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INTERIM REPORT
ORBIT TRANSFER ROCKET ENGINE
TECHNOLOGY PROGRAM
PHASE II

ADVANCED ENGINE STUDY
TASK D.4

Prepared By:

C. Erickson, A. Martinez, B. Hines
ROCKWELL INTERNATIONAL CORPORATION
Rocketdyne Division

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D. D. Sheer, Project Manager

ROCKETDYNE DIVISION OF ROCKWELL INTERNATIONAL CORPORATION
6633 Canoga Avenue; Canoga Park, CA 91303

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Project Manager: D. D. Scheer, NASA-Lewis Research Center; Cleveland, OH
Co-Manager : S. McIntyre, NASA-Marshall Space Flight Center; Huntsville, AL

16. Abstract

In Phase II of the Advanced Engine Study, the Failure Modes and Effects Analysis (FMEA) Maintenance-driven engine design, preliminary maintenance plan, and concept for space operable disconnects generated in Phase I were further developed. Based on the results of the vehicle contractors Orbit Transfer Vehicle (OTV) Concept Definition and System Analysis Phase A studies, minor revisions to the engine design were made. Additional refinements in the engine design were identified through further engine concept studies. These included an updated engine balance incorporating experimental heat transfer data from the Enhanced Heat Load Thrust Chamber Study and a Rao optimum nozzle contour. The preliminary maintenance plan generated in Phase I was further developed through additional studies. These included a compilation of critical component lives and life limiters and a review of the Space Shuttle Main Engine (SSME) operations and maintenance manual in order to begin outlining the overall maintenance procedures for the Orbit Transfer Vehicle Engine (OTVE) and identifying technology requirements for streamlining space-based operations. Phase II efforts also provided further definition to the advanced fluid coupling devices including the selection and preliminary design of a preferred concept and a preliminary test plan for its further development.

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FOREWORD

The work reported herein was conducted by the Advanced Programs and Engineering personnel of Rocketdyne, a Division of Rockwell International Corporation, under Contract NAS3-23773 from February 1986 to February 1987. D. D. Scheer, Lewis Research Center, was the NASA Project Manager. Mr. A. T. Zachary was the Rocketdyne Program Manager, and Mr. A. Martinez, as Study Manager was responsible for the technical direction of the program.

Important contributions to the conduct of the program, and to the preparation of the material, were made by the following Rocketdyne personnel:

Engine System Analysis	C. Erickson, D. Nguyen
Engine System Design	B. Hines
Nozzle Analysis	R. O'Leary
Secretarial Support	E. Ponyman, L. Schindler

INTRODUCTION

The Advanced Engine Study has been outlined as a four year effort in which the engine design will be iterated four times to allow resolution of vehicle/engine integration issues as well as advanced engine performance, operation and maintenance technology issues. When completed, the conceptual engine system design description will include all the engine subsystems. Each successive iteration will provide as output an updated engine system design.

OBJECTIVES

Objectives of the Advanced Engine Study are indicated in Table 1. The overall objective is to develop a space-baseable engine design and to define and update its advanced technology and technology development plans.

APPROACH

The approach to performance of the objectives is to develop the engine design and technology plan in four study phases as outlined in Table 1.

Each phase will be driven respectively by the timing and results of four main occurrences: (1) the completion of advanced engine FMEA (Failure Mode and Effects Analysis) and maintenance studies; (2) the completion of Orbit Transfer Vehicle (OTV) definition and Aeroassist OTV studies; (3) the completion of near-term advanced technology evaluation studies of NAS3-23773 Contract Tasks B.1/B.4, C.1, B.2, and F.2/F.4; and (4) the completion of longer- range advanced technology studies of NAS3-23773 contract Tasks E.1/ E.2/E.3, E.4 and B.3/B.5 (Table 2).

TABLE 1.

ADVANCED ENGINE STUDIES

OBJECTIVES

- PROVIDE A SPACE BASEABLE/MAINTAINABLE ENGINE DESIGN
- IDENTIFY ADVANCED TECHNOLOGY REQUIRED
- PREPARE TECHNOLOGY AND ENGINE DEVELOPMENT PLANS
- UPDATE ENGINE DESIGN AND TECHNOLOGY THROUGH 1990

APPROACH

- DEVELOP ENGINE DESIGN IN FOUR PHASES
  - PHASE I FMEA-MAINTENANCE DRIVEN DESIGN
  - PHASE II THRUST LEVEL ENGINE DESIGN UPDATE
  - PHASE III PERFORMANCE, LIFE, OPERATIONS DESIGN UPDATE
  - PHASE IV FINAL ICHM/MAINTENANCE/FMEA UPDATE

TABLE 2.

OTV ROCKET ENGINE TECHNOLOGY TASKS, NAS3-23773

Task B.1/B.4 - Two-Stage Partial Admission Turbine (Completed)

A comprehensive design, fabrication, and test program has been conducted to demonstrate the capabilities of the two-stage partial admission turbine concept at the size and flow conditions required by the OTV engine.

Task C.1 - Enhanced Heat Load Thrust Chamber

A program has been formulated and implemented to characterize the ribbed combustor and coolant-side fin concepts through design, fabrication and test of hot-air ribbed panel models, hot-firing ribbed calorimeter inserts, and ultimately a full-scale ribbed combustor.

Task E.1/E.2/E.3 - Integrated Control and Health Monitoring (ICHM) System

A study has been established to provide a preliminary description of the advanced ICHM system and its functions. This description will include definition of advanced controller and sensor technology required. In addition, a present state-of-the-art ICHM system will be defined to provide a point of technology and benefit reference.

Task F.2/F.4. - Integrated Components Evaluator

Rocketdyne has designed and fabricated a test bed engine for the expander cycle called the Integrated Component Evaluator (ICE). A test program is planned to accomplish turbomachinery demonstrations and characterizations using the ICE. The program consists of childown tests, low power pump mapping (head vs. flow) and high power pump mapping tests.

TABLE 2. (contd.)

Task B.2 - High Velocity Diffusing Crossover

A program is being conducted to design, fabricate and test under laboratory conditions, crossover network hardware of design like the OTV MK-49 fuel pump first and second stage designs.

Task B.3/B.5 - Soft-Wear Ring Seals

A program is being conducted to design, fabricate and test soft seals and supporting test hardware that will enable assessment of polymer materials and seal designs for implementation in the OTV engine fuel and oxidizer pump and turbine stages.

Task E.4 - I.C.R Spectrometry Test

Spectrographic analysis of the exhaust gas plume during the I.C.E. testing will be conducted. These efforts will help develop the capability to identify engine anomalies through plume analysis.

SUMMARY OF ACCOMPLISHMENTS

A survey of the vehicle studies was conducted in order to identify any revisions in the propulsion system requirements since completion of the Phase I study. No major changes have been established. Minor revisions affecting gimballing and throttling requirements were identified.

Updated heat transfer data generated in the Enhanced Heat Load Thrust Chamber Study (Task C.1) were reviewed and incorporated into the Steady State Design and Optimization Code. The engine was then reoptimized with a new heat transfer correlation for the combustor cooling circuit. A slight reduction in the predicted performance was observed.

The minor changes identified in the Engine Design Update and Engine Concept Studies described above did not warrant an updated engine layout at this time. Instead, the effort originally budgeted for the layout was redirected toward component studies in preparation for the forthcoming Point-Design Engine Task. A nozzle contour analysis was chosen as the study that could be completed with remaining funds. In this task, a Rao optimum contour was generated for the fixed nozzle envelope. Results of this more sophisticated analysis have superseded the parabolic contour generated in Phase I of the study.

In support of the maintenance plan, a compilation of component lives and life limiters for critical components including the combustor, nozzle, injector, turbomachinery, and valves/actuators has been generated. Most of the components evaluated will be able to meet the ultimate life goal of 20 hours/ 500 cycles, with some requiring inspections and possible servicing prior to replacement.

In addition, a review of the Space Shuttle Main Engine (SSME) operations and maintenance manual was conducted with two purposes in mind: (1) to begin to outline the overall maintenance procedures for the Orbit Transfer Vehicle Engine (OTVE), and (2) to identify technology requirements for streamlining space based Orbit Transfer Vehicle (OTV) operations.

In the area of space operable disconnects, a preliminary design and test plan has been generated for the preferred configuration.

A summary of the Phase II accomplishments is presented in Table 3. A program schedule highlighting the milestones completed is shown in Figure 1.

TABLE 3.

PHASE II ADVANCED ENGINE STUDY ACCOMPLISHMENTS

- UPDATED ENGINE GIMBALLING AND THROTTLING REQUIREMENTS
- REOPTIMIZED ENGINE WITH UPDATED COMBUSTOR HEAT TRANSFER DATA
- GENERATED RAO OPTIMUM NOZZLE CONTOUR
- DETERMINED CRITICAL COMPONENT LIVES AND LIFE LIMITERS
- REVIEWED SSME OPERATIONS AND MAINTENANCE MANUAL TO IDENTIFY TASKS COMMON WITH OTV
- GENERATED PRELIMINARY DESIGN OF PREFERRED CONCEPT FOR SPACE OPERABLE DISCONNECTS
- GENERATED TEST PLAN FOR PREFERRED SPACE OPERABLE DISCONNECT CONCEPT

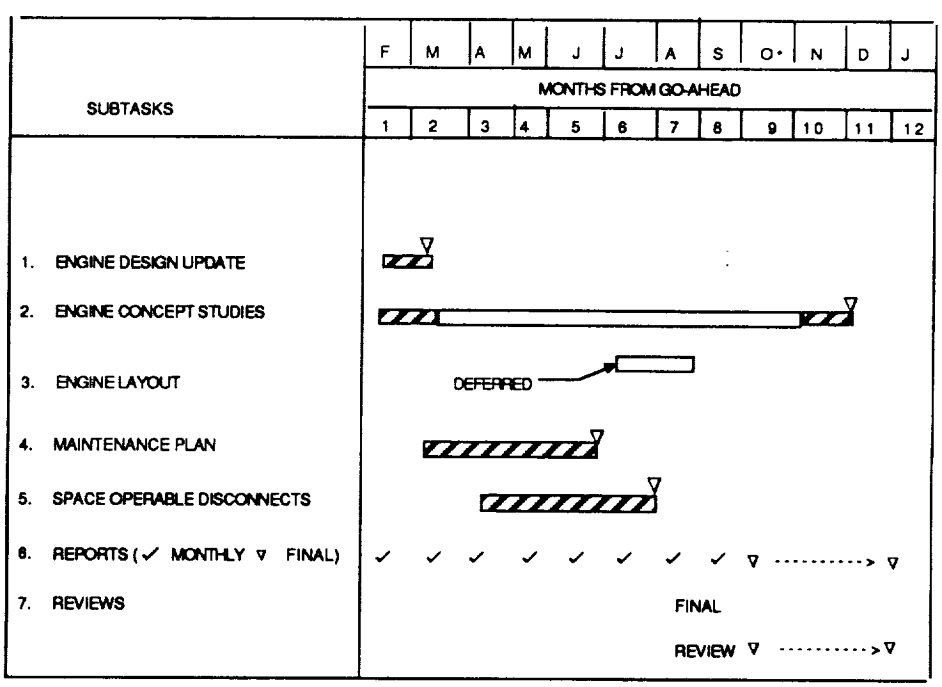


FIGURE 1. TASK D.4 -ADVANCED ENGINE STUDY SCHEDULE

TECHNICAL DISCUSSION

The overall approach followed on Phase II of the Advanced Engine Study is presented in Figure 2. Outputs from Phase I of the study included the Failure Modes and Effects Analysis (FMEA)-Maintenance driven engine design/layout, a preliminary space maintenance plan, and several preliminary concepts for space operable disconnects. The Phase II revisions generated in the Engine Design Update and Engine Concept Studies subtasks were incorporated into a Phase II engine design. These relatively minor revisions did not warrant an updated engine layout.

The preliminary maintenance plan generated in Phase I was further developed through additional studies. These included a compilation of critical component lives and life limiters and a review of the Space Shuttle Main Engine (SSME) operations and maintenance manual.

Phase II efforts also provided further definition to the advanced fluid coupling devices studied in Phase I.

In addition, these subtasks helped define technology requirements necessary for development of the advanced space based engine.

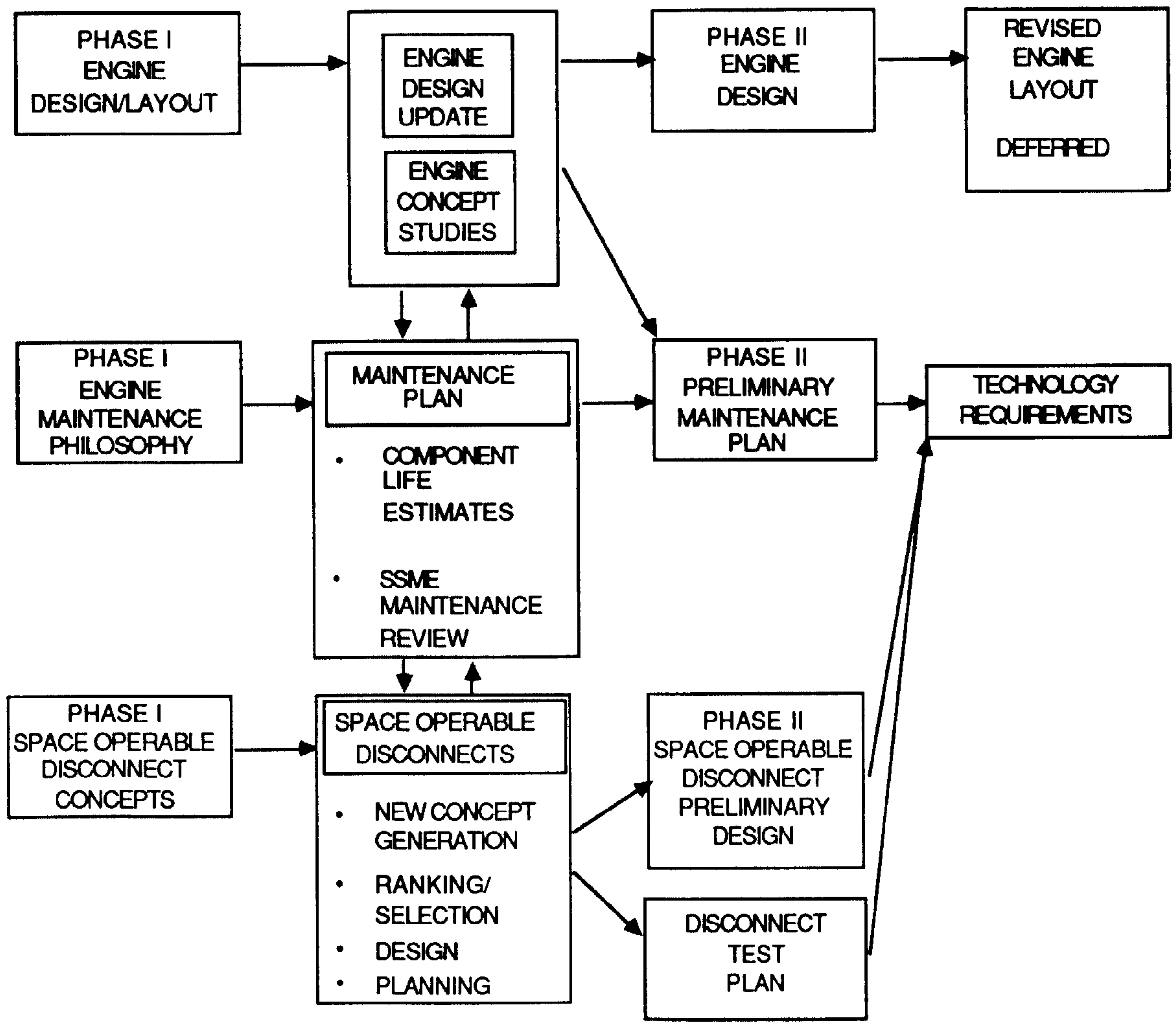


FIGURE 2. PHASE II STUDY LOGIC DIAGRAM

ENGINE DESIGN UPDATE

A comprehensive review of the vehicle contractors' Orbit Transfer Vehicle Concept Definition and Systems Analysis Study final reports was conducted (Ref. 1, 2, and 3). The purpose of this effort was to identify any updated propulsion system requirements which need to be incorporated into the baseline engine concept generated on Phase 1. In addition, the vehicle contractors have been contacted to determine if any additional updated requirements have been established since the completion of the Phase A study.

No major changes have been established. A thrust level of 5000 to 7500 lb_f is still considered optimal by all the three vehicle contractors participating in the study. Based on life cycle cost analyses, an advanced engine with high specific impulse is desired as early as possible.

GIMBAL ANGLE REQUIREMENTS

Results of the contractor survey indicate that the 6° - square gimbal used in the baseline engine is inadequate and will have to be increased. Current vehicle designs require a gimballing capability of 15° x 20°. This pattern has been incorporated into the engine design update.

THROTTLING REQUIREMENTS

Of the three vehicle contractors, only one provided any definitive throttling requirements. That contractor has determined that the minimum thrust requirement for low acceleration missions could be fulfilled by pump-idle mode operation (10% F = 750 lbf) and the mainstage throttling would not be necessary. This supersedes any previous requirements of non-continuous step throttling to levels between full thrust and pump-idle mode. Intermediate thrust levels were previously being considered for assist during aerobraking maneuvers. Thus, until additional requirements are established by the vehicle contractors, it will be assumed that main stage continuous throttling will not be necessary.

Generic requirements for the OTVE were provided by NASA-Lewis in 1981 (Ref. 4, page 4). These original requirements were complemented by requirements from NASA-HQRTS which are presented as initial requirements in Table 4. During subsequent studies the initial requirements were updated as indicated in the last two columns.

TABLE 4.

ENGINE CHARACTERISTICS - 1990's OTV

	INITIAL	PHASE I UPDATES	PHASE II UPDATES
PROPELLANTS	LO_2/LH_2	✓*	✓
THRUST, LB			
NOMINAL	10,000-25,000	7500	5000-7500
LOW THRUST	2,000	✓	750 (IDLE)
THROTTLING (CONTINUOUS)	NONE	✓	NOT REQUIRED
THRUST BUILDUP TIME, SEC	1-2	✓	✓
BOOST PUMPS			
VEHICLE	NONE	✓	✓
ENGINE	LOW NPSH	✓	✓
APPLICATION COMPATIBILITY	AFT CARGO CARRIER, AEROASSIST	✓	✓
STOWED SIZE, IN			
ENGINE LENGTH	55	60	✓
ENGINE DIAMETER	71	✓	✓
THRUST VECTOR CONTROL, DEG	± 4	± 6	15 X 20
INERT GAS REQUIREMENT			
VALVE ACTUATION	HELIUM	✓	✓
PURGES	NONE	YES	YES

* ✓ = No Change

ENGINE CONCEPT STUDIES

UPDATED COMBUSTOR HEAT TRANSFER

Based on heat load maximization studies conducted under the Enhanced Heat Load Thrust Chamber Study (Task C.1), a projected heat transfer coefficient profile for the ribbed surface of the OTV combustor has been generated. Experimental data indicate that with an optimal rib height of 0.040 in., heat transfer can be enhanced by 60 percent over that of a smooth cylindrical combustor. When the entire 20.0 in. combustor is considered including the throat and nozzle to an expansion ratio of 6.0, the net heat transfer enhancement is projected at 41.6 percent.

REVISED ENGINE BALANCE

In the Steady State Design and Optimization Code, the enhancement factor which was used in modeling the ribbed combustor was:

$$Q_{ribbed} = Q_{smooth} * (1.0 + RH)^{8.93671}$$

where RH is the rib height. The rib height used in the baseline optimization was 0.054 in., which corresponds to an enhancement factor of 60.2 percent. This expression was replaced with a constant equal to 1.416, the experimentally projected heat transfer enhancement factor. After modifying the code, a full design optimization was then conducted. Results of this study indicate that the combustor heat load dropped from 6502 BTU/sec to 5491. The attainable chamber pressure dropped from 1831 psia to 1704, and the concurrent impact on engine I_{sp} was a drop from 490.4 sec to 489.0. A detailed printout of the engine description is provided in Table 5.

TABLE 5. COMPLETE ENGINE PERFORMANCE BALANCE FOR 7500-LB THRUST ENGINE

MAIN TURBINES ON-DESIGN OPTIONS AND LIMITS

	(UNITS)	OXIDIZER	FUEL
TYPE		1 ROW	2 STAGE IMPULSE
SIZE		3+ INCH. DIAMETER	3+ INCH. DIAMETER
MINIMUM ADMISSION RATE	(NONE)	.10	.10
MINIMUM PRESSURE RATIO	(NONE)	1.16	1.30
MINIMUM HUB/TIP RATIO	(NONE)	.60	.60
MINIMUM BLADE HEIGHT	(INCHES)	.15	.15
MINIMUM PITCH DIAMETER	(INCHES)	2.50	2.50
MAXIMUM ADMISSION RATE	(NONE)	1.00	1.00
MAXIMUM PRESSURE RATIO	(NONE)	1.40	3.72
MAXIMUM HUB/TIP RATIO	(NONE)	.90	.90
MAXIMUM TIP SPEED	(FT/SEC)	1200.00	2000.00
MAXIMUM AN**2*E-10	((RPM-IN)SQ)	4.00	10.00
MAXIMUM BEARING DN*E-6	(MM*RPM)	1.50	10000.00

MAIN PUMPS ON-DESIGN OPTIONS AND LIMITS

	(UNITS)	OXIDIZER	FUEL
THROTTLING DESIGN		NO	NO
INDUCER		YES	YES
BOOST PUMP USED		YES	YES
NUMBER OF CENTRIFUGAL STAGES		1.	4.
MINIMUM SPEED	(RPM)	30000.00	30000.00
MINIMUM IMPELLER TIP DIAMETER	(INCHES)	1.00	1.00
MINIMUM IMPELLER STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	400.00	400.00
MINIMUM IMPELLER TIP WIDTH	(INCHES)	.03	.03
MINIMUM INDUCER DIAMETER	(INCHES)	.75	.75
MAXIMUM SPEED	(RPM)	70000.00	200000.00
MAXIMUM IMPELLER TIP DIAMETER	(INCHES)	100000.00	100000.00
MAXIMUM IMPELLER STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	2000.00	2000.00
MAXIMUM IMPELLER TIP SPEED	(FT/SEC)	1870.00	2200.00
MAXIMUM INDUCER TIP SPEED	(FT/SEC)	1870.00	1870.00
MAXIMUM INLET/OUTLET DIAMETER RATIO	(NONE)	.80	.80

TABLE 5. COMPLETE ENGINE PERFORMANCE BALANCE FOR 7500-LB THRUST ENGINEAN

(CONTINUED)

BOOST PUMPS ON-DESIGN OPTIONS AND LIMITS

TYPE		FULL FLOW	GAS DRIVEN
MINIMUM DIAMETER	(INCHES)	.75	.75
MAXIMUM DIAMETER	(INCHES)	100000.00	100000.00
MAXIMUM TIP SPEED	(FT/SEC)	1870.00	1870.00

COOLANT JACKETS ON-DESIGN OPTIONS AND LIMITS

	(UNITS)	COMBUSTOR	NOZZLE
MAXIMUM BULK TEMPERATURE	(DEG-R)	5000.00	5000.00
REFERENCE DELTA-P	(PSID)	380.20	36.00
REFERENCE HEAT LOAD	(BTU/SEC)	7346.40	0.00
REFERENCE DENSITY	(LBM/FT**3)	1.876	.876
REFERENCE CHAMBER PRESSURE	(PSIA)	1550.00	1550.00
REFERENCE CHAMBER TEMPERATURE	(DEG-R)	6495.00	6495.00
REFERENCE CHARACTERISTIC VELOCITY	(FT/SEC)	7560.00	7560.00
REFERENCE THRUST	(LBF)	15000.00	15000.00
REFERENCE WALL TEMPERATURE	(DEG-R)	1100.00	1100.00
REFERENCE INLET TEMPERATURE	(DEG-R)	70.00	571.00
REFERENCE ENHANCEMENT FACTOR	(NONE)	1.00	
REFERENCE CONTRACTION RATIO	(NONE)	4.00	
REFERENCE CHAMBER LENGTH	(INCHES)	20.00	
REFERENCE AREA RATIO (REGEN.)	(NONE)		769.00
REFERENCE AREA RATIO (ATT.)	(NONE)		14.70
REFERENCE NOZZLE LENGTH (REGEN.)	(INCHES)		60.40
RIBBED FLAG (1=RIBBED, 0=SMOOTH)	(NONE)	1.0	
REFERENCE RIB HEIGHT	(INCHES)	.0400	
REFERENCE LIFE	(CYCLES)	1600.0	
DESIRED LIFE	(CYCLES)	2000.0	
INPUT RIB HEIGHT	(INCHES)	.0540	

TABLE 5. COMPLETE ENGINE PERFORMANCE BALANCE FOR 7500-LB THRUST ENGINE (CONTINUED)

ENGINE DESCRIPTION

	(UNITS)		
CYCLE TYPE		EXPANDER CYCLE	
TURBINE ARRANGEMENT		SERIES	
OXYGEN PROPERTIES COMPUTED			
CHAMBER IS NOT TAPERED			
CHAMBER IS RIBBED			
THRUST	(LBF)	7500.00 (ENG)	7500.00 (T/C)
MIXTURE RATIO	(NONE)	6.00 (ENG)	6.10 (T/C)
DELIVERED SPECIFIC IMPULSE	(LB-SEC/LBM)	489.00 (ENG)	490.47 (T/C)
MAIN TURBINES BYPASS	(PERCENT)	10.028	
MAIN OX TURBINE BYPASS	(PERCENT)	10.263	
		OXIDIZER	FUEL
INLET PROPELLANT TEMPERATURE	(DEG R)	162.70	37.80
INLET NPSH	(FT)	2.00	15.00
PROPELLANT FLOW RATE	(LBS/SEC)	13.14	2.15 (T/C)
PROPELLANT FLOW RATE	(LBS/SEC)	13.16	2.18 (ENG)
PRESSURIZATION FLOWRATE	(LBS/SEC)	.13	.03
OVERBOARD LEAKAGE FLOWS	(LBS/SEC)	.018	.027

COMBUSTOR AND NOZZLE DESCRIPTION

CHAMBER PRESSURE	(PSIA)	1704.25
CHAMBER TEMPERATURE	(DEG R)	6718.36
AREA RATIO	(AE/AT)	1066.84
BREAKPOINT EPSILON	(NONE)	435.25
NUMBER OF ENGINE SEGMENTS	(NONE)	2
INPUT LIFE	(CYCLES)	2000.00
RIB HEIGHT	(INCHES)	.0540
NOZZLE PERCENT LENGTH	(PERCENT)	91.28
FUEL INLET HEAT OF FORMATION	(KCAL/MOLE)	1.156
DUMP COOLING FLOW RATE	(LBS/SEC)	0.00
NOZZLE LENGTH	(INCHES)	89.54
COMBUSTOR LENGTH	(INCHES)	20.00
ENGINE LENGTH (EXT)	(INCHES)	117.00
ENGINE LENGTH (RET)	(INCHES)	60.00
CONTRACTION RATIO	(NONE)	4.00
C SUB F	(NONE)	2.033
THROAT AREA	(IN**2)	2.165
HEAT LOSS BEFORE BL ATTACH	(BTU/SEC)	495.81
HEAT LOSS DUE TO LEAKS AND PRESS.	(BTU/SEC)	0.00

TABLE 5. COMPLETE ENGINE PERFORMANCE FOR 7500-LB THRUST ENGINE (CONTINUED)

		COMBUSTOR	NOZZLE
COOLANT FLOW RATE	(LBS/SEC)	2.19	2.19
COOLANT DELTA P	(PSID)	932.24	50.39
HEAT INPUT	(BTU/SEC)	5490.80	1368.77
OUTLET PRESSURE	(PSIA)	5975.30	5916.30
INLET TEMPERATURE	(DEG R)	131.57	797.18
OUTLET TEMPERATURE	(DEG R)	797.12	974.54
EXIT WALL TEMPERATURE	(DEG F)	886.98	
DELTA-T EXIT TO MAX	(DEG F)	40.09	
MAX WALL TEMPERATURE	(DEG F)	927.07	
INLET ENTHALPY	(BTU/LBS)	323.36	2833.57
OUTLET ENTHALPY	(BTU/LBS)	2833.57	3459.32
COOLANT DENSITY	(LBS/FT**3)	2.872	1.076

PUMP DESCRIPTION	(UNITS)	MAIN PUMP OXIDIZER	MAIN PUMP FUEL	BOOST PUMP OXIDIZER	BOOST PUMP FUEL	AUXILIARY FUEL PUMP
PUMP						
WHEEL SPEED	(RPM)	60693.7	199105.6	9695.6	40464.6	0.0
EFFICIENCY	(FRACTION)	.7008	.5901	.7049	.7081	0.000
HORSEPOWER	(HP)	186.47	1335.79	4.91	10.31	0.00
INLET PRESSURE	(PSIA)	71.34	63.82	16.34	18.82	0.00
OUTLET PRESSURE	(PSIA)	2912.85	6957.60	86.34	73.82	0.00
FLOW RATE	(LBS/SEC)	13.290	2.215	13.290	2.215	0.000
DIAMETER	(IN)	2.38	2.33	2.26	1.93	0.00
EFFECTIVE DENSITY	(LB/FT**3)	72.27	5.07			0.00
INDUCER						
INLET FLOW VELOCITY	(FT/SEC)	39.10	120.44	7.48	27.36	
TIP SPEED	(FT/SEC)	260.02	800.85	95.48	341.61	
FLOW COEFFICIENT	(NONE)	.15	.15	.08	.08	
HEAD COEFFICIENT	(NONE)	.10	.10	.50	.50	
DELTA P	(PSID)	103.83	60.45	70.00	55.00	
EFFICIENCY	(FRACTION)	.752	.752	.705	.708	
DELIVERED NPSH	(FT)	54.50	289.79	2.00	15.00	
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	10070.23	10070.23			
IMPELLER						
INLET FLOW VELOCITY	(FT/SEC)	35.03	118.34			0.00
TIP SPEED	(FT/SEC)	631.51	2028.56			0.00
FLOW COEFFICIENT	(NONE)	.11	.10			0.00
HEAD COEFFICIENT	(NONE)	.44	.44			0.00
HEAD RISE PER STAGE	(FT)	5455.08	56621.70			0.00
EFFICIENCY	(FRACTION)	.70	.59			0.00
DELIVERED NPSH	(FT)	32.91	194.52			0.00
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	875.59	818.44			0.00
TIP WIDTH	(IN)	.096	.086			0.000

TABLE 5. COMPLETE ENGINE PERFORMANCE FOR 7500-LB THRUST ENGINE (CONTINUED)

TURBINE DESCRIPTION		MAIN TURBINE OXIDIZER	MAIN TURBINE FUEL	BOOST TURBINE OXIDIZER	BOOST TURBINE FUEL	AUXILIARY HPFT
TYPE				FF HYD	COOLANT	
PITCH DIAMETER	(IN)	4.201	2.059	2.134	1.624	0.000
FLOW RATE	(LBS/SEC)	1.513	1.937	13.290	.203	0.000
ADMISSION	(FRACTION)	.323	.329	.900	.080	0.000
BEARING DN*E-6	(MM*RPM)	.707	2.818	.039	.131	0.000
ANNULUS AREA SPEED SQUARED*E-10	((RPM-IN)SQ)	1.121	7.854	.034	.209	0.000
PITCH LINE VELOCITY	(FT/SEC)	1113.44	1789.89	90.35	331.10	0.00
FIRST STG BLADE HEIGHT	(INCHES)	.200	.184	.031	.250	0.000
SECOND STG BLADE HEIGHT	(INCHES)	.231	.306	0.000	0.000	0.000
VELOCITY RATIO	(NONE)	.416	.288	.470	.110	0.000
INLET PRESSURE	(PSIA)	2344.23	5310.81	2912.85	2344.23	0.00
OUTLET PRESSURE	(PSIA)	1988.23	2358.03	2785.51	1988.23	0.00
EFFICIENCY	(FRACTION)	.609	.633	.800	.251	0.000
PRESSURE RATIO	(NONE)	1.18	2.25	1.05	1.18	0.00
MAIN TURBINE INLET TEMP	(DEG R)	860.25	979.11	0.00	860.25	0.00
MAIN TURBINE EXIT TEMP	(DEG R)	837.48	860.16	0.00	852.15	0.00
HORSE POWER	(HP)	186.47	1335.79	4.91	10.31	0.00
GAS SPECIFIC HEAT	(BTU/LB-DEG R)	3.691	3.857	0.000	3.691	0.000
GAS PROCESS GAMMA	(NONE)	1.388	1.390	0.000	1.388	0.000
INLET ENTHALPY	(BTU/LBS)	2971.87	3459.32	0.00	2971.87	0.00
OUTLET ENTHALPY	(BTU/LBS)	2884.75	2971.87	0.00	2935.99	0.00
INLET ENTROPY	(BTU/LBS-DEG R)	12.12	11.77	0.00	0.00	0.00
GAS MOLECULAR WEIGHT	(NONE)	2.02	2.02	0.00	2.02	0.00

GASEOUS OXIDIZER HEAT EXCHANGER DESCRIPTION		FUEL	OXIDIZER
HEAT RATE	BTU/SEC	24.28	24.28
FLOW RATE	LBM/SEC	.22	.13
PRESSURE LOSS	PSIA	1.14	1.00
INLET PRESSURE	PSIA	1980.52	2785.51
INLET TEMPERATURE	DEG R	1002.19	176.74
OUTLET TEMPERATURE	DEG R	969.94	665.07
SPECIFIC HEAT	BTU/LB-R	3.49	.37

TABLE 5. COMPLETE ENGINE PERFORMANCE FOR 7500-LB THRUST ENGINE
(CONTINUED)

PERFORMANCE

THRUST	(LBF)	7500.00	
CHAMBER PRESSURE	(PSIA)	1704.25	
ENGINE MIXUTRE RATIO	(BY WEIGHT)	6.00	
AREA RATIO	(AE/AT)	1066.84	
ODE SPECIFIC IMPULSE	(LBF-SEC/LBM)	510.96	
ODE CHARACTERISTIC VELOCITY	(FT/SEC)	7771.21	
SPECIFIC IMPULSE ENERGY RELEASE EFFICIENCY	(PERCENT)	99.900	
SPECIFIC IMPULSE REACTION KINETIC EFFICIENCY	(PERCENT)	99.521	
SPECIFIC IMPULSE DIVERGENCE EFFICIENCY	(PERCENT)	99.514	
SPECIFIC IMPULSE HEAT LOSS EFFICIENCY	(PERCENT)	99.737	
SPECIFIC IMPULSE BOUNDARY LAYER EFFICIENCY	(PERCENT)	97.050	
EFFECTIVE TDK SPECIFIC IMPULSE	(LBF-SEC/LBM)	505.54	
BOUNDARY LAYER IS LOSS	(LBF-SEC/LBM)	15.07	
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	490.47	(T/C)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	534.64	(DUMP)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	489.00	(ENGINE)

SYSTEM PRESSURES	(UNITS)	PROPELLANT		GAS	
		OXIDIZER	FUEL	OXIDIZER	FUEL
ENGINE INLET PRESSURE	(PSIA)	16.	19.		
BOOST PUMP DISCHARGE PRESSURE	(PSIA)	86.	74.		
MAIN PUMP INLET PRESSURE		71.	64.		
MAIN PUMP DISCHARGE PRESSURE	(PSIA)	2786.	6958.		
COOLING JACKET INLET PRESSURE	(PSIA)		6908.		
COMBUSTOR DISCHARGE PRESSURE	(PSIA)				5975.
NOZZLE DISCHARGE PRESSURE	(PSIA)				5916.
BOOST TURBINE INLET PRESSURE	(PSIA)			2913.	2344.
BOOST TURBINE DISCHARGE PRESSURE	(PSIA)			2786.	1988.
MAIN TURBINE INLET PRESSURE	(PSIA)			2344.	5311.
MAIN TURBINE DISCHARGE PRESSURE	(PSIA)			1988.	2358.
CHAMBER INJECTION PRESSURE	(PSIA)	2351.			1979.
CHAMBER COMBUSTION PRESSURE	(PSIA)				1704.

TABLE 5. COMPLETE ENGINE PERFORMANCE FOR 7500-LB THRUST ENGINE
(CONTINUED)

HEAT EXCHANGER DESIGN	(UNITS)		
HEAT RATE	(BTU/SEC)	1.00	
DELTA-T	(DEG-R)	710.43	
DELTA-T (AVERAGE)	(DEG-R)	710.43	
THERMAL EFFICIENCY	(FRACTION)	.000	
LENGTH	(INCH)	.00	
FRONTAL AREA	(IN**2)	16.00	
MATERIAL FLAG	(NONE)	0.00	
CHANNEL DIAMETER	(INCH)	.100	
WALL THICKNESS	(INCH)	.025	
CHANNEL SPACING	(INCH)	.050	
WEIGHT	(LBM)	.006	
		COLD SIDE	HOT SIDE
CHANNEL HEIGHT	(INCH)	.100	.100
LOSS FACTOR	(NONE)	.500	.500
FRICTION FACTOR	(NONE)	.020	.020
FLOW RATE	(LBM/SEC)	2.187	1.937
HEAT TRANSFER COEF	(BTU/SQIN-R-SEC)	.008	.009
FLOW AREA	(IN**2)	4.267	4.267
DELTAP	(PSID)	.06	.55
OUTLET PRESSURE	(PSIA)	6921.64	1983.38
INLET TEMPERATURE	(DEG R)	131.31	841.89
OUTLET TEMPERATURE	(DEG R)	131.46	841.75
INLET ENTHALPY	(BTU/LBM)	322.90	2900.06
OUTLET ENTHALPY	(BTU/LBM)	323.36	2899.54
INLET ENTROPY	(BTU/LBM-R)	3.88	12.21
OUTLET ENTROPY	(BTU/LBM-R)	3.89	12.21
AVERAGE DENSITY	(LBM/FT**3)	4.573	.417
AVERAGE SPECIFIC HEAT	(BTU/LBM-R)	3.050	3.640

TABLE 5. COMPLETE ENGINE PERFORMANCE FOR 7500-LB THRUST ENGINE
(CONTINUED)

PROPELLANT PROPERTIES SUMMARY	LOCATION	PRESSURE (PSIA)	TEMPERATURE (DEG R)	NBS ENTHALPY (BTU/LB)	DELTA-H (BTU/LB)	ENERGY (BTU/SEC)	ENTROPY (BTU/LB-R)	DENSITY (LB/FT3)	FLOWRATE (LB/SEC)
ENGINE OXIDIZER INLET	(O1)	16.3	162.70	-57.75	-174.85	(-2323.87)	.70	71.149	(13.290)
BOOST OXIDIZER PUMP OUTLET	O2	86.3	163.05	-57.49	-174.59	-2320.44	.70	71.157	13.290
MAIN OXIDIZER PUMP LEAKAGE	(O3)	2785.5	176.74	-47.58	-164.68	(3.04)	.72	71.415	(-.018)
MAIN OXIDIZER PUMP OUTLET	O4	2785.5	176.74	-47.58	-164.68	-2163.54	.72	71.415	13.138
OXIDIZER TANK PRESSURIZATION	(O5)	2784.5	665.07	133.64	16.54	(-2.22)	1.24	12.331	(-.134)
MAIN OXIDIZER VALVE OUTLET	O6	2367.7	178.38	-47.58	-164.68	-2163.54	.73	70.802	13.138
MAIN OXIDIZER INJECTOR INLET	(O7)	2350.7	180.89	-47.58	-164.68	(2163.54)	.74	70.402	(-13.138)
ENGINE FUEL INLET	(F1)	18.8	37.80	-106.67	-1919.65	(-4252.17)	2.00	4.367	(2.215)
BOOST FUEL PUMP OUTLET	F2	73.8	38.55	-103.38	-1916.36	-4244.88	2.02	4.370	2.215
MAIN FUEL PUMP OUTLET	F3	6957.6	131.01	322.90	-1490.08	-3259.39	3.87	4.585	2.187
MAIN FUEL PUMP LEAKAGE	(F4)	6957.6	131.01	322.90	-1490.08	(40.11)	3.87	4.585	(-.027)
MAIN FUEL VALVE OUTLET	F5	6932.6	131.22	322.90	-1490.08	-3259.39	3.88	4.578	2.187
HEAT EXCH OUTLET (COLD)	(F6)	6921.6	131.46	323.36	-1489.62	(3258.39)	3.89	4.572	(-2.187)
COMBUSTOR OUTLET	F7	5975.3	797.12	2833.57	1020.59	2232.42	10.93	1.180	2.187
NOZZLE OUTLET	(F8)	5916.3	974.54	3459.32	1646.34	(3601.19)	11.64	.982	(2.187)
MAIN FUEL TURBINE INLET	F9	5310.8	979.11	3459.32	1646.34	3545.21	11.77	.891	2.153
FUEL TANK PRESSURIZATION	(F10)	5310.8	979.11	3459.32	1646.34	(-55.98)	11.77	.891	(-.034)
MAIN FUEL TURBINE OUTLET	F11	2358.0	860.16	2971.87	1158.89	2245.28	12.12	.481	1.937
MAIN OXIDIZER TURBINE INLET	F12	2344.2	860.25	2971.87	1158.89	2245.28	12.12	.478	1.937
MAIN OXIDIZER TURBINE OUTLET	F13	1988.2	837.48	2884.75	1071.77	1621.77	12.19	.420	1.513
BOOST FUEL TURBINE OUTLET	F14	1988.2	852.15	2935.99	1123.01	228.27	12.25	.413	.203
OXIDIZER HEAT EXCHANGER INLET	F15	1979.4	969.94	3346.87	1533.89	331.24	12.71	.364	.216
HEAT EXCH OUTLET (HOT)	F16	1983.4	841.75	2899.54	1086.56	2105.15	12.21	.417	1.937
MAIN FUEL INJECTOR INLET	(F17)	1979.4	856.25	2944.40	1131.42	(-2436.40)	12.42	.410	(-2.153)
SUMMATION (W,E) AT CONTROL SURFACE			(SHOWN IN () AND FLOW OUT IS NEG)			-4.36			.00
ENERGY AND MASS BALANCE ACCURACY AT CONTROL SURFACE					(PERCENT)	99.93			100.00

TABLE 5. COMPLETE ENGINE PERFORMANCE FOR 7500-LB THRUST ENGINE
(CONTINUED)

CONTROL SURFACE SUMMARY	LOCATION	PRESSURE (PSIA)	TEMPERATURE (DEG R)	NBS ENTHALPY (BTU/LB)	DELTA-H (BTU/LB)	ENERGY (BTU/SEC)	FLOWRATE (LB/SEC)	HEAT OF FORMATION (CAL/MOLE)
ENGINE OXIDIZER INLET	(01)	16.3	162.70	-57.75	-174.85	(-2323.87)	(13.290)	-3108.5
MAIN OXIDIZER PUMP LEAKAGE	(03)	2785.5	176.74	-47.58	-164.68	(3.04)	(-.018)	-2927.6
OXIDIZER TANK PRESSURIZATION	(05)	2784.5	665.07	133.64	16.54	(-2.22)	(-.134)	294.0
MAIN OXIDIZER INJECTOR INLET	07	2350.7	180.89	-47.58	-164.68	2163.54	-13.138	-2927.6
MAIN OXIDIZER INJECTOR	(08)	2350.7	152.81	-57.75	-174.85	(2297.21)	(-13.138)	-3108.5
T/C OXIDIZER - B.L. ATTACHMENT	09	1704.2	155.66	-57.75	-174.85	-2297.21	13.138	-3102.0 (NBP)
ENGINE FUEL INLET	(F1)	18.8	37.80	-106.67	-1919.65	(-4252.17)	(2.215)	-2150.0
MAIN FUEL PUMP LEAKAGE	(F4)	6957.6	131.01	322.90	-1490.08	(40.11)	(-.027)	-1668.9
HEAT EXCH OUTLET (COLD)	(F6)	6921.6	131.46	323.36	-1489.62	(3258.39)	(-2.187)	-1668.4
NOZZLE OUTLET	(F8)	5916.3	974.54	3459.32	1646.34	(3601.19)	(2.187)	1843.9
FUEL TANK PRESSURIZATION	(F10)	5310.8	979.11	3459.32	1646.34	(-55.98)	(-.034)	1843.9
MAIN FUEL INJECTOR INLET	F17	1979.4	856.25	2944.40	1131.42	-2436.40	-2.153	1267.2
MAIN FUEL INJECTOR	(F18)	1979.4	872.38	3006.48	1193.50	(-2570.07)	(-2.153)	1336.7
T/C FUEL - B.L. ATTACHMENT	F19	1704.2	808.10	2776.23	963.25	2074.26	2.153	1078.8
SUMMATION (W,E) AT CONTROL SURFACE		(SHOWN IN () AND FLOW OUT IS NEG)				-4.36	.00	
ENERGY AND MASS BALANCE ACCURACY AT CONTROL SURFACE					(PERCENT)	99.93	100.00	

TABLE 5. COMPLETE ENGINE PERFORMANCE FOR 7500-LB THRUST ENGINE (CONTINUED)

NOZZLE SEGMENTATION SUMMARY

		SEGMENT 1	SEGMENT 2	SEGMENT
SEGMENT TYPE		REGEN	RADIATION	
BREAKPOINT EPSILON	NONE	435.3	1066.8	
SEGMENT LENGTH	INCHES	32.54	89.54	
RADIATION SEGMENT AREA	IN**2	2356.45	8073.52	
DELTA-H ODE	BTU/LBM	5397.17	5397.17	
B/L Q	BTU/SEC	3648.081	715.123	
TOTAL Q	BTU/SEC	6363.762	715.123	
PER-SEGMENT DELTA ADIAB	NONE	.01729	.02315	
K2 FACTOR	NONE	.97970	.98262	
DELTA-ETA-QBL	NONE	.02282	.00445	
DELTA-DELTA PER SEG	NONE	.01729	.00586	

NOZZLE CONTOUR DEFINITION

THETA MAX	DEGREES	45.632
THETA EXIT	DEGREES	5.557
RCIRC/RT	NONE	0.000
M-SUB-X	INCHES	.36382
M-SUB-Y	INCHES	1.05928
P	NONE	-.23946
Q	INCHES	-17.26029
S	INCHES	43.55752
T	IN**2	297.9175

PARABOLIC CONTOUR EQUATION IS'
R = MY + P*(X-MX) + Q + SQRT(S*(X-MX) + T)

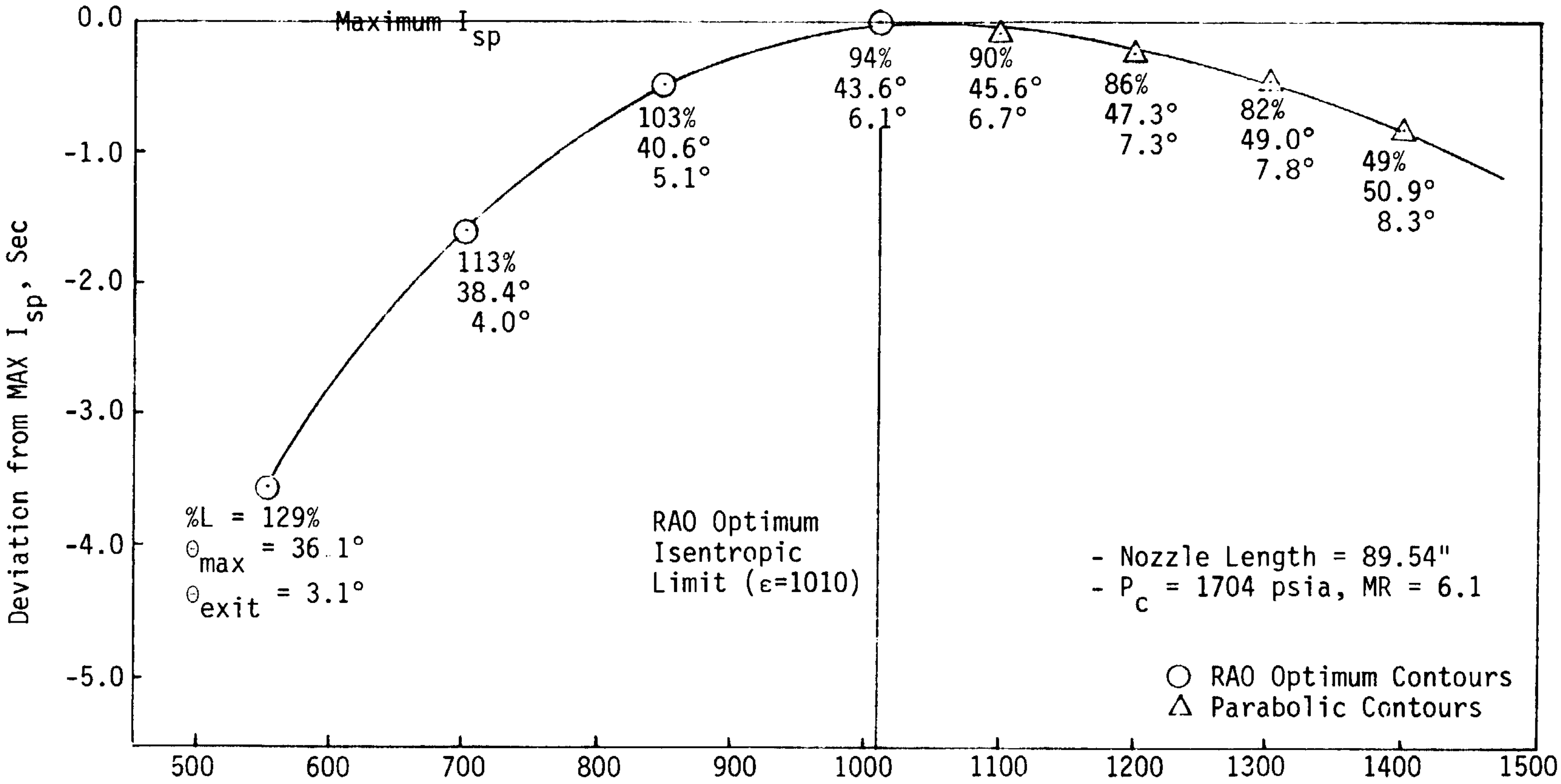
NOZZLE CONTOUR ANALYSIS

In this effort the area ratio of the OTVE nozzle was optimized for the specified length (from throat to nozzle exit) of 89.54 inches (117 inch engine less combustor and gimbal lengths). The output from the study was selection of the optimum area ratio and design of a nozzle contour which maximizes thrust for the specified length and optimum area ratio.

The Rao optimum design procedure was used to find a series of nozzle area ratios for the allowable length of 89.54 inches. This procedure was used to select area ratios ranging from ϵ= 550 to ϵ= 1010. The isentropic limit for the Rao design procedure is reached at ϵ= 1010. Beyond this area ratio, the procedure yields a shock wave and the isentropic assumption upon which the procedure is based is violated.

To obtain nozzle designs and performance past the isentropic limit, parabolic contours were used. The contour angles, both initial maximum angle on the throat radius of curvature (θ_{max}) and final nozzle wall exit angle (θ_e), were obtained by extrapolating the values obtained by the Rao procedure at lower area ratios. It was noted that the difference between a Rao optimum and a parabolic contour with equivalent contour angles was about 0.1 second of specific impulse (I_{sp}) at ϵ=1010. This indicates that the parabolic results beyond ϵ= 1010 are within 0.1 seconds I_{sp} of the maximum achievable if further contour optimization was undertaken.

Results of the study are summarized in Figure 3. Performance is referenced to the maximum achievable specific impulse and is shown as a function of nozzle area ratio for a specified length of 89.54 inches. Losses include divergence and drag as predicted by the Rocketdyne method of characteristics and boundary layer programs. Equilibrium chemistry was used in both the design and analysis of each contour. The performance is shown to be relatively flat between ϵ=1000 and ϵ=1100. The Rao isentropic limit was reached at ϵ=1010 and it is this contour which was



Nozzle Area Ratio, ε

Figure 3. OTV 7,500 lb_f Engine

Nozzle Area Ratio Selection for Specified Length selected as optimum for the current OTVE application. This Rao optimum contour yields an isentropic, shock-free flowfield within that portion of the nozzle which influences thrust.

Shown also in Figure 3 are % L (percent of the length of a 15 degree cone with the same area ratio), θ_{max}, and θ_e. The ϵ=1010 nozzle is a 94% length contour with θ_{max} and θ_e equal to 43.6° and 6.1°, respectively.

A final verification of these results using the JANNAF analysis codes (TDK/BLM/BLIMP-J) is planned in future OTV efforts. A slight shift in the peak performance may occur as a result of kinetic effects and use of the JANNAF boundary layer codes. Although these effects are not expected to be significant, a final verification using TDK/BLM, as a minimum, is planned.

A trade study which considers I_{sp} variation with area ratio and impact of weight, and nozzle envelope is also necessary in area ratio selection. The study reported herein did not consider weight penalty versus performance gain.

MAINTENANCE PLAN

ENGINE COMPONENT LIFE ESTIMATES

Introduction

In order to establish a maintenance plan for the space based engine, a knowledge of the critical component lives is required. A compilation of component lives and life limiters for critical components including the combustor, nozzle, injector, turbomachinery, and valves/actuators has been generated. This effort is summarized in Table 6. Included in the compilation are the environments to which the various components will be exposed and their probable failure mechanisms. The ultimate life goal of the full capacity space based engine is 20 hours/500 cycles. Most of the components evaluated thus far will be able to meet these requirements. All thrust chamber components, except the lower radiation cooled nozzle, are expected to survive the life goal but will require inspections and possible servicing prior to replacement.

Turbomachinery Life Estimates

Three critical areas impacting turbopump life were addressed. These include: (1) bearings, (2) seals, and (3) structural fatigue life.

Bearings. It is expected that hydrostatic bearings will be applied in the advanced high pressure fuel pump assuming negligible bearing wear during starts and shutdowns (the validity of this assumption is to be addressed in a future task). Life calculations for the 20 mm bearings that may be used in the high pressure LOX pump indicate that these bearings exhibit a B-1 (fatigue) life of thirty hours.

TABLE 6

FULL CAPABILITY SPACE BASED OTV ENGINE COMPONENT LIFE ESTIMATES

SUBSYSTEM	COMPONENT	SERVICE	LIFE/CYCLES	PROBABLE FAILURE MECHANISMS
TURBO-PUMPS (1990's tech., soft wear ring seals, hydrostc. bearing, etc.).	LPFTP	PUMP: LH2 40k rpm 75 psi out and TURBINE: 990 R in 2170 psi	>>20 HRS/ 500 cyc	High Cycle Fatigue (HCF) of pump impeller, Abrasion of bearings and seals, HCF, Low Cycle Fatigure (LCF), and creep of turbine rotor, Pitting of inducer
	HPFTP	PUMP: LH2 200k rpm 6600 psi and TURBINE: 1130 R in 4900 psi	30 hours/ 500 cyc	
	LPOTP	PUMP: LOX 10K rpm 90 psi out and TURBINE: hydraulic (LOX)	20 hours/ 500 cyc	
	HPOTP	PUMP: 66.5K rpm 2700 psi out and TURBINE: 990 R in 2170 psi	20 hours/ 500 cyc	

TABLE 6

FULL CAPABILITY SPACE BASED OTV ENGINE COMPONENT LIFE ESTIMATES

SUBSYSTEM	COMPONENT	SERVICE	LIFE/CYCLES	PROBABLE FAILURE MECHANISMS
THRUST CHAMBER	ENHANCED HEAT TRANSFER	6800 R, 1576 psia, H_2O/H_2, MR=6.0-7.0	20 hours(1)/ 500 cyc	LCF cracks
	INJECTOR	GOX, LOX, GH_2	20 hours(2)/ 500 cyc	LCF cracks
	INJECTOR MANIFOLD	GOX, LOX, GH_2	20 hours/ 500 cyc	LCF cracks, Errosion
	NOZZLE (fixed, metallic, regen. cooled)	H_2O, GH_2	20 hours(1)/ 500 cyc	LCF cracks
	NOZZLE (lower rad cooled, carbon/ carbon	H_2O, GH_2	10 hours(3)/ 250 cyc	LCF cracks, Oxidation, flaking
	IGNITER	LOX, GH_2	20 hours/ 500 cyc	

(1) Inspection at 250 starts - pollish wall if roughening exists
(2) Inspection at 250 starts - remove from service if errosion exists
(3) Inspection at 5 hours or 125 starts - remove from service if costing is damaged

TABLE 6

FULL CAPABILITY SPACE BASED OTV ENGINE COMPONENT LIFE ESTIMATES

SUBSYSTEM	COMPONENT	SERVICE	LIFE/CYCLES	PROBABLE FAILURE MECHANISMS
HEAT TRANSFER SYSTEM	LOX HEX	GH_2 1830 psi 1150 R, LOX 2580 psi 180 R, GOX 2580 psi 665 R	20 hours/ 500 cyc	LCF cracks
VALVES and FILTERS	LOX/GOX VALVES	LOX/GOX	20 hours/ 500 cyc	Leakage, Obstruction
	LH2 VALVES	LH_2	20 hours/ 500 cyc	Leakage, Obstruction
	FILTERS	LH_2/LOX	20 hours/ 500 cyc	Plugging
SYSTEM	PROPELLANT DUCTS	LH_2, GH_2, LOX, GOX	20 hours/ 500 cyc	HCF cracking
	TURBINE EXHAUSTE DUCTS	GH_2 900 R 2600 psi	TBD	LCF cracks
	GIMBAL BEARING		20 hours/ 500 cyc	HCF, Abrasion
	ACTUATORS		20 hours/ 500 cyc	HCF, Abrasion
	CONTROLLER		20 hours/ 500 cyc	HCF, Electronic Component Failure

TABLE 6

FULL CAPABILITY SPACE BASED OTV ENGINE COMPONENT LIFE ESTIMATES

SUBSYSTEM	COMPONENT	SERVICE	LIFE/CYCLES	PROBABLE FAILURE MECHANISMS
	SENSORS (standard)	LOX, GOX, LH_2, GH_2, Vacuum, 6600 psi, cryogenic 6800 R	TBD	LCF, HCF, Abrasion, over temp
	SENSORS (advanced)	Same as above	TBD	Same as above

Seals. The principle of the operation of the shaft riding carbon seals to be used in both the advanced high pressure fuel and LOX pumps is similar to that of the shaft riding seals currently used in the SSME HPFTP and HPOTP. Experience with the SSME seals show that while some minimal scuffing, assumed to occur at start and stop, is evident, the surfaces of these seals remain essentially unworn. The replacement of these seals has not been prompted by wear. It may be concluded that this type of seal could sustain twenty hours of operation but the question of surviving five hundred cycles remains unanswered.

Applying life considerations to the abradable soft seals in the advanced high pressure fuel pump reveals that these seals, after some initial wear-in, should not sustain any additional wear and these seals, because they are radially fixed, should be able to sustain the five hundred cycle requirements.

Structural Fatigue Life. Stress calculations for the existing MK49 high pressure LOX and fuel pumps used on the ICE (Integrated Component Evaluator) indicate that for high cycle fatigue, the structure is designed for infinite life, and for low cycle fatigue these existing turbopumps will sustain three hundred cycles. It is expected, however, that the turbopumps ultimately to be used on the full capability engine can be successfully designed for five hundred cycles.

REVIEW OF SSME MAINTENANCE PLAN

A review of the Space Shuttle Main Engine (SSME) operations and maintenance manual was conducted with two purposes in mind: (1) to begin to outline the overall maintenance procedures for the OTVE, and (2) to identify technology requirements for streamlining space based OTV engines. The SSME document contains the requirements and specifications for the SSME at the organizational level (installed engines). Routine maintenance requirements (after each engine firing), periodic maintenance requirements (time/cycle oriented), and contingency requirements (unscheduled to isolate/rectify a condition) are covered. Each of the seventy-six tasks were reviewed and their relevancy to the OTV engine established. It was then determined whether the individual tasks would be affected by an advanced integrated control and health monitoring (ICHM) system incorporating advanced sensors. In addition, the impact of an advanced ICHM upon extra vehicular activity (EVA) requirements for each of the OTV applicable maintenance tasks was assessed. Finally, pertinent comments were included for clarity.

Maintenance Tasks

Introduction. Of the seventy-six maintenance tasks reviewed, twenty were determined as not being relevant to the OTV engines. Of the remaining fifty-six tasks, forty-six are applicable to the OTV, and for ten the status is yet to be determined. Of course, there will be additional maintenance tasks which will be OTV specific, but for the effort of identifying technology drivers for streamlined maintenance, the SSME derived requirements list was deemed sufficient for this initial effort. Additional tasks will be identified as the maintenance plan evolves.

The SSME maintenance requirements fall into five major categories: 1) Automatic/Electrical Checkouts, 2) Handling, 3) Leak Tests, 4) Torque Tests, and 5) Visual Inspections. A sixth category, which will have tasks more specific to the OTV, is servicing. A summary of the types of maintenance and these categories is provided in Figure 4.

The review of the SSME operations and maintenance tasks is presented in Appendix 1. The requirements structure and a list of abbreviations and acronyms used in this effort are also provided.

Automatic/Electrical Checkouts. Most of the automatic/electrical checkouts are applicable to the OTV and would be effected by the ICHM, but are conducted through the controller and would not require EVA. These tasks include valve sequence tests, sensor checks, memory dumps, and checks for short circuits.

Handling. The second category of maintenance tasks, handling, entails the installation and removal of protective coverings. Handling tasks will most likely apply to the OTV when "hands on" type of EVA repairs are required. These first two categories mentioned would not be greatly affected by an advanced ICHM and therefore precipitated no technology requirements. The remaining categories are discussed below.

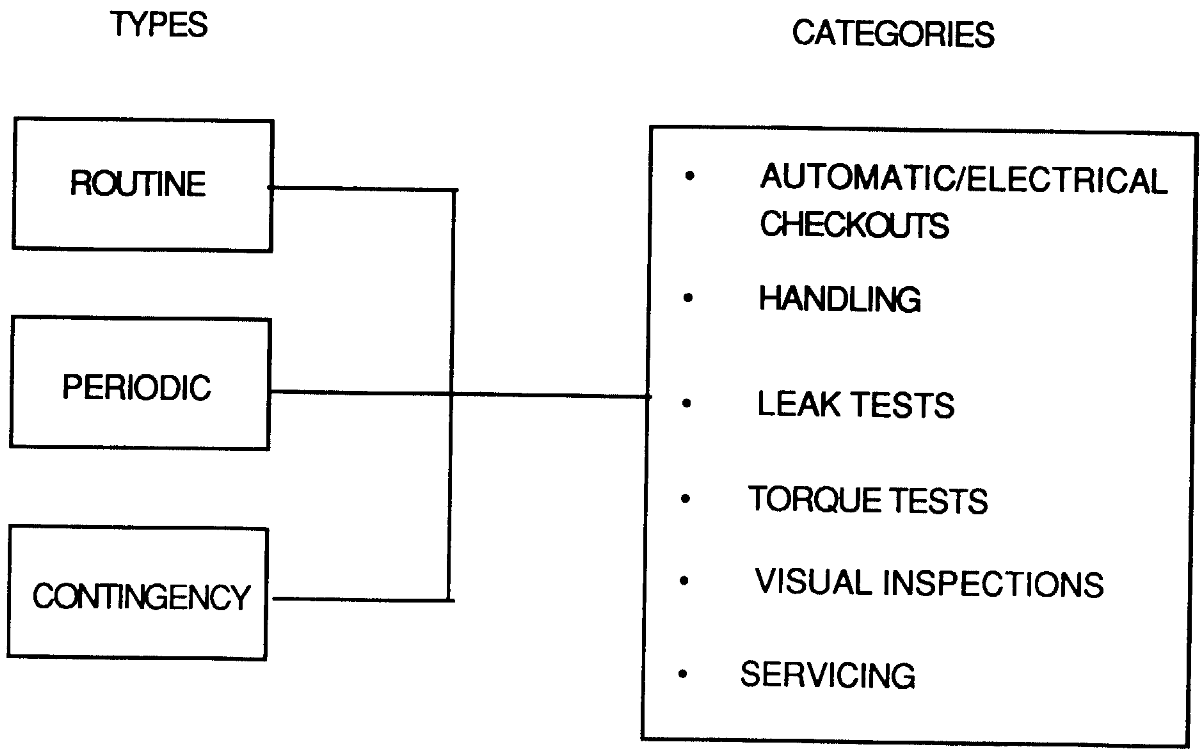


FIGURE 4. MAINTENANCE TYPES AND CATEGORIES

Leak Detection. Leak tests account for the largest single category of maintenance tasks required. These tests provide a good measure of the integrity of many components such as combustor and nozzle cooling circuits, turbopump seals, valves, and propellant ducting. These important tests are necessary but they currently require extensive "hands on" type work such as installation of blind flanges, pressurization, and "bubble" tests with leak-detection solution. With a space based engine scenario, this approach would prove to be very costly and time consuming since extensive EVA would be required. This area is amenable to vast improvement through the use of advanced techniques such as holographic leak detection. With this approach, leak detection could be done remotely by quantitative analysis of holographic interference patterns and distortions associated with leaks. Considering the large portion of the maintenance tasks associated with leak detection and the benefits to be gained by streamlining those efforts, it is apparent that remote leak detection is one of the key advanced technologies worthy of development.

Torque Tests. Another category of maintenance tasks which would be costly if the present day approach were used in space basing is the torque tests. These tests are used to evaluate the condition of the turbomachinery. By measuring the break away and running torques of the turbopumps, evidence of any binding of bearings, seals, or labyrinths (indications of incipient failures) are detected. The current procedures entail the removal of access ports and the manual insertion of a hand held torque wrench type tool for break away and running torque measurements. After completion of the required measurements and replacement of the access ports, leak checks must be conducted. This labor intensive approach, requiring EVA for a space based engine, can be obviated through the use of ferromagnetic torque meters installed permanently on the turbopumps. Additional direct condition monitoring equipment such as isotopic wear detectors and fiberoptic deflectometers for bearing wear detection could supplement the torque meters for on-line turbomachinery health monitoring.

Visual Inspection. The final category of maintenance tasks which would be significantly affected by the adoption of advanced ICHM techniques is visual inspections. These include general external inspections of the overall engine to identify any damage to exposed and accessible areas, and to verify that all protective covers, test plates, plugs, etc. have been removed prior to engine start. These general inspections could possibly be done remotely in a space based setting through the use of robotics coupled with high resolution video equipment. Current maintenance techniques also include internal boroscopic inspections of critical life limiting components such as turbine blades, pump impellers, bearings, and injector elements. These labor intensive tasks, currently done on the SSME's prior to every launch, would be much more difficult and costly if conducted through EVA on space based OTV engines. The OTV maintenance plan intends to phase these tasks out by determining component integrity not through inspections, but by health monitoring with advanced sensors such as exoelectron fatigue and isotopic wear detectors.

Servicing. The category of servicing covers additional routine type tasks which will be more specific to the OTV. One example of such a task which was identified in the component life estimate effort is polishing of the nozzle and combustor walls after 250 engine starts.

MAINTENANCE PHILOSOPHY

The philosophy of the evolving maintenance plan is presented in Figure 5. In this approach, the initial ground based OTV would have a maintenance plan similar to the current SSME. A few of the advanced sensors mentioned above would be incorporated into the engines but would be mainly used to generate a data base for component life predictions. As this data base develops and confidence in the health monitoring and life predicting capabilities grows, the intervals between routine maintenance tasks would be extended. Additional advanced sensors would be added as their technology develops. Ultimately this would evolve into a maintenance

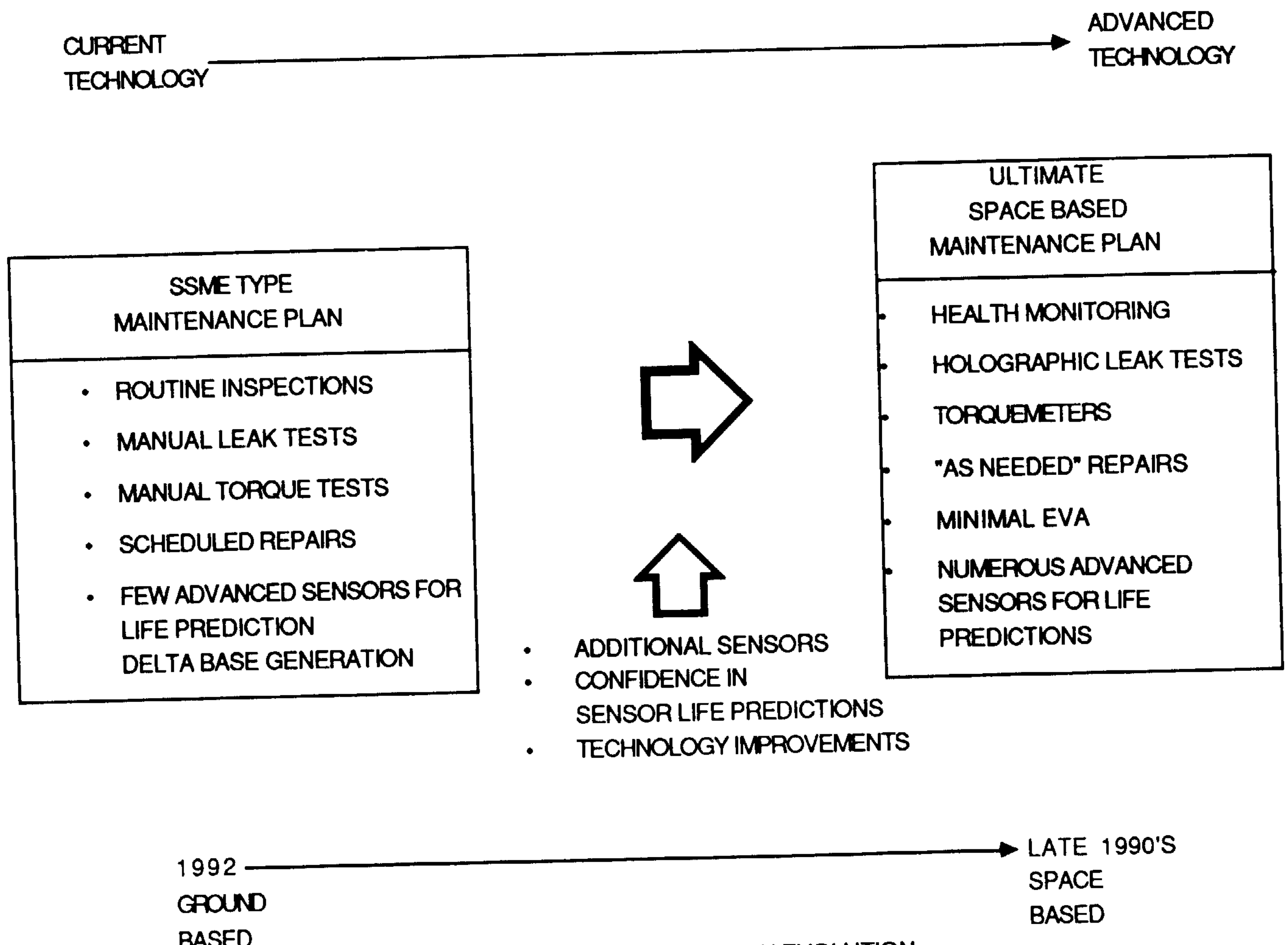


FIGURE 5. MAINTENANCE PLAN EVOLUTION

program in which nearly all component condition evaluation tasks would be eliminated through the use of health monitoring instrumentation coupled with a mature data base. With this approach, confident predictions of the remaining lives of critical components would enable repairs and change outs to be conducted on an efficient as-needed basis.

The impact of health monitoring upon the SSME/OTV applicable maintenance tasks is summarized in Table 7. In this table, the 46 maintenance tasks, which were identified as being applicable to the OTV engine, are represented in the six previously mentioned categories. The total number of tasks in each category are provided in the first column. The second column provides the number of tasks in each category which would require EVA on a space based OTV engine if the current SSME type maintenance plan was adopted. In the final column, the number of tasks requiring EVA with an advanced ICHM and maintenance plan are presented. As can be seen, the advanced maintenance plan has the potential of eliminating nearly all EVA which would be required to assess the condition of the engines. It is this type of approach which will be necessary to make space based OTV operations economically feasible.

TABLE 7

IMPACT OF ADVANCED MAINTENANCE PLAN

SSME/OTV MAINTENANCE TASK CATEGORY	TOTAL NUMBER OF TASKS IN EACH CATEGORY	NUMBER OF TASKS REQUIRING EVA WITH CURRENT MAINTENANCE APPROACH	NUMBER OF TASKS REQUIRING EVA WITH ADVANCED MAINTENANCE PLAN	TECHNOLOGIES REQUIRED FOR ADVANCEMENTS
AUTOMATIC/ELECTRICAL CHECKOUTS	6	0	0	NONE
HANDLING	3	3	3	NONE
LEAK TESTS	25	25	0	REMOTE DETECTION: HOLOGRAPHIC, SPECTROGRAPHIC, AND/OR ACOUSTIC
TORQUE TESTS	4	4	0	TORQUEMETERS
VISUAL INSPECTIONS	7	7	0	ROBOTICS & HIGH RESOLUTION VIDEO EQUIPMENT, EXO-ELECTRON FATIGUE DETECTORS, ISOTOPIC WEAR DETECTORS
ABORT TURN-AROUND (INCLUDES MANY OF ABOVE TASKS)	1	1	1	ALL OF THE ABOVE
TOTAL	46	40	4	DOES NOT APPLY

SPACE OPERABLE DISCONNECTS

This subtask provides further definition to the advanced fluid coupling devices studied in Task D.1/D.3. Preliminary designs and a test plan outline are the key outputs. Both previously high-rated and new coupling concepts were assessed and ranked. A preliminary design of the preferred configuration, as well as a test version of it, was prepared. Lastly, a test plan to demonstrate the selected concept was defined.

DISCONNECT APPLICATION

The study focused on a single disconnect application in order to provide identifiable design requirements and goals without redundant study effort. The program goals affect selection of the coupling configuration. Of the three coupling evaluation groups defined in the previous study, two were candidates for this focused effort. The small line joints of Group III were considered of low development priority because their small size reduces concerns over weight versus function and assembly operation. The other two categories were identified as either vehicle/engine or component/component joints. For these, applicable designs are impacted in three areas (temperature, size, and pressure), as shown in Table 8. This is more evident by examining a specific design such as the "Carriage Hook" concept shown in Figure 6. Required features for both uses of this coupling are compared in Table 9. The most significant consideration is the added importance of structural design versus weight of the component/component version due to much higher operating pressures. With respect to program impacts, focusing on the vehicle/engine couplings satisfies near term requirements, provides a basis for growth to component/component joint requirements, and permits the furthest development with funds available. Alternately, focusing on the component/component needs leads to additional technology advancement which, as a by-product, also demonstrates vehicle/engine disconnect capabilities.

TABLE 8. DIFFERENCES IN COUPLING GROUP DESIGN REQUIREMENTS

	Design Impacts	Vehicle/Engine Needs	Comp./Comp. Needs
Temperature	Seals Thermal Growth	Cryogenic	Cryogenic or Hot Gas
Size	Mechanism Volume Coupling Operation	Ø2.125 Ducts	Ø1.125 Ducts (Typ.)
Pressure	Structural Loads Seals	18 psi	Up to 6958 psi

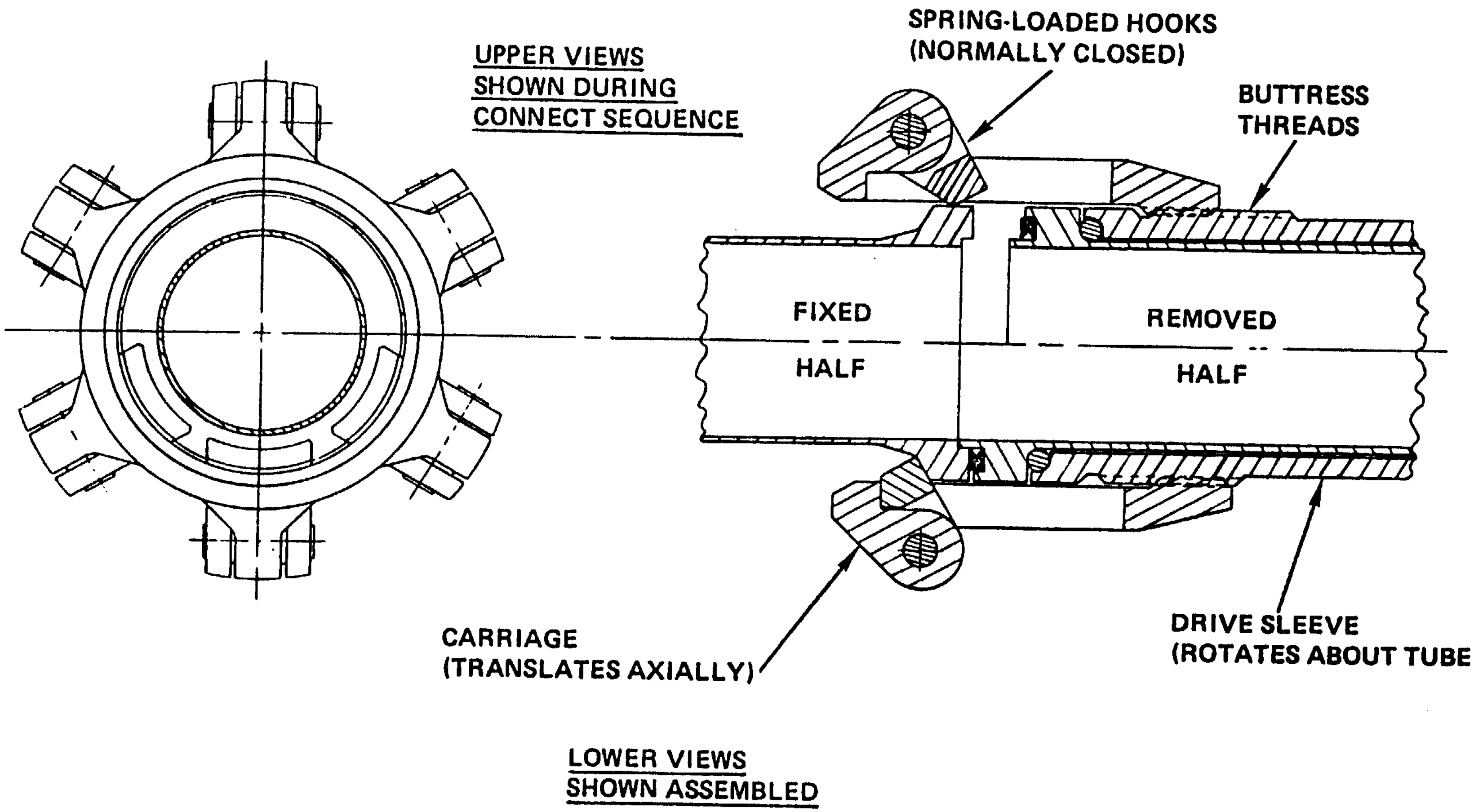


FIGURE 6

US PATENT NO. 4,765,145
(Connector Assembly*)

CARRIAGE/HOOK COUPLING CONCEPT*

TABLE 9. COMPARISON OF FEATURES FOR CARRIAGE-HOOK COUPLING APPLICATIONS

Required Features Vehicle/Engine Configuration	Comp./Comp Configuration	Remarks
L.P. Cryogenic Seal	H.P. Cryogenic Seal H.P. Hot Gas Seal	Joint mechanism, not seal, is technology of interest
Gall-Resistant Threads	Same, loads much higher	Smooth, gall-resistant operation desired
High load thrust bearing surfaces	Same, ball bearings possibly req'd. for higher loads	Smooth, gall-resistant operation desired
Wrenching provisions	Same, loads much higher	Capable of normal or robotic operation
Precision machined/ assembled carriage assembly	Same	Symmetrically distribute joint loads
Hook Clamping Adjustment	Same	Alternate for precision machining
Large Diameter Joint reduces hook design constraints	Small diameter limits number of hooks - high load/hook	Design adequate for Comp/ Comp. configuration
Load measurement provisions	Same	Req'd to verify joint preload.

With these considerations in mind, requirements for a cryogenic, high pressure component/component joint were selected as the most efficient means to advance space-operable disconnect technology. This will require only a small amount of additional effort in the design and test phases to both demonstrate far term needs and prepare for development of near term hardware.

CONCEPT DESCRIPTIONS

The study approach progressed from the Task D.1/D.3 foundation by starting with the top-ranking concepts, considering new ones, and then applying a refined assessment methodology to identify a preferred design. Although several new concepts were identified, none were judged to be competitive with the top ranking candidates from the Task D.1/D.3 study. Conceptual design effort then concentrated on derivatives of these high scoring concepts in an attempt to combine their advantageous features into a single design. These concepts are briefly described below.

Concept 1 - "Carriage-Hook" (Figure 6).

This was the top candidate from the Task D.1/D.3 study. It operates by using a rotating drive sleeve to translate a carriage fore or aft. Splines prevent rotation of the carriage. Hooks are mounted to the carriage with springs to normally hold them in the assembled, or closed, position. As shown in the upper view, the hooks are forced to rotate clear of the fixed flange as the coupling begins to connect. When the fixed flange nears seating, the hooks are free to snap back against their stops. Actuation of the drive sleeve causes the carriage to translate until the hooks contact and load the back of the fixed flange. Proper loading of the joint can be determined by torquing the drive sleeve or by measuring the strain on each of the easily accessible tension legs of the carriage. To disconnect, a split-sleeve tool (not shown) is slipped around the fixed half tube. As the drive sleeve moves the carriage to the open position, the tool forces the hooks to open until the coupling halves are separated.

This concept uses a moderately complex mechanism, entirely contained on the removable half, which is simple and fast to operate. Loads are applied close to the seal nearly continuously around the joint so that flange size is minimized. Manipulations required to operate the coupling are sequential - not requiring application of two or more motions or forces at any time - a key advantage for EVA tasks. Initial positioning and angulation of the mating halves need not be precise. A negative feature is the close tolerances required to assure symmetrical loading on the hooks. This results in high fabrication costs compared with some of the other concepts. Another drawback is the need for a separate tool to open the hooks at disconnect.

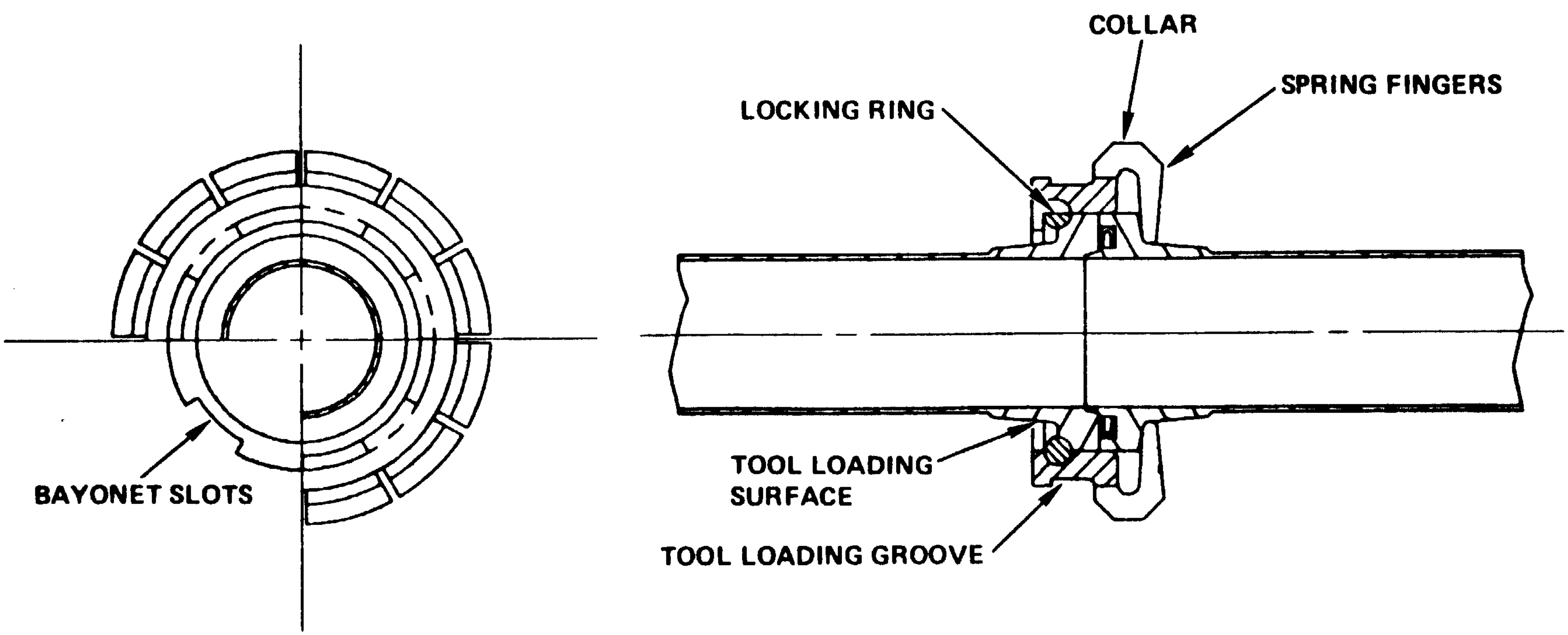
Concept 2a - "Spring Collar" (Figure 7).

This concept was a closely ranked second in the earlier study. It utilizes 12 "U" shaped spring elements, incorporated in a collar, to preload the flanges. The collar slides over the flanges and a tool applies the preload force. A locking ring with slots matching the slots in the collar is rotated 30 degrees, prior to removal of the tool, to lock the preload. Friction on the ring due to the preload between the collar and the flange is sufficient to prevent the ring from turning in high vibration environments.

The primary feature of this design is that joint preload is a function of joint configuration and not installation technique. The concept eliminates the need to torque individual fasteners to a close monitored value because the preload is provided by spring elements that apply an equal force (as a function of collar displacement) around the back side of the flange. The design also features an inherently simple configuration with few parts required.

A disadvantage of the Spring Collar concept is that since the preload is a function of joint configuration, the parts must be manufactured with close

SPRING-COLLAR INTERFACE COUPLING CONCEPT



US PATENT NO. 4,763,470

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FIGURE 7. CONCEPT 2a - SPRING COLLAR

Rockwell International
Rocketdyne Division

dimensional tolerances. To ensure a smooth finish and matching contact, the locking ring and the surfaces that it bears against must be ground. Also, damage to the spring elements may not be visually detected, but change joint preload.

Concept 2b - "Cylindrical Spring Collar" (Figure 8).

This concept is very similar to Concept 2a, except that it uses a cylindrical spring element rather than the "U"-shaped springs. The cylindrical spring provides the same function with less weight and slightly reduced envelope. The disadvantage is some loss in the capability to accommodate non-uniformities around the joint (e.g., contamination) through the use of individual springs.

Concept 3a - "Carriage - Spring Hook" (Figure 9).

This design is simply Concept 1 using "U"-shaped springs rather than solid hooks. This feature provides additional compensation for fabrication tolerances in order to provide uniform preload around the joint at the expense of slightly more weight and envelope.

Concept 3b - "Spring Carriage - Hook" (Figure 10).

This concept, following the reasoning of Concept 3a, employs a cylindrical spring element as in Concept 2b to minimize weight and envelope. As for concept 2b, however, capability to accommodate non-uniformities is somewhat compromised.

Concept 4 - "Preset Carriage-Hook" (Figure 11).

This derivative of Concept 1 uses compression members, installed on earth, to preset the load in the coupling. After the joint is assembled to obtain light-snug flange contact, the compression members are unloaded so that the preload is carried to the flanges and seal. Inasmuch as the preload is lost

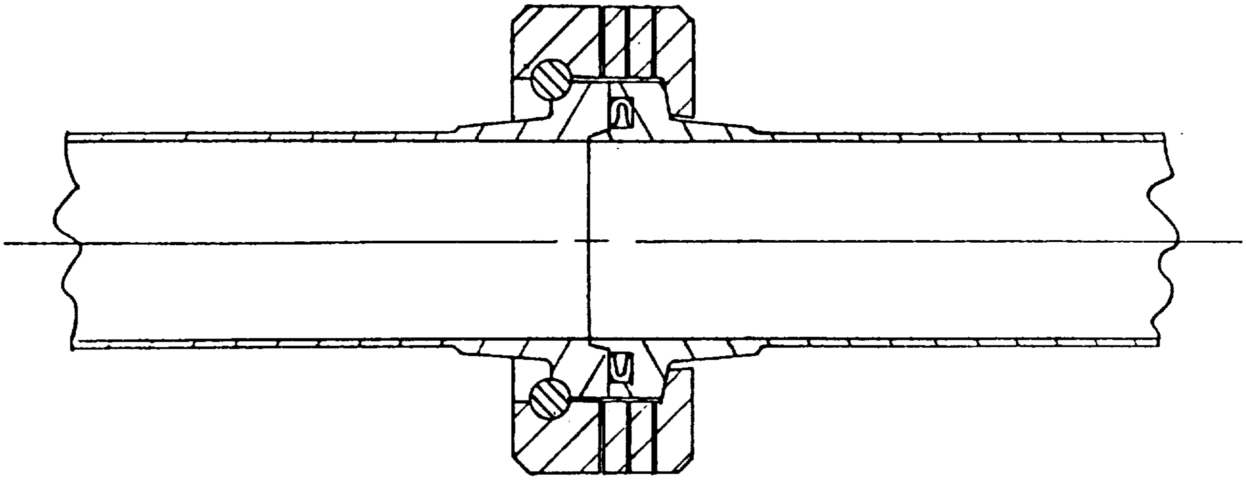

FIGURE 8. CONCEPT 2b - CYLINDRICAL SPRING-COLLAR

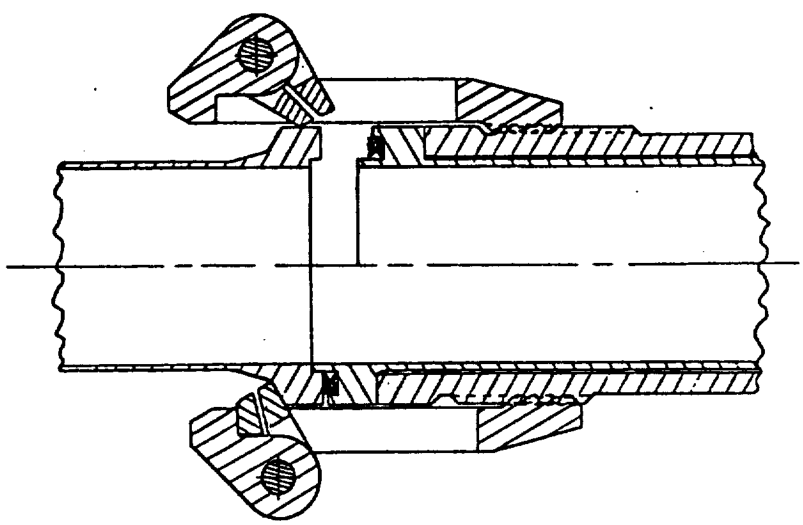

FIGURE 9. CARRIAGE-SPRING HOOK

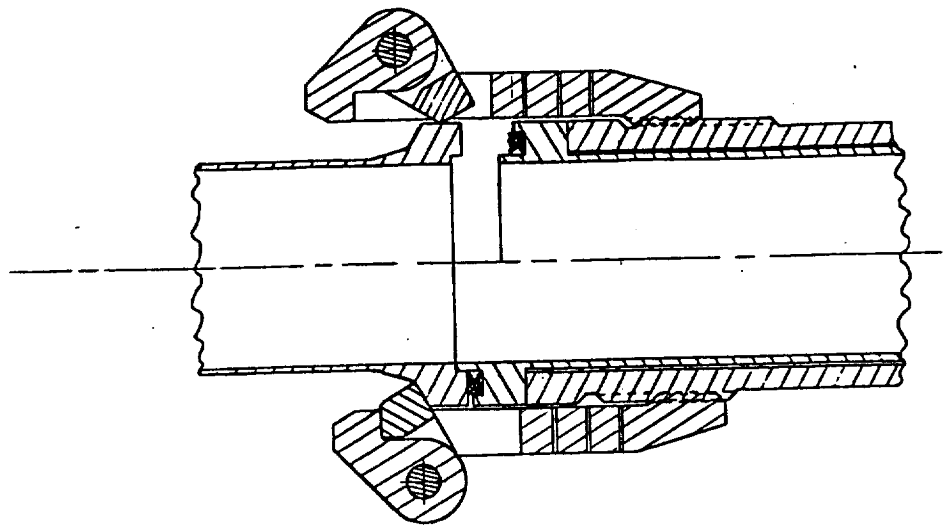

FIGURE 10. CONCEPT 3b - SPRING CARRIAGE-HOOK

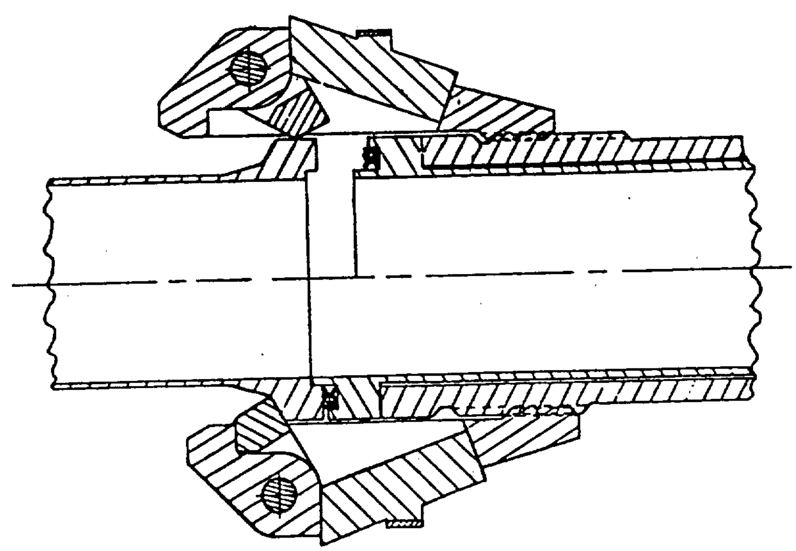

FIGURE 11. CONCEPT 4 - PRESET CARRIAGE-HOOK

after each use, the preloaded portion of the joint is contained on the replaceable component half of the interface. The benefit of this type of coupling lies in the ability to preset the desired joint preload on the ground or as an intra vehicular activity task, rather than as a less cost-effective extra vehicular activity effort. On the other hand, weight of the joint is increased through the elements added. Additional structure is also required on the carriage to allow for the compression strain lost when the compression members are released. In other words, the compression strain of the compression members must be added to the tension legs of the carriage, hence loading them more than required to preload the joint, to allow for compression of the drive sleeve and flanges at joint coupling.

<u>Concept 5 - "Preset Carriage - Spring Hook"</u> (Figure 12).

This concept is a combination of Concepts 3a and 4, using preset compression members on a carriage-hook coupling with spring hooks. Uniform joint load capability is improved with the spring hooks, preload can be preset, but additional weight is incurred by the additional structure and elements involved.

<u>Concept 6 - Carriage-Axial Hook</u> (Figure 13).

This design is similar to Concept 1 but configures the hooks so as to carry most of the preload through the hook pivots rather than by a "clamping ring". Because the pivot on the basic Concept 1 also reacts some of the preload, this concept reduces weight slightly due to fewer and more closely coupled load points. However, tolerances on the pivot holes, which cannot be machined together in a singular operation, must be stringent to provide the preload uniformity needs.

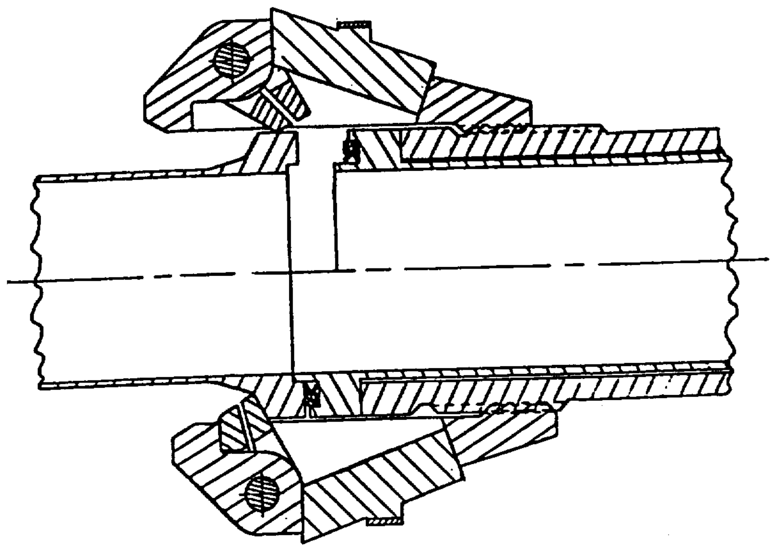

FIGURE 12. CONCEPT 5 - PRESET CARRIAGE SPRING-HOOK

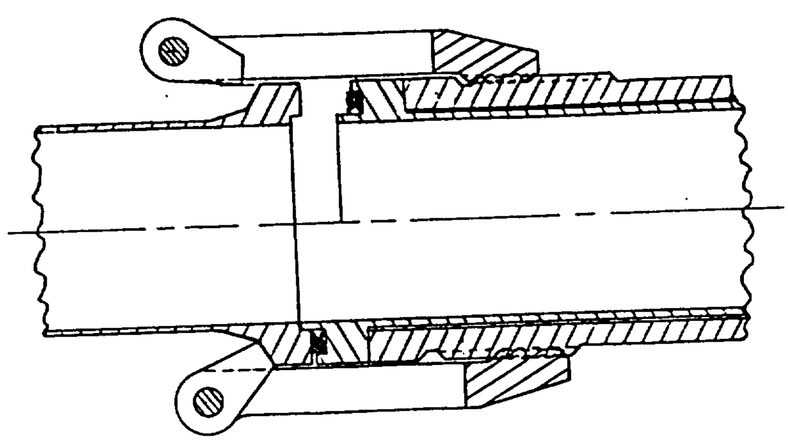

FIGURE 13. CONCEPT 6 - CARRIAGE AXIAL-HOOK

CONCEPT EVALUTION AND RANKING

Assessment of the candidate concepts was performed using the same approach as employed in the Task D.1/D.3 study. In general, the same evaluation criteria were used, with the differences as noted below:

"Coupling Operation" was split into separate "Assembly" and "Disassembly" categories so as to differentiate the judgments for these two distinct tasks. However, "Misalignment Accommodation", "Assembly Verification", and "Damage Sensitivity-Seal" were not pertinent to disassembly operations.

"Misalignment Accommodation" was subdivided into the three modes of misalignment so as to better evaluate where the differences between concepts occur.

"Assembly Verification" was split to note both the "Ease" of determining when the coupling is properly assembled and preloaded as well as the "Alternatives" available to make or provide secondary checks of this verification.

"Damage Sensitivity" was divided to differentiate between "Seal" and coupling "Mechanism" damage probability.

"Preload Reliability" was split to note the number of "Modes" which affect joint preload (i.e., how many different ways preload can be lost) as well as the "Value" of reliability offered by the design. Fewer modes and the high reliability were awarded the most points.

"Fabrication Costs" and "Development Costs" were each subdivided to assign the costs to either the coupling or its associated tools.

"Development Risk" was added as a criteria to indicate the difficulty in proceeding to successful implementation. The least risk was awarded the most points.

One to five points were awarded to each coupling for each evaluation criterion based on comparison with the competing concepts. Separately, each criterion was assigned a scaling factor to reflect its relative importance with respect to overall goals. The individual points awarded were multiplied by the scaling factors to give evaluation scores for each concept for each criterion. These scores were then summed to indicate overall concept results and relative rankings. The evaluation is shown in Table 10.

The resulting scores are tightly grouped; as should be expected because the evaluated concepts are derivations of the two highest, close-scoring designs of the previous study. Ranking indicates that concept 3a, which is a carriage hook coupling using spring elements as the hooks, is the best overall. This is due to very good ratings in most of the coupling operation criteria as well as very good preload reliability during engine operation. Together with good fabrication and development ratings, this coupling seems to provide the best combination of features over all the space operable disconnect concepts studied in Task D.1/D.3/D.4.

As noted in the previous study, the assessment is admittedly subjective. This is inevitable when evaluating design concepts. However, the method breaks the comparison down to permit clear identification of the subjective scaling factors and point awards as well as to help force a detailed sense of uniformity throughout. The resulting selection may thus be contested, but it was made using supporting detailed judgments tied together by a structured procedure.

PRELIMINARY DESIGN

A preliminary design of the selected configuration was developed. This is shown in Figure 14, which includes the wrenching, locking, and light-spring features, essential for coupling operation, which were omitted from the conceptual sketches to improve clarity. As common with all the Carriage-Hook concepts, mating is preceded by translating the

TABLE 10.

COUPLING CONCEPT ASSESSMENT

Bracketed items represent scaled Points.

Evaluation Criteria	Scaling Factor	1	2a	2b	3a	3b	4	5	6
COUPLING ASSEMBLY OPERATION									
Misalignment Acc. - Axial	2	5 (10)	3 (6)	3 (6)	5 (10)	5 (10)	5 (10)	5 (10)	5 (10)
Lateral	2	5 (10)	4 (8)	4 (8)	5 (10)	5 (10)	5 (10)	5 (10)	5 (10)
Angular	2	5 (10)	4 (8)	4 (8)	5 (10)	5 (10)	5 (10)	5 (10)	5 (10)
Required Motions	8	4 (32)	3 (24)	3 (24)	4 (32)	4 (32)	3 (24)	3 (24)	4 (32)
Required Forces	8	3 (24)	4 (32)	4 (32)	3 (24)	3 (24)	5 (40)	5 (40)	3 (24)
Required Steps	6	4 (24)	3 (18)	3 (18)	4 (24)	4 (24)	3 (18)	3 (18)	4 (24)
Assy. Verication - Ease	5	3 (15)	5 (25)	5 (25)	4 (20)	4 (20)	5 (25)	5 (25)	3 (15)
Alternatives	2	4 (8)	2 (4)	3 (6)	4 (8)	4 (8)	4 (8)	4 (8)	4 (8)
Assembly Time	9	4 (36)	3 (27)	3 (27)	4 (36)	4 (36)	3 (27)	3 (27)	4 (36)
Tool Envelope	2	4 (8)	3 (6)	3 (6)	4 (8)	4 (8)	4 (8)	4 (8)	4 (8)
Damage Sensitivity - Seal	6	4 (24)	4 (24)	4 (24)	4 (24)	4 (24)	4 (24)	4 (24)	4 (24)
Mechanism	3	3 (9)	4 (12)	4 (12)	3 (9)	3 (9)	2 (6)	2 (6)	3 (9)
Subtotal [Perfect Score 60(275)]		48 (210)	42 (194)	43 (196)	49 (215)	49 (215)	48 (210)	48 (210)	48 (210)
COUPLING DISASSEMBLY OPERATION									
Required Motions	8	4 (32)	3 (24)	3 (24)	4 (32)	4 (32)	4 (32)	4 (32)	4 (32)
Required Forces	8	3 (24)	4 (32)	4 (32)	3 (24)	3 (24)	3 (24)	3 (24)	3 (24)
Required Steps	6	3 (18)	3 (18)	3 (18)	3 (18)	3 (18)	3 (18)	3 (18)	3 (18)
Disassembly Time	9	3 (27)	3 (27)	3 (27)	3 (27)	3 (27)	3 (27)	3 (27)	3 (27)
Tool Envelope	2	4 (8)	3 (6)	3 (6)	4 (8)	4 (8)	4 (8)	4 (8)	4 (8)
Damage Sensitivity - Mech.	3	3 (9)	4 (12)	4 (12)	3 (9)	3 (9)	3 (9)	3 (9)	3 (9)
Subtotal [Perfect Score 30(180)]		20 (118)	20 (119)	20 (119)	20 (118)	20 (118)	20 (118)	20 (118)	20 (118)
PERFORMANCE DURING ENGINE OPERATION									
Sealing Redundancy	3	5 (15)	5 (15)	5 (15)	5 (15)	5 (15)	5 (15)	5 (15)	5 (15)
Sealing Reliability	10	3 (30)	3 (30)	3 (30)	3 (30)	3 (30)	3 (30)	3 (30)	3 (30)
Preload Reliability -Modes	3	3 (9)	4 (12)	3 (9)	4 (12)	3 (9)	3 (9)	4 (12)	3 (9)
Value	8	3 (24)	4 (32)	3 (24)	4 (32)	3 (24)	3 (24)	4 (32)	3 (24)
Vibration Sensitivity	7	2 (14)	4 (28)	4 (28)	3 (21)	3 (21)	2 (14)	3 (21)	2 (14)
Weight	7	3 (21)	3 (21)	4 (28)	3 (21)	3 (21)	2 (14)	2 (14)	4 (28)
Envelope	4	3 (12)	3 (12)	4 (16)	3 (12)	3 (12)	3 (12)	3 (12)	3 (12)
Subtotal [Perfect Score 35(210)]		22 (125)	26 (150)	26 (150)	25 (143)	23 (132)	21 (118)	24 (136)	23 (132)
FABRICATION/DEVELOPMENT/MAINTENANCE									
Fabrication Costs - Joint	4	3 (12)	3 (12)	3 (12)	3 (12)	3 (12)	3 (12)	3 (12)	2 (8)
Tools	2	4 (8)	2 (4)	2 (4)	4 (8)	4 (8)	4 (8)	4 (8)	4 (8)
Development Risk	5	3 (15)	2 (10)	2 (10)	2 (10)	2 (10)	3 (15)	2 (10)	2 (10)
Development Costs - Joint	4	3 (12)	3 (12)	3 (12)	3 (12)	3 (12)	3 (12)	3 (12)	3 (12)
Tools	2	4 (8)	3 (6)	3 (6)	4 (8)	4 (8)	4 (8)	4 (8)	4 (8)
Tool Inventory	2	4 (8)	3 (6)	3 (6)	4 (8)	4 (8)	4 (8)	4 (8)	4 (8)
Adaptability	3	3 (9)	2 (6)	2 (6)	3 (9)	3 (9)	3 (9)	3 (9)	3 (9)
Life Cycle Costs	3	3 (9)	3 (9)	3 (9)	3 (9)	3 (9)	3 (9)	3 (9)	3 (9)
Subtotal [Perfect Score 40(125)]		27 (81)	21 (65)	21 (65)	26 (76)	26 (76)	27 (81)	26 (76)	25 (72)
Total [Perfect Score 155(790)]		117 (534)	109 (528)	110 (530)	120 (552)	118 (541)	116 (527)	118 (540)	116 (532)

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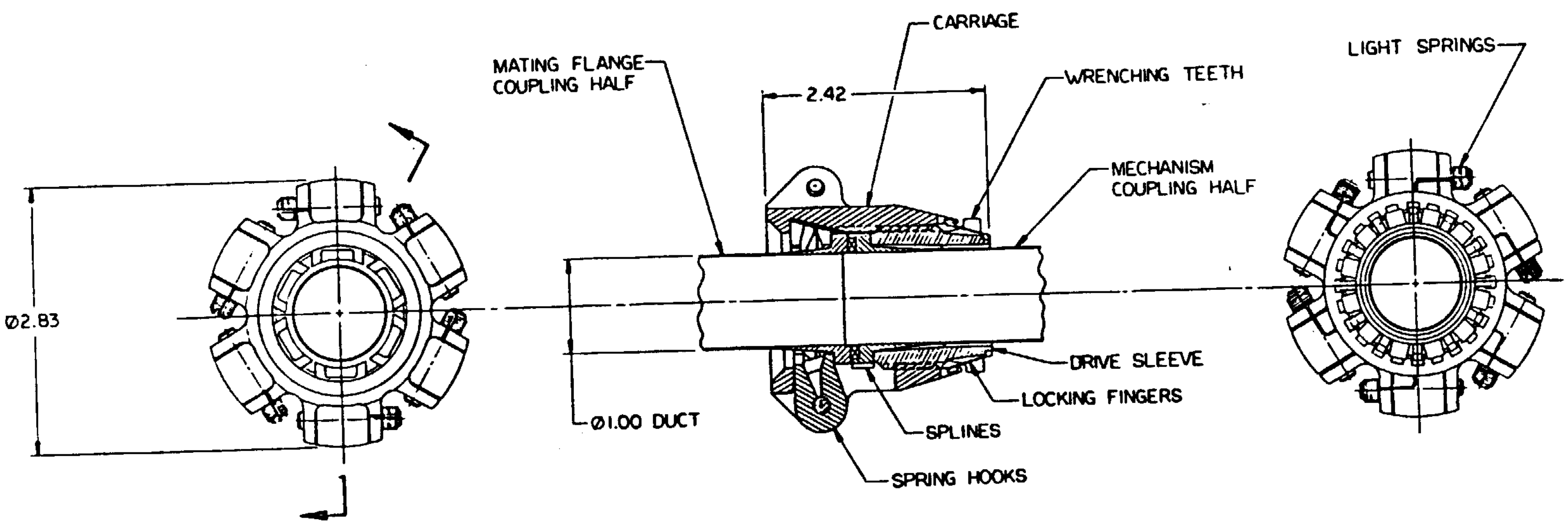

FIGURE 14. SPACE-OPERABLE COUPLING PRELIMINARY DESIGN

carriage to the fully open position, Figure 15a. As the mating flange is inserted into the mechanism half of the coupling, it forces the hooks to swing clear, Figure 15b. The arms of the hooks which contact the flange first are extended to a radius smaller than that necessary for joint loading only to insure non-binding rotation. This surface is thus the only area of each hook to contact the flange during this stage of operation. As the flange nears mating with the seal, the hooks are released to snap back, powered by light tension springs. As shown in Figure 15c, this captures the mating flange.

The carriage is closed by translating it to the closed position, thereby loading the back side of the mating flange. This translation is caused by rotating the drive sleeve until the desired joint preload (as determined by wrench torque or carriage strain measurement) is achieved. The drive sleeve carries the preload from the carriage to the back side of the seal flange through the actuating threads. Splines on the outer diameter of the seal flange prevent rotation of the carriage. Twelve spring fingers on the drive sleeve fit into slots at the end of the carriage to lock the joint. The additional rotation to match the fingers to the slots can be accommodated without excessive joint loading due to the deflection capability afforded by use of the spring hooks.

Torque to the drive sleeve is provided through a 12-point clamshell wrench. When inserted at the end of the drive sleeve, the wrench teeth force the spring fingers to deflect radially inward so they are clear of the locking tabs on the carriage. Removal of the wrench allows them to again lock the joint. Detents on the wrench hold it in the proper position for torquing. Reaction loads are carried through tangs on the wrenching tool which fit into the hook slots of the carriage. The wrench can be actuated manually or, preferably, by a motor drive.

To disconnect the coupling, the drive sleeve is rotated so as to translate the carriage to the fully open position. A clamshell sleeve tool is then inserted over the mating flange so that it forces the hooks to pivot open, Figure 16d. The mating flange and sleeve tool may then be pulled away from the mechanism

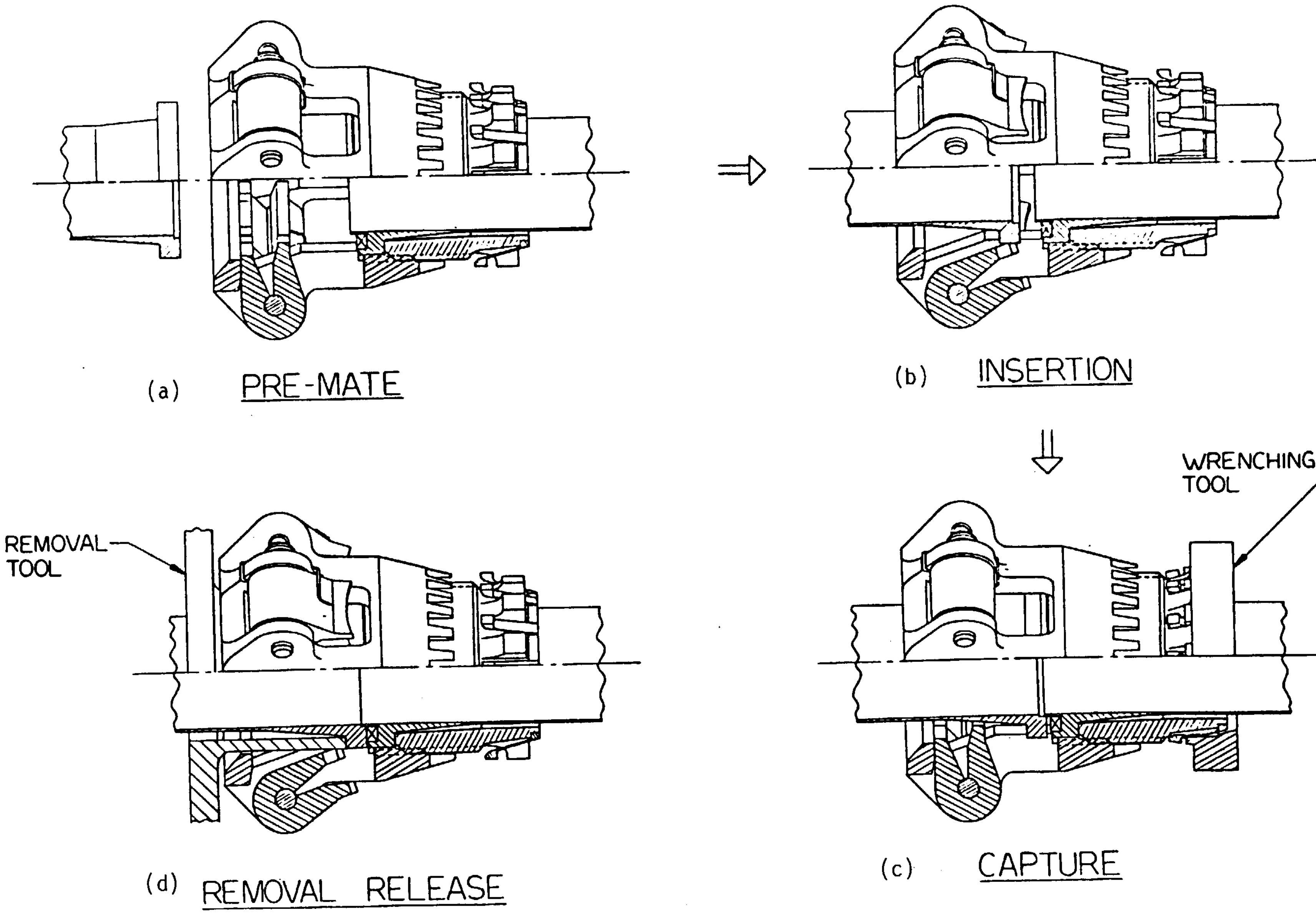

FIGURE 15. COUPLING OPERATION SEQUENCE

half of the coupling. The sleeve tool is removed to complete the demate operation.

Even though use of spring elements as the hooks helps to distribute the preload uniformly around the joint, tolerance stackups in the coupling must be controlled. This concern has been incorporated into the preliminary design through configuration of the mechanism elements. The hooks are designed to be produced as a set; machined from a single bar. They are then cut to width and radiused at the contact arm diameter. The hook pivot pins are pressed into the hooks during coupling fabrication so as to provide pin retention as well as to reduce the criticality of hole locations on the carriage. All other preload contact surfaces on the carriage, drive sleeve, and flanges may be lathe-machined for ease in maintaining concentricity and parallelism requirements. Desired tolerances can thus be achieved with minimum fabrication expense.

Materials used in the coupling depend somewhat where it is to be used. The ducting and flanges for the OTV engine are nominally INCO 718 or Incoloy 903 for high duct strength and weldability. The coupling preliminary design uses titanium for the drive sleeve, carriage, and hooks because of its high strength to weight, reduced need for fluid compatibility, and lack of weldability requirements to the duct material. Although specific selections will be made at the detail design level, likely candidates are Ti-5Al-2.5Sn ELI for cryogenic couplings (due to better fracture toughness) and Ti-6Al-4V above 250°R (due to higher strength). For joint temperatures above 1200°R (the OTV engine currently has none), or should material compatibility with the oxidizer prove to be a concern, INCO 718 is the preliminary choice. For the 1-inch, 7000 psi duct under study, weight for the coupling is estimated at .72 lb (titanium) or 1.19 lb (INCO 718).

A preliminary design of the test version of this design is shown in Figure 16. The design is identical in most respects to the flight configuration described above except for the wrenching and locking provisions. These features are not

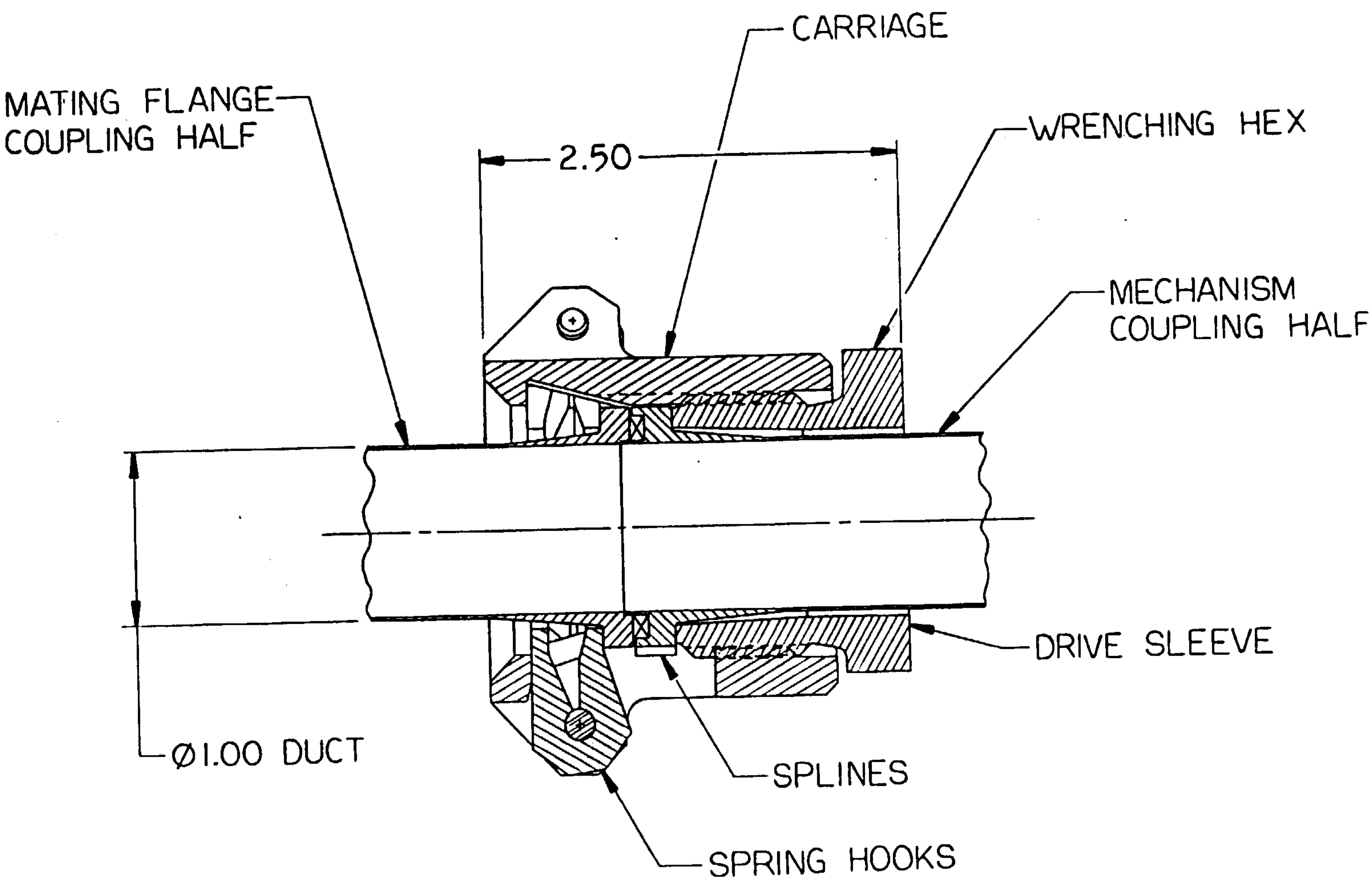

FIGURE 16. TEST COUPLING PRELIMINARY DESIGN

considered key aspects (hook, carriage, drive sleeve, and flange operation and interaction) which must be demonstrated. Therefore, to reduce the cost of the joint and to avoid fabricating a matching tool, wrenching is provided through the use of standard hex wrenching flats. Locking, when required for testing, can be achieved with safety wire. Note, however, that the hex flats and carriage of this test version have been configured to permit rework to the flight-type wrenching/locking features. Therefore, advanced operational testing requiring demonstration of the complete flight design can utilize this unit with only small additional fabrication effort for the coupling. Fabrication at this level would concentrate on the specifics of the wrench design and its optimization for use by EVA personnel and/or manipulator devices.

TEST PLAN

Introduction

A preliminary space-operable disconnect test plan was completed to indicate the types of tests required to demonstrate the feasability and advantages, as well as potential problems, related to the selected coupling design. The two major areas of concern are covered by the plan: 1) operation of the coupling at mate/demate and 2) performance of the coupling as a fluid joint during engine operation. The tests can be performed sequentially in terms of complexity and cost to permit design refinements to be incorporated as data is evaluated. A summary of these tests is given in Table 11. Hot-fire engine testing and on-orbit zero-G mate/demate operational trials are not included in this plan as they would be encompassed in a full-scale development program. The test plan which follows is intended to be a "stand alone" document and therefore contains some information which has been covered in the previous section on Concept Evaluation and Ranking.

TABLE 11.

SPACE-OPERABLE FLUID DISCONNECT TESTS

TEST NAME	TEST OBJECTIVE	HARDWARE	FACILITY REQTS.	INSTRUMENTATION
Coupling Operation (Shirtsleeve)	Evaluation of basic coupling operating features: Preloading, Steps, Motions, Time, Damage tolerance, Tool envelope	Test Coupling Standard Wrench Release Tool	Bench Setup	Load (I.e. Strain) Measuring System
Misalignment Accomodation	Determine the limits of lateral and angular misalignment where successful coupling is possible	Test Coupling Standard Wrench	Bench Setup	Distance and Angle Measurement Jigs
Wrenching Torque	Measure the torquing loads needed to preload at assembly and release at disassembly	Test Coupling Standard Wrench	Bench Setup	Torque Measuring Device Load Measuring System
Coupling Operation (EVA Suited)	Evaluation of basic coupling operation when constrained in EVA suit: Preloading, Steps, Motions, Time, Damage tolerance, Work envelope	Flight-Type Coupling Coupling Wrench and Release Tool EVA Suit	Bench Setup	Load Measuring System
Coupling Operation (Zero-G)	Evaluation of basic coupling operation when constrained by EVA suit and zero-G: Preloading, Steps, Motions, Time, Damage tolerance, Work envelope, Ease of reacting loads, Work restraint needs	Flight-Type Coupling Coupling Wrench and Release Tool EVA Suit System Mockup	Neutral Buoyancy Tank and Facility	Load Measuring System
Static Leak Check	Verify Joint Integrity	Test Coupling	Bench Setup with High Pressure GN2	Leak Detector
Coupling Integrity at Cryogenic Temp.	Determine effect on joint preload and sealing in cryogenic environment	Test Coupling	Bench Setup with High Pressure LN2	Leak Detector Load Measuring System
Coupling Integrity at High Temp.	Determine effect on joint preload and sealing at high temperature	Test Coupling	Furnace or Heater with High Pressure GN2	Leak Detector Load Measuring System
Coupling Integrity in Vibrating Environment	Determine effect on joint preload and sealing in vibrating environment	Test Coupling	Vibration Table with High Pressure GN2	Leak Detector Load Measuring System Accelerometers

Test Objectives

The primary objective of this test series is to demonstrate the feasibility and features of the space-operable disconnect coupling for use in space-based engine systems. A secondary objective is to identify limitations and potential requirements which should be incorporated into the design. Two types of tests are planned:

- Coupling Operation Tests
- Coupling Integrity Tests

The Coupling Operation Tests are conducted to determine the ease of mating and demating the device when encumbered by an EVA space suit in a zero-G environment. Fast, safe, and reliable coupling operations are the features to be demonstrated.

The Coupling Integrity Tests are conducted to determine the performance of the coupling as a fluid line joint during engine operation. Although no hot-fire engine tests are to be made, coupling integrity under high pressure cryogenic, high temperature, and vibration environments is to be verified.

The overall objective of these tests is to demonstrate that the selected space-operable coupling design can successfully satisfy the requirements of the advanced space-based OTV engine system.

Test Hardware

The test hardware consists of a test version of the flight-type space-operable coupling design. A simple "removal tool" is also required to permit evaluation of demate operation. For testing using an EVA space suit, the test unit is reworked to resemble the flight-type unit. Wrenching/locking provisions and a matching special wrench must be provided.

The flight-type design to be tested, called a "Carriage-Spring Hook" coupling is shown in Figure 14. It operates by using a rotating drive sleeve to translate a carriage along the joint axis. Splines prevent rotation of the carriage. "U"-shaped spring hooks are mounted to the carriage with light torsion springs to normally hold them in their closed position. Mating is preceded by translating the carriage to the fully open position, Figure 15a. As the mating flange is inserted into the mechanism half of the coupling, it forces the hooks to swing clear, Figure 15b. As the flange nears mating with the seal, the hooks are released to snap back, powered by light torsion springs. As shown in Figure 15c, this captures the mating flange.

The carriage is closed by translating it to the closed position, thereby loading the back side of the mating flange. This translation is caused by rotating the drive sleeve until the desired joint preload (as determined by wrench torque or carriage strain measurement) is achieved. The drive sleeve carries the preload from the carriage to the back side of the seal flange through the actuating threads. Splines on the outer diameter of the flange prevent rotation of the carriage. Twelve spring fingers on the drive sleeve fit into slots at the end of the carriage to lock the joint. The additional rotation to match the fingers to the slots can be accommodated without excessive joint loading due to the deflection capability afforded by use of the spring hooks.

Torque to the drive sleeve is provided through a 12-point clam shell wrench. When inserted at the end of the drive sleeve, the wrench teeth force the spring fingers to deflect radially inward so they are clear of the locking tabs on the carriage. Removal of the wrench allows them to again lock the joint. Detents on the wrench hold it in the proper position for torquing. Reaction loads are carried through tangs on the wrenching tool which fit into the hook slots of the carriage. The wrench can be actuated manually or, preferably, by a motor drive.

To disconnect the coupling, the drive sleeve is rotated so as to translate the carriage to the fully open position. A clam shell sleeve is then inserted over the mating flange so that it forces the hooks to pivot open, Figure 15d. The mating flange and sleeve tool may then be pulled away from the mechanism half of the coupling. The sleeve tool is removed to complete the demate operation.

The test version of this design is shown in Figure 16. The design is identical in most respects to the flight configuration described above except for the wrenching and locking provisions. These features are not considered key aspects (hook, carriage, drive sleeve, and flange operation and interaction) which must be demonstrated. Wrenching is provided through the use of standard hex wrenching flats. Locking, when required for testing, can be achieved with safety wire. This test version is designed to be easily reworkable to the flight-type configuration needed for EVA space suit and zero-G tests.

Test Facility Requirements

Most of the tests require only a relatively simple bench setup to mount the device and plumb in a pressurization system. The mounting fixture must firmly support the mechanism half of the coupling yet allow access for all mating, wrenching, and demating tasks. High pressure GN_2 and LN_2 systems are required for leakage tests. A furnace or heater capable of elevating joint temperature to approximately 1200°R is required for high temperature tests. A vibration table to simulate the engine dynamics environment is also required.

In order to more accurately evaluate ease of operation in space, a neutral buoyancy test facility is required. Upon successful completion of the simpler bench tests, the flight-type coupling will be mounted in a simple mock-up system and zero-G tests using EVA space suits will be conducted. Detailed requirements TBD.

Instrumentation Requirements

Instrumentation requirements consist of systems to measure joint loading and seal leakage. A load measuring system (i.e., strain gage or holographic deformation) is needed for each of the six carriage tension legs to verify joint loading. Also, a means of accurately determining wrenching torque is required to record coupling tightening ease. Accelerometers are required during vibration testing to determine both input and inducing loading. Some means of measuring the limits of acceptable misalignment must also be supplied. A leak detection system is required for both cryogenic and high temperature joint integrity tests. Detailed instrumentation requirements TBD.

Test Requirements

To accomplish the objectives of validating the design, two test series will be conducted:

1) Coupling Operation Tests

    a) Basic operation
    b) Misalignment accommodation
    c) Wrenching torque
    d) EVA space suit
    e) Zero-G

2) Coupling Integrity Tests

    a) Static leak
    b) Cryogenic temperature
    c) High temperature
    d) Vibration

The test will be performed sequentially in terms of test complexity so that the tests which more nearly simulate actual flight conditions may be specifically tailored to incorporate results of the early demonstrations. Only inert fluids, no propellants, will be used for pressurization of the coupling. Detailed test requirements TBD.

Test Matrix

Test matrix TBD.

Safety Considerations

Rocketdyne Procedures have been established for the systems and methods to be employed for these tests. These procedures, based on many years of experience, are documented in Safety Manuals and checklists. These safety requirements will be part of the Test Procedures and Protocols. Detailed safety measures TBD.

Schedule

The test schedule is TBD.

References

1. "Orbit Transfer Vehicle Concept Definition and Systems Analysis Study", Phase II Final Review, General Dynamics Space Systems Division, July 1986.

2. "Orbital Transfer Vehicle Concept Definition and Systems Analysis Study", Phase II Final Review, Martin Marietta Corporation, July 1986

3. "Orbit Transfer Vehicle Concept Definition and Systems Analysis Study", Phase II Final Review, Boeing Aerospace Company, July 1986

4. "Orbit Transfer Rocket Engine Technology Program (Volume I: Study Results)" Final Report, Rockwell International Corporation, Rocketdyne Division, March 1984

APPENDIX I

REVIEW OF SSME OPERATIONS AND MAINTENANCE TASKS

REQUIREMENTS STRUCTURE

The requirements for the SSME are separated in the following categories:

Routine Requirements - - requirements accomplished before or after each firing.

Periodic Maintenance Requirements - - requirements which are time/cycle oriented (as opposed to before or after each firing).

Continency Requirements - - unscheduled requirements generally necessary to Isolate/rectify a condition. In general, such requirements need not be accomplished when the routine and periodic maintenance requirements are successfully met.

ABBREVIATIONS

The abbreviations and acronyms used in this appendix described as follows:

AFV	Anti-Flood Valve
ASI	Augmented Spark Igniter
CCV	Chamber Coolant Valve
DFRC	Dryden Flight Research Center
DNA	Does Not Apply
EVA	Extra Vehicular Activity
FBV	Fuel Bleed Valve
FPOV	Fuel Preburner Oxidizer Valve
GCV	Gox Control Valve
GOX	Gaseous Oxygen
HGM	Hot-Gas Manifold
HPFTP	High Pressure Fuel Turbopump
HPOTP	High Pressure Oxidizer Turbopump
HPV	Helium Precharge Valve
ICHM	Integrated Controls & Health Monitoring

APPENDIX I (Cont.)

ABBREVIATIONS (continued)

LOX	Liquid Oxygen
LPFTP	Low Pressure Fuel Turbopump
LPOTP	Low Pressure Oxidizer Turbopump
MCC	Main Combustion Chamber
MFV	Main Fuel Valve
MOV	Main Oxidizer Valve
MPTA	Main Propulsion Test Article
NSTL	National Space Technology Laboratories
OBV	Oxidyzer Bleed Valve
OMRSD	Operation and Maintenance Requirements and Specifications Document
OPOV	Oxidizer Preburner Oxidizer Valve
OTVE	Orbit Transfer Vehicle Engine
PCA	Pneumatic Control Assembly
RI-RKDN	Rockwell International, Rocketdyne
RI-SO/ I&SSD	Rockwell International, Space Operations/Integration and Satellite Systems Division
RIV	Recirculation Isolation Valve
SSME	Space Shuttle Main Engine
TBD	To Be Determined
TC	Thrust Chamber

REQUIREMENT NUMBER	REQUIREMENT TITLE	POST ENGINE INSTAL-LATION	FRF PRE	FRF POST	ROUTINE EVERY FLT PRE	ROUTINE EVERY FLT POST	PERIODIC AFTER EVERY 6 ENGINE STARTS	PERIODIC OTHER	APPLICABLE TO OTVE	AFFECTED BY ICHM? (ADVANCED SENSORS)	EVA REQUIRED NEAR TERM ICHM	EVA REQUIRED FAR TERM ICHM	COMMENTS
	ROUTINE MAINTENANCE REQUIREMENTS												
	Automatic/Electrical Checkout:												
E41100.004	Flight Readiness Test (FRT)		X	X		X			YES	YES	NO	NO	Sequence Test
E41100.005	Redundancy and Malifunction Limits Verification		X	X		X			YES	YES	NO	NO	Includes Sensor Checkout
E41100.003	Controller Memory Readout and Verification Test	X	X	X	X	X			YES	YES	NO	NO	Memory Dump
E41100.007	Controller Power Application	X	X	X	X	X			YES	YES	NO	NO	Controller T&P for power on
E41100.008	Pre-Cryo Loading Requirements		X		X				YES	YES	NO	NO	Purge, bleed valves check-outs
E41100.10	Turbine Discharge Temp Sensor Insulation Resistance Test			X		X			TBD	TBD	TBD	TBD	Check for short circuit
E41GHB.001	MFV Actuator Heater Check		X		X				TBD	TBD	TBD	TBD	OTV MFV may not have heater
E41X00.003	DFI Verification		X		X				TBD	TBD	TBD	TBD	
	Leak Tests:												
E41AV0.001	Heat Exchanger Leak Test			X		X			NO	DNA	DNA	DNA	No heat exchanger
E41AR0.002	TC Nozzle Leak Test			X		X			YES	YES	YES	NO	Far term maintenance may use remote holo-graphic, spectro-graphic, and/or optical acoustic leak detection.
E41G30.003	AFV Seat Leak Test			X		X			TBD	TBD	TBD	TBD	TBD

REQUIREMENT NUMBER	REQUIREMENT TITLE	POST ENGINE INSTAL-LATION	FRF PRE	FRF POST	ROUTINE EVERY FLT PRE	ROUTINE EVERY FLT POST	PERIODIC AFTER EVERY 6 ENGINE STARTS	PERIODIC OTHER	APPLICABLE TO OTVE	AFFECTED BY ICHM? (ADVANCED SENSORS)	EVA REQUIRED NEAR TERM ICHM	EVA REQUIRED FAR TERM ICHM	COMMENTS
	<u>ROUTINE MAINTENANCE REQUIREMENTS</u> (continued)												
E41000.001	Combined MOV, FPOV, and OPOV Ball Seals Leak Test	X		X		X			YES	YES	YES	NO	Same as above (See E41630.003)
E41000.006	Combined LPFTP and HPFTP Lift-off Nose Seals and MFV Ball Seal Leak Test	X		X		X			YES	YES	YES	NO	" " "
E41BAP.001	MCC-to-Nozzle Seal Leak Test			X		X			YES	YES	YES	NO	" " "
E41000.014	Post-Internal Inspection Leak Tests					X			YES	YES	YES	NO	DNA to Far Term ICHM Since No Turbine Inspections with advanced sensors
	<u>Inspections</u>												
E41000.001	External Inspection			X		X			YES	YES	YES	NO	Far term inspections may be done remotely with remotes
E41000.002	Engine Compartment Precloseout Inspection		X		X				YES	YES	YES	NO	" " "
E41000.003	Humidity Indicator Inspection	X	X	X	X	X			NO	DNA	DNA	DNA	DNA to vacuum environment
E41A00.002	Internal (Boroscope) Inspection			X		X			YES	YES	YES	NO	DNA Adv. ICHM: No internal inspection with optical Pyro, isotope wear detector, torquemeter, etc.
									YES	YES	YES	NO	" " "
	A) Turbines								YES	YES	YES	NO	Far Term Maintenance may use remote electronic inspections
	B) Pumps								YES	YES	YES	NO	
	C) MCC & Injector												

REQUIREMENT NUMBER	REQUIREMENT TITLE	POST ENGINE INSTAL-LATION	FRF		ROUTINE EVERY FLT		PERIODIC		APPLICABLE TO OTVE	AFFECTED BY ICHM? (ADVANCED SENSORS)	EVA REQUIRED		COMMENTS
			PRE	POST	PRE	POST	AFTER EVERY 6 ENGINE STARTS	OTHER			NEAR TERM ICHM	FAR TERM ICHM	
	<u>ROUTINE MAINTENANCE REQUIREMENTS</u> (continued)												
	<u>Torque Tests:</u>												
E41AA0.002	Low Pressure Fuel Turbopump Torque Test	X		X		X			YES	YES	YES	NO	Torquemeter will eliminate need for manual
E41AC0.003	High Pressure Fuel Turbopump shaft position, Torque and axial travel test.	X		X		X			YES	YES	YES	NO	
E41AF0.001	Low Pressure Oxidizer Turbopump Torque and Rotor Axial Position Test	X(a)		X		X			YES	YES	YES	NO	" " "
	<u>Handling:</u>												
EPEAE0.001	Protective Covers Installation, Aft Section			X		X			YES	NO	YES	YES	May not be required if no EVA maintenance
EPEA00.001	TC Covers and Exit Closure Installation	X		X		X			YES	NO	YES	YES	" " "
EPEA00.001	TC Covers and Exit Closure Removal		X		X				YES	NO	YES	YES	" " "
	<u>Servicing:</u>												
E41G30.002	AFV Inlet Filter Replacement			X		X			TBD	TBD	TBD	TBD	Anti Flood Valve may not be used.
E41000.004	Propellant System Drying, Post-FRF and Post-Orbit Landing			X		X			NO	DNA	DNA	DNA	Vacuum Environment Eliminates Need.

(a) Rotor axial test not required post engine installation

REQUIREMENT NUMBER	REQUIREMENT TITLE	POST ENGINE INSTAL-LATION	FRF		ROUTINE EVERY FLT		PERIODIC		APPLICABLE TO OTVE	AFFECTED BY ICHM? (ADVANCED SENSORS)	EVA REQUIRED		COMMENTS
			PRE	POST	PRE	POST	AFTER EVERY 6 ENGINE STARTS	OTHER			NEAR TERM ICHM	FAR TERM ICHM	
	<u>PERIODIC MAINTENANCE REQUIREMENTS</u>												
E41000.007	<u>Leak and Function Tests:</u> Combined LPFTP and HPFTP fuel Side Liftoff Piston Seals, LPFTP Double Naflex Seal, and MFV Primary Shaft Seal Leak Test			X			X		YES	YES	YES	NO	Far term maintenance May use advanced sensors for leak detection (See E41G30.003)
E41DH0.001	Fuel Bleed Valve Seat Leak Test						X		TBD	TBD	TBD	TBD	NONE
E41000.008	Combined FPOV, OPOV, and MOV Primary Shaft Seals and Oxidizer System Purge Check Valves Leak Test			X			X		YES	YES	YES	NO	See E41G30.003
E41000.009	Combined LPFTP and HPFTP Turbine Side Liftoff Piston Seals, CCV Primary Shaft Seal, and Fuel System Purge Check Valve Leak Test.			X			X		YES	YES	YES		" " "
E41000.021	AFV, GCV, and HPV Leak and Function and RIV Override Seals Leak Tests			X			X		YES	YES	YES		" " "
E41000.012	OBV and RIV Seat Leak Test						X		YES	YES	YES		" " "
E41AR0.003	TC Nozzle Hot Wall Tube Leak Test						X		YES	YES	YES		" " "

REQUIREMENT NUMBER	REQUIREMENT TITLE	POST ENGINE INSTAL-LATION	FRF		ROUTINE EVERY FLT		PERIODIC		APPLICABLE TO OTVE	AFFECTED BY ICHM? (ADVANCED SENSORS)	EVA REQUIRED		COMMENTS
			PRE	POST	PRE	POST	AFTER EVERY 6 ENGINE STARTS	OTHER			NEAR TERM ICHM	FAR TERM ICHM	
	<u>PERIODIC MAINTENANCE REQUIREMENTS</u> (continued)												
E41KYD.001	GOX Control Package Check Valve Valve Leak Test			X			X		TBD	TBD	TBD	TBD	NONE
E41KU0.001	RIV Shaft Seal Leak Test			X			X		TBD	TBD	TBD	TBD	NONE
E41N00.001	Propellant Valve Actuator, HPV, and PCA Helium Leak Tests			X			X		NO	DNA	DNA	DNA	Electric Valves: No Hydraulics
E41000.024	Engine External Leak Tests			X			X		YES	YES	YES	NO	See E41G30.003
E41000.015	Post-Engine Installation Leak Tests	X							YES	YES	YES	NO	" "
	<u>Automatic Checkout:</u>												
E41000.016	Component Functional Checkout and Redundancy and Malfunction Limits Verification	X		X					YES	YES	NO	NO	Sequence Tests conducted remotely by controller
	<u>Inspections:</u>												
E41A00.003	Preburner ASI Line Inspection						X		TBD	TBD	TBD	TBD	NONE

REQUIREMENT NUMBER	REQUIREMENT TITLE	POST ENGINE INSTALLATION	FRF PRE	FRF POST	ROUTINE EVERY FLT PRE	ROUTINE EVERY FLT POST	PERIODIC AFTER EVERY 6 ENGINE STARTS	PERIODIC OTHER	APPLICABLE TO OTVE	AFFECTED BY ICHM? (ADVANCED SENSORS)	EVA REQUIRED NEAR TERM ICHM	EVA REQUIRED FAR TERM ICHM	COMMENTS
	<u>PERIODIC MAINTENANCE REQUIREMENTS</u> (continued)												
E41000.017	HPOTP Inlet Borescope Inspection			X			X		YES	YES	YES	NO	Advanced sensors for T/P's such as torquemeters, isotope wear detectors, exoelectron fatigue, etc. will eliminate inspections.
E41Q00.001	Hydraulic Drain Line Exit Inspection			X			X		NO	DNA	DNA	DNA	Electric valves
E41AC0.001	HPFTP Turbine Inspection							(b)	YES	YES	YES	NO	See E41000.017
	<u>CONTINGENCY REQUIREMENTS</u>												
E41000.019	HPFTP Liftoff Seal and MFV Ball Seal Isolation Seal Test							As Reqd	YES	YES	YES	NO	See E41G30.003
E41000.020	LPFTP and HPFTP Fuel Side Liftoff Piston Seal, LPTFP Double Naflex Seal, and MFV Primary Shaft Seal Isolation Leak Tests							As Reqd	YES	YES	YES	NO	" "
E41000.023	LPFTP and HPFTP Turbine Side Liftoff Piston Seals, CCV Primary Shaft Seal, and Fuel System Purge Check Valve Isolation Leak Test							As Reqd	YES	YES	YES	NO	" "

(b) After 3 pump starts and every third pump start thereafter.

REQUIREMENT NUMBER	REQUIREMENT TITLE	POST ENGINE INSTAL-LATION	FRF		ROUTINE EVERY FLT		PERIODIC		APPLICABLE TO OTVE	AFFECTED BY ICHM? (ADVANCED SENSORS)	EVA REQUIRED		COMMENTS
			PRE	POST	PRE	POST	AFTER EVERY 6 ENGINE STARTS	OTHER			NEAR TERM ICHM	FAR TERM ICHM	
	CONTINGENCY REQUIREMENTS (continued)												
E41AA0.001	LPFTP Liftoff Seal Isolation Leak Test							As Reqd	YES	YES	YES	NO	See E41G30.003
E41G00.002	FPOV, OPOV, and MOV Primary Shaft Seals Isolation Leak Tests							As Reqd	YES	YES	YES	NO	" "
E41G00.003	MOV and OPOV Ball Seal Isolation Leak Test							As Reqd	YES	YES	YES	NO	" "
E41G50.001	FPOV Ball Seal Isolation Leak Test							As Reqd	YES	YES	YES	NO	" "
E41K00.001	Oxidizer System Purge Check Valves Isolation Leak Tests							As Reqd	YES	YES	YES	NO	" "
E41AT0.001	MCC Injector Water/Contam-ination Inspection							As Reqd	NO	DNA	DNA	DNA	Vacuum Environment
E41000.026	Launch Scrub Turnaround/ Recycle							As Reqd	NO	DNA	DNA	DNA	Ground Based Related
E41000.018	Abort Turnaround/Recycle							As Reqd	YES	YES	YES	NO	Many Procedures (Leak tests, torque measurements, etc)
E41000.027	MCC Pressure Sensor Drying							As Reqd	NO	DNA	DNA	DNA	Vacuum Environment
E41AC0.002	HPFTP Turbine Bearing Drying							As Reqd	NO	DNA	DNA	DNA	" "
E41100.006	Special Flight Readiness Test (FRT2)							As Reqd	TBD	TBD	TBD	TBD	Readiness Check by Controller
E41N0D.002	PCA/HPV Isolation Leak Test							As Reqd	YES	YES	YES	NO	See E41G30.003

REQUIREMENT NUMBER	REQUIREMENT TITLE	POST ENGINE INSTAL-LATION	FRF PRE	FRF POST	ROUTINE EVERY FLT PRE	ROUTINE EVERY FLT POST	PERIODIC AFTER EVERY 6 ENGINE STARTS	PERIODIC OTHER	APPLICABLE TO OTVE	AFFECTED BY ICHM? (ADVANCED SENSORS)	EVA REQUIRED NEAR TERM ICHM	EVA REQUIRED FAR TERM ICHM	COMMENTS
	CONTINGENCY REQUIREMENTS (continued)												
E41G00.004	FPOV and OPOV Outlet Sleeve Flow Test							As Reqd	NO	DNA	DNA	DNA	No Preburners
E41000.005	SSME Ferry Flight Pressurization							As Reqd	NO	DNA	DNA	DNA	No ferry flight
E41AV0.003	Heat Exchanger Proof Test (Post HPOTP Installation)							As Reqd	NO	DNA	DNA	DNA	No heat exchanger
EPE000.001	Environmental Protection Equipment Installation							As Reqd	NO	DNA	DNA	DNA	No rain protection Required
E41Q00.002	Hydraulic System Bleed							As Reqd	NO	DNA	DNA	DNA	No Hydraulics
E41100.009	System Reverification							As Reqd	NO	DNA	DNA	DNA	Space Based
EPEC00.001	Ferry Flight Set Installation							As Reqd	NO	DNA	DNA	DNA	No Ferry Flights

REQUIREMENT NUMBER	REQUIREMENT TITLE	POST ENGINE INSTAL-LATION	FRF PRE	FRF POST	ROUTINE EVERY FLT PRE	ROUTINE EVERY FLT POST	PERIODIC AFTER EVERY 6 ENGINE STARTS	PERIODIC OTHER	APPLICABLE TO OTVE	AFFECTED BY ICHM? (ADVANCED SENSORS)	EVA REQUIRED NEAR TERM ICHM	EVA REQUIRED FAR TERM ICHM	COMMENTS
	CONTINGENCY REQUIREMENTS (continued)												
E41000.028	Propellant System Drying, Post-Ferry Landing							As Reqd	NO	DNA	DNA	DNA	No Ferry Flights
E41000.029	Propellant System Drying, Post-Launch Abort							As Reqd	NO	DNA	DNA	DNA	Vacuum Environment
E41AH0.005	HPOTP Primary Oxidizer Seal Leak Test							As Reqd	YES	YES	YES	NO	See E41G30.003
E41AH0.004	Fuel Preburner Inspections with HPFTP Removed							As Reqd	NO	DNA	DNA	DNA	No Preburners
E41A00.005	Oxidizer Preburner Inspections with HPOTP Removed							As Reqd	NO	DNA	DNA	DNA	No Preburners
E41AH0.004	HPOTP Turbine Seals Leak Test							As Reqd	YES	YES	YES	NO	See E41G30.003
E41AT0.004	Main Injector LOX Post Leak Test							As Reqd	YES	YES	YES	TBD	Possibly can be done remotely with advanced sensors and robotics

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Technology Program

Advanced Engine Study - Phase II
Contract NAS3-23773

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