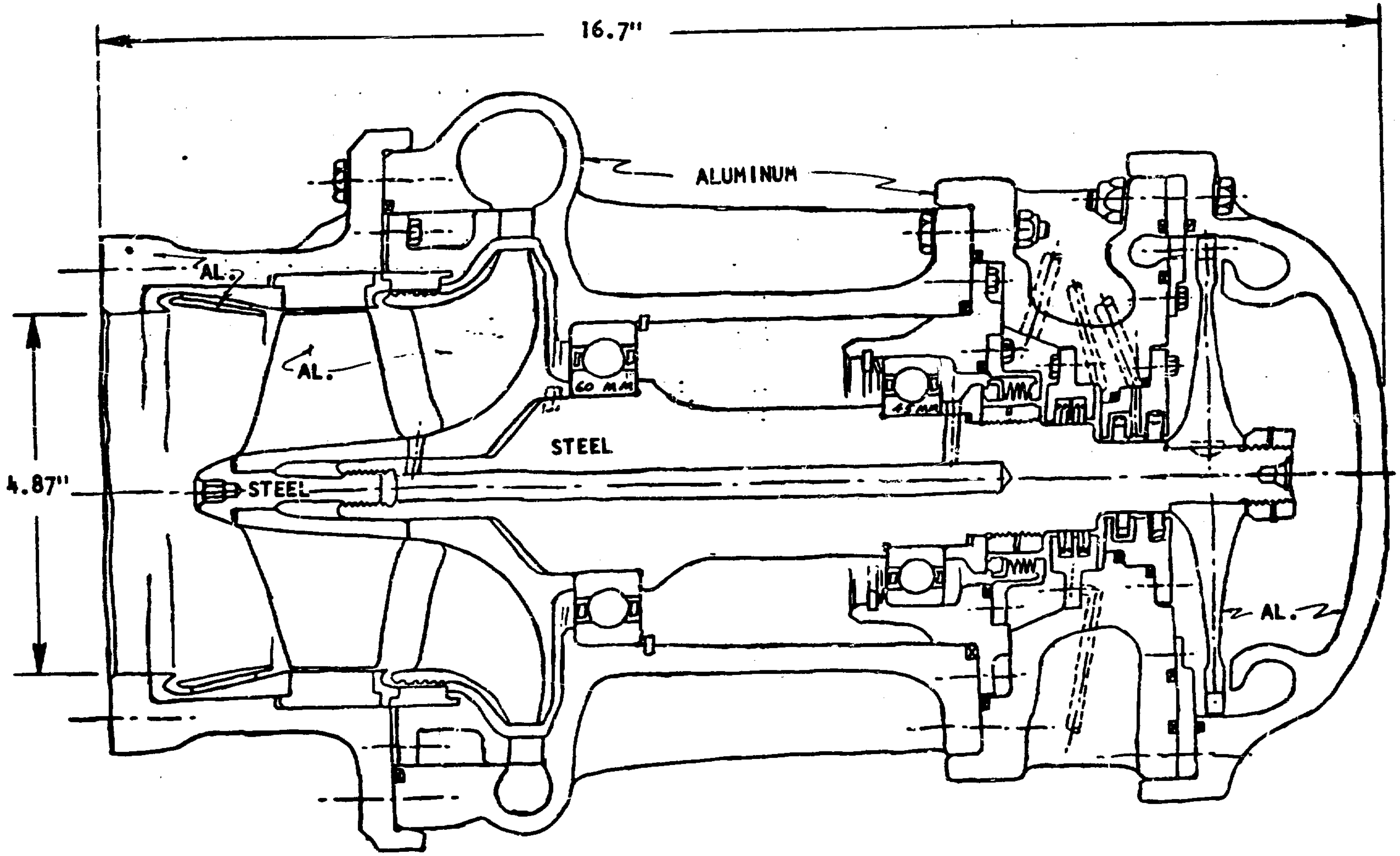
CONFIGURATION NO. 2



THE CRITICAL SPEEDS OF THE FIRST TWO CONFIGURATIONS WERE SUBSTANTIALLY HIGHER THAN THE OPERATING SPEED. THE TURBINE SHAFT DIAMETER WAS THEREFORE REDUCED TO MINIMIZE THE AXIAL THRUST AND A 60mm BEARING WAS USED TO TAKE THE THRUST. THIS WAS THE RECOMMENDED CONFIGURATION.

LO-PRESSURE OXIDIZER TURBOPUMP

CONFIGURATION NO. 3



Rocketdyne
North American Rockwell

THIS CHART COMPARES THE THREE OXYGEN TURBOINDUCER DESIGNS.

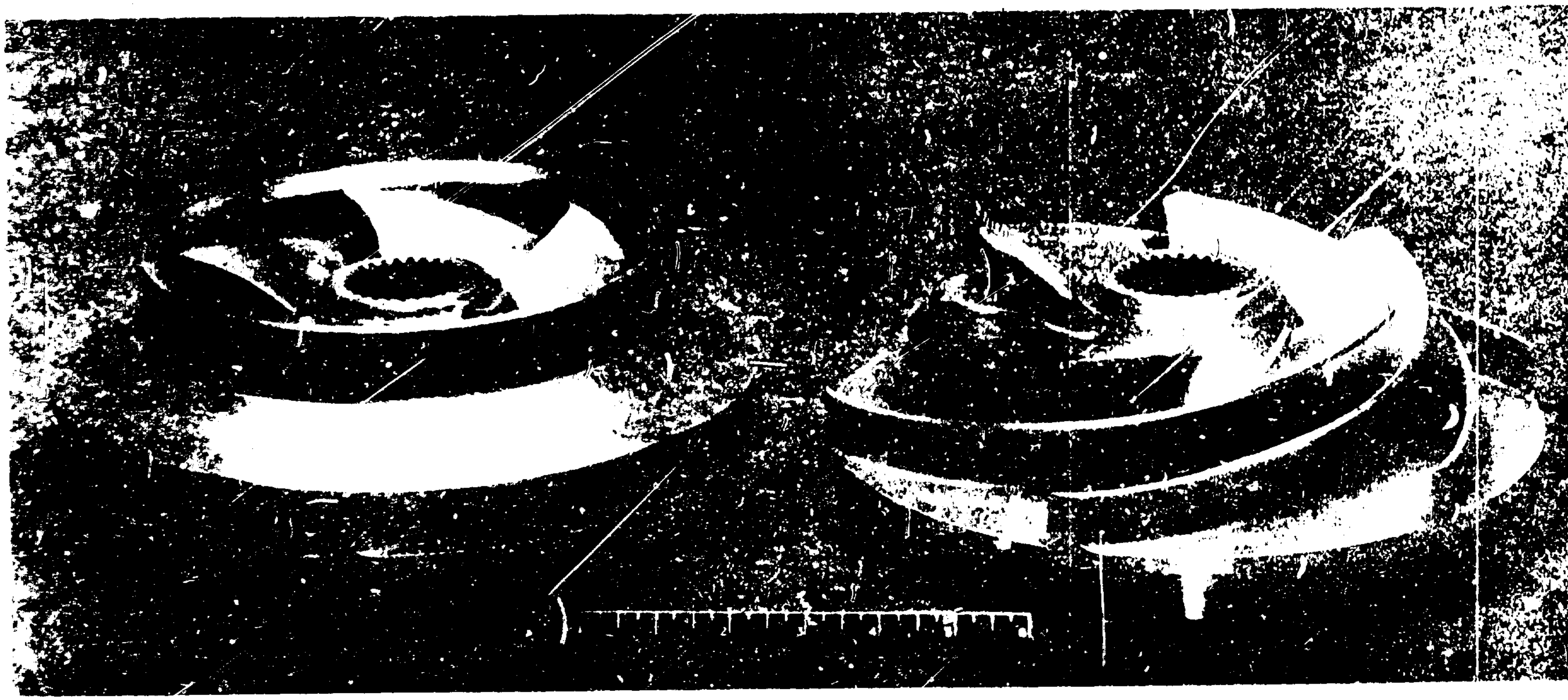
OXYGEN LOW-SPEED INDUCER
MECHANICAL DESIGN EVALUATION

CONFIGURATION	1	2	3 (Recommended)
TURBINE BEARING	OUTBOARD	UPSTREAM INDUCER	UPSTREAM TURBINE
LUBRICATION	GREASE PACKED OR GH_2	LOX	LOX
THRUST BEARING	BEHIND IMPELLER LOX LUBED	BEHIND IMPELLER, LOX LUBED	BEHIND IMPELLER, LOX LUBED
MAXIMUM SPEED	4000 RPM	4000 RPM	4000 RPM
CRITICAL SPEED	20,000 RPM	20,000 RPM	15,000 RPM
AXIAL LOAD	NIL	NIL	3000 LB
BREAK-AWAY TORQUE	NIL	NIL	5 IN.-LB
TWO-PHASE FLOW	-	INLET RESTRICTION BEARING FLOW	-

A PHOTOGRAPH OF THE SAME LOX IMPELLER WITH
AND WITHOUT A SHROUD.

J-2 LOX IMPELLER

SHROUDED UNSHROUDED

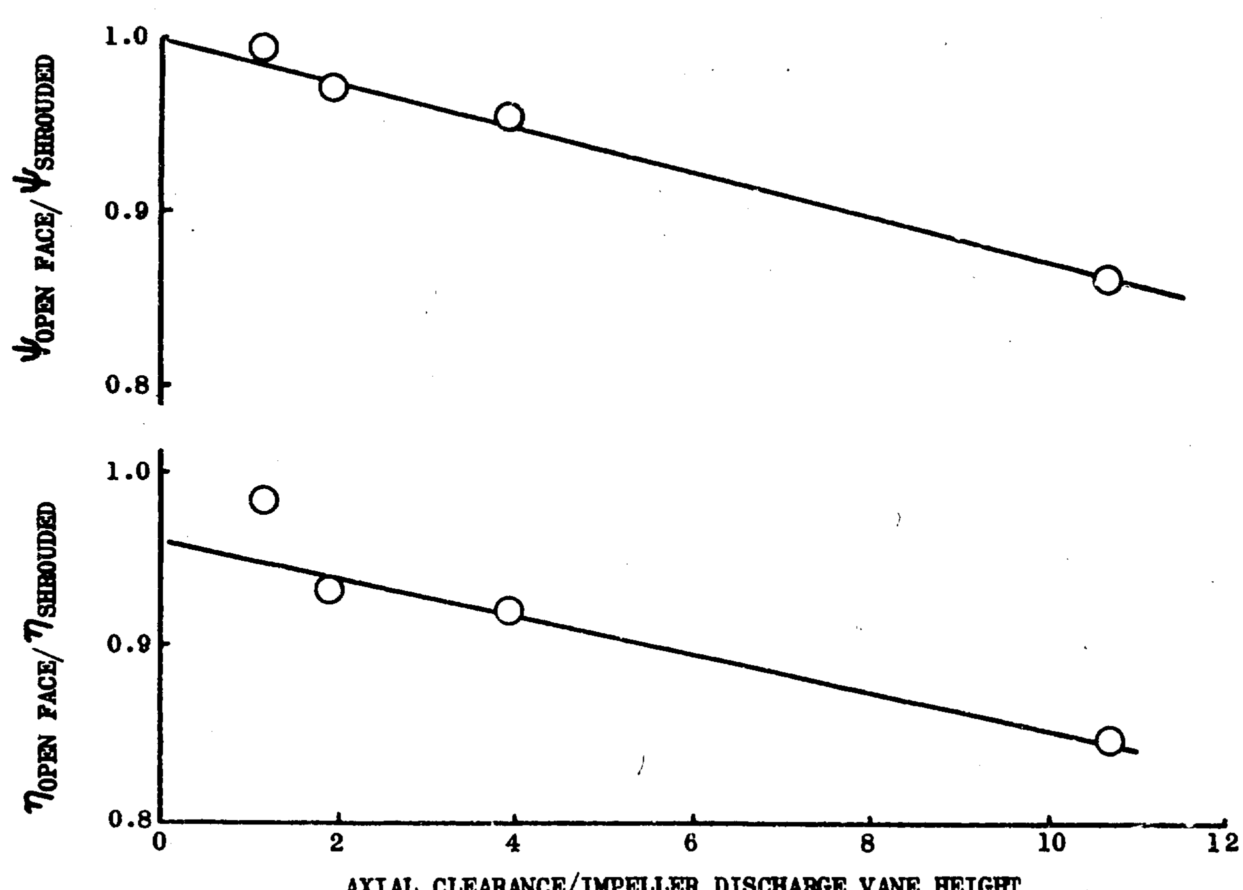


254-512

Rocketdyne
North American Rockwell

A FULLY SHROUDED IMPELLER, BESIDES BEING MORE EASY
TO SEAL, IS MORE EFFICIENT THAN AN OPEN FACE IMPELLER.

J-2 OXIDIZER PUMP OPEN FACE
AND SHROUDED IMPELLER PERFORMANCE



THE FEATURES OF THE SEAL PACKAGE ON THE OXYGEN TURBOINDUCER.

O_2 - LOW SPEED INDUCER SEAL DESIGN

- FAIL SAFE SEPARATION OF OXIDIZER AND FUEL
- RUBBING CONTACT LOX SEAL WITHIN CURRENT STATE-OF-THE-ART
  - PV = 560 COMPARED TO RECOMMENDED LIMIT OF 600,000
  - LOW PV FACTOR ENSURES 10 HOUR LIFE
- FACE CONTACT SEAL ENSURES MINIMUM LEAKAGE LOSSES
- FLOATING RING PURGED INTERMEDIATE SEAL FOR POSITIVE SEPARATION OF OXIDIZER AND FUEL DRAIN CAVITIES
  - FLOATING RING DESIGN ENSURES MINIMUM STARTING TORQUE LOSSES AND 10 HOUR LIFE
- DOUBLE FLOATING RING TURBINE SEAL WILL WITHSTAND HIGH PRESSURE AND ENSURE 10 HOUR LIFE
  - REDUNDANT SEAL RING AND DRAIN ENSURES FAIL SAFE OPERATION

A LIST OF SOME OF THE FEATURES ON THE OXYGEN TURBOINDUCER.

SELECTED O_2 - LOW SPEED INDUCER
DESIGN FEATURES

FEATURE	REASON
• SHROUDED IMPELLER	PERFORMANCE CONSISTENT FROM PUMP TO PUMP, CLOSE CLEARANCES NOT REQUIRED
• BACKFLOW DEFLECTOR	IMPROVED SUCTION CAPABILITY OVER WIDE FLOW RANGE (APS AND F-1 EXPERIENCE)
• REDUNDANT SEAL PACKAGE	ASSURES POSITIVE SEPARATION OF PROPELLANTS
• AXIAL THRUST CONTROL	THRUST BEARING SELECTED FOR LONG LIFE-AVOIDS COMPLEX THRUST BALANCING SYSTEM
• LOX LUBRICATED BEARINGS	POSITIVE FLOW THROUGH BOTH BEARINGS FROM PUMP DISCHARGE TO IMPELLER INLET THROUGH HOLLOW SHAFT
• HOUSING	MATERIAL: ALUMINUM TENS 50 (LIGHT WEIGHT, LOW COST)
• SHAFT	MATERIAL: A286 (TO MINIMIZE TURBINE SEAL DIAMETER FOR MINIMUM AXIAL THRUST)

SUMMARY

- PRELIMINARY DESIGNS OF TWO INDUCERS CAPABLE OF PUMPING TWO-PHASE HYDROGEN AND OXYGEN HAVE BEEN COMPLETED

- CONCEPTUAL DESIGNS OF THE BEARINGS, SEAL PACKAGES AND TURBINES TO DRIVE THESE INDUCERS HAVE BEEN COMPLETED, AND RECOMMENDATIONS HAVE BEEN MADE.

- BOTH TURBOPUMPS ARE APPLICABLE TO THE 15K OR THE 20K SPACE TUG ENGINES OR ON THE RL-10.

SUPPLEMENT

INTRODUCTION

At the Conceptual Design Review it was decided that making the inducers capable of operating on the 20K Space TUG design with its high head re-requirements and high gas pressures (4000 psi) placed too many restrictions on the design; the result was long and complicated seal packages and relatively large pumps. The program was therefore redirected to satisfy only the 15K and the RL-10 requirements.

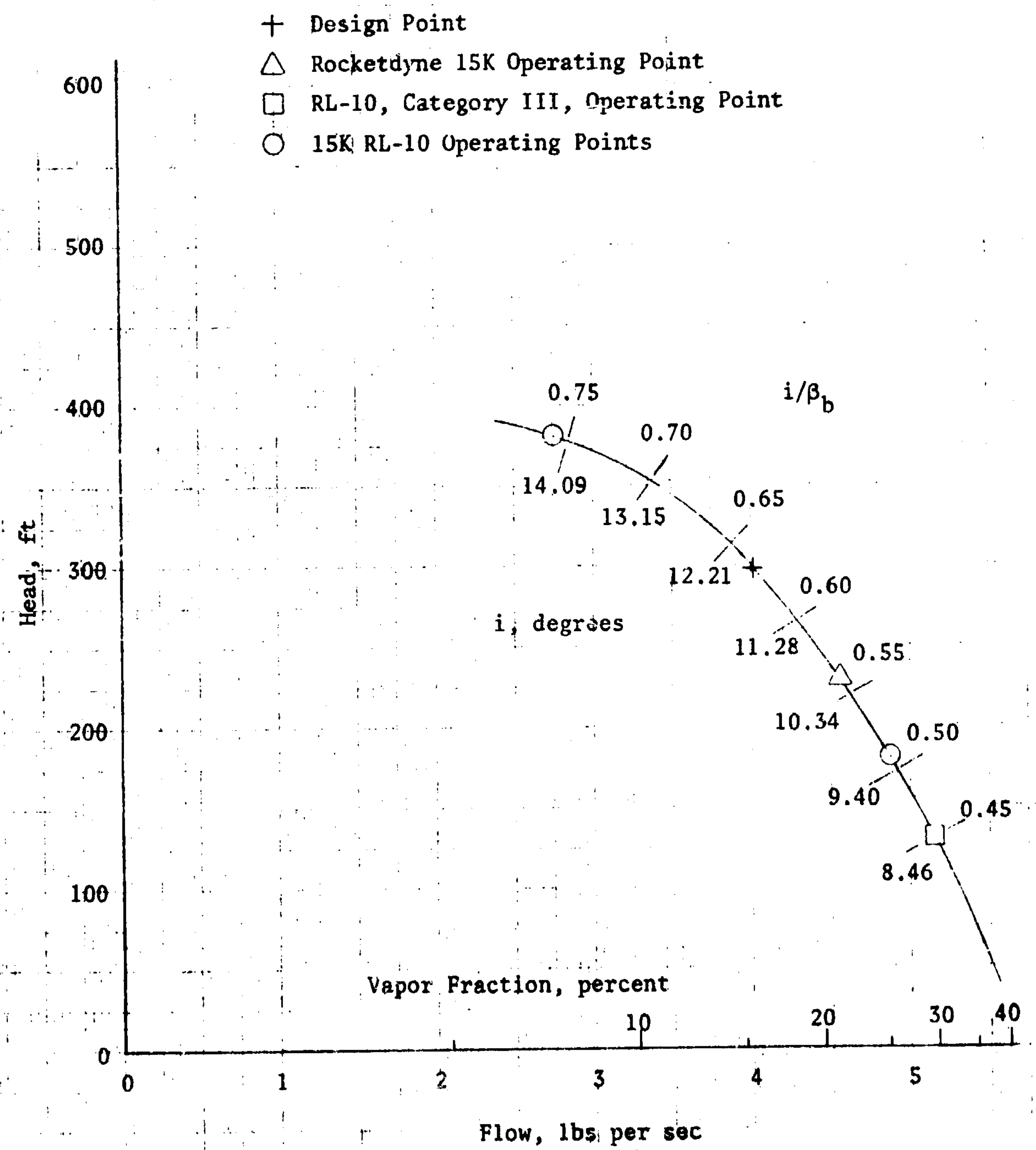
INDUCER DESIGN

Studies made on the 15K RL-10 indicated that during the start transient, the main hydrogen pump required 381 feet of head at the inlet when the flow was 2.76 lb/sec and during mainstage operation it required 182 feet at 4.87 ft/sec. The RL-10, Category III engine requires 53.6 feet at mainstage. The two-phase inducer that satisfies these requirements has a constant tip diameter of 3.078 in. and an inlet hub diameter of 0.927 inch. It runs at a speed of 14,085 rpm with a peak efficiency estimated to be 74 percent. The following figure shows the calculated constant-speed performance map for this inducer. Shown on the map are the inducer design point, the two-points for the 15K RL-10, the point where the RL-10, Category III engine would operate (130 feet) and the point for the Rocketdyne (work statement) 15K engine. The latter is at 230 feet of head which is below the work statement requirement of 300 feet but is sufficient for the 15K main pump. The inducer horsepower is fairly constant over the entire range with a maximum of 2.98 and a minimum of 2.42.

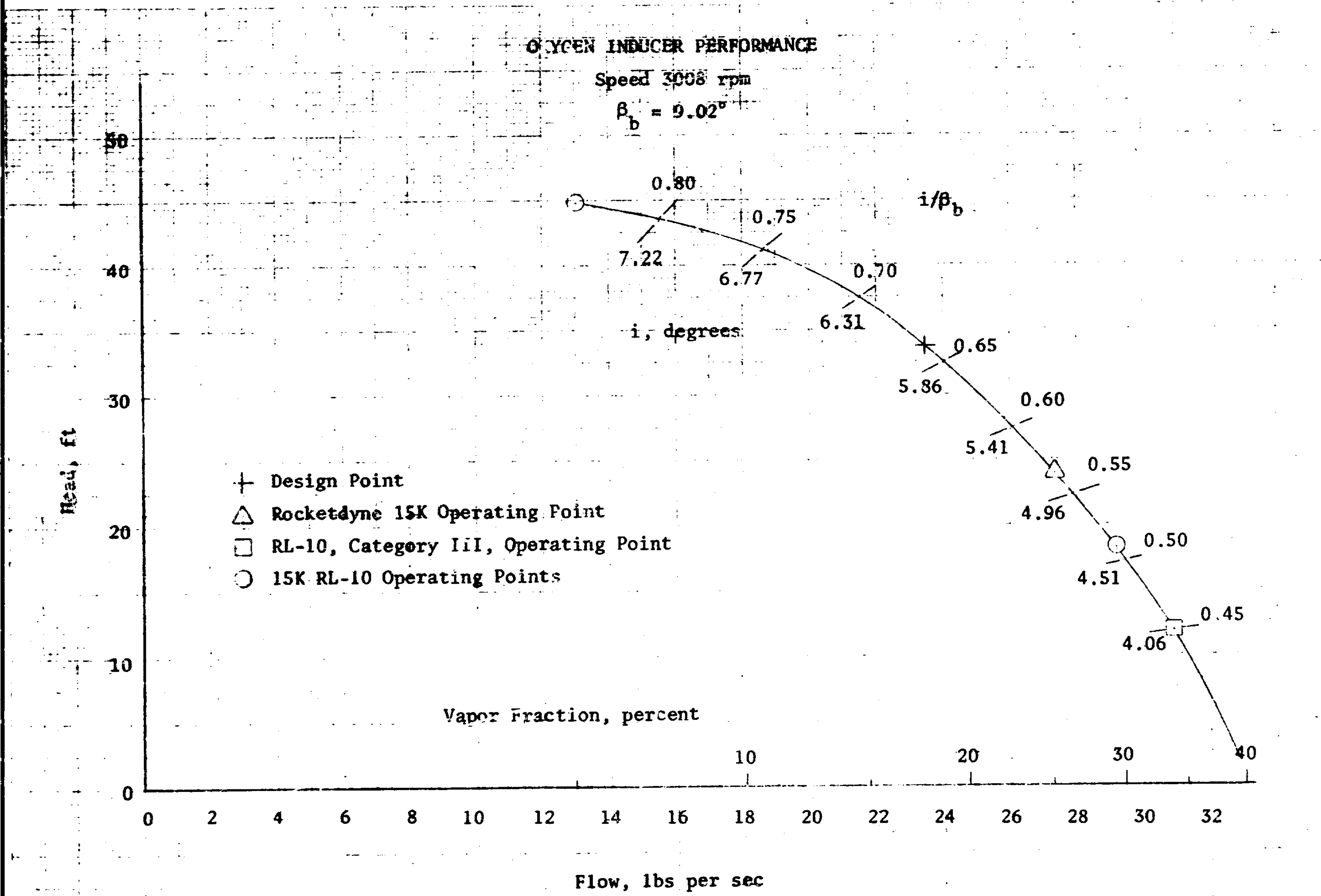
HYDROGEN INDUCER PERFORMANCE

Speed 14,058 rpm

$\beta_b = 18.79°$



Studies made on the 15K RL-10 also indicated that during the start transient, the main oxygen pump required 44.7 feet of head at the inlet when the flow was 13.0 lb/sec and during mainstage operation, it required 18.2 feet at 29.2 lb/sec. The RL-10, Category III engine requires 9.5 feet at mainstage. The two-phase inducer that satisfies these requirements has a constant tip diameter of 4.849 in. and an inlet hub diameter of 1.460 inches. It runs at a speed of 3008 rpm with a peak efficiency estimated to be 63 percent. The following figure shows the calculated constant-speed performance map for this inducer. Shown on the map are the inducer design point, the two points for the 15K RL-10, the point where the RL-10, Category III engine would operate (12 feet) and the point for the Rocketdyne (work statement) 15K engine. The latter is at 24 feet of head which is below the work statement requirement of 95 feet but is sufficient for the 15K main pump. The inducer horsepower varies from a minimum of 1.90 to a maximum of 2.33.


OXYGEN INDUCER PERFORMANCE
Speed 3008 rpm
$\beta_b = 9.02°$
i/β_b
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
7.22
6.77
6.31
5.86
5.41
4.96
4.51
4.06
i, degrees
Design Point
Rocketdyne 15K Operating Point
RL-10, Category III, Operating Point
15K RL-10 Operating Points
Vapor Fraction, percent
10
20
30
40
Head, ft
0
10
20
30
40
50
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
Flow, lbs per sec

INDUCER DRIVE SYSTEM

Two methods of driving the inducers were considered, hydrogen gas turbines with warm hydrogen gas being tapped from a 1400 psi source on the RL-10 engine and electric motors. The warm hydrogen gas turbine drive is compared to the electric motor drive in the following table.

Comparison of GH_2 Turbine Drive to Electric Motor Drive

	GH_2 TURBINE DRIVE	ELECTRIC MOTOR DRIVE
WEIGHT	H_2 turbine ≅ 3 lb. O_2 turbine ≅ 8 lb • O_2 turbine requires a helium purge, so add the weight of the helium plus bottle.	H_2 motor ≅ 9.6 lb O_2 motor ≅ 20 lb • Hydrogen gas lines, engine tap-off and valves probably offset weight of wires and inverters.
SIZE	Approximately the same. Motors are slightly longer; turbine plus manifolds have a larger O.D.	
SEALS	• Turbines have complicated seal packages particularly the O_2 turbine which has a helium purge. There is a slight danger of seal failure and O_2 and H_2 mixing. • There are also overboard vents on the O_2 turbine. • In the H_2 turboinducer, the turbine gases mix with pump flow reducing NPSH. Amount of reduction can be substantial. • End thrust can be high at start or at high speed. • Break-away torque can be critical if only low-pressure gas is available at start.	• Motors are hemetically sealed--no seal packages. • No turbine end thrust at either start or steady state. • No break-away torque caused by rubbing seals. • Heat from motors has only small effect on NPSH.

	GH_2 TURBINE DRIVE	ELECTRIC MOTOR DRIVE
OPERATIONAL FEATURES	• Turbines are engine-mounted only. • Turbines need a pressure bottle for starting. • Turbines could operate at a variety of speeds during the start transient to satisfy peak requirements. However, they would have to be sequenced and controlled. Control system could be complicated if the start is from a bottle and then to the engine bypass which pressure is changing during the transient. • Turbines could "run away" (particularly during the test program) when pump head drops suddenly at the two-phase pumping limits. An overspeed trip would be necessary.	• Motors can be mounted at the engine, in the pipe or in the tank. • Motors can operate before engine start to childown system. • Motors are constant-speed even at no load. Control is possible only by the shape of the H-Q map. • Motors will not "run away".
TESTING	• Turbines are more difficult to control because of the variable supply pressure. • Hydrogen gas at high pressures is available at only a few locations. Burn-off stacks are necessary. Gas must be replenished at intervals. • Hydrogen gas lines.	• Electric motors are more flexible. They can be controlled to the exact speed required by varying the frequency of the inverter. • Electricity is in constant supply at many locations. • Wires.

	GH_2 TURBINE DRIVE	ELECTRIC MOTOR DRIVE
TECHNOLOGY ADVANCEMENT	• Turbines would provide partial admission turbine efficiency data, acceration rates, break-away torque information and control and sequencing data plus cost and weight data. • Future trade-off studies would include weight and cost of helium and tanks for purges and hydrogen and bottle weights and costs for starting purposes.	• Only a few experimental cryogenic motors have been tested and the data are not readily available. Weights and particularly costs are very approximate. Acceleration rates (zero to full speed) are not known. Motor and system efficiencies are vague. Methods of getting the lead wires out of the motor have not been studied. Motor running temperature and resultant heat soak-back are unknowns. • Future trade-off studies might include the weight and cost of 400 cps current and a 16-pole motor vs a 4-pole motor and extra inverter weight.

The trade-off studies showed that there was no great difference between the hydrogen gas turbine drive and the electric motor drive as to size and weight. It was apparent, however, that the electric motor drive would be more flexible in its application to a "breadboard" turbomachinery package. It was, therefore, decided that electric motors would be used for driving the inducers. Preliminary specifications for the motors are as follows:

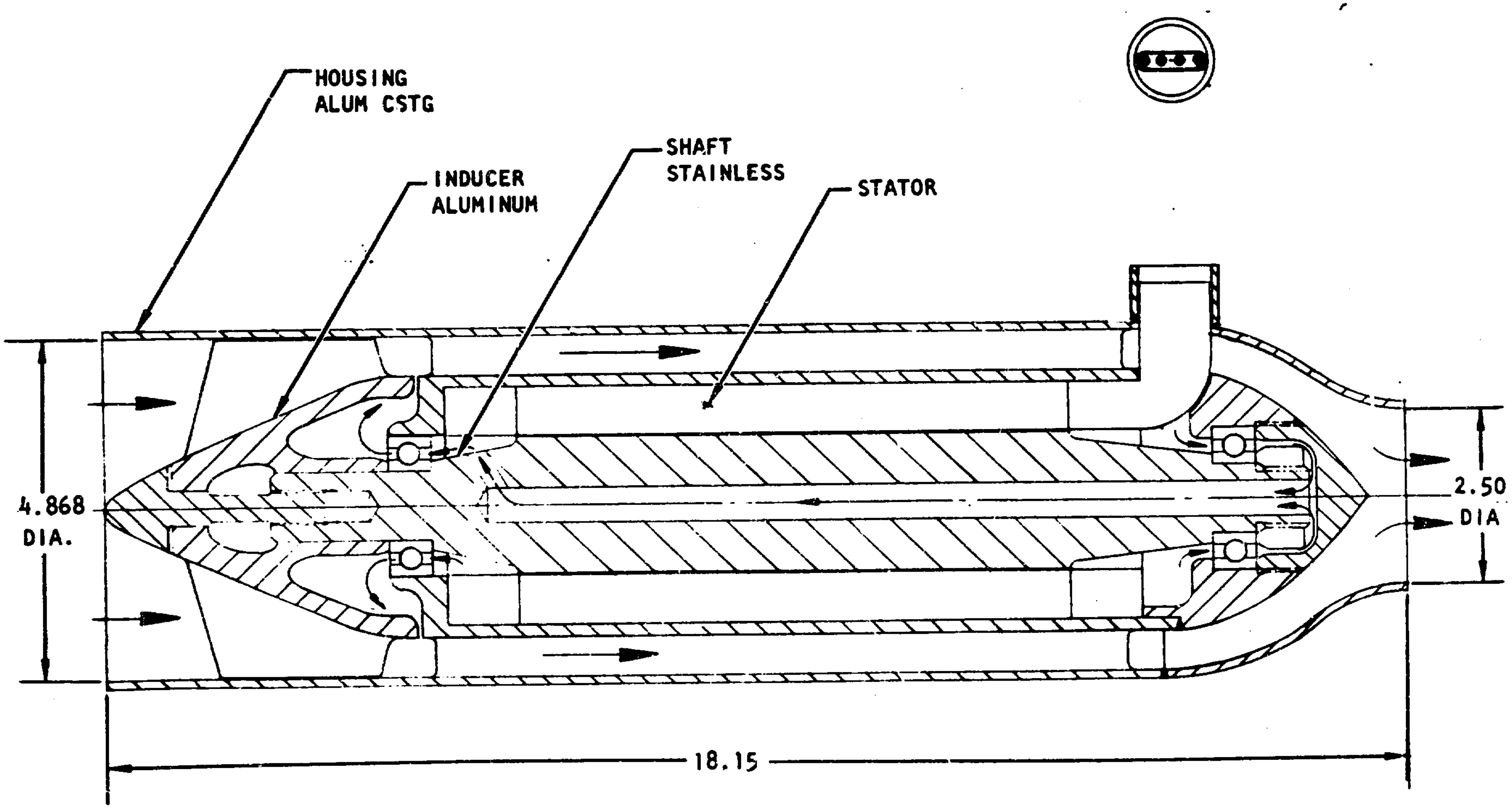
<u>Hydrogen Motor</u>:	14,058 rpm	Shaft = 1.5 in.
	3 HP	Stator OD = 3.15 in.
	2 poles	Radial air gap = 0.010 in.
	89% efficiency	Center length = 4.2 in.
	0.86 power factor	Wires on each side = 1.3 in.
	247 cps	Weight = 9.6 lb
<u>Oxygen Motor</u>:	3008 rpm	Shaft = 2.0 in.
	2.4 HP	Stator OD = 3.4 in.
	4 poles	Radial air gap = 0.010 in.
	72% efficiency	Center length = 7.7 in.
	0.81 power factor	Wires on each side = 1.0 in.
	106 cps	Weight 20 lb

The oxygen motor stator would be "canned", probably with Hastelloy. The can is included in the weight.

DESCRIPTION OF ELECTRIC DRIVEN INDUCERS

Conceptual design layouts have been made of both hydrogen and oxygen inducers. The following figure is a reproduction of the oxygen inducer layout. The inducer adds rotation and pressure to the two-phase oxygen. The stator blades that remove the rotation act as supports for the bearings and the electric motor. The electric motor stator is "canned" with Hastelloy as are the lead wires entering the motor. This will prevent oxygen from coming in contact with the windings. The motor is held in place by an interference fit with the cast aluminum housing. At cryogenic temperatures, the aluminum will contract more than the Hastelloy, thus maintaining the fit. The bearings are lubricated with liquid oxygen that enters from the highest pressure region at the stator blade exit, passes through the rear bearing, the shaft, the front bearing and reenters the main stream between the inducer and the stator. The flow will be metered by the holes out of the shaft so no labyrinth will be necessary between the inducer and its inner cavity. The size of the 2.50-inch hole at the exit was determined by the inner assembly which can be removed through this hole. The bearings at either end can, therefore, be replaced and the shaft can be removed through the front end. No bearing preload is necessary because of the low speed, so the rear bearing is locked in place and the front bearing is free to move axially.

PUMP-LOW PRESSURE OXIDIZER ELECTRIC DRIVE



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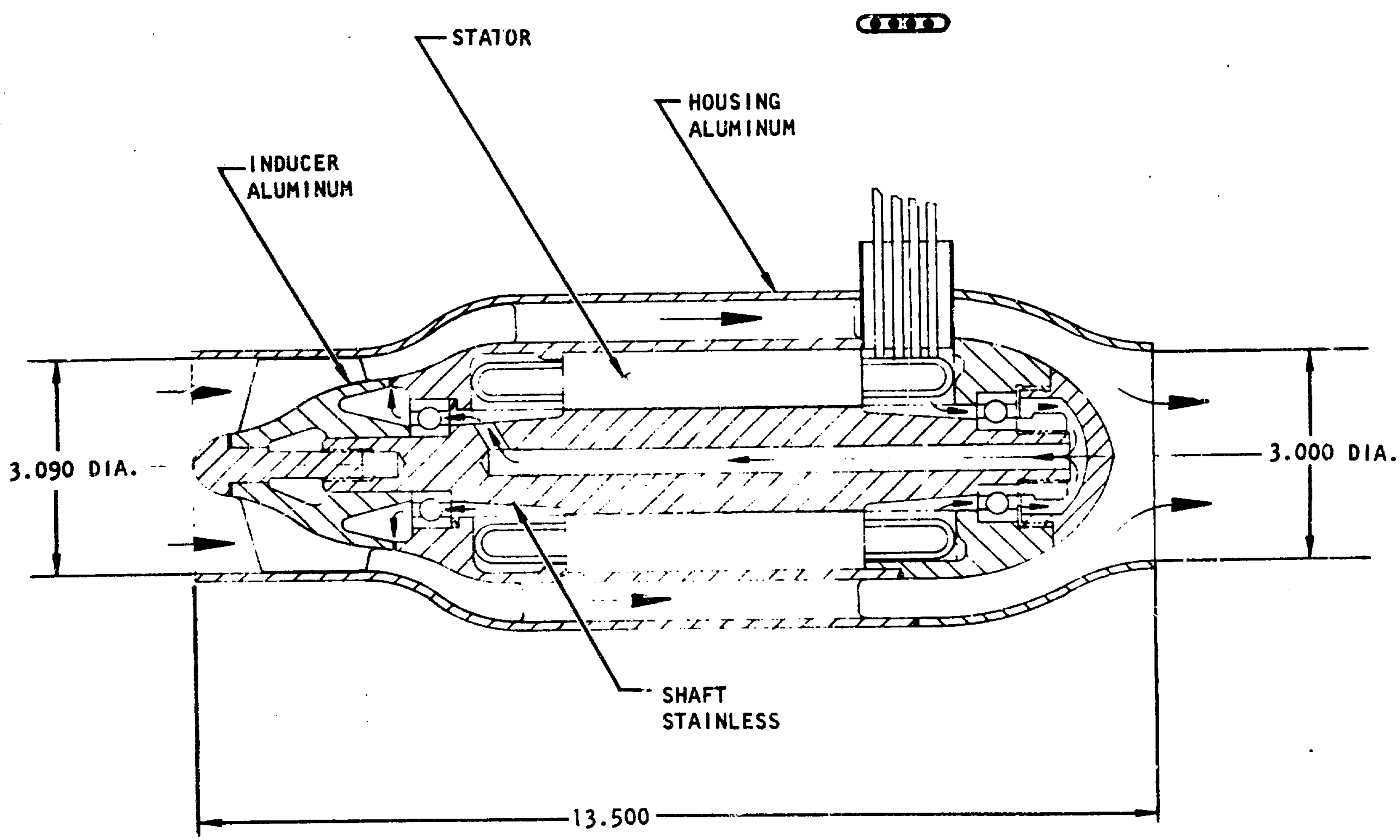
The hydrogen inducer layout is shown in the next figure. The motor is not "canned" but is still held by an interference fit. Because of the higher speed, the bearings are preloaded. In other respects the design is similar to that of the oxygen inducer. Studies have shown that the long line from the inducer (line-mounted near the tank) to the engine should be about 3 inches in diameter, and this governed the size of the exit hole. It is probable that, in the final design, the diffuser will also diffuse in the axial direction so that the annular area at the stator blade exit will be equal to the are of the 3-inch exit line. Losses due to sudden expansion will thus be avoided.

PUMP-LOW PRESSURE HYDROGEN ELECTRIC DRIVE



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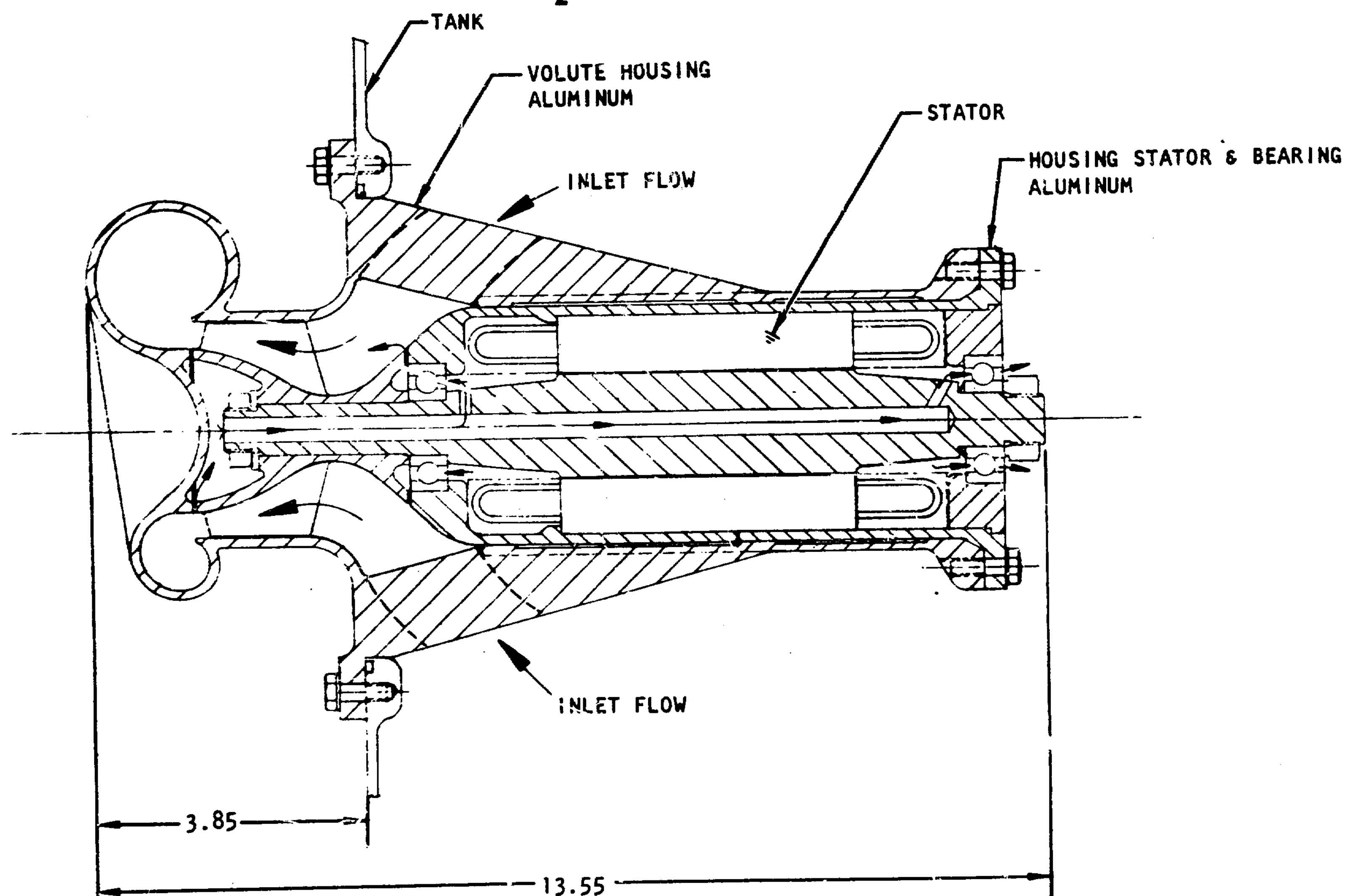
To complete the study, a conceptual design layout was made of a tank-mounted hydrogen inducer driven by an electric motor. This is shown in the next figure. In this concept, the inducer is driven through the inlet and the inducer itself acts as a sump. The inducer discharges into a volute, making the right angle turn between the hydrogen and oxygen tanks which are probably about 8 inches apart. The lead wires would be taken out at the end of the motor near the inducer, run along or between struts and out of the tank at a point near where the strut meets the end plate. Bearing lubrication is indicated by arrows. The outer housing, struts and volute would be cast and bored and the inducer-motor assembly inserted and bolted into place. The entire package would then be bolted to the tank.

PUMP-LH$_2$ ELECTRIC DRIVE



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