NUCLEAR DIVISION

REPORT NO. RN-S-0488

TO AEC-NASA Space Nuclear Propulsion Office

E & R SYSTEM ANALYSIS

NERVA Program

Contract SNP-1

November 1968

MASTER

NUCLEAR ROCKET OPERATIONS

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REPORT NO. RN-S-0488

E & R SYSTEM ANALYSIS

R. Stiger

A handwritten signature in black ink, appearing to read "C. M. Rice", with a stylized flourish at the end.

C. M. Rice
Program Manager
Nuclear Rocket Operations

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ABSTRACT

The attached status report is submitted as a milestone for the systems analysis of E and R systems. These studies were performed in support of the NERVA engine task force to establish the design requirements baseline.

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CONTENTS

	<u>Page</u>
I. Introduction	1
II. Technical Discussion	3
A. Engine Systems Analysis	3
1. Determination of Design-Point Tolerance	3
2. Comparison of Methods of Engine Operation and Their Effect on Impulse and Specific Impulse	19
3. Methods of Achieving 825 sec I_{sp}	29
4. Thermodynamic Afterheat Removal and Thrust Spoiling	45
5. Effects of Internal Pressure Drops on Turbine Inlet Conditions	55
6. Turbine Power Control Valve Override	65
7. Elimination of the Structural Support Bypass System	73
8. Back-Pressure Requirements for NERVA Engine Test Facilities	81
9. Facility Fluid Requirements for Cooldown of the NERVA Engine in ETS-1	89
10. LH_2 Topping Modification to ETS-1	113
11. Parametric Study of the Full-Flow Engine Cycle	153
B. Reactor Systems Analysis	177
1. Determination of Steady-State Operating Summary of 75K NERVA R-Test Article at 100% and 60% Power	177
2. Determination of Effect of Core Peripheral Bypass Flow on Core Exit Temperature for R-Test Article	181

TABLES

<u>Table No.</u>		<u>Page</u>
1	Specific Impulse Performance	25
2	Influence Coefficients for Specific Impulse	30
3	Results of Specific Impulse Studies	44

FIGURES

<u>Figure No.</u>		<u>Page</u>
1	Tolerance Study Flow Diagram for the 75K NERVA Engine	5
2	Nominal NERVA Engine Design Point	6
3	Thrust Chamber Temperature vs Chamber Pressure	8
4	Corner Points for the Envelope	9
5	Summary Tolerance Study for 75K NERVA Engine	18
6	Fission Product Decay Heat vs Time after Shutdown	21
7	Chamber Temperature and Pressure vs Time, 75K NERVA Engine	23
8	Specific Impulse and Thrust vs Time, 75K NERVA Engine	24
9	Steady-State Values with Varied Engine Design Points	31
10	Flow Rate vs Power	49
11	Radiator Surface Area	50
12	Integrated Decay Heat vs Time after SCRAM	52
13	Integrated Total Power vs Time after SCRAM	54
14	Pump Discharge Pressure	56
15	Nozzle Tube Pressure Drop	57
16	Core Pressure Drop	60
17	Gate Position and Pump Speed vs Time	67
18	System Pressures vs Time	68
19	System Flow Rates vs Time	69
20	System Temperatures vs Time	70
21	Flow Schematic of the Proposed NERVA Engine	74
22	Steady-State Values, Structural Coolant Flow	75
23	Engine Delta I_{sp} vs Structural Support Flow	79
24	Tank Pressure vs Cell Pressure for CFDTS	83
25	Time to Peak Speed vs Back Pressure Based on CFDTS Data	85
26	System Cold Flow Operating Paths	86
27	Integrated Total Power vs Time after SCRAM	92
28	Cooldown Situations (1545 Mw for 60 min ETS-1)	93
29	Cooldown Situations (2200 Mw for 30 min ETS-1)	100
30	LH ₂ Storage Tank	116

FIGURES (cont.)

<u>Figure No.</u>		<u>Page</u>
31	Liquid Hydrogen Fill Line (Existing)	117
32	LH ₂ Run Tank	119
33	GH ₂ Pressurization Line	120
34	Pressurization and Venting System	122
35	Topping Flow Rate vs Differential Pressure between V-3801 and V-5001	127
36	Topping Flow Rate vs Differential Pressure	128
37	Capability of Topping System for a Steady-State Run Consuming 90,200 lb	130
38	Capability of Topping System to Utilize all Available Propellant During a Steady-State Run	132
39	Hydrogen Vapor Pressure vs Temperature	133
40	NPSP Map for Various Tank Pressures and Pump-Inlet Temperatures	134
41	NPSP vs Pump Inlet Temperature	135
42	Topping Flow Rate vs Temperature Rise (V-3801 to V-5001)	137
43	Rate of Change in the Liquid Head	139
44	Initiation and Termination of Topping	142
45	Initiation of Topping	143
46	Termination of Topping and V-5001 Outflow	144
47	Termination of V-5001 Outflow with Topping	145
48	Example of 75K Mapping Test with Propellant Topping	148
49	Throttle Valve	154
50	Turbine Bypass	156
51	Variable Area Turbine	157
52	Full-Flow Engine Cycle Throttling Valve System Design Point Summary	158
53	Full Power Throttling Valve, Engine Performance Map	159
54	Variable Area Turbine, Engine Performance Map	160
55	Full-Flow Engine Cycle Turbine Bypass System Design Point Summary	164
56	Bypass Valve, Engine Performance Map	165

FIGURES (cont.)

<u>Figure No.</u>		<u>Page</u>
57	Full-Flow Engine Cycle Variable Turbine Inlet Nozzle System Design Point Summary	167
58	Variable Area Turbine Full-Flow Engine System Turbine Inlet Area vs Chamber Pressure	169
59	Vary Reflector and Structural Support Power Fraction	171
60	Vary Core K/A^2	172
61	Vary Reflector and Structural Support K/A^2	173
62	Throttling Valve, Engine Performance Map	174
63	R-Test Article Steady-State Summary 100% Power	178
64	R-Test Article Steady-State Summary 60% Power	179
65	Core Exit Temperature Required to Maintain Mixed Mean Exit Temperature of 4500°R vs Core Bypass Flow Rate	182

I. INTRODUCTION

The purpose of this report is to summarize the system analyses investigations performed during the past year in support of the E and R systems.

The technical discussion is divided into two major sections: E (Engine) Systems and R (Reactor) Systems. Each of these sections is further divided into separate studies that are relatively independent. No attempt has been made to present the data in chronological order; rather, a subject-oriented order has been maintained. Some of the current restrictions or engine constraints that now exist were not adhered to in some of the studies because these requirements resulted from the studies contained in this report.

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II. TECHNICAL DISCUSSION

A. ENGINE SYSTEMS ANALYSIS

1. Determination of Design Point Analysis

a. Scope

This study presents the evaluation of the design point tolerance based on the NERVA Program Requirements Document.

b. Functional and Technical Design Requirements

In accordance with NERVA Program Requirements Document, dated 5 June 1968, page 2, Performance Requirements at Rated Conditions:

Rated conditions shall be based on MSFC Spec. 356A (liquid) hydrogen, delivered at the tank outlet (upstream of the main propellant shutoff valve (PSOV)) at 30 psia, and saturation temperature, containing zero % vapor; with the engine at zero ambient pressure; zero gimbal angle; and single module (engine) operation, utilizing a hot bleed cycle to drive the turbopump and assuming a contoured nozzle expansion ratio of 100:1.

(1) Thrust, F	75,000 $\pm$ 2000 lb
(2) Minimum Mixed Mean Chamber Inlet Temp., T _c	4500°R
(3) Nominal Chamber Pressure, P _c	450 psia
(4) Engine Weight Max.	(tbd) lb
(5) Shield Weight Max.	(tbd) lb

In accordance with NERVA Program Requirements Document, dated 5 June 1968, page 6, Controllability, Steady State:

Specific Impulse	<u>+0.75%</u>
Thrust	<u>+2%</u>

c. Approaches and Significant Characteristics

A flow diagram was prepared in order to interpret the functional design requirements given above (Figure 1). The specific impulse defines the maximum, nominal, and minimum range acceptable and the thrust branch gives the maximum, nominal, and minimum acceptable thrust values.

Using the thrust levels of $75K \pm 2K$ (to account for as-built engine variations) and the nominal chamber pressure of 450 psia and minimum specific impulse of 825 sec, nozzle throat areas were determined. These areas provide the throat area variations allowable, assuming all other components meet the nominal values. The results obtained were:

Area No. 1	=	98.339 in. ²	(77K thrust)
Area No. 2	=	95.935 in. ²	(75K thrust)
Area No. 3	=	93.400 in. ²	(73K thrust)

The runs made used the preliminary engine system design program with a constant pump efficiency of 68% and turbine efficiency of 52%. The nominal NERVA engine design point 75K, $I_{sp} = 825$, is included for reference as Figure 2.

Control tolerances were then applied to thrust and specific impulse for the engine operation (e.g., nozzle areas) obtained. For example, the thrust of 77K was increased by 2% to give 78.54K, and engine operating values were analyzed at engine specific impulses of 825 sec minimum, 831.2 sec nominal, and 837.4 sec maximum. Engine chamber pressure and chamber temperature values were calculated using the various combinations of specific impulse and thrust for each of the throat areas determined.

Figure 1 - Tolerance Study Flow Diagram for the 75K NERVA Engine

NERVA ENGINE STEADY STATE VALUES TOLERANCE STUDY (20)NERVA; FIND AN; TC; PC=450 & THRUST=75000

ENGINE PC= 450.0 TC= 4443. THRUST 75000. LBS; IMPULSE 824.99 SEC
POWER LEVEL= 1552.2 MWTURBOPUMP= 18500. RPM

TURBOPUMP	OVERALL
SHAFT POWER, MW	5.4754
TURBINE EFFICIENCY	0.5200
PUMP EFFICIENCY	0.6730

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	90.91	29.4	39.2	-101.1
PUMP OUTLET	90.41	921.1	53.1	-44.0
TPA BEARING COOLANT	0.50	921.1	53.1	-44.0
STRUCTURE SUPPORT INLET	24.00	921.1	53.1	-44.0
STRUCTURE BYPASS INLET	6.00	921.1	53.1	-44.0
NOZZLE MANIFOLD INLET	60.40	886.9	53.1	-44.0
NOZZLE OUTLET	57.40	693.1	200.5	518.7
SKIRT OUTLET	0.00	693.1	200.5	518.7
BOLT COOLANT OUTLET	3.00	693.1	53.1	-44.0
REFLECTOR INLET	57.75	693.1	193.2	490.8
REFLECTOR OUTLET	57.75	648.6	306.9	936.3
PERIPHERAL SHIELD OUTLET	57.75	638.4	316.7	975.0
SUPPORT PLATE INLET	87.75	638.4	284.3	846.5
STRUCTURE SUPPORT OUTLET	24.00	638.4	262.5	759.8
CENTRAL SHIELD INLET	87.75	628.9	290.2	869.7
CORE INLET	87.75	616.8	295.0	889.1
CORE OUTLET	87.75	450.0	4497.7	17078.1
NOZZLE CHAMBER	86.49	450.0	4443.7	16823.1
MAIN NOZZLE EXIT	86.49	450.0	4404.6	16638.6
DILUENT BLEED INLET	2.65	693.1	193.2	490.8
HOT BLEED INLET	1.25	450.0	4443.7	16823.1
TURBINE INLET	3.91	304.8	1660.0	5729.7
MAIN TURBINE EXIT	3.91	39.8	1285.6	4402.8
TURBINE EXIT (AT COLLECTOR)	4.41	39.8	1141.2	3898.9
SKIRT EXTEN. EXIT (NOZZ. IN.)	4.41	7.8	1511.2	5191.9

NOZZLE TUBE Q=32310. SKIRT TUBE Q= 0. MAIN NOZZLE THROAT AREA 95.935 IN2
MAIN NOZZLE IDEAL ISP 869.48, TPCV K/A2 VALUE 0.319869E 00, PUMP EXIT DENSITY 4.294
MAIN NOZZLE ACTUAL ISP 845.31 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 426.81

Figure 2 - Nominal NERVA Engine Design Point

d. Comparison of Results

Using the requirements listed above, the following are the possible variations in design conditions. However, all parameters cannot be varied independently and meet the PRD tolerances at design.

I_{sp}	825 to 837.4 sec
Thrust	71,540 to 78,540 lb
Flow rate (total)	85.4 to 95.2 lb/sec
Power level	1480 to 1650 Mw
Pump ΔP	873 to 960 psid
Turbine flow	3.70 to 4.41 lb/sec
Core exit temperature	4500 to 4604°R
Nozzle throat area	93.40 to 98.34 in. ²
Chamber pressure	442 to 460 psia

The outlines defined by the maximum and minimum areas, as shown in Figure 3, indicate that the area defined by the specifications is virtually the same. With the maximum $I_{sp} = 837.4$ sec, the maximum envelope thrust chamber temperature of 4600°R is obtained. At the maximum thrust 78.54K and at the lower $I_{sp} = 825$ sec, the thrust chamber temperature drops below the 4500°R minimum at the lower thrust = 71.54K. The 4500°R lower temperature limit, in accordance with the NERVA Program Requirements Document, forms the bottom line of the envelope. Two envelopes are shown in Figure 3, one for the minimum nozzle throat area and the other for the maximum nozzle throat area. The higher chamber pressure, 460 psia on the envelope, is defined from the smallest area with its associated highest thrust = 74.46K. The lowest chamber pressure, 442 psia on the envelope, is defined from the largest nozzle area with its associated lowest thrust = 75.46K.

Figure 4 defines the corner points for the envelopes. Point 9 dips below the 4500°R minimum by about 20°R at the lower thrust chamber

Figure 3 - Thrust Chamber Temperature vs Chamber Pressure

NERVA ENGINE STEADY STATE VALUES TOLERANCE STUDY(1) NERVA, A₁=98.339 (1) THRUST=78540 LB

ENGINE PC= 459.9 TC= 4551. THRUST 78,540 . LBS, IMPULSE 837.4 SEC
 POWER LEVEL= 1650.5 MW TURBOPUMP= 18500. RPM

TURBOPUMP OVERALL
 SHAFT POWER, MW 6.0671
 TURBINE EFFICIENCY 0.5200
 PUMP EFFICIENCY 0.6730

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	93.76	29.4	39.2	-101.1
PUMP OUTLET	93.26	988.8	54.1	-39.8
TPA BEARING COOLANT	0.50	988.8	54.1	-39.8
STRUCTURE SUPPORT INLET	24.00	988.8	54.1	-39.8
STRUCTURE BYPASS INLET	6.00	988.8	54.1	-39.8
NOZZLE MANIFOLD INLET	63.26	988.8	54.1	-39.8
NOZZLE OUTLET	60.26	715.0	201.5	522.0
SKIRT OUTLET	0.00	715.0	201.5	522.0
BOLT COOLANT OUTLET	3.00	715.0	54.1	-39.8
REFLECTOR INLET	60.60	715.0	194.6	495.3
REFLECTOR OUTLET	60.60	637.5	309.7	946.8
PERIPHERAL SHIELD OUTLET	60.60	636.7	319.5	986.0
SUPPORT PLATE INLET	90.60	656.7	290.9	872.8
STRUCTURE SUPPORT OUTLET	24.00	656.7	276.4	814.4
CENTRAL SHIELD INLET	90.60	646.8	297.0	896.7
CORE INLET	90.60	634.3	302.0	916.7
CORE OUTLET	90.60	459.0	4603.6	17588.7
NOZZLE CHAMBER	89.40	459.0	4551.0	17326.1
MAIN NOZZLE EXIT	89.40	459.00	4512.9	17147.1
DILUENT BLEED INLET	2.65	715.0	194.6	495.3
HOT BLEED INLET	1.20	459.9	4551.0	17326.1
TURBINE INLET	3.85	300.6	1660.0	5729.6
MAIN TURBINE EXIT	3.85	39.2	1238.7	4239.0
TURBINE EXIT (AT COLLECTOR)	4.35	39.2	1097.8	3748.1
SKIRT EXTEN. EXIT (NOZZ. IN.)	4.35	7.2	1467.8	5037.5

NOZZLE TUBE Q=33857. SKIRT TUBE Q= 0. MAIN NOZZLE THROAT AREA 98.339 IN²
 MAIN NOZZLE IDEAL ISP 882.41, TPCV K/A2 VALUE 0.369159E 00, PUMP EXIT DENSITY 4.301
 MAIN NOZZLE ACTUAL ISP 857.88 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 420.61

Figure 4 - Corner Points for the Envelope (Sheet 1 of 8)

NERVA ENGINE STEADY STATE VALUES TOLERANCE STUDY(3) NERVA, AN=98.339 (1) THRUST=78540 LB

ENGINE PC= 440.3 TC= 4439. THRUST 78538. LBS, IMPULSE 825.07 SEC
POWER LEVEL= 1624.3 WATTURBOCOMP= 18500. RPM

TURBOPUMP OVERALL
SHAFT POWER, VW 6.1624
TURBINE EFFICIENCY 0.5200
PUMP EFFICIENCY 0.6730

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEAR OUTLET	95.18	29.4	39.2	-101.1
PUMP OUTLET	94.68	989.3	54.1	-39.7
TPA BEARING COOLANT	0.50	989.3	54.1	-39.7
STRUCTURE SUPPORT INLET	24.00	989.3	54.1	-39.7
STRUCTURE BYPASS INLET	6.00	989.3	54.1	-39.7
NOZZLE MANIFOLD INLET	64.68	955.3	54.1	-39.7
NOZZLE OUTLET	61.68	715.5	201.5	522.0
SKIRT OUTLET	0.00	715.5	201.5	522.0
BOLT COOLANT OUTLET	3.00	715.5	54.1	-39.7
REFLECTOR INLET	62.02	715.5	194.8	495.9
REFLECTOR OUTLET	62.02	668.1	305.4	930.0
PERIPHERAL SHIELD OUTLET	62.02	657.2	314.9	967.7
SUPPORT PLATE INLET	92.02	657.2	287.4	858.6
STRUCTURE SUPPORT OUTLET	24.00	657.2	273.0	801.4
CENTRAL SHIELD INLET	92.02	647.3	293.2	881.8
CORE INLET	92.02	634.7	298.1	901.2
CORE OUTLET	92.02	460.3	4493.4	17054.3
NOZZLE CHAMBER	90.77	460.3	4439.4	16799.6
MAIN NOZZLE EXIT	90.77	460.3	4399.0	16609.7
DILUENT BLEED INLET	2.66	715.5	194.8	495.9
HOT BLEED INLET	1.25	460.3	4439.4	16799.6
TURBINE INLET	3.91	305.3	1660.0	5729.8
MAIN TURBINE EXIT	3.91	39.8	1238.7	4239.0
TURBINE EXIT (AT COLLECTOR)	4.41	39.8	1099.8	3754.8
SKIRT EXTEN. EXIT (NOZZ. IN.)	4.41	7.8	1469.8	5044.3

NOZZLE TUBE C=34657. SKIRT TURF C= 0. MAIN NOZZLE THROAT AREA 98.339 IN2
MAIN NOZZLE IDEAL ISP 868.90, TPCV K/A2 VALUE 0.348751E 00, PUMP EXIT DENSITY 4.301
MAIN NOZZLE ACTUAL ISP 844.75 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 420.88

Figure 4 - Corner Points for the Envelope (Sheet 2 of 8)

NERVA ENGINE STEADY STATE VALUES TOLERANCE STUDY(7) NERVA, AN=93.405 (3) THRUST=71540 LB

ENGINE PC= 441.9 TC= 4537. THRUST 71525. LRS, IMPULSE 837.39 SEC
POWER LEVEL= 1503.5 TURBOPUMP P= 18500. RP

TURBOPUMP OVERALL
SHAFT POWER, MW 5.0344
TURBINE EFFICIENCY 0.5200
PUMP EFFICIENCY 0.6730

STATE POINT DESCRIPTION	FLOW LRS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	7.41	20.4	30.2	-101.1
PUMP OUTLET	84.91	902.0	52.8	-45.2
TPA BEARING COOLANT	0.50	902.0	52.8	-45.2
STRUCTURE SUPPORT INLET	24.00	902.0	52.8	-45.2
STRUCTURE BYPASS INLET	6.00	902.0	52.0	-45.2
NOZZLE MANIFOLD INLET	54.91	967.5	52.8	-45.2
NOZZLE OUTLET	51.91	632.7	200.2	517.9
SKIRT OUTLET	0.00	683.7	200.2	517.9
BOLT COOLANT OUTLET	3.00	683.7	52.8	-45.2
REFLECTOR INLET	52.71	683.7	192.2	487.1
REFLECTOR OUTLET	52.71	639.2	312.9	960.0
PERIPHERAL SHIELD OUTLET	52.71	629.0	323.4	1001.0
SUPPORT PLATE INLET	82.71	629.0	264.5	847.5
STRUCTURE SUPPORT OUTLET	24.00	629.0	255.8	733.3
CENTRAL SHIELD INLET	82.71	619.6	290.6	871.4
CORE INLET	82.71	607.6	295.6	891.3
CORE OUTLET	82.71	441.9	4591.8	17527.8
NOZZLE CHAMBER	91.71	441.9	4537.8	17270.0
MAIN NOZZLE EXIT	51.71	441.9	4504.2	17111.5
DILUENT BLEED INLET	2.20	683.7	192.2	487.1
HOT BLEED INLET	0.99	441.9	4537.8	17270.0
TURBINE INLET	3.20	249.4	1660.0	5728.3
MAIN TURBINE EXIT	3.20	32.5	1238.4	4257.6
TURBINE EXIT (AT COLLECTOR)	3.70	32.5	1072.3	3659.1
SKIRT EXTEN. EXIT (NOZZ. IN.)	3.70	0.5	1442.3	4949.2

NOZZLE TUBE Q=29239. SKIRT TUBE Q= 0. MAIN NOZZLE THROAT AREA 93.400 IN2
MAIN NOZZLE IDEAL ISP 880.92, TPCV K/A2 VALUE 0.614169E 00, PUMP EXIT DENSITY 4.294
MAIN NOZZLE ACTUAL ISP 856.44 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 417.14

Figure 4 - Corner Points for the Envelope (Sheet 3 of 8)

NERVA ENGINE STEADY STATE VALUES TOLERANCE STUDY(9) NERVA, AN=93.405 (3) THRUST=71540 LB

ENGINE PC= 442.3 TC= 4427. THRUST 71525. LBS, IMPULSE 824.97 SEC
POWER LEVEL= 1430.0 TURBOPUMP= 1500. PP

TURBOPUMP OVERALL
SHAFT POWER, MW 5.1127
TURBINE EFFICIENCY 0.5200
PUMP EFFICIENCY 0.6750

STATE POINT DESCRIPTION	FL	LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEAP OUTLET		86.70	29.4	59.2	-101.1
PUMP OUTLET		86.20	902.4	52.8	-45.2
TPA BEARING COOLANT		0.50	902.4	52.8	-45.2
STRUCTURE SUPPORT INLET		24.00	902.4	52.8	-45.2
STRUCTURE BYPASS INLET		6.00	902.4	52.8	-45.2
NOZZLE ANIFOLD INLET		56.20	867.9	52.8	-45.2
NOZZLE OUTLET		53.20	684.2	200.2	517.9
SKIRT OUTLET		0.00	684.2	200.2	517.9
BOLT COOLANT OUTLET		3.00	684.2	52.8	-45.2
REFLECTOR INLET		53.99	684.2	192.4	487.8
REFLECTOR OUTLET		53.99	639.7	308.4	742.2
PERIPHERAL SHIELD OUTLET		53.99	629.4	318.4	781.7
SUPPORT PLATE INLET		83.99	629.4	281.1	635.9
STRUCTURE SUPPORT OUTLET		24.00	629.4	252.8	721.2
CENTRAL SHIELD INLET		83.99	620.1	287.0	657.1
CORE INLET		83.99	608.0	291.8	676.4
CORE OUTLET		83.99	442.3	4481.2	17002.2
NOZZLE CHAMBER		82.94	442.3	4427.2	16746.9
MAIN NOZZLE EXIT		82.94	442.3	4392.4	16582.6
DILUENT BLEED INLET		2.20	684.2	192.4	487.8
HOT BLEED INLET		1.04	442.3	4427.2	16746.9
TURBINE INLET		3.25	253.3	1660.0	5728.4
MAIN TURBINE EXIT		3.25	33.0	1238.4	4257.6
TURBINE EXIT (AT COLLECTOR)		3.75	33.0	1074.5	3666.7
SKIRT EXTEN. EXIT (NOZZ. IN.)		3.75	1.0	1444.5	4956.9

NOZZLE TUBE Q=29962. SKIRT TUBE Q= 0. MAIN NOZZLE THROAT AREA 93.400 IN2
MAIN NOZZLE IDEAL ISP 867.52, TPCV K/A2 VALUE 0.586880E 00, PUMP EXIT DENSITY 4.294
MAIN NOZZLE ACTUAL ISP 843.41 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 417.45

Figure 4 - Corner Points for the Envelope (Sheet 4 of 8)

NERVA ENGINE STEADY STATE VALUES TOLERANCE STUDY(40) NERVA, AN=93.4 (3) THRUST=744460

ENGINE PC= 460.0 TC= 4542. THRUST 74,460 LBS, IMPULSE 837.47 SEC
POWER LEVEL= 1565.7 MW TURBOPUMP= 18500. RPM

TURBOPUMP OVERALL
SHAFT POWER, MW 5.4175
TURBINE EFFICIENCY 0.5200
PUMP EFFICIENCY 0.6730

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAP OUTLET	88.96	29.4	39.2	-101.1
PUMP OUTLET	88.46	931.1	53.2	-43.4
TPA BEARING COOLANT	0.50	931.1	53.2	-43.4
STRUCTURE SUPPORT INLET	24.00	931.1	53.2	-43.4
STRUCTURE BYPASS INLET	6.00	931.1	53.2	-43.4
NOZZLE MANIFOLD INLET	58.46	896.9	53.2	-43.4
NOZZLE OUTLET	55.46	703.1	200.6	519.0
SKIRT OUTLET	0.00	703.1	200.6	519.0
BOLT COOLANT OUTLET	3.00	703.1	53.2	-43.4
REFLECTOR INLET	56.09	703.1	193.2	490.2
REFLECTOR OUTLET	56.09	658.6	311.1	952.9
PERIPHERAL SHIELD OUTLET	56.09	648.4	321.3	993.0
SUPPORT PLATE INLET	86.09	648.4	287.2	857.9
STRUCTURE SUPPORT OUTLET	24.00	648.4	264.4	767.4
CENTRAL SHIELD INLET	86.09	638.9	293.2	881.8
CORE INLET	86.09	626.8	298.2	901.8
CORE OUTLET	86.09	459.7	4596.7	17545.7
NOZZLE CHAMBER	85.02	459.7	4542.7	17287.0
MAIN NOZZLE EXIT	85.02	459.7	4507.0	17119.0
DILUENT BLEED INLET	2.36	703.1	193.2	490.2
HOT BLEED INLET	1.07	460.0	4542.7	17287.0
TURBINE INLET	3.44	268.2	1660.0	5728.8
MAIN TURBINE EXIT	3.44	35.0	1238.1	4236.8
TURBINE EXIT (AT COLLECTOR)	3.94	35.0	1082.3	3693.9
SKIRT EXTEN. EXIT (NOZZ. IN.)	3.94	3.0	1452.3	4984.2

NOZZLE TUBE Q=31197. SKIRT TUBE Q= 0. MAIN NOZZLE THROAT AREA 93.400 IN2
MAIN NOZZLE IDEAL ISP 881.40, TPCV K/A2 VALUE 0.553848E 00, PUMP EXIT DENSITY 4.295
MAIN NOZZLE ACTUAL ISP 856.90 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 418.54

NERVA ENGINE STEADY STATE VALUES TOLERANCE STUDY(41) NERVA, AN=93.4 (3) THRUST=744460

ENGINE. PC= 460.0 TC= 4455. THRUST 74,460 LBS, IMPULSE 825.0 . SEC
POWER LEVEL= 1545.0 MWTURBOPUMP= 18500. RPM

TURBOPUMP	OVERALL
SHAFT POWER, MW	5.4775
TURBINE EFFICIENCY	0.5200
PUMP EFFICIENCY	0.6730

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	89.94	29.4	39.2	-101.1
PUMP OUTLET	89.44	931.1	53.2	-43.4
TPA BEARING COOLANT	0.50	931.1	53.2	-43.4
STRUCTURE SUPPORT INLET	24.00	931.1	53.2	-43.4
STRUCTURE BYPASS INLET	6.00	931.1	53.2	-43.4
NOZZLE MANIFOLD INLET	59.44	896.9	53.2	-43.4
NOZZLE OUTLET.	56.44	703.1	200.6	519.0
SKIRT OUTLET	0.00	703.1	200.6	519.0
BOLT COOLANT OUTLET	3.00	703.1	53.2	-43.4
REFLECTOR INLET	57.08	703.1	193.3	490.6
REFLECTOR OUTLET	57.08	658.6	307.7	939.4
PERIPHERAL SHIELD OUTLET	57.08	648.4	317.6	978.3
SUPPORT PLATE INLET	87.08	648.4	284.4	846.8
STRUCTURE SUPPORT OUTLET	24.00	648.4	261.7	756.7
CENTRAL SHIELD INLET	87.08	638.9	290.3	870.2
CORE INLET	87.08	626.8	295.2	889.6
CORE OUTLET	87.08	461.54	4485.2	17128.0
NOZZLE CHAMBER	85.96	461.54	4431.2	16873.3
MAIN NOZZLE EXIT	85.96	461.54	4417.9	16698.9
DILUENT BLEED INLET	2.36	703.1	193.3	490.6
HOT BLEED INLET	1.11	460.0	4455.0	16873.3
TURBINE INLET	3.48	271.1	1660.0	5728.9
MAIN TURBINE EXIT	3.48	35.4	1238.1	4236.8
TURBINE EXIT (AT COLLECTOR)	3.98	35.4	1083.8	3699.1
SKIRT EXTEN. EXIT (NOZZ. IN.)	3.98	3.4	1453.8	4989.4

NOZZLE TUBE Q=31751. SKIRT TUBE Q= 0. MAIN NOZZLE THROAT AREA 93.400 IN2
MAIN NOZZLE IDEAL ISP 870.78, TPCV K/A2 VALUE 0.534280E 00, PUMP EXIT DENSITY 4.295
MAIN NOZZLE ACTUAL ISP 846.58 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 418.75

Figure 4 - Corner Points for the Envelope (Sheet 6 of 8)

NERVA ENGINE STEADY STATE VALUES TOLERANCE STUDY(42) NERVA, AN=98.339 (1) THRUST=75460

ENGINE PC= 442.8 TC= 4542. THRUST 75,460 LBS, IMPULSE 837.4 SEC
POWER LEVEL= 1586.7 MW TURBOPUMP= 18500. RPM

TURBOPUMP OVERALL
SHAFT POWER, MW 5.3815
TURBINE EFFICIENCY 0.5200
PUMP EFFICIENCY 0.6730

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	90.07	29.4	39.2	-101.1
PUMP OUTLET	89.57	913.9	53.0	-44.5
TPA BEARING COOLANT	0.50	913.9	53.0	-44.5
STRUCTURE SUPPORT INLET	24.00	913.9	53.0	-44.5
STRUCTURE BYPASS INLET	6.00	913.9	53.0	-44.5
NOZZLE MANIFOLD INLET	59.57	879.7	53.0	-44.5
NOZZLE OUTLET	56.57	685.9	200.4	518.5
SKIRT OUTLET	-0.00	685.9	200.4	518.5
BOLT COOLANT OUTLET	3.00	685.9	53.0	-44.5
REFLECTOR INLET	57.22	685.9	193.0	490.0
REFLECTOR OUTLET	57.22	641.4	310.3	949.7
PERIPHERAL SHIELD OUTLET	57.22	631.2	320.5	989.6
SUPPORT PLATE INLET	87.22	631.2	287.7	860.0
STRUCTURE SUPPORT OUTLET	24.00	631.2	266.9	777.2
CENTRAL SHIELD INLET	87.22	621.7	293.7	883.9
CORE INLET	87.22	609.6	298.7	903.9
CORE OUTLET	87.22	442.7	4592.0	17553.0
NOZZLE CHAMBER	86.15	442.7	4542.7	17293.0
MAIN NOZZLE EXIT	86.15	442.7	4507.0	17124.5
DILUENT BLEED INLET	2.35	685.9	193.0	490.0
HOT BLEED INLET	1.06	442.8	4542.7	17293.0
TURBINE INLET	3.42	266.6	1660.0	5728.8
MAIN TURBINE EXIT	3.42	34.8	1238.5	4238.0
TURBINE EXIT (AT COLLECTOR)	3.92	34.8	1081.8	3692.1
SKIRT EXTEN. EXIT (NOZZ. IN.)	3.92	2.8	1451.8	4982.4

NOZZLE TUBE Q=31856. SKIRT TUBE Q= -0. MAIN NOZZLE THROAT AREA 98.339 IN²
MAIN NOZZLE IDEAL ISP 881.52, TPCV K/A2 VALUE 0.497378E 00, PUMP EXIT DENSITY 4.294
MAIN NOZZLE ACTUAL ISP 857.02 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 418.46

Figure 4 - Corner Points for the Envelope (Sheet 7 of 8)

NERVA ENGINE STEADY STATE VALUES TOLERANCE STUDY(43) NERVA, AN=98.339 (1) THRUST=75460

ENGINE PC= 440.4 TC= 4427. THRUST 75,460 LBS, IMPULSE 825.05 SEC
POWER LEVEL= 1550.8 MW TURBOPUMP= 18500. RPM

TURBOPUMP	OVERALL
SHAFT POWER, MW	5.4153
TURBINE EFFICIENCY	0.5200
PUMP EFFICIENCY	0.6730

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	90.89	29.4	39.2	-101.1
PUMP OUTLET	90.39	911.5	52.9	-44.6
TPA BEARING COOLANT	0.50	911.5	52.9	-44.6
STRUCTURE SUPPORT INLET	24.00	911.5	52.9	-44.6
STRUCTURE BYPASS INLET	6.00	911.5	52.9	-44.6
NOZZLE MANIFOLD INLET	60.39	877.3	52.9	-44.6
NOZZLE OUTLET	57.39	683.5	200.4	518.4
SKIRT OUTLET	-0.00	683.5	200.4	518.4
BOLT COOLANT OUTLET	3.00	683.5	52.9	-44.6
REFLECTOR INLET	58.05	683.5	193.0	490.0
REFLECTOR OUTLET	58.05	639.0	306.0	932.8
PERIPHERAL SHIELD OUTLET	58.05	628.8	315.8	971.2
SUPPORT PLATE INLET	88.05	628.8	283.7	844.0
STRUCTURE SUPPORT OUTLET	24.00	628.8	262.1	758.4
CENTRAL SHIELD INLET	88.05	619.3	289.5	867.2
CORE INLET	88.05	607.2	294.4	886.5
COPE OUTLET	88.05	443.1	4481.6	17004.9
NOZZLE CHAMFER	86.94	443.1	4427.6	16749.5
MAIN NOZZLE EXIT	86.94	443.1	4390.6	16574.7
DILUENT BLEED INLET	2.33	683.5	193.0	490.0
HOT BLEED INLET	1.10	440.4	4427.6	16749.5
TURBINE INLET	3.44	268.3	1660.0	5728.9
MAIN TURBINE EXIT	3.44	35.0	1238.5	4238.2
TURBINE EXIT (AT COLLECTOR)	3.94	35.0	1082.7	3695.3
SKIRT EXTEN. EXIT (NOZZ. IN.)	3.94	3.0	1452.7	4985.6

NOZZLE TUBE Q=32318. SKIRT TUBE Q= -0. MAIN NOZZLE THROAT AREA 98.341 IN2
MAIN NOZZLE IDEAL ISP 867.59, TPCV K/A2 VALUE 0.477679E 00, PUMP EXIT DENSITY 4.294
MAIN NOZZLE ACTUAL ISP 843.49 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 418.60

Figure 4 - Corner Points for the Envelope (Sheet 8 of 8)

pressure because less proportional flow is required to drive the turbine, thus increasing the I_{sp} . The acceptable engine operating area on the P_c, T_c map in Figure 3 is crosshatched. Figure 5 is a summary of runs made, including the effect of reducing the tank pressure to 24 psia (its lower limit) in Runs 31, 32 and 33.

Run	Option	Dewar		Thrust F (K-lb)	I _{sp} (sec)	P _c (psia)	T _c (°R)	Nozzle Throat Area	
		P _T (psia)	T _T (°R)					No.	(in. ²)
1	(P _c , T _c)	30	41	78.54	837.4	459.0	4603.6	1	98.339
2		30	41	78.54	831.2	460.19	4549.2	1	98.339
3		30	41	78.54	825.0	460.3	4493.4	1	98.339
4		30	41	75.0	837.4	450.9	4594.2	2	95.935
5		30	41	75.0	831.2	451.1	4538.4	2	95.935
6		30	41	75.0	825.0	450.0	4498.0	2	95.935
7		30	41	71.54	837.4	441.99	4591.8	3	93.400
8		30	41	71.54	831.2	442.23	4536.8	3	93.400
9		30	41	71.54	825.0	442.39	4481.47	3	93.400
19	(T _c , A _N)	30	41	77	825.0	450.0	4507.0	(1)	98.339
20		30	41	75	825.0	450.0	4497.7	(2)	95.935
21		30	41	73	825.0	450.0	4496.0	(3)	93.400
25	(P _c , F)	30	41	78.54	825.79	460.35	4500.0	1	98.339
26		30	41	71.54	827.33	430.7	4500.0	2	95.935
27		30	41	75.0	826.59	463.7	4500.0	3	93.400
31		24	39.5	77	823.1	449.5	4500.0	1	98.339
32	(P _c , T _c)	24	39.5	75	824.17	449.5	4500.0	2	95.935
33		24	39.5	73	824.29	449.53	4500.0	3	93.400
37		30	41	75	837.4	463.0	4596.5	3	93.400
38		30	41	75	837.4	439.96	4596.72	1	98.339
39	(P _c , T _c)	30	41	75	825.0	440.39	4481.58	1	98.339
40		30	41	74.46	837.4	459.75	4596.7	3	93.400
41		30	41	74.46	825.0	461.5	4485.2	3	93.400
42		30	41	75.46	837.4	442.68	4592.0	1	98.339
43		30	41	75.46	825.0	443.16	4481.6	1	98.339

Figure 5 - Summary Tolerance Study for 75K NERVA Engine

2. Comparison of Methods of Engine Operation and Their Effect on Impulse and Specific Impulse

a. Scope

A study has been made of the overall specific impulse performance including startup, full-power operation, shutdown and cooldown for the NERVA engine. This included determination of the accuracy requirements to guarantee a given specific impulse and total thrust. Because of the different missions being considered, the study considered a short-duration run and long-duration run. The short-duration run was based on approximately 300 sec or 438K Mw-sec of operation; the long-duration run was for approximately 1 hr at full power or 5671K Mw-sec.

b. Functional and Technical Design Requirements

The following performance parameters are quoted from the NERVA Program Requirements Document, dated 5 June 1968, page 2:

(1) Endurance at Rated Conditions (page 2)

The operating time shall be utilizable in either one cycle or multiple cycles up to ten, of varying lengths totaling a minimum of 50 minutes.

(2) Shutdown Transient (page 5)

During the shutdown transient, impulse lost by using propellant at less than full I_{sp} shall be minimized.

The engine shall be able to perform the missions listed on Drawing No. 1135437, sheet 1, Missions Table - Functional Flow Diagrams for Nuclear Vehicle Missions.

(3) Controllability (page 6)

The limits on total impulse during shutdown shall be +20,000 lbf.

c. Approaches and Significant Characteristics

Various operating cycles, including retreats to part power but maintaining full impulse, were considered to give the same integrated power from the time of reaching full power until the time of reduction of chamber temperature. Figure 6 shows power decay assuming a 1575 Mw reactor with a 27-sec shutdown to 50% of the steady state. Following the retreat to 50% power at maximum chamber temperature, the power was held constant for various hold times before the reactor was scrammed. Curves 1 through 5 in Figure 6 represent the total integrated power of 438K Mw-sec prior to scram and curves 6 through 8 represent the total integrated power of 5671K Mw-sec. Figure 6 indicates that after approximately 500 sec from Scram the amount of heat to be removed for a given integrated power does not change.

Since the mission requirements indicate variable steady-state holds, four different hold times were considered: two long-duration and two short-duration holds:

(1)	Full-power hold - 150 sec	
(2)	Full-power hold - 300 sec	438K Mw-sec
(3)	Full-power hold - 3450 sec	
(4)	Full-power hold - 3600 sec	5671K Mw-sec

To illustrate the effect of chamber temperature on pulse cooling, two different pulse chamber temperatures were used: 1600°R and 2000°R.

The remaining pairs of long- and short-duration runs differed from each other in the method of retreat from the design point:

Figure 6 - Fission Product Decay Heat vs Time after Shutdown

- (1) Retreat to pulse temperature along a normal operating line with no holds;
- (2) Retreat to 50% power for a hold at full impulse and then retreat to low temperature and scram.

Figures 7 and 8 show the chamber pressure, chamber temperature, and resulting thrust I_{sp} profiles for Case I. They are indicative of the profiles prepared for each case.

d. Comparison of Results

The eight profiles considered are shown in Table 1. The performance is listed in three columns: time until pulse cooldown, pulse cooling period, and total for 24 hours.

e. Recommendations and Conclusions

The full-power specific impulse reference point for this study was 818 sec. (The study was performed using a reduced nozzle area ratio.) Comparing Cases I and III, an advantage of having the 50% power-level hold before shutdown results in a 3-sec increase in overall I_{sp} . The disadvantage of going to a hold level at part power at full temperature is that the corrosion of the reactor is increased for a given impulse. For the 1-hr operation, comparison of Cases V and VII prior to pulse cooldown shows 0.8-sec increase in overall I_{sp} when the 50% power hold is introduced.

Considering the pulse cooldown period, a 1600°R average chamber exit temperature will give an average I_{sp} of around 475 sec; if the chamber temperature can be increased to 2000°R the I_{sp} is increased to 535 sec. The effect of this on overall performance for a total operational period of 24 hr from startup to shutdown is shown in the last column of Table 1; for the short-duration runs approximately 6 sec. of I_{sp} improvement results from the higher pulse cooling conditions; for the 1-hr run, the resultant improvement is 3 sec of overall I_{sp} .

Figure 7 - Chamber Temperature and Pressure vs Time, 75K NERVA Engine

Figure 8 - Specific Impulse and Thrust vs Time, 75K NERVA Engine

TABLE 1
SPECIFIC IMPULSE PERFORMANCE

Case No.	(1)	(2)	(3)	(4) (5) (6) (7)				(8) (9) (10) (11)				(12) (13) (14) (15)			
	Full Power Run Time, sec	50% Power Hold Time, sec	Pulse Chamber Temp, °R	Time Until Pulse Cooldown				Pulse Cooling Period				Total for 24 Hours			
				Time, sec	Flow, lbm	Impulse, 10 ⁶ lbf-sec	I_{sp}^* , $\frac{\text{lbf-sec}}{\text{lbm}}$	Time, sec	Flow, lbm	Impulse, 10 ⁶ lbf-sec	I_{sp}^* , $\frac{\text{lbf-sec}}{\text{lbm}}$	Flow, lbm	Impulse, 10 ⁶ lbf-sec	I_{sp}^* , $\frac{\text{lbf-sec}}{\text{lbm}}$	% I_{sp}^* Overall
I	150	300	1600	567	30,995	24.85	801.6	461	1,845	0.88	475	32,840	25.72	783.3	95.6
II	150	300	2000	551	30,752	24.67	802.2	377	1,507	0.81	535	32,259	25.48	789.7	96.5
III	300	0	1600	443	32,050	25.58	798.2	501	2,005	0.95	475	34,055	26.54	779.2	95.2
IV	300	0	2000	419	31,721	25.37	799.9	416	1,662	0.89	535	33,383	26.26	786.7	96.2
V	3450	300	1600	4023	334,271	272.88	816.4	1394	5,574	2.65	475	339,845	275.53	810.8	99.1
VI	3450	300	2000	3922	333,270	272.51	817.7	1209	4,838	2.59	535	338,108	275.10	813.6	99.5
VII	3600	0	1600	3973	335,955	273.98	815.5	1485	5,940	2.82	475	341,895	276.80	809.6	99.0
VIII	3600	0	2000	3850	334,719	273.37	816.7	1282	5,127	2.74	535	339,846	276.11	812.5	99.3

* 100% I_{sp} = 818 lbf-sec/lbm

To maximize the total overall specific impulse, more detailed studies are needed to determine how to efficiently use the LH₂ during the pulse cooldown. From Table 1, Case I, 18 sec of overall specific impulse are lost during the pulse cooldown period. Studies to date indicate that the structural support system is the limiting component for raising the chamber temperature during pulse cooldown. A method for introducing the pulse cooldown flow directly into the structural support system should be considered. If this will increase the chamber temperature to 2000°R, the gain in engine overall specific impulse will be 6 sec. Such a scheme would probably show the structural support system entering on the reactor side of the SSCV. Coolant would not be required by the nozzle as long as chamber temperatures were below the nozzle operating limit of 1800°F (2260°R). Areas in the reflector that might overheat could be monitored and a pulse of coolant could be put through the reflector by the pump discharge line as required. This would increase the total amount of coolant through the structural support system and allow for higher pulse cooldown chamber temperatures.

The requirement in the preliminary version of the NERVA Program Requirements Document indicated that the total impulse shall not deviate from the predicted total impulse by more than +20,000 lb-sec. Considering the uncertainty in the total impulse generated during the period from startup until the initiation of pulse cooldown, a thrust chamber temperature measurement uncertainty of +90°R, or 2% at full power, and chamber pressure uncertainty of +9 psia, or 2%, was estimated. From this, it was determined that the flow rate uncertainty would be +2.5 lb/sec. The specific impulse can vary by +9.9 lbf-sec/lbm. A deviation of +9.9 sec, or about +1.2% in specific impulse, will result in impulse variations for the 300-sec run of +320,000 lb-sec. This does not include the pulse cooldown period. To meet the +20,000 lb-sec requirement, the overall I_{sp} would need to be held to +1.5 sec. This would indicate that the chamber temperature, including all measurement uncertainties, would have to be about +14°R. The 1-hr run requirements were even more severe.

Since mission success depends on achieving a certain velocity at a given position using the nuclear engine, it appears that the most reasonable way to guarantee mission success for long-duration firings would be measurement of the vehicle's performance rather than the engine's performance. Therefore, some method is required to meet the total impulse specification that would be independent of the run time and would be based on the performance of the vehicle. On a long-duration firing of the nuclear engine, to meet the total impulse accuracy requirement of $\pm 20,000$ lb-sec, the time to achieve the desired vehicle velocity could be determined by the vehicle guidance system, with the engine manufacturer guaranteeing an overall specific impulse performance level and a controlled amount of thrust during shutdown. Based on this mode of operation, the engine could be reduced to about 50% power level once a given velocity is reached, and held there as a trim to achieve the final vehicle velocity at the high I_{sp} levels, considering the thrust that will be generated during the final shutdown. To achieve the $\pm 20,000$ lb-sec overall impulse during the pulse cooling period, a thrust-spoiling system would be required.

For rendezvous-type missions, where the trim on thrust is very important, the final rendezvous may be performed during pulse cooldown. A variable control on the thrust level can be achieved by varying the width of the pulses, using different chamber temperatures. For instance, an average pulse-cooldown chamber temperature of 1600°R can be achieved by varying chamber temperatures between 1500 and 1700°R and would result in a variable size thrust per pulse.

Relative to nuclear afterheat during long-term reactor cooldown, a comparison of pulse cooling and the use of continuous coolant indicates that the former method is usually better.

This conclusion is based on laminar flow, when flow rates are low and the simplified control scheme that can be used with pulse cooling. With continuous cooling the flow rate eventually would drop so low that a special system would be required to maintain control.

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3. Methods of Achieving 825 sec I_{sp}

a. Scope

This study was made to show various engine designs and design changes that will enable a steady-state design specific impulse of 825 sec.

b. Functional and Technical Design Requirements

NERVA Program Requirements Document, dated 5 June 1968, page 2, Performance Requirements at Rated Conditions, states that the minimum specific impulse shall be 825 lb-sec/lb.

The functional flow diagrams for Nuclear Vehicle Missions (AGC Drawing No. 1135437, sheet 1 - Stage Definition Block) call for a nuclear stage I_{sp} of 825 lb-sec/lb.

c. Approaches and Significant Characteristics

A series of steady-state design-point runs were made on the simplified NERVA engine balance program. From this series of computer steady-state calculations, approximate influence coefficients for variations in major engine component characteristics were computed (Table 2).

Using the influence coefficients from the previous paragraph, an additional series of steady-state runs were made varying the basic engine design point (Figure 9) to obtain 825 sec I_{sp} .

TABLE 2

INFLUENCE COEFFICIENTS FOR SPECIFIC IMPULSE

Chamber Temperature (ΔT_c)	0.11 sec/°R
Turbine Inlet Temperature (ΔT_{11})	0.0113 sec/°R
Turbopump Efficiency (' η_p, η_T)	0.3 sec/%
Pump Discharge Pressure (ΔPD)	-0.02 sec/psid
Nozzle Tube Pressure Drop	-0.0158 sec/psid
Chamber Pressure	-0.031 sec/psid
Structural Coolant Flow Rate	-0.001 sec/lb/sec
Area Ratio - Main Nozzle	
from 70:1 to 100:1	4.63 sec
from 60:1 to 100:1	6.72 sec

MAIN NOZZLE EXPANSION RATIO 100.0 AND TURBINE NOZZLE EXPANSION RATIO 8.00

TURBINE INLET $W \cdot \sqrt{T} / P$ 0.5550, PRESS. RATIO 8.120, EFF. 0.5000, INLET TEMP. 1660.0

MAIN NOZZLE TUBES FLOW SPLIT FRACTION 0.650, DESIGN DELTA P 240.0, AND DESIGN DELTA T 155.0

NERVA ENGINE STEADY STATE VALUES 75K NERVA 100 1 TC + 31R ISP = 825 11 MARCH 1968

ENGINE PC= 450.0 TC= 4477. THRUST 75000. LBS, IMPULSE 824.98 SEC
POWER LEVEL= 1557.7 MW TURBOPUMP= 19000. RPM

TURBOPUMP	OVERALL
SHAFT POWER, MW	6.0565
TURBINE EFFICIENCY	0.5000
PUMP EFFICIENCY	0.6440

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	90.91	30.0	40.0	-98.8
PUMP OUTLET	90.41	960.0	55.8	-35.7
TPA BEARING COOLANT	0.50	960.0	55.8	-35.7
STRUCTURE SUPPORT INLET	26.80	960.0	55.8	-35.7
STRUCTURE BYPASS INLET	3.20	960.0	55.8	-35.7
NOZZLE MANIFOLD INLET	60.41	920.0	55.8	-35.7
NOZZLE OUTLET	37.31	680.0	210.8	557.4
SKIRT OUTLET	20.09	680.0	210.8	557.4
BOLT COOLANT OUTLET	3.00	680.0	55.8	-35.7
REFLECTOR INLET	57.38	680.0	203.1	527.9
REFLECTOR OUTLET	57.38	640.0	315.1	968.4
PERIPHERAL SHIELD OUTLET	57.38	635.0	322.6	997.8
SUPPORT PLATE INLET	87.38	635.0	307.4	938.3
STRUCTURE SUPPORT OUTLET	26.80	635.0	304.6	927.1
CENTRAL SHIELD INLET	87.38	628.0	313.0	960.5
CORE INLET	87.38	620.0	318.0	979.9
CORE OUTLET	87.38	450.0	4531.0	17235.1
NOZZLE CHAMBER	85.98	450.0	4477.0	16980.1
MAIN NOZZLE EXIT	85.98	450.0	4438.6	16799.0
DILUENT BLEED INLET	3.02	680.0	203.1	527.9
HOT BLEED INLET	1.40	450.0	4477.0	16980.1
TURBINE INLET	4.43	325.2	1660.0	5730.3
MAIN TURBINE EXIT	4.43	40.8	1294.6	4434.3
TURBINE EXIT (AT COLLECTOR)	4.93	40.8	1164.8	3981.0
SKIRT EXTEN. EXIT (NOZZ. IN.)	4.93	28.8	1364.8	4679.2

NOZZLE TUBE Q=22135. SKIRT TUBE Q=11918. MAIN NOZZLE THROAT AREA 95.766 IN²
MAIN NOZZLE IDEAL ISP 873.49, TPCV K/A2 VALUE 0.199378E 00, PUMP EXIT DENSITY 4.232
MAIN NOZZLE ACTUAL ISP 849.21 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 402.57

Figure 9 - Steady-State Values with Varied Engine Design Points (Sheet 1 of 12)

MAIN NOZZLE EXPANSION RATIO 70.0 AND TURBINE NOZZLE EXPANSION RATIO 8.00

TURBINE INLET $W \cdot \sqrt{T} / P$ 0.5550, PRESS. RATIO 8.120, EFF. 0.5000, INLET TEMP. 1660.0

MAIN NOZZLE TUBES FLOW SPLIT FRACTION 0.650, DESIGN DELTA P 240.0, AND DESIGN DELTA T 155.0

NERVA ENGINE STEADY STATE VALUES 75K NERVA 70 1 TC + 76R ISP = 825 11 MARCH 1968

ENGINE PC= 450.0 TC= 4522. THRUST 75000. LBS, IMPULSE 825.00 SEC
POWER LEVEL= 1577.0 MWTURBOPUMP= 19000. RPM

TURBOPUMP	OVERALL
SHAFT POWER, MW	6.0564
TURBINE EFFICIENCY	0.5000
PUMP EFFICIENCY	0.6440

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	90.90	30.0	40.0	-98.8
PUMP OUTLET	90.40	960.0	55.8	-35.7
TPA BEARING COOLANT	0.50	960.0	55.8	-35.7
STRUCTURE SUPPORT INLET	26.80	960.0	55.8	-35.7
STRUCTURE BYPASS INLET	3.20	960.0	55.8	-35.7
NOZZLE MANIFOLD INLET	60.40	920.0	55.8	-35.7
NOZZLE OUTLET	37.31	680.0	210.8	557.4
SKIRT OUTLET	20.09	680.0	210.8	557.4
BOLT COOLANT OUTLET	3.00	680.0	55.8	-35.7
REFLECTOR INLET	57.36	680.0	203.1	527.8
REFLECTOR OUTLET	57.36	640.0	316.5	973.9
PERIPHERAL SHIELD OUTLET	57.36	635.0	324.1	1003.7
SUPPORT PLATE INLET	87.36	635.0	309.3	945.8
STRUCTURE SUPPORT OUTLET	26.80	635.0	307.6	939.0
CENTRAL SHIELD INLET	87.36	628.0	315.0	968.3
CORE INLET	87.36	620.0	320.0	988.0
CORE OUTLET	87.36	450.0	4576.0	17448.0
NOZZLE CHAMBER	85.97	450.0	4522.0	17192.7
MAIN NOZZLE EXIT	85.97	450.0	4483.6	17011.9
DILUENT BLEED INLET	3.04	680.0	203.1	527.8
HOT BLEED INLET	1.38	450.0	4522.0	17192.7
TURBINE INLET	4.43	325.2	1660.0	5730.3
MAIN TURBINE EXIT	4.43	40.8	1294.6	4434.3
TURBINE EXIT (AT COLLECTOR)	4.93	40.8	1164.8	3981.0
SKIRT EXTEN. EXIT (NOZZ. IN.)	4.93	28.8	1364.8	4679.2

NOZZLE TUBE Q=22134. SKIRT TUBE Q=11918. MAIN NOZZLE THROAT AREA 96.309 IN²
MAIN NOZZLE IDEAL ISP 873.50, TPCV K/A2 VALUE 0.199397E 00, PUMP EXIT DENSITY 4.232
MAIN NOZZLE ACTUAL ISP 849.23 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 402.58

Figure 9 - Steady-State Values with Varied Engine Design Points (Sheet 2 of 12)

MAIN NOZZLE EXPANSION RATIO 60.0 AND TURBINE NOZZLE EXPANSION RATIO 8.00

TURBINE INLET $W \cdot \sqrt{T}/P$ 0.5550, PRESS. RATIO 8.120, EFF. 0.5000, INLET TEMP. 1660.0

MAIN NOZZLE TUBES FLOW SPLIT FRACTION 0.650, DESIGN DELTA P 240.0, AND DESIGN DELTA T 155.0

 NERVA ENGINE STEADY STATE VALUES 75K NERVA 60 1 TC +100R ISP = 825 11 MARCH 1968

ENGINE PC= 450.0 TC= 4546. THRUST 75000. LBS, IMPULSE 825.38 SEC
 POWER LEVEL= 1587.0 MW TURBOPUMP= 19000. RPM

TURBOPUMP OVERALL
 SHAFT POWER, MW 6.0536
 TURBINE EFFICIENCY 0.5000
 PUMP EFFICIENCY 0.6440

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	90.86	30.0	40.0	-98.8
PUMP OUTLET	90.36	960.0	55.8	-35.7
TPA BEARING COOLANT	0.50	960.0	55.8	-35.7
STRUCTURE SUPPORT INLET	26.80	960.0	55.8	-35.7
STRUCTURE BYPASS INLET	3.20	960.0	55.8	-35.7
NOZZLE MANIFOLD INLET	60.36	920.0	55.8	-35.7
NOZZLE OUTLET	37.28	680.0	210.8	557.4
SKIRT OUTLET	20.07	680.0	210.8	557.4
ROLT COOLANT OUTLET	3.00	680.0	55.8	-35.7
REFLECTOR INLET	57.31	680.0	203.1	527.9
REFLECTOR OUTLET	57.31	640.0	317.3	977.3
PERIPHERAL SHIELD OUTLET	57.31	635.0	325.0	1007.2
SUPPORT PLATE INLET	87.31	635.0	310.4	950.0
STRUCTURE SUPPORT OUTLET	26.80	635.0	309.2	945.2
CENTRAL SHIELD INLET	87.31	628.0	316.1	972.6
CORE INLET	87.31	620.0	321.2	992.4
CORE OUTLET	87.31	450.0	4600.0	17566.8
NOZZLE CHAMBER	85.93	450.0	4546.0	17306.0
MAIN NOZZLE EXIT	85.93	450.0	4508.8	17130.8
DILUENT BLEED INLET	3.05	680.0	203.1	527.9
HOT BLEED INLET	1.37	450.0	4546.0	17306.0
TURBINE INLET	4.42	325.1	1660.0	5730.3
MAIN TURBINE EXIT	4.42	40.8	1294.6	4434.3
TURBINE EXIT (AT COLLECTOR)	4.92	40.8	1164.7	3980.8
SKIRT EXTFN. EXIT (NOZZ. IN.)	4.92	28.8	1364.7	4679.0

NOZZLE TUBE Q=22118. SKIRT TUBE Q=11909. MAIN NOZZLE THROAT AREA 96.555 IN²
 MAIN NOZZLE IDEAL ISP 873.92, TPCV K/A2 VALUE 0.199882E 00, PUMP EXIT DENSITY 4.232
 MAIN NOZZLE ACTUAL ISP 849.63 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 402.56

Figure 9 - Steady-State Values with Varied Engine Design Points (Sheet 3 of 12)

MAIN NOZZLE EXPANSION RATIO 100.0 AND TURBINE NOZZLE EXPANSION RATIO 8.00

TURBINE INLET $W \cdot \sqrt{T} / P$ 0.5550, PRESS. RATIO 8.120, EFF. 0.6000, INLET TEMP. 1660.0

MAIN NOZZLE TUBES FLOW SPLIT FRACTION 0.650, DESIGN DELTA P 200.0, AND DESIGN DELTA T 155.0

 NERVA ENGINE STEADY STATE VALUES 75K NERVA ISP = 825 100 1 8 MARCH 1968

ENGINE PC= 450.0 TC= 4446. THRUST 75000. LBS, IMPULSE 825.31 SEC
 POWER LEVEL= 1555.0 MWTURBOPUMP= 19000. RPM

TURBOPUMP	OVERALL
SHAFT POWER, MW	5.7397
TURBINE EFFICIENCY	0.6000
PUMP EFFICIENCY	0.6500

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	90.87	30.0	40.0	-98.8
PUMP OUTLET	90.37	920.0	54.9	-39.0
TPA BEARING COOLANT	0.50	920.0	54.9	-39.0
STRUCTURE SUPPORT INLET	26.80	920.0	54.9	-39.0
STRUCTURE BYPASS INLET	3.20	920.0	54.9	-39.0
NOZZLE MANIFOLD INLET	60.37	880.0	54.9	-39.0
NOZZLE OUTLET	37.29	680.0	209.9	554.1
SKIRT OUTLET	20.08	680.0	209.9	554.1
BOLT COOLANT OUTLET	3.00	680.0	54.9	-39.0
REFLECTOR INLET	57.98	680.0	202.2	524.5
REFLECTOR OUTLET	57.98	640.0	312.8	959.7
PERIPHERAL SHIELD OUTLET	57.98	635.0	320.2	988.7
SUPPORT PLATE INLET	87.98	635.0	305.6	931.1
STRUCTURE SUPPORT OUTLET	26.80	635.0	303.4	922.1
CENTRAL SHIELD INLET	87.98	628.0	311.2	953.1
CORE INLET	87.98	620.0	316.1	972.4
CORE OUTLET	87.98	450.0	4500.0	17088.8
NOZZLE CHAMBER	86.86	450.0	4446.0	16833.7
MAIN NOZZLE EXIT	86.86	450.0	4410.1	16664.8
DILUENT BLEED INLET	2.39	680.0	202.2	524.5
HOT BLEED INLET	1.12	450.0	4446.0	16833.7
TURBINE INLET	3.51	257.7	1660.0	5728.6
MAIN TURBINE EXIT	3.51	32.3	1221.5	4178.6
TURBINE EXIT (AT COLLECTOR)	4.01	32.3	1070.5	3652.8
SKIRT EXTEN. EXIT (NOZZ. IN.)	4.01	20.3	1270.5	4349.5

NOZZLE TUBE Q=22120. SKIRT TUBE Q=11910. MAIN NOZZLE THROAT AREA 96.369 IN²
 MAIN NOZZLE IDEAL ISP 869.75, TPCV K/A2 VALUE 0.508541E 00, PUMP EXIT DENSITY 4.232
 MAIN NOZZLE ACTUAL ISP 845.58 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 386.56

Figure 9 - Steady-State Values with Varied Engine Design Points (Sheet 4 of 12)

MAIN NOZZLE EXPANSION RATIO 70.0 AND TURBINE NOZZLE EXPANSION RATIO 8.00
 TURBINE INLET $W\sqrt{T}/P$ 0.5550, PRESS. RATIO 8.120, EFF. 0.7000, INLET TEMP. 1800.0
 MAIN NOZZLE TUBES FLOW SPLIT FRACTION 0.650, DESIGN DELTA P 175.0, AND DESIGN DELTA T 155.0

NERVA ENGINE STEADY STATE VALUES 75K NERVA ISP = 825 70 1 8 MARCH 1968

ENGINE PC= 450.0 TC= 4446. THRUST 75000. LBS, IMPULSE 825.31 SEC
 POWER LEVEL= 1569.3 MWTURBOPUMP= 19000. RPM

TURBOPUMP	OVERALL
SHAFT POWER, MW	5.1070
TURBINE EFFICIENCY	0.7000
PUMP EFFICIENCY	0.7000

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	90.87	30.0	40.0	-98.8
PUMP OUTLET	90.37	895.0	52.7	-45.6
TPA BEARING COOLANT	0.50	895.0	52.7	-45.6
STRUCTURE SUPPORT INLET	26.80	895.0	52.7	-45.6
STRUCTURE BYPASS INLET	3.20	895.0	52.7	-45.6
NOZZLE MANIFOLD INLET	60.37	855.0	52.7	-45.6
NOZZLE OUTLET	37.29	680.0	207.7	546.0
SKIRT OUTLET	20.08	680.0	207.7	546.0
ROLT COOLANT OUTLET	3.00	680.0	52.7	-45.6
REFLECTOR INLET	58.76	680.0	200.1	516.6
REFLECTOR OUTLET	58.76	640.0	310.4	949.9
PERIPHERAL SHIELD OUTLET	58.76	635.0	317.7	978.8
SUPPORT PLATE INLET	88.76	635.0	304.2	925.5
STRUCTURE SUPPORT OUTLET	26.80	635.0	303.9	924.4
CENTRAL SHIELD INLET	88.76	628.0	309.7	947.5
CORE INLET	88.76	620.0	314.6	966.8
CORE OUTLET	88.76	450.0	4500.0	17088.7
NOZZLE CHAMBER	87.89	450.0	4446.0	16833.6
MAIN NOZZLE EXIT	87.89	450.0	4413.1	16678.9
DILUENT BLEED INLET	1.61	680.0	200.1	516.6
HOT BLEED INLET	0.86	450.0	4446.0	16833.6
TURBINE INLET	2.48	189.5	1800.0	6225.5
MAIN TURBINE EXIT	2.48	23.8	1248.6	4273.2
TURBINE EXIT (AT COLLECTOR)	2.98	23.8	1040.6	3548.6
SKIRT EXTEN. EXIT (NOZZ. IN.)	2.98	11.8	1240.6	4244.8

NOZZLE TUBE Q=22063. SKIRT TUBE Q=11880. MAIN NOZZLE THROAT AREA 97.512 IN2
 MAIN NOZZLE IDEAL ISP 864.39, TPCV K/A2 VALUE 0.121319E 01, PUMP EXIT DENSITY 4.292
 MAIN NOZZLE ACTUAL ISP 840.36 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 381.51

Figure 9 - Steady-State Values with Varied Engine Design Points (Sheet 5 of 12)

MAIN NOZZLE EXPANSION RATIO 60.0 AND TURBINE NOZZLE EXPANSION RATIO 8.00

TURBINE INLET $W\sqrt{T}/P$ 0.5550, PRESS. RATIO 8.120, EFF. 0.7500, INLET TEMP. 1850.0

MAIN NOZZLE TUBES FLOW SPLIT FRACTION 0.650, DESIGN DELTA P 150.0, AND DESIGN DELTA T 155.0

NERVA ENGINE STEADY STATE VALUES 75K NERVA ISP = 825 60 1 8 MARCH 1968

ENGINE PC= 450.0 TC= 4446. THRUST 75000. LBS, IMPULSE 825.14 SEC
POWER LEVEL= 1575.9 MW TURBOPUMP= 19000. RPM

TURBOPUMP	OVERALL
SHAFT POWER, MW	4.5669
TURBINE EFFICIENCY	0.7500
PUMP EFFICIENCY	0.7500

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	90.89	30.0	40.0	-98.8
PUMP OUTLET	90.39	870.0	50.9	-51.2
TPA BEARING COOLANT	0.50	870.0	50.9	-51.2
STRUCTURE SUPPORT INLET	26.80	870.0	50.9	-51.2
STRUCTURE BYPASS INLET	3.20	870.0	50.9	-51.2
NOZZLE MANIFOLD INLET	60.39	830.0	50.9	-51.2
NOZZLE OUTLET	37.30	680.0	205.9	539.2
SKIRT OUTLET	20.08	680.0	205.9	539.2
BOLT COOLANT OUTLET	3.00	680.0	50.9	-51.2
REFLECTOR INLET	59.10	680.0	198.3	509.9
REFLECTOR OUTLET	59.10	640.0	308.5	942.6
PERIPHERAL SHIELD OUTLET	59.10	635.0	315.8	971.4
SUPPORT PLATE INLET	89.10	635.0	302.8	920.1
STRUCTURE SUPPORT OUTLET	26.80	635.0	303.5	922.8
CENTRAL SHIELD INLET	89.10	628.0	308.4	942.1
CORE INLET	89.10	620.0	313.3	961.4
CORE OUTLET	89.10	450.0	4500.0	17088.7
NOZZLE CHAMBER	88.37	450.0	4446.0	16833.6
MAIN NOZZLE EXIT	88.37	450.0	4414.5	16685.4
DILUENT BLEED INLET	1.28	680.0	198.3	509.9
HOT BLEED INLET	0.72	450.0	4446.0	16833.6
TURBINE INLET	2.01	156.4	1850.0	6402.8
MAIN TURBINE EXIT	2.01	19.6	1244.2	4257.5
TURBINE EXIT (AT COLLECTOR)	2.51	19.6	998.4	3402.0
SKIRT EXTEN. EXIT (NOZZ. IN.)	2.51	7.6	1198.4	4097.6

NOZZLE TUBE Q=22029. SKIRT TUBE Q=11861. MAIN NOZZLE THROAT AREA 98.045 IN²
MAIN NOZZLE IDEAL ISP 861.95, TPCV K/A2 VALUE 0.193345E 01, PUMP EXIT DENSITY 4.351
MAIN NOZZLE ACTUAL ISP 837.99 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 374.45

Figure 9 - Steady-State Values with Varied Engine Design Points (Sheet 6 of 12)

MAIN NOZZLE EXPANSION RATIO 100.0 AND TURBINE NOZZLE EXPANSION RATIO 8.00
 TURBINE INLET $W \cdot \sqrt{T}/P$ 0.5550, PRESS. RATIO 8.120, EFF. 0.5500, INLET TEMP. 1730.0
 MAIN NOZZLE TUBES FLOW SPLIT FRACTION 0.650, DESIGN DELTA P 200.0, AND DESIGN DELTA T 155.0

NERVA ENGINE STEADY STATE VALUES 75K NERVA 100 1 TUR. EFF. -5 TUR. INLET + 70R 11 MARCH 1968

ENGINE PC= 450.0 TC= 4446. THRUST 75000. LBS, IMPULSE 825.17 SEC
 POWER LEVEL= 1554.4 MW TURBOPUMP= 19000. RPM

TURBOPUMP	OVERALL
SHAFT POWER, MW	5.7409
TURBINE EFFICIENCY	0.5500
PUMP EFFICIENCY	0.6500

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	90.89	30.0	40.0	-98.8
PUMP OUTLET	90.39	920.0	54.9	-39.0
TPA BEARING COOLANT	0.50	920.0	54.9	-39.0
STRUCTURE SUPPORT INLET	26.80	920.0	54.9	-39.0
STRUCTURE BYPASS INLET	3.20	920.0	54.9	-39.0
NOZZLE MANIFOLD INLET	60.39	880.0	54.9	-39.0
NOZZLE OUTLET	37.30	680.0	209.9	554.1
SKIRT OUTLET	20.08	680.0	209.9	554.1
BOLT COOLANT OUTLET	3.00	680.0	54.9	-39.0
REFLECTOR INLET	57.94	680.0	202.2	524.6
REFLECTOR OUTLET	57.94	640.0	312.9	959.9
PERIPHERAL SHIELD OUTLET	57.94	635.0	320.3	988.9
SUPPORT PLATE INLET	87.94	635.0	305.6	931.1
STRUCTURE SUPPORT OUTLET	26.80	635.0	303.2	921.7
CENTRAL SHIELD INLET	87.94	628.0	311.2	953.1
CORE INLET	87.94	620.0	316.1	972.4
CORE OUTLET	87.94	450.0	4500.0	17088.7
NOZZLE CHAMBER	86.71	450.0	4446.0	16833.6
MAIN NOZZLE EXIT	86.71	450.0	4409.7	16662.6
DILUENT BLEED INLET	2.44	680.0	202.2	524.6
HOT BLEED INLET	1.22	450.0	4446.0	16833.6
TURBINE INLET	3.67	275.2	1730.0	5978.4
MAIN TURBINE EXIT	3.67	34.5	1312.4	4496.2
TURBINE EXIT (AT COLLECTOR)	4.17	34.5	1156.7	3952.7
SKIRT EXTEN. EXIT (NOZZ. IN.)	4.17	22.5	1356.7	4650.8

NOZZLE TUBE Q=22126. SKIRT TUBE Q=11914. MAIN NOZZLE THROAT AREA 96.207 IN²
 MAIN NOZZLE IDEAL ISP 869.75, TPCV K/A2 VALUE 0.406298E 00, PUMP EXIT DENSITY 4.232
 MAIN NOZZLE ACTUAL ISP 845.57 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 401.19

Figure 9 - Steady-State Values with Varied Engine Design Points (Sheet 7 of 12)

MAIN NOZZLE EXPANSION RATIO 70.0 AND TURBINE NOZZLE EXPANSION RATIO 8.00

TURBINE INLET $W \cdot \sqrt{T}/P$ 0.5550, PRESS. RATIO 8.120, EFF. 0.6500, INLET TEMP. 1900.0

MAIN NOZZLE TUBES FLOW SPLIT FRACTION 0.650, DESIGN DELTA P 175.0, AND DESIGN DELTA T 155.0

 NERVA ENGINE STEADY STATE VALUES 75K NERVA 70 1 TUR. EFF. -5 TUR. INLET +100R 11 MARCH 1968

ENGINE PC= 450.0 TC= 4446. THRUST 75000. LBS, IMPULSE 825.60 SEC

POWER LEVEL= 1569.2 MW TURBOPUMP= 19000. RPM

TURBOPUMP	OVERALL
SHAFT POWER, MW	5.1052
TURBINE EFFICIENCY	0.6500
PUMP EFFICIENCY	0.7000

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	90.84	30.0	40.0	-98.8
PUMP OUTLET	90.34	895.0	52.7	-45.6
TPA BEARING COOLANT	0.50	895.0	52.7	-45.6
STRUCTURE SUPPORT INLET	26.80	895.0	52.7	-45.6
STRUCTURE BYPASS INLET	3.20	895.0	52.7	-45.6
NOZZLE MANIFOLD INLET	60.34	855.0	52.7	-45.6
NOZZLE OUTLET	37.27	680.0	207.7	546.0
SKIRT OUTLET	20.06	680.0	207.7	546.0
BOLT COOLANT OUTLET	3.00	680.0	52.7	-45.6
REFLECTOR INLET	58.75	680.0	200.0	516.6
REFLECTOR OUTLET	58.75	640.0	310.4	949.9
PERIPHERAL SHIELD OUTLET	58.75	635.0	317.7	978.8
SUPPORT PLATE INLET	88.75	635.0	304.2	925.4
STRUCTURE SUPPORT OUTLET	26.80	635.0	303.9	924.3
CENTRAL SHIELD INLET	88.75	628.0	309.7	947.5
CORE INLET	88.75	620.0	314.6	966.8
CORE OUTLET	88.75	450.0	4500.0	17088.7
NOZZLE CHAMBER	87.81	450.0	4446.0	16833.6
MAIN NOZZLE EXIT	87.81	450.0	4413.0	16678.3
DILUENT BLEED INLET	1.59	680.0	200.0	516.6
HOT BLEED INLET	0.94	450.0	4446.0	16833.6
TURBINE INLET	2.53	198.7	1900.0	6581.8
MAIN TURBINE EXIT	2.53	24.9	1362.0	4669.4
TURBINE EXIT (AT COLLECTOR)	3.03	24.9	1139.2	3891.5
SKIRT EXTEN. EXIT (NOZZ. IN.)	3.03	12.9	1339.2	4589.3

NOZZLE TUBE Q=22050. SKIRT TUBE Q=11873. MAIN NOZZLE THROAT AREA 97.420 IN²
 MAIN NOZZLE IDEAL ISP 864.39, TPCV K/A2 VALUE 0.107457E 01, PUMP EXIT DENSITY 4.292
 MAIN NOZZLE ACTUAL ISP 840.36 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 398.19

Figure 9 - Steady-State Values with Varied Engine Design Points (Sheet 8 of 12)

MAIN NOZZLE EXPANSION RATIO 60.0 AND TURBINE NOZZLE EXPANSION RATIO 8.00

TURBINE INLET $W\sqrt{T}/P$ 0.5550, PRESS. RATIO 8.120, EFF. 0.7000, INLET TEMP. 1950.0

MAIN NOZZLE TUBES FLOW SPLIT FRACTION 0.650, DESIGN DELTA P 150.0, AND DESIGN DELTA T 155.0

NERVA ENGINE STEADY STATE VALUES 75K NERVA 60 1 TUR. EFF. -5 TUR. INLET +100R 11 MARCH 1968

ENGINE PC= 450.0 TC= 4446. THRUST 75000. LBS, IMPULSE 825.41 SEC
POWER LEVEL= 1575.8 MWTURBOPUMP= 19000. RPM

TURBOPUMP	OVERALL
SHAFT POWER, MW	4.5654
TURBINE EFFICIENCY	0.7000
PUMP EFFICIENCY	0.7500

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	90.86	30.0	40.0	-98.8
PUMP OUTLET	90.36	870.0	50.9	-51.2
TPA BEARING COOLANT	0.50	870.0	50.9	-51.2
STRUCTURE SUPPORT INLET	26.80	870.0	50.9	-51.2
STRUCTURE BYPASS INLET	3.20	870.0	50.9	-51.2
NOZZLE MANIFOLD INLET	60.36	830.0	50.9	-51.2
NOZZLE OUTLET	37.28	680.0	205.9	539.2
SKIRT OUTLET	20.07	680.0	205.9	539.2
ROLT COOLANT OUTLET	3.00	680.0	50.9	-51.2
REFLECTOR INLET	59.09	680.0	198.3	509.9
REFLECTOR OUTLET	59.09	640.0	308.5	942.6
PERIPHERAL SHIELD OUTLET	59.09	635.0	315.8	971.4
SUPPORT PLATE INLET	89.09	635.0	302.8	920.0
STRUCTURE SUPPORT OUTLET	26.80	635.0	303.5	922.7
CENTRAL SHIELD INLET	89.09	628.0	308.4	942.1
CORE INLET	89.09	620.0	313.3	961.4
CORE OUTLET	89.09	450.0	4500.0	17088.7
NOZZLE CHAMBER	88.31	450.0	4446.0	16833.6
MAIN NOZZLE EXIT	88.31	450.0	4414.4	16685.0
DILUENT BLEED INLET	1.26	680.0	198.3	509.9
HOT BLEED INLET	0.78	450.0	4446.0	16833.6
TURBINE INLET	2.05	163.3	1950.0	6759.0
MAIN TURBINE EXIT	2.05	20.5	1356.7	4650.7
TURBINE EXIT (AT COLLECTOR)	2.55	20.5	1092.7	3729.8
SKIRT EXTEN. EXIT (NOZZ. IN.)	2.55	8.5	1292.7	4426.9

NOZZLE TUBE Q=22018. SKIRT TUBE Q=11855. MAIN NOZZLE THROAT AREA 97.974 IN²
MAIN NOZZLE IDEAL ISP 861.95, TPCV K/A2 VALUE 0.174593E 01, PUMP EXIT DENSITY 4.351
MAIN NOZZLE ACTUAL ISP 837.99 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 390.31

Figure 9 - Steady-State Values with Varied Engine Design Points (Sheet 9 of 12)

MAIN NOZZLE EXPANSION RATIO 60.0 AND TURBINE NOZZLE EXPANSION RATIO 8.00
 TURBINE INLET W*SQRT(T)/P 0.5550, PRESS. RATIO 8.120, EFF. 0.7000, INLET TEMP. 1950.0
 MAIN NOZZLE TURBS FLOW SPLIT FRACTION 0.650, DESIGN DELTA P 150.0, AND DESIGN DELTA T 155.0

NERVA ENGINE STEADY STATE VALUES 75K NERVA 60 1 TUR. EFF. -5 TUR. INLET +100R 11 MARCH 1968
 ENGINE PC= 450.0 TC= 4446. THRUST 75000. LBS, IMPULSE 825.41 SEC
 POWER LEVEL= 1575.8 MW TURBOPIUMP= 19000. RPM

TURBOPIUMP	OVERALL
SHAFT POWER, MW	4.5654
TURBINE EFFICIENCY	0.7000
PUMP EFFICIENCY	0.7500

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	90.86	30.0	40.0	-98.8
PUMP OUTLET	90.36	870.0	50.9	-51.2
TPA BEARING COOLANT	0.50	870.0	50.9	-51.2
STRUCTURE SUPPORT INLET	26.80	870.0	50.9	-51.2
STRUCTURE BYPASS INLET	3.20	870.0	50.9	-51.2
NOZZLE MANIFOLD INLET	60.36	830.0	50.9	-51.2
NOZZLE OUTLET	37.28	680.0	205.9	539.2
SKIRT OUTLET	20.07	680.0	205.9	539.2
ROLT COOLANT OUTLET	3.00	680.0	50.9	-51.2
REFLECTOR INLET	59.09	680.0	198.3	509.9
REFLECTOR OUTLET	59.09	640.0	308.5	942.6
PERIPHERAL SHIELD OUTLET	59.09	635.0	315.8	971.4
SUPPORT PLATE INLET	89.09	635.0	302.8	920.0
STRUCTURE SUPPORT OUTLET	26.80	635.0	303.5	922.7
CENTRAL SHIELD INLET	89.09	628.0	308.4	942.1
CORE INLET	89.09	620.0	313.3	961.4
CORE OUTLET	89.09	450.0	4500.0	17088.7
NOZZLE CHAMBER	88.31	450.0	4446.0	16833.6
MAIN NOZZLE EXIT	88.31	450.0	4414.4	16685.0
DILUENT BLEED INLET	1.26	680.0	198.3	509.9
HOT BLEED INLET	0.78	450.0	4446.0	16833.6
TURBINE INLET	2.05	163.3	1950.0	6759.0
MAIN TURBINE EXIT	2.05	20.5	1356.7	4650.7
TURBINE EXIT (AT COLLECTOR)	2.55	20.5	1092.7	3729.8
SKIRT EXTN. EXIT (NOZZ. IN.)	2.55	8.5	1292.7	4426.9

NOZZLE TUBE Q=22018. SKIRT TUBE Q=11855. MAIN NOZZLE THROAT AREA 97.974 IN²
 MAIN NOZZLE IDFAL ISP 861.95, TPCV K/A2 VALUE 0.174593E 01, PUMP EXIT DENSITY 4.351
 MAIN NOZZLE ACTUAL ISP 837.99 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 390.31

Figure 9 - Steady-State Values with Varied Engine Design Points (Sheet 10 of 12)

MAIN NOZZLE EXPANSION RATIO 100.0 AND TURBINE NOZZLE EXPANSION RATIO 8.00

TURBINE INLET $W \cdot \sqrt{T} / P$ 0.6600, PRESS. RATIO 8.100, EFF. 0.5500, INLET TEMP. 1660.0

MAIN NOZZLE TUBES FLOW SPLIT FRACTION 0.650, DESIGN DELTA P 200.0, AND DESIGN DELTA T 155.0

NERVA ENGINE STEADY STATE VALUES 75K NERVA 100 1 TC=+75 ISP=825 PD=1160 14 MARCH 1968

ENGINE PC= 450.0 TC= 4521. THRUST 75000. LBS, IMPULSE 825.29 SEC
 POWER LEVEL= 1563.1 MWTURBOPUMP= 19000. RPM

TURBOPUMP OVERALL
 SHAFT POWER, MW 7.9899
 TURBINE EFFICIENCY 0.5500
 PUMP EFFICIENCY 0.6050

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	90.87	30.0	40.0	-98.8
PUMP OUTLET	90.37	1160.0	61.0	-15.5
TPA BEARING COOLANT	0.50	1160.0	61.0	-15.5
STRUCTURE SUPPORT INLET	26.80	1160.0	61.0	-15.5
STRUCTURE BYPASS INLET	3.20	1160.0	61.0	-15.5
NOZZLE MANIFOLD INLET	60.37	880.0	61.0	-15.5
NOZZLE OUTLET	37.29	680.0	216.0	576.8
SKIRT OUTLET	20.08	680.0	216.0	576.8
BOLT COOLANT OUTLET	3.00	680.0	61.0	-15.5
REFLECTOR INLET	56.71	680.0	208.3	547.4
REFLECTOR OUTLET	56.71	640.0	321.8	994.6
PERIPHERAL SHIELD OUTLET	56.71	635.0	329.4	1024.5
SUPPORT PLATE INLET	86.71	635.0	313.7	963.3
STRUCTURE SUPPORT OUTLET	26.80	635.0	310.5	950.6
CENTRAL SHIELD INLET	86.71	628.0	319.5	985.7
CORE INLET	86.71	620.0	324.5	1005.4
CORE OUTLET	86.71	450.0	4575.0	17443.2
NOZZLE CHAMBER	85.05	450.0	4521.0	17187.9
MAIN NOZZLE EXIT	85.05	450.0	4480.2	16995.7
DILUENT BLEED INLET	3.66	680.0	208.3	547.4
HOT BLEED INLET	1.65	450.0	4521.0	17187.9
TURBINE INLET	5.32	328.7	1660.0	5730.4
MAIN TURBINE EXIT	5.32	44.2	1258.4	4307.9
TURBINE EXIT (AT COLLECTOR)	5.82	44.2	1152.1	3936.9
SKIRT EXTEN. EXIT (NOZZ. IN.)	5.82	32.2	1352.1	4634.9

NOZZLE TUBE Q=22093. SKIRT TUBE Q=11896. MAIN NOZZLE THROAT AREA 95.259 IN2
MAIN NOZZLE IDEAL ISP 878.82, TPCV K/A2 VALUE 0.118613E 00, PUMP EXIT DENSITY 4.147
MAIN NOZZLE ACTUAL ISP 854.39 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 400.42

Figure 9 - Steady-State Values with Varied Engine Design Points (Sheet 11 of 12)

MAIN NOZZLE EXPANSION RATIO 100.0 AND TURBINE NOZZLE EXPANSION RATIO 8.00
 TURBINE INLET $W \cdot \sqrt{T} / P$ 0.6600, PRESS. RATIO 8.100, EFF. 0.5500, INLET TEMP. 1730.0
 MAIN NOZZLE TUBES FLOW SPLIT FRACTION 0.650, DESIGN DELTA P 200.0, AND DESIGN DELTA T 155.0

NERVA ENGINE STEADY STATE VALUES 75K NERVA 100 1 TC=+60R ISP=825 PD=1160 14 MARCH 1968

ENGINE PC= 450.0 TC= 4506. THRUST 75000. LBS. IMPULSE 825.17 SEC
 POWER LEVEL= 1560.9 MW TURBOPUMP= 19000. RPM

TURBOPUMP	OVERALL
SHAFT POWER, MW	7.9908
TURBINE EFFICIENCY	0.5500
PUMP EFFICIENCY	0.6050

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	90.89	30.0	40.0	-98.8
PUMP OUTLET	90.39	1160.0	61.0	-15.5
TPA BEARING COOLANT	0.50	1160.0	61.0	-15.5
STRUCTURE SUPPORT INLET	26.80	1160.0	61.0	-15.5
STRUCTURE BYPASS INLET	3.20	1160.0	61.0	-15.5
NOZZLE MANIFOLD INLET	60.39	880.0	61.0	-15.5
NOZZLE OUTLET	37.30	680.0	216.0	576.8
SKIRT OUTLET	20.08	680.0	216.0	576.8
BOLT COOLANT OUTLET	3.00	680.0	61.0	-15.5
REFLECTOR INLET	56.95	680.0	208.3	547.4
REFLECTOR OUTLET	56.95	640.0	321.1	992.1
PERIPHERAL SHIELD OUTLET	56.95	635.0	328.7	1021.8
SUPPORT PLATE INLET	86.95	635.0	313.2	961.2
STRUCTURE SUPPORT OUTLET	26.80	635.0	310.2	949.3
CENTRAL SHIELD INLET	86.95	628.0	318.9	983.6
CORE INLET	86.95	620.0	323.9	1003.2
CORE OUTLET	86.95	450.0	4560.0	17372.3
NOZZLE CHAMBER	85.27	450.0	4506.0	17117.0
MAIN NOZZLE EXIT	85.27	450.0	4465.8	16927.7
DILUENT BLEED INLET	3.43	680.0	208.3	547.4
HOT BLEED INLET	1.67	450.0	4506.0	17117.0
TURBINE INLET	5.11	322.2	1730.0	5979.6
MAIN TURBINE EXIT	5.11	43.3	1312.8	4497.9
TURBINE EXIT (AT COLLECTOR)	5.61	43.3	1197.8	4095.8
SKIRT EXTEN. EXIT (NOZZ. IN.)	5.61	31.3	1397.8	4794.5

NOZZLE TUBE Q=22098. SKIRT TUBE Q=11899. MAIN NOZZLE THROAT AREA 95.332 IN²
 MAIN NOZZLE IDEAL ISP 876.99, TPCV K/A2 VALUE 0.133427E 00, PUMP EXIT DENSITY 4.147
 MAIN NOZZLE ACTUAL ISP 852.61 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 408.21

Figure 9 - Steady-State Values with Varied Engine Design Points (Sheet 12 of 12)

<u>Case</u>	<u>Figure</u>	<u>Parameter Varied</u>
1	9	Area Ratio and T_c
2		Area Ratio and T_c
3		Area Ratio and T_c
4		Area Ratio, Turbopump Efficiency, and Nozzle Tube ΔP
5		Area Ratio, Turbopump Efficiency, Nozzle Tube ΔP , and Turbine Inlet Temperature
6		Area Ratio, Turbopump Efficiency, Nozzle Tube ΔP , and Turbine Inlet Temperature
7		Area Ratio, Turbopump Efficiency, Nozzle Tube ΔP , and Turbine Inlet Temperature
8		Area Ratio, Turbopump Efficiency, Nozzle Tube ΔP , and Turbine Inlet Temperature
9		Area Ratio, Turbopump Efficiency, Nozzle Tube ΔP , and Turbine Inlet Temperature
10		Area Ratio, Turbopump Efficiency, Nozzle Tube ΔP , and Turbine Inlet Temperature
11		Area Ratio, Turbopump Efficiency, Nozzle Tube ΔP , and Turbine Inlet Temperature

d. Comparison of Results

The performance of the base case compared with the modified cases is listed in Table 3. The main nozzle area ratio of 100:1 is required in accordance with the NERVA Program Requirements Document. However, area ratios of 60:1 and 70:1 are included to show their relative effect on I_{sp} .

e. Results and Conclusions

In each of these 11 cases the objective of a specific impulse of 825 sec was reached. These cases do not represent the only way to achieve this goal but only show the magnitude of changes that must be made in component design to increase specific impulse to meet the program requirement.

TABLE 3

RESULTS OF SPECIFIC IMPULSE STUDIES

Parameter	Case											
	Base	1	2	3	4	5	6	7	8	9	10	11
Specific Impulse (sec)	816.6	825.0	825.4	825.4	825.3	825.3	825.1	825.2	825.6	825.4	825.3	825.2
Thrust (lb)	75,000	75,000	75,000	75,000	75,000	75,000	75,000	75,000	75,000	75,000	75,000	75,000
Area Ratio	70:1	100:1*	70:1*	60:1*	100:1*	70:1*	60:1*	100:1*	70:1*	60:1*	100:1*	100:1*
Chamber Temp. (°R)	4500	4531*	4576*	4600*	4500	4500	4500	4500	4500	4500	4575*	4560*
Turbopump Efficiency	.322	.322	.322	.322	.390*	.490*	.5625*	.350*	.455*	.455*	.333*	.333*
Nozzle Tube ΔP (psid)	240	240	240	240	200*	175*	150*	200*	175*	150*	200*	200*
Turbine Inlet Temp. (°R)	1660	1660	1660	1660	1660	1800*	1850*	1730*	1900*	1950*	1660	1730*
Total Flow (lb/sec)	91.8	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9
Turbine Flow (lb/sec)	4/47	4.43	4.43	4.42	3.51	2.48	2.01	3.67	2.53	2.05	5.32	5.11
Power Level (Mw)	1560	1558	1577	1587	1555	1569	1576	1554	1569	1576	1563	1561

*Parameters Perturbated

4. Thermodynamic Afterheat Removal and Thrust Spoiling

a. Scope

This study was conducted to examine methods of afterheat removal without generating thrust.

b. Functional and Technical Design Requirements

In accordance with NERVA Program Requirements Document, dated 5 June 1968, page 5:

During the shutdown transient, impulse lost by using propellant at less than full I_{sp} shall be minimized. However, after (tbd) seconds of coolant flow, the system should provide for either using the available impulse or for dissipating the coolant flow with zero thrust. The user shall have the option of either using the available impulse or counteracting the thrust.

The same document, Appendix B calls for three missions:

- (1) Synchronous orbit ferry mission (orbital start)
- (2) One way to synchronous orbit mission (suborbital start)
- (3) Manned Mars landing mission

c. Approaches and Significant Characteristics

Two thermo-fluid methods of absorbing the afterheat without producing thrust were considered: (1) space radiator, and (2) heat dump into the LH_2 storage Dewar.

(1) Space Radiator

To compute the minimum surface area of the radiators (and not the minimum weight of the radiators), it was not necessary to consider radiators of complex geometry that would require the calculation of geometrical view factors, effectiveness of extended surfaces, meteorite protection, etc. The following assumptions were made in estimating the surface area:

(a) The thermal conductivity of the radiator material is large.

(b) The thickness of the fluid passage wall is small.

(c) The convective heat-transfer coefficient between the hot fluid and the radiator surface is large compared with the radiative heat transfer coefficient.

(d) Solar radiation received by the radiator surface is small.

(e) Heat is radiated into space at absolute zero temperature. These assumptions have the effect of establishing a minimum surface area for the radiator.

The energy balance equations may be represented as follows:

- (1) Rate of heat transfer, q_1 , from hot fluid to the radiating surface

$$\begin{aligned} q_1 &= \dot{w} C_p dT_b \\ &= 1/(1/h + t/k) (T_b - T) dA \end{aligned}$$

- (2) Rate of heat transfer, q_2 , from the radiator into space

$$q_2 = \sigma \epsilon dA T^4$$

Where:

$A = b \cdot L$,	Surface area of radiator
b ,	Width of radiator
C_p ,	Heat capacity of working fluid
h ,	Convective heat-transfer coefficient
k ,	Thermal conductivity of radiator
L ,	Length of radiator
T_b ,	Bulk temperature of fluid
T ,	Surface temperature of fluid
t ,	Thickness of fluid passage wall
$\dot{w}$,	Fluid flow rate
X ,	Length along flow direction
ϵ	Emissivity of radiating surface
σ ,	Stefan-Boltzmann constant

Based on the above assumptions, these equations may be represented as follows (since $q_1 = q_2$):

$$dA = b \cdot dX = \frac{\dot{w} C_P}{\sigma \epsilon} T^{-4} dT$$

Boundary conditions:

$$\text{At } X = 0, T = (T_b)_{in}$$

$$\text{At } X = L, T = (T_b)_{out}$$

Integration of Equation (4) yields:

$$A = b \cdot L = \frac{\dot{w} C_P}{3 \sigma \epsilon} \left[\frac{1}{(T_b)_{out}^3} - \frac{1}{(T_b)_{in}^3} \right]$$

The results are presented graphically in Figures 10 and 11. Figure 10 shows the fluid-flow rate for a specified inlet temperature and outlet temperature as a function of radiator power. Figure 11 shows the required radiator surface area as a function of fluid-flow rate and the emissivity of the radiator surface.

(2) Heat Dump into the LH_2 Storage Dewar

The second method for removing the heat given off by the delayed neutrons, beta, and gamma between engine runs would be to transfer the heat to the storage tank LH_2 by rechilling the circulating hydrogen in a heat exchanger in the propellant feed tank.

(INLET AND OUTLET TEMPERATURES SHOWN ON CURVES)

Figure 10 - Flow Rate vs Power

(INLET TEMPERATURES SHOWN ON CURVES)

Figure 11 - Radiator Surface Area

To determine the feasibility of this system, a manned one-way-to-synchronous orbit mission was assumed with the following burn times:

Suborbital start (first burn)	1227 sec
Coast in earth orbit	1-1/2 to 6 hr
Depart from earth orbit (second burn)	414 sec
Coast to synchronous orbit	5 hr
Enter synchronous orbit (third burn)	554 sec
Disposal to higher earth orbit	---

Tank LH_2 temperatures were calculated at the end of each coasting period or initiation of the next firing. The heat input to the LH_2 tank was calculated at 1, 2, and 3 hours from shutdown to initiation of the next firing. The tank LH_2 temperature was calculated, assuming slush hydrogen having a latent heat of 25.0 Btu/lb and a sensible heat of 24.86 Btu/lb from 24.86°R to 36.5°R. For temperatures above 36.5°R, a $C_p = 2.256$ Btu/lb-°R was used. The heat to be dissipated was obtained from the values shown in Figure 12 and the total weight of propellant was calculated from the firing times and the total flow rate.

Figure 12 - Integrated Decay Heat vs Time after SCRAM

d. Comparison of Results

Assuming a manned one way-to-synchronous orbit mission the size of the space radiator needed was calculated assuming that emissivity was 0.9 and thrust spoiling was initiated at 100, 1000, and 10,000 seconds after shutdown. The radiator inlet and outlet temperatures used were 200°R and 1000°R, respectively; the decay heats used are shown in Figure 13.

SURFACE AREA OF SPACE RADIATOR NEEDED (ft²)

<u>Firing</u>	<u>Time after Shutdown</u>		
	<u>100 sec</u>	<u>1000 sec</u>	<u>10,000 sec</u>
First	22 x 10 ⁵	6.3 x 10 ⁵	0.5 x 10 ⁵
Second	27 x 10 ⁵	7.8 x 10 ⁵	0.7 x 10 ⁵
Third	30 x 10 ⁵	9.5 x 10 ⁵	1.0 x 10 ⁵

Using the same assumed mission, the resultant heat rise in the propellant tank was calculated if the decay heat were to be absorbed by the propellant:

<u>Firing</u>	<u>Propellant Temperature at Beginning of Firings as Initiated after 1, 2, or 3 hr</u>		
	<u>1 hr</u>	<u>2 hr</u>	<u>3 hr</u>
First	24.86	24.86	24.86
Second	105	86	70
Third	145	114	89

e. Conclusions

Neither method appears to dissipate enough energy to absorb all of the decay heat. However, either method could conceivably be used as a trim on thrust.

Figure 13 - Integrated Total Power vs Time after SCRAM

5. Effects of Internal Pressure Drops on Turbine Inlet Conditions

a. Scope

This study examines the relationship between internal pressure drops of the NERVA engine system and the turbine inlet conditions.

b. Function and Technical Design Requirements

Functional diagrams, AGC Drawing No. 1135437, Sheet 1 - Function 6.0, Fab, Checkout, Ship, and Assemble Nuclear Stage Elements. To support this design activity, it is necessary to determine the possible variations a particular component may be subjected to as a result of irregularities in companion components.

NERVA Program Requirements Document, dated 5 June 1968, page 7, (III. Technical Performance Requirements, paragraph J) Reliability. To assure the high reliability called for in the referenced document, confidence level need not be established by attribute testing, the conditions a particular component may be subjected to must be defined.

c. Approaches and Significant Characteristics

Three constant turbine inlet temperatures were considered: 1600°R, 1660°R, and 1700°F.

Using these three turbine inlet temperatures, a series of steady-state runs were performed and variations in turbine flow rate (W_{TI}), diluent flow rate (W_C), hot flow rate (W_H), and turbine inlet pressure (P_{TI}) were monitored for changes in pump discharge pressure (Figure 14); nozzle tube pressure drop (Figure 15); and core pressure drop (Figure 16).

Figure 14 - Pump Discharge Pressure

Figure 15 - Nozzle Tube Pressure Drop (Sheet 1 of 3)

Figure 15 - Nozzle Tube Pressure Drop (Sheet 2 of 3)

Figure 15 - Nozzle Tube Pressure Drop (Sheet 3 of 3)

Figure 16 - Core Pressure Drop (Sheet 1 of 3)

Figure 16 - Core Pressure Drop (Sheet 2 of 3)

Figure 16 - Core Pressure Drop (Sheet 3 of 3)

d. Comparison of Results

The results shown on Figures 14, 15 and 16 were reduced to obtain rate-of-change of turbine inlet pressure, turbine flow rate, and diluent flow rate with the indicated parameter.

T_{TI} ($^{\circ}R$)	Pump Discharge Pressure			Nozzle Tube ΔP			Core ΔP	
	$\frac{d P_{TI}}{d P_D}$	$\frac{d \dot{w}_{TI}}{d P_D}$	$\frac{d \dot{w}_C}{d P_D}$	$\frac{d P_{TI}}{d(\Delta P_{NT})}$	$\frac{d \dot{w}_{TI}}{d(\Delta P_{NT})}$	$\frac{d \dot{w}_C}{d(\Delta P_{NT})}$	$\frac{d \dot{w}_{TI}}{d(\Delta P_c)}$	$\frac{d \dot{w}_C}{d(\Delta P_c)}$
1600	.34	.005	.0032	.36	.005	.0035	.004	.004
1600	.35	.0047	.0033	.35	.0047	.0035	.0057	.0037
1700	.34	.0048	.005	.34	.0048	.0033	.005	.004
$d \dot{w}_H$ for all temps	.0015			.0017			.001	

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6. Turbine Power Control Valve Override

a. Scope

This study was prepared to determine the effect of a TPCV override for the NERVA engine.

b. Functional Requirements

In accordance with NERVA Program Requirements Document, dated 5 June 1968, page 10, III. Technical Performance Requirements, paragraph P, Safety:

The probability of an engine failure that either (a) causes injury to the crew or damages the spacecraft, or (b) prevents return of the spacecraft to Earth shall not exceed 1×10^{-4} per flight...

c. Approach and Significant Characteristics

To investigate the effect of a TPCV override two similar cases were considered:

(1) The TPCV was allowed to move to its full-open position (80°) in 0.02 sec;

(2) The TPCV was limited to traveling 8° past its design steady-state position (45.3°) in 0.02 sec. This represents the position where the override is expected to be effective.

For each mode, two cases were studied: one in which the nozzle chamber temperature was kept constant, and another in which power was kept constant. These four cases bracket the operation of the system with the controllers.

Sample time plots of the data for the first case are shown in Figures 17 through 20.

NOMENCLATURE

$P_{\text{pump out}}$	- Pump discharge pressure	$P_{\text{pump out}}$	- Pump discharge temperature
$P_{\text{pump in}}$	- Pump inlet pressure	$P_{\text{pump in}}$	- Pump inlet temperature
P_{RI}	- Reflector inlet pressure	T_{RI}	- Reflector inlet temperature
P_{dome}	- Dome pressure (Shield I outlet)	T_{dome}	- Dome temperature
P_{11}	- Turbine inlet pressure	T_{11}	- Turbine inlet temperature
P_{12}	- Turbine outlet pressure	T_{12}	- Turbine outlet temperature
P_c	- Chamber pressure	T_c	- Chamber temperature
$\dot{w}_C$	- Diluent flow rate to turbine		
$\dot{w}_H$	- Hot flow rate to turbine		
$\dot{w}_T$	- Turbine flow rate		

d. Comparison of Results

Peak values of pump flow, pump speed, turbine inlet temperature, turbine inlet pressure, and chamber pressure are as follows at their respective times after the turbine power control valve began its step.

Figure 17 - Gate Position and Pump Speed vs Time

Figure 19 - System Flow Rates vs Time

Figure 20 - System Temperatures vs Time

PEAK VALUES OF $\dot{w}_P$, N, T_{11} , P_{11} AND P_c

Case Parameter	I	II	III	IV
	TPCV $\rightarrow$ 53.3° in 0.02 sec T_c Constant	TPCV $\rightarrow$ 80° in 0.02 sec T_c Constant	TPCV $\rightarrow$ 53.3° in 0.02 sec Power Constant	TPCV $\rightarrow$ 80° in 0.02 sec Power Constant
$\dot{w}_P$ (lb/sec)	107 @ 1.6 sec	115 @ 1.0 sec	106 @ 0.6 sec	114 @ 0.7 sec
N (rpm)	19,560 @ 3.0 sec	20,500 @ 1.0 sec	19,409 @ 0.7 sec	20,277 @ 0.7 sec
T_{11} (°R)	1,900 @ 1.0 sec	1,986 @ 0.2 sec	1,879 @ 0.2 sec	1,966 @ 0.2 sec
P_{11} (psia)	417 @ 1.6 sec	474 @ 0.9 sec	411 @ 0.7 sec	462 @ 0.6 sec
P_c (psia)	525 @ 1.6 sec	565 @ 1.0 sec	518 @ 0.6 sec	552 @ 0.6 sec

e. Results and Conclusions

The parameters listed in the preceding table in all cases peaked at lower values when a TPCV override limited the TPCV travel to 8° past its steady-state value. The need for a TPCV override, however, cannot be determined until operating limits are developed for the system.

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7. Elimination of the Structural Support Bypass System

a. Scope

This study was made to determine the effect of elimination of the structural support bypass system in order to simplify the system and increase engine reliability.

b. Function and Technical Requirements

NERVA Program Requirements Document, dated 5 June 1968, page 6, III, Technical Performance Requirements, paragraph g, Leakage, states that "To minimize leakage the engine shall be designed to minimize joints where leakage may occur."

Functional Flow Diagrams, AGC Drawing No. 1135437, Sheet 1, Function 9.0 - Safety and Approvals is relevant to this parameter.

c. Approaches and Design Requirements

A flow schematic of the proposed NERVA engine is shown on Figure 21. The present design allows for a fixed amount of flow to be extracted from the pump discharge line, and control of the structural coolant flow is obtained by splitting the flow between the structural coolant circuit and the bypass circuit. The modification under consideration in this study is to eliminate the bypass circuit and enable the flow extracted for the structural coolant circuit to vary.

Three computer runs were made using the present conceptual 75K NERVA engine component input to the transient engine computer program, E31201, with structural coolant flow rates of 5, 10, and 30 lb/sec. The state points were then input into the simplified NERVA engine program on the IBM 1130 and they are contained in Figure 22. The 30 lb/sec structural support flow

Figure 21 - Flow Schematic of the Proposed NERVA Engine

NERVA ENGINE STEADY STATE VALUES

75K NERVA ENGINE STRUCTURAL COOLANT FLOW=30 LBS/SEC

ENGINE PC= 450.0 TC= 4446. THRUST 75402. LBS, IMPULSE 824.5 SEC
POWER_LEVEL= 1555.1 MWTURBOPUMP= 18031. RPM

TURBOPUMP	OVERALL
SHAFT POWER, MW	5.4978
TURBINE EFFICIENCY	0.4900
PUMP EFFICIENCY	0.6733

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	91.47	29.4	39.2	-101.1
PUMP OUTLET	90.97	919.9	53.0	-44.1
TPA BEARING COOLANT	0.50	919.9	53.0	-44.1
STRUCTURE SUPPORT INLET	24.00	919.9	53.0	-44.1
STRUCTURE BYPASS INLET	6.00	919.9	53.0	-44.1
NOZZLE MANIFOLD INLET	60.97	885.7	53.0	-44.1
NOZZLE OUTLET	57.97	691.9	220.9	595.0
SKIRT OUTLET	57.97	877.3	85.0	
BOLT COOLANT OUTLET	3.00	691.9	53.0	-44.1
REFLECTOR INLET	58.11	691.9	212.7	563.6
REFLECTOR OUTLET	58.11	647.4	324.9	1007.0
PERIPHERAL SHIELD OUTLET	58.11	638.2	334.7	1045.5
SUPPORT PLATE INLET	88.11	638.2	298.3	902.1
STRUCTURE SUPPORT OUTLET	24.00	638.2	270.5	791.5
CENTRAL SHIELD INLET	88.11	628.7	304.1	925.3
CORE INLET	88.11	616.6	309.0	944.7
CORE OUTLET	88.11	450.0	4500.0	17088.7
NOZZLE CHAMBER	86.78	450.0	4446.0	16833.6
MAIN NOZZLE EXIT	86.78	450.0	4394.7	16591.7
DILUENT BLEED INLET	2.85	691.9	212.7	563.6
HOT BLEED INLET	1.32	450.0	4446.0	16833.6
TURBINE INLET	4.18	326.0	1660.0	5730.3
MAIN TURBINE EXIT	4.18	42.6	1309.1	4485.0
TURBINE EXIT (AT COLLECTOR)	4.68	42.6	1170.7	4001.7
SKIRT EXTEN. EXIT (NOZZ. IN.)	4.68	6.9	1540.5	5297.3

NOZZLE TUBE Q=37058. SKIRT TUBE Q= 0. MAIN NOZZLE THROAT AREA 96.281 IN2
MAIN NOZZLE IDEAL ISP 869.75, TPCV K/A2 VALUE 0.235459E 00, PUMP EXIT DENSITY 4.295
MAIN NOZZLE ACTUAL ISP 845.57 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 431.05

Figure 22 - Steady-State Values, Structural Coolant Flow (Sheet 1 of 3)

NERVA ENGINE STEADY STATE VALUES

75K NERVA ENGINE STRUCTURAL COOLANT FLOW=10 LBS/SEC

ENGINE PC= 450.0 TC= 4446. THRUST 75524. LBS, IMPULSE 822.31 SEC
POWER LEVEL= 1553.2 MW TURBOPUMP= 18999. RPM

TURBOPUMP OVERALL
SHAFT POWER, MW 5.9997
TURBINE EFFICIENCY 0.5130
PUMP EFFICIENCY 0.6788

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	91.75	29.4	39.2	-101.1
PUMP OUTLET	91.25	1026.5	54.2	-39.1
TPA BEARING COOLANT	0.50	1026.5	54.2	-39.1
STRUCTURE SUPPORT INLET	10.00	1026.5	54.2	-39.1
STRUCTURE BYPASS INLET	0.00	1026.5	54.2	-39.1
NOZZLE MANIFOLD INLET	81.25	989.1	54.2	-39.1
NOZZLE OUTLET	78.25	720.1	188.2	472.8
SKIRT OUTLET	78.25	973.0	82.2	
BOLT COOLANT OUTLET	3.00	720.1	54.2	-39.1
REFLECTOR INLET	78.22	720.1	183.1	453.8
REFLECTOR OUTLET	78.22	657.6	268.9	784.9
PERIPHERAL SHIELD OUTLET	78.22	643.1	276.0	813.6
SUPPORT PLATE INLET	88.22	643.1	320.9	991.3
STRUCTURE SUPPORT OUTLET	10.00	643.1	700.4	2380.9
CENTRAL SHIELD INLET	88.22	633.0	326.8	1014.6
CORE INLET	88.22	620.1	331.8	1034.1
CORE OUTLET	88.22	450.0	4500.0	17088.8
NOZZLE CHAMBER	86.78	450.0	4446.0	16833.7
MAIN NOZZLE EXIT	86.78	450.0	4386.5	16553.0
DILUENT BLEED INLET	3.02	720.1	183.1	453.8
HOT BLEED INLET	1.43	450.0	4446.0	16833.7
TURBINE INLET	4.46	347.7	1660.0	5730.9
MAIN TURBINE EXIT	4.46	44.9	1301.1	4456.9
TURBINE EXIT (AT COLLECTOR)	4.96	44.9	1171.4	4004.1
SKIRT EXTEN. EXIT (NOZZ. IN.)	4.96	7.3	1541.2	5299.8

NOZZLE TUBE Q=40061. SKIRT TUBE Q= -0. MAIN NOZZLE THROAT AREA 96.281 IN2
MAIN NOZZLE IDEAL ISP 869.75, TPCV K/A2 VALUE 0.164751E 00, PUMP EXIT DENSITY 4.385
MAIN NOZZLE ACTUAL ISP 845.58 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 431.15

Figure 22 - Steady-State Values, Structural Coolant Flow (Sheet 2 of 3)

NERVA ENGINE STEADY STATE VALUES

75K NERVA ENGINE STRUCTURAL COOLANT FLOW=5 LBS/SEC

ENGINE PC= 450.0 TC= 4446. THRUST 75717. LBS, IMPULSE 821.54 SEC
POWER LEVEL= 1554.4 MWTURBOPUMP= 19222. RPM

TURBOPUMP OVERALL
SHAFT POWER, MW 6.2020
TURBINE EFFICIENCY 0.5390
PUMP EFFICIENCY 0.6796

STATE POINT DESCRIPTION	FLOW LBS/SEC	TOTAL PRESSURE	TEMPERATURE	ENTHALPY BTU/LB
DEWAR OUTLET	92.15	29.4	39.2	-101.1
PUMP OUTLET	91.65	1051.9	54.6	-37.3
TPA BEARING COOLANT	0.50	1051.9	54.6	-37.3
STRUCTURE SUPPORT INLET	5.00	1051.9	54.6	-37.3
STRUCTURE BYPASS INLET	0.00	1051.9	54.6	-37.3
NOZZLE MANIFOLD INLET	86.65	1013.8	54.6	-37.3
NOZZLE OUTLET	83.65	725.7	182.5	453.3
SKIRT OUTLET	83.65	999.0	81.0	
BOLT COOLANT OUTLET	3.00	725.7	54.6	-37.3
REFLECTOR INLET	83.35	725.7	178.1	436.3
REFLECTOR OUTLET	83.35	658.7	259.5	747.7
PERIPHERAL SHIELD OUTLET	83.35	643.0	266.3	774.9
SUPPORT PLATE INLET	88.35	643.0	325.0	1007.4
STRUCTURE SUPPORT OUTLET	5.00	643.0	1418.7	4882.6
CENTRAL SHIELD INLET	88.35	632.9	331.0	1030.8
CORE INLET	88.35	619.9	336.1	1050.7
CORE OUTLET	88.35	450.0	4500.0	17088.7
NOZZLE CHAMBER	86.78	450.0	4446.0	16833.6
MAIN NOZZLE EXIT	86.78	450.0	4382.8	16535.5
DILUENT BLEED INLET	3.29	725.7	178.1	436.3
HOT BLEED INLET	1.57	450.0	4446.0	16833.6
TURBINE INLET	4.86	379.1	1660.0	5731.7
MAIN TURBINE EXIT	4.86	48.9	1320.1	4523.6
TURBINE EXIT (AT COLLECTOR)	5.36	48.9	1198.5	4098.6
SKIRT EXTEN. EXIT (NOZZ. IN.)	5.36	8.0	1568.3	5396.4

NOZZLE TUBE Q=41043. SKIRT TUBE Q= 0. MAIN NOZZLE THROAT AREA 96.281 IN2
MAIN NOZZLE IDEAL ISP 869.75, TPCV K/A2 VALUE 0.833554E-01, PUMP EXIT DENSITY 4.363
MAIN NOZZLE ACTUAL ISP 845.57 AND TURBINE EXHAUST NOZZLE ACTUAL ISP 435.06

Figure 22 - Steady-State Values, Structural Coolant Flow (Sheet 3 of 3)

rate was decreased with chamber pressure and temperature held constant at 450 psia and 4500°R, respectively.

d. Comparison of Results

The thrust, I_{sp} , pump discharge pressure, and component pressure drops most affected by a change in structural coolant flow rate are as follows:

75K NERVA ENGINE

WITH STRUCTURAL FLOW AT 30, 10, and 5 LB/SEC

Structural Flow (lb/sec)	Total Thrust (lb)	Engine I_{sp} (sec)	Total Flow Rate (lb/sec)	Pump Exit Pressure (psia)	Pressure Drop	
					Nozzle & Skirt (psid)	Reflector (psid)
30	75,402	824.5	91.47	919.9	193.8	44.5
10	75,524	822.31	91.75	1026.5	269.0	62.5
5	75,717	821.54	92.15	1051.9	288.1	67.0

e. Results and Conclusions

A plot of Engine ΔI_{sp} vs structural support flow is shown in Figure 23. The 30 lb/sec structural support flow is taken as the reference engine. As the structural support flow rate is decreased at a constant chamber pressure of 450 psia and constant chamber temperature of 4500°R from 30 to 5 lb/sec, the engine I_{sp} decreases by 2.67 sec; the nozzle and skirt ΔP increases by 14 psid; and the reflector ΔP increases by 22.5 psid. If the structural support coolant is limited to a variation between 5 and 10 lb/sec and the bypass is eliminated, the loss in I_{sp} is 0.8 sec.

75K NERVA ENGINE

Figure 23 - Engine Delta I_{sp} vs Structural Support Flow

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8. Back-Pressure Requirements for NERVA Engine Test Facilities

a. Scope

This study presents the analysis that was performed to determine the back-pressure requirements for the NERVA engine test facilities.

b. Functional and Design Requirements

Functional Flow Diagrams, AGC Drawing No. 1135443, Ground Test Sheet, Function 6.0 - Provide Subsystem Segments, First-Level Blocks 6.1 and 6.7. The back pressure requirements for the engine test facility must be adequate to demonstrate engine performance for orbital and suborbital operation, and prevent the introduction of destructive vibrations that would not occur in a flight engine.

In accordance with the NERVA Program Requirements Document, dated 5 June 1968, page 46, IV, Programmatic Requirements, paragraph B, Facilities and Ground Support Equipment:

To the maximum extent possible existing facilities and equipment will be utilized as is or modified to perform ... and testing of NERVA parts, components, subsystems, systems and engine will be in accordance with the requirements of this document.

c. Approach and Significant Characteristics

A review has been made of the technology engine and studies for the large NERVA engine to be used as a guide for the selection of the facility back pressure design. The following information has been reviewed to establish the back pressure requirements.

(1) CFDTs performance data showing the effects of variation of back pressure and tank pressure on the initial bootstrap.

(2) The NERVA engine bootstrap analysis

(3) Facility pull-in at the minimum thrust and maximum specific impulse operating point.

(4) Criteria used for E/STS 2-3.

(5) Engine stability for NRX/EST.

(6) Flight condition requirements.

After reviewing this information, it appears that startup is the major criteria for establishing the back-pressure requirements in the facility: To do a thorough investigation of the requirements requires a detailed analysis of the engine system performance during startup or the use of a NERVA cold-flow engine system. Information including low-speed turbopump performance data is required if the analysis is to be meaningful.

(1) CFDTs Performance Data

A review of CFDTs data indicates that on a typical run when bootstrap is achieved the flow is initially dependent mainly on the tank pressure, but a point is reached in time where the turbopump provides the main driving pressure to the system. In runs where bootstrap did not occur, the tank pressure was the main driving force throughout the run. The starting characteristics of the engine are significantly different in tests where the turbopump becomes the main driving pressure. As back pressures are lowered, lower tank pressures result in successful bootstraps. Figure 24 shows the regions of successful and unsuccessful bootstraps. There is a band of uncertainty in which no data were obtained. Thus, for a tank pressure of 25 psia with a back pressure of 0.25 psia, the engine will bootstrap. However, the engine will not bootstrap with the 25 psia tank pressure and the back pressure increased from 0.25 to 7.5 psia.

Figure 24 - Tank Pressure vs Cell Pressure for CFDTs

Tank pressures between 23 and 35 psia have been discussed in the past during stage studies. For tank pressure of 23 psia the back pressure required is uncertain. At 30 psia, the back pressure could go to 8 psia and still bootstrap will occur.

A second consideration is the timing for the engine to bootstrap. It affects the whole timing of the control system. Figure 25 shows the effect of back pressure on the time to reach the peak speed for different tank pressures. Assuming that a satisfactory facility would match times within 25%, the cross-hatched area shows that a 30 psia tank pressure requires a facility with 1 psia back pressure; a 35 psia tank pressure requires 3 psia back pressure; and a 40 psia tank pressure requires 7.5 psia back pressure.

(2) NERVA Engine Bootstrap Analysis

The analysis of the 200,000-lb thrust NERVA engine indicates that the system is more difficult to bootstrap than the technology engine.

Analyses were made at a tank pressure of 35 psia and back pressures of 0.1, 1.0, and 7.6 psia. The results (Figure 26) show that for back pressures of 0.1 and 1.0 psia the engine bootstrapped, reaching peak chamber pressures in 4 and 5 seconds, respectively. However, for the 7.6 psia back pressure, the engine would not bootstrap. For the technology engine, bootstrap occurs with a 35 psia tank pressure and 7.6 psia back pressure. Thus, the analysis indicates that the NERVA engine is more difficult to bootstrap and that the facilities must simulate flight conditions more closely.

The NERVA engine startup characteristics are different because:

Figure 25 - Time to Peak Speed vs Back Pressure Based on CFDTS Data

Figure 26 - System Cold Flow Operating Paths

(a) The turbine exit is unchoked, making it much more sensitive to back pressure. The exit nozzle for a 1 psia back pressure would choke at 2 psia. For 2 psia at the nozzle, the engine needs 9 psia at the turbine exit or 64 psia at the chamber. A back pressure of 2 psia raises this to 75 psia chamber pressure.

(b) The diluent extraction point occurs in the engine system at a point where colder fluid temperatures are manifest; thus, the fluid delivered to the turbine is colder at any particular time during the bootstrap than would be expected during XE engine operation.

One factor tending to help the NERVA engine bootstrap is the zero NPSP inducer. This guarantees a positive NPSP to the turbopump.

(3) Minimum Thrust at Maximum Specific Impulse

The pull-in at the chamber pressure where the structural limit (or pump stall) intersects with the chamber temperature limit was investigated. The nozzle should flow full at this point. This chamber pressure is 240 psia for XE-1. The use of a different structural design would lower it to about 200 psia. Using the start-pressure ratio of 33 requires a cell pressure of $200/33$, or 6 psia.

(4) Criteria for E/STS 2-3

The criteria for the E/STS 2-3 facility are based on scale-model test data and nozzle considerations. Scale-model tests indicated that a back pressure of 2 psia was the lowest reasonably obtainable back pressure. Since the facility was being designed to simulate flight conditions as closely as possible, the 2 psia back pressure was used as a facility design criteria.

(5) Engine Stability

During NRX/EST, flow oscillations occurred at a chamber pressure of about 140 psia. These oscillations are associated with the fluid conditions in the nozzle at that point. Conditions in the NERVA engine are such that similar oscillations would be expected. It is desirable that the pull-in point for the facility occur before this chamber pressure is reached. Dividing 140 by 33, indicates that a cell pressure of 4 psi or less is required.

(6) Flight Conditions

Reviewing the conditions for flight, there are possibilities of starting the engine under a variety of back pressures which depend on the mission and vehicle configuration. In an orbital start, the engine will be started under conditions of essentially zero back pressure (vacuum). However, in a suborbital start, the shroud surrounding the engine could result in a build-up of back pressure. This indicates the desirability of testing the engine under various back pressure conditions. At this point, insufficient mission and vehicle data are available to define the upper limits for flight conditions.

d. Summary

The tank pressure must be established as an essential step in establishing the facility design criteria for back pressure. Considering engine bootstrap performance and timing, on the basis of CFDTS data, for a 30 psia tank pressure a 1 psia back pressure is required; for a 35-psia tank pressure a 3 psia facility back pressure would suffice. NERVA analysis of the 200,000-lb thrust engine indicated that this engine would be more difficult to bootstrap so that the technology numbers are probably upper limits. Other conditions, such as having the facility pulled in at maximum temperature, engine oscillations, and the criteria for E/STS 2-3, are not as restrictive in the selection of the facility design criteria.

9. Facility Fluid Requirements for Cooldown of the NERVA Engine in ETS-1

a. Scope

This study was prepared to estimate the facility fluid requirements for cooldown of the NERVA engine in Engine Test Stand No. 1.

b. Functional and Technical Design Requirements

In accordance with NERVA Program Requirements Document, dated 5 June 1968, page 46, IV, Programmatic Requirements, paragraph B, Facilities and Ground Support Equipment:

To the maximum extent possible existing facilities and equipment will be utilized as is or modified to perform ... and testing of NERVA parts, components, subsystems, systems and engine will be in accordance with the requirements of this document.

In accordance with NERVA Program Requirements Document, dated 5 June 1968, page 47, IV, Programmatic Requirements, paragraph 3, Management Control of Facilities and Equipment:

To the maximum practical extent, new facilities shall be designed and existing facilities modified to be available as required to meet the test schedule ...

c. Approaches and Significant Characteristics

To cool the NERVA engine, it was assumed that the engine was operating at full power and then Scrammed. Three contingencies were accounted for:

(1) LH_2 was used to remove the stored heat in the reactor and continued flowing until 1100°R thrust chamber temperature was achieved.

The flow rate was then reduced while the thrust chamber temperature was held at 1100°R until GH_2 was introduced to warm up the line and to prevent the LH_2 from freezing when it was introduced (GH_2 - min.).

(2) Initially, LH_2 was introduced to remove the latent heat of the reactor. A switch to GHe was made as soon as it was feasible to do so without exceeding 1200 psia at the nozzle tube inlet torus.

(3) Initially LH_2 was used to remove the stored heat in the reactor and GH_2 was introduced as soon as the driving pressure constraint permitted (minimum GH_2).

Estimates of cooldown fluid requirements were calculated for the 2200 Mw and 1545 Mw NERVA engines in the ETS-1 test facility. For some of the cooldown cases for the 2200 Mw NERVA engine the ETS-1 LN_2 facility supply line was changed from 6-in. to 8-in. to reduce the LH_2 or GHe required. It was determined that the minimum GH_2 required to warm the lines before introducing the LN_2 flow is 600 lb. The flow of GHe was limited by a maximum driving pressure of 1200 psia due to the nozzle and skirt minimum flow areas. The minimum flow areas for the nozzle and skirt were scaled down from the 4200 Mw 200K NERVA engine.

The heat-removal capacitance of 1 lb of coolant to maintain the 1100°R temperature at the thrust chamber is as follows:

Coolant Capacitance		
Gas	Heat Removal (Mw/lb)	ΔT
LH_2	3.69	1000
GH_2	2.22	600
GHe	0.735	560
LN_2	0.233	850

The LH₂ values shown below are estimated for engine startup and run just prior to Scram:

LH ₂ Required to Start and Run Engine		
Power (Mw)	Run Time (minutes)	*LH ₂ Required (lb)
1545	60	361,000
1545	45	271,000
1545	15	90,200
2200	60	523,000
2200	30	262,000
2200	15	131,000

* ETS-1 run tank and storage tank capacity = 173,900 lb.

The heat-generating rates were obtained from Figure 27 and the engine core heat capacities of 5120 Mw (sink temp = 1100°R) for a 1545 Mw reactor and 5990 Mw for the 2200 Mw reactor was accounted for.

Eighteen different cooldown situations were calculated and are summarized below. Each is graphically shown in Figures 28 and 29. These figures pertain to cooldown requirements for reactor operation at full reactor power at durations ranging from 15 to 60 minutes.

d. Comparison of Results

Case		LH ₂ (lb)	GH ₂ (lb)	GHe (lb)	LN ₂ (lb)	Time* (sec)
<u>1545 Mw for 60 Minutes ETS-1</u>						
1.	GH ₂ (Min.)	2500	600	-	380,000	481,500
2.	Max. GH ₂	950	3200	-	380,000	481,500
**3.	GHe (Fire)	2400	-	3700	380,000	481,500

* Time to reduce decay power to 15 Kw.

**A facility modification is necessary in order to deliver GHe in 11 seconds from Scram at 79.7 lb/sec, or a total LH₂ = 567 lb and GHe = 6,750 lb for the 1545 Mw case and a total LH₂ = 567 lb and GHe = 7,587 lb for the 2200 Mw case.

Figure 27 - Integrated Total Power vs Time after SCRAM

CASE 1

93

Figure 28 - Cooldown Situations (1545 Mw for 60 min ETS-1) (Sheet 1 of 7)

Figure 28 - Cooldown Situations (1545 Mw for 60 min ETS-1) (Sheet 2 of 7)

Figure 28 - Cooldown Situations (1545 Mw for 60 min ETS-1) (Sheet 3 of 7)

Figure 28 - Cooldown Situations (1545 Mw for 60 min ETS-1) (Sheet 4 of 7)

GHe (Fire)

Figure 28 - Cooldown Situations (1545 Mw for 60 min ETS-1) (Sheet 5 of 7)

GH₂ (Min.)

CASE 6

Figure 28 - Cooldown Situations (1545 Mw for 60 min ETS-1) (Sheet 6 of 7)

CASE 7

GHe (Fire)

66

Figure 28 - Cooldown Situations (1545 Mw for 60 min ETS-1) (Sheet 7 of 7)

CASE 8

Figure 29 - Cooldown Situations (2200 Mw for 30 min ETS-1) (Sheet 1 of 11)

Figure 29 - Cooldown Situations (2200 Mw for 30 min ETS-1) (Sheet 2 of 11)

GHe (Fire)

Figure 29 - Cooldown Situations (2200 Mw for 30 min ETS-1) (Sheet 3 of 11)

CASE 11

GHe (Fire)
(8" LN₂ Line)

PRESSURE SCHEDULE		
Coolant	Pressure (psia)	
	Start	End
LN ₂	800	80
GH ₂	1200	250
GHe	1200	250
LN ₂	300	60

Figure 29 - Cooldown Situations (2200 Mw for 30 min ETS-1) (Sheet 4 of 11)

CASE 12

Max. GH_2
(8" LN_2 Line)

PRESSURE SCHEDULE		
Coolant	Pressure (psia)	
	Start	End
LH_2	800	80
GH_2	1200	250
GHe	1200	250
LN_2	300	60

Figure 29 - Cooldown Situations (2200 Mw for 30 min ETS-1) (Sheet 5 of 11)

Figure 29 - Cooldown Situations (2200 Mw for 30 min ETS-1) (Sheet 6 of 11)

Figure 29 - Cooldown Situations (2200 Mw for 30 min ETS-1) (Sheet 7 of 11)

CASE 15

Figure 29 - Cooldown Situations (2200 Mw for 30 min ETS-1) (Sheet 8 of 11)

Figure 29 - Cooldown Situations (2200 Mw for 30 min ETS-1) (Sheet 9 of 11)

Figure 29 - Cooldown Situations (2200 Mw for 30 min ETS-1) (Sheet 10 of 11)

CASE 18

GHe (Fire)
(8" LN₂ Line)

Figure 29 - Cooldown Situations (2200 Mw for 30 min ETS-1) (Sheet 11 of 11)

<u>Case</u>		<u>LH₂</u> <u>(lb)</u>	<u>GH₂</u> <u>(lb)</u>	<u>GHe</u> <u>(lb)</u>	<u>LN₂</u> <u>(lb)</u>	<u>Time*</u> <u>(sec)</u>
	<u>1545 Mw for 45 Minutes ETS-1</u>					
4.	GH ₂ (Min.)	2500	600	-	370,000	452,500
5.	GHe (Fire)	2400	-	3700	370,000	452,500
	<u>1545 Mw for 15 Minutes ETS-1</u>					
6.	GH ₂ (Min.)	2500	600	-	120,000	232,000
**7.	GHe (Fire)	2500	-	3700	120,000	232,000
	<u>2200 Mw for 60 Minutes ETS-1</u>					
8.	GH ₂ (Min.)	7500	600	-	405,000	500,000
9.	Max. GH ₂	1400	8100	-	405,000	500,000
10.	GHe (Fire)	1400	-	19,000	405,000	500,000
**11.	GHe (Fire) 8 in. LN ₂ Line	1400	-	6200	430,000	500,000
12.	Max. GH ₂ 8 in. LN ₂ Line	1400	2160	-	430,000	500,000
	<u>2200 Mw for 30 Minutes ETS-1</u>					
13.	GH ₂ (Min.)	3900	600	-	280,000	439,700
14.	GH ₂ (min.) 8 in. LN ₂ Line	2340	600	-	302,000	439,700
**15.	GHe (Fire)	1400	-	6200	302,000	439,700
	<u>2200 Mw for 15 Minutes ETS-1</u>					
16.	GH ₂ (Min.)	3900	600	-	136,000	315,870
17.	GH ₂ (Min.) 8 in. LN ₂ Line	2340	600	-	160,000	315,870
**18.	GHe (Fire) 8 in. LN ₂ Line	1400	-	6200	160,000	315,870
	ETS-1 Facility Storage Capacity for Cooldown	2330	5540	8000	187,600	

* Time to reduce decay power to 15 Kw.

**A facility modification is necessary in order to deliver GHe in 11 seconds from Scram at 79.7 lb/sec, or a total LH₂ = 567 lb and GHe = 6,750 lb for the 1545 Mw case and a total LH₂ = 567 lb and GHe = 7,587 lb for the 2200 Mw case.

e. Conclusions

The coolant flow rates, total coolant required, pressures at the engine interface, and time from reactor Scram are for the purpose of assessing and modifying the ETS-1 facility for testing a NERVA engine. Using the indicated engine requirements, the ETS-1 modification can be forecast.

10. LH₂ TOPPING MODIFICATION TO ETS-1

a. Scope

The purpose of this study is to analytically verify that the LH₂ topping system described in Report RD-DR-0150, ETS-1 Modifications for 75K NERVA Conceptual Study, (U) dated 8 April 1968, is adequate to accommodate testing of the 75K NERVA engine system in ETS-1 and to provide sufficient preliminary analysis to establish an operational mode for the proposed system.

b. Functional and Technical Design Requirements

In accordance with NERVA Program Requirements Document, dated 5 June 1968, page 46, IV, Programmatic Requirements, paragraph B, Facilities and Ground Support Equipment:

To the maximum extent possible existing facilities and equipment will be utilized as is or modified to perform ... and testing of NERVA parts, components, subsystems, systems and engine will be in accordance with the requirements of this document.

In accordance with NERVA Program Requirements Document, dated 5 June 1968, page 47, IV, Programmatic Requirements, paragraph 3, Management Control of Facilities and Equipment:

To the maximum practicable extent, new facilities shall be designed and existing facilities modified to be available as required to meet the test schedule ...

The maximum requirements for the 75K thrust NERVA engine have been established at a flow rate of 100 lb/sec, a run tank pressure of 65 psia, a run duration of 17 minutes, and a total propellant quantity of 90,200 lb for the run.

The current design criteria for the 75K NERVA engine system is based on a zero minimum NPSP turbopump. This imposes a constraint on the propellant supply system in that LH_2 flow must be supplied to the pump inlet at a pressure equal to or greater than the vapor pressure of the propellant at the existing local propellant temperature.

The topping systems to be considered shall have the capability of being operated manually from the test operations consoles located in the control point. To allow for controlled bootstrap starts, topping flow will not be initiated until 3 minutes of steady-state engine operations have been achieved. The topping system must be capable of maintaining specified run tank liquid levels through Scram, flow, programmed shutdowns, and their associated cooldown periods.

The run tank V-5001 will be filled from the storage tank V-3801 immediately prior to the run without subsequent refilling of V-3801.

The maximum design pressure for V-3801 is 115 psia and for V-5001 is 65 psia. When these operational limits are exceeded the test will be terminated.

To provide reasonable operating margins, the design operating pressure of V-3801 shall be considered at 100 psia yielding a ΔP of 35 psi at the maximum specified run tank pressure. The system design shall permit the minimum required topping rate at this ΔP . The minimum liquid level in V-5001 shall not be permitted to drop below the 10% level (or 7000 gallons) and the topping rate shall be such as to keep the level in V-5001 above this minimum limit at a ΔP of 35 psi.

c. Approaches and Significant Characteristics

(1) Description of the Propellant Supply System

(a) Low-Pressure Liquid Hydrogen System

The main storage tank, V-3801, a spherical, double-wall, perlite-insulated Dewar is shown in Figure 30. Maximum volume is 250,688 gallons. However, with an allowable 10% ullage volume (the instrumented 100% level, or full mark), the Dewar capacity is 245,934 gallons (143,014 lb). At other Dewar levels below full mark, the fluid levels are measured with an instrumented probe inserted into the Dewar. The instrumentation data in Figure 30 provide the instrument number, gallon-amount, and other pertinent information at the various Dewar levels.

The low-pressure liquid hydrogen system provides liquid hydrogen to fill the engine run tank (V-5001) and the high-pressure emergency cooldown Dewar (V-5002). The system also supplies liquid hydrogen to the vaporizer for conversion to gaseous hydrogen. The low-pressure liquid hydrogen system consists primarily of the main storage Dewar (V-3801) and transfer piping.

The present 3-LH-6LV low-pressure liquid hydrogen transfer line, consisting of the piping line lengths, valves, and other pertinent components from the storage Dewar (V-3801) to the run tank (V-5001) and to the high-pressure Dewar (V-5002) is shown in Figure 31.

The modified line will utilize part of the present ETS-1 facility transfer line system, 3-LH-6LV, part of a new one, plus an existing ETS-1 system, 7-LH-12HV. The new system has been established to meet the 75K thrust NERVA engine requirements for topping. It will provide 91 lb/sec of flow at a pressure drop from V-3801 to V-5001 of 36.5 psi.

Figure 30 - LH₂ Storage Tank

NOTE:
DIMENSIONS ARE IN
INCHES MEASURED
JULY, 1967

Figure 31 - Liquid Hydrogen Fill Line (Existing)

(b) Propellant Run Tank

The liquid hydrogen run tank (V-5001) is the directly connected source of propellant for engine testing. The run tank is a double-wall, vacuum-insulated vessel, as shown in Figure 32. Nominal, maximum tank volume is 77,000 gallons. With a 10% ullage volume (the instrumented 100% level or full mark), it contains 69,534 gallons (40,900 lb) of liquid hydrogen. At other run-tank levels below the full mark, the fluid levels are measured with an instrumented probe inserted into the tank. The instrumentation data presented in Figure 32 provide the instrument number, gallon-amount, and other pertinent information at the various tank levels.

(c) V-5001 and V-3801 Pressurization and Venting Systems

The gaseous hydrogen system provides hydrogen for the pressurization of three liquid hydrogen Dewars: (1) the main storage Dewar (V-3801), to facilitate the transfer of liquid hydrogen to the propellant run-tank (V-5001) and the high-pressure liquid hydrogen Dewar (V-5002); (2) the propellant run-tank (V-5001) to provide the desired engine tank pressure; and (3) the high-pressure liquid hydrogen Dewar (V-5002) for emergency engine cooldown. The gaseous hydrogen system shown in Figure 33 consists primarily of three high-pressure vessels (V-3207, V-3208 and V-3209) and the transfer piping.

The pressurization of V-5001 is controlled by two valves, PCV-165 to pressurize the tank and PCV-180 to vent the tank. Two modes of control of these valves are available to the operator. One method of control is a manual valve position mode, while the other is an automatic V-5001 pressure control mode. In both the manual and pressure control modes, valves 180 and 165 are controlled with a common analog signal that ranges over both positive and negative voltages. This signal is the voltage on the arm of a

Figure 32 - LH₂ Run Tank

NOTES:
 DIMENSIONS ARE IN INCHES,
 MEASURED JULY, 1967

Figure 33 - GH₂ Pressurization Line

pot during manual operation; it is the output voltage of the pressure controller when operating in the pressure control mode. One polarity of this signal causes valve 165 to open, pressurizing the tank, while demanding 180 to close. The other polarity causes the valve 180 to open, venting the tank, while demanding the valve 165 to close.

The V-3801 LH_2 storage tank is pressurized and vented in similar fashion and is controlled by the two valves: PCV-248 to pressurize the tank and PCV-179 to vent the tank. Figure 34 is a schematic showing the inlet line from the high-pressure GH_2 vessels and the pressurization and venting system for V-3801 and V-5001.

1 50 PCV-165

PCV-165 is a 2-in. globe valve manufactured by Annin Valve Company having a maximum C_v of 13.

2 50 PCV-180

PCV-180 is a 6-in. globe valve manufactured by Annin Valve Company having a maximum C_v of 400.

3 38 PCV-248

PCV-248 is a 2-in. pressure control valve manufactured by Annin Valve Company having a maximum C_v of 13.

4 38 PCV-179

PCV-179 is a 12-in. pressure control valve manufactured by Annin Valve Company having a maximum C_v of 1500.

Figure 34 - Pressurization and Venting System

(2) Mode of Operation

In keeping with the basic approach of providing only minimum changes required for the present system, it is recommended that propellant topping be accomplished in manual control with the topping flow controlled by adjustment of the pressure in the V-3801 LH₂ storage tank and by opening and closing the valves in the propellant transfer line.

Review of data pertinent to topping system characteristics obtained during the test conducted in FEP-III-2, together with consideration of the test requirements for the 75K NERVA engine and the flow impedance of the proposed modified propellant transfer line, shows that manual control will be adequate based on the following considerations:

The V-5001 run tank volume is large compared with the required maximum engine flow rate; therefore, a very slow response time is required with respect to initiation or termination of topping. For example, at the maximum flow rate of 100 lb/sec only 10% of the tank volume is consumed in 41 seconds with no topping, or about 328 seconds are required to deplete the tank from the 90% liquid level to the 10% liquid level. Since the depletion rate of V-5001 is the net effect between engine flow and topping flow the time available for operator action becomes greater if topping is in process.

Analysis of the modified transfer line shows that for engine flow rates of 100 lb/sec or less and V-5001 pressures of 55 psia or less the amount of LH₂ in the run tank can be increased by topping at a flow rate greater than the engine flow being consumed.

Operating room procedures established prior to each test conducted will provide the test operator in charge of propellant supply management with an expected schedule of engine usage and allow him to establish

a schedule for achieving the amount of topping required for the test. Deviations from the planned engine consumption schedule can readily be accommodated for the reasons already presented.

Inspection of the data from topping tests shows that initiation or termination of topping results in less than 1 psi temporary deviation in V-5001 pressure when the tank pressurization is in automatic control.

Calculations show that the liquid head effects on pump NPSP due to changes in the liquid level in V-5001 are negligible compared with the controllable variation of propellant temperature and pressure.

The only operational constraints that appear to be required for this mode of operation indicate that topping should not be initiated or should be suspended when the liquid level in V-5001 is greater than 80%, and that a maximum operating run tank pressure of 60 psia should be established. These recommendations are suggested to ensure that the V-500 tank could not accidentally be flooded or pressurized in excess of 65 psia.

Control of the propellant supply system, including topping, can adequately be maintained by a single test operator, who would be responsible for control of the V-3801 pressurization and vent system, the V-5001 pressurization and vent system, and the propellant transfer line shutoff valves and vent valve. As feedback information this operator would have on display at his console the following measurements:

- a Pressure in V-3801 and V-5001
- b Feed pressure to V-3801 and V-5001
- c Positions of V-3801 and V-5001 pressurization and vent valves, and transfer line security and vent valves

- d On-line calculated flow of the propellant supply line (FE-014)
- e On-line calculated topping flow rate. (Based on the pressure differential between V-3801 and V-5001)
- f Liquid-level measurement of V-3801 and V-5001
- g On-line calculated NPSP at the pump inlet.

The test operator in charge of propellant management would establish a schedule for propellant topping prior to a test based on the predicted engine flow data for the test planned, and control the necessary tank pressures and transfer line valves during the test. For tests conducted at a constant engine flow rate this would consist of bleeding in the transfer line, establishing the V-3801 pressure to provide a topping flow rate equal to engine flow, initiating topping when the liquid level in V-5001 reaches a predetermined level, and terminating topping when sufficient propellant has been transferred to ensure completion of the test.

For mapping tests in which the engine flow rate is frequently varied, it may be necessary to vary the V-3801 pressure or to suspend and reinitiate topping. However, since for this type of test the average engine flow is less than that for full power, the topping requirements can easily be fulfilled.

If an emergency shutdown of the engine occurs during a test, topping would immediately be terminated, and if necessary the tanks and transfer line would be vented.

(3) Steady-State Operation

(a) Topping Capability

The flow impedance of the proposed modified LH₂ transfer line between V-3801 and V-5001 was calculated based on test data obtained on the present transfer line.

Data was analyzed from FEP-III-2 performed on 24 March 1967, to determine the LH_2 topping flow rate in the transfer line between V-3801 and V-5001 with V-5001 at pressures of 10, 25, and 45 psig. The topping flow rates were determined by the V-3801 level change and by the V-5001 level change and FE-14. Figure 35 shows the pressure differential between V-3801 and V-5001 versus the topping flow rate. There is good agreement between the methods of topping flow rate determination. Also shown is the predicted curve from Appendix IV of the Test Summary Report (NTO-R-0092). There is generally good agreement between the predicted and test results. All topping tests performed during FEP-III-2 are shown in Figure 35. The topping flow rate varies from about 60 to 75 pps at V-3801/V-5001 differential pressures of 50 psi to 83 psi.

The friction factor for the existing transfer line was calculated based on the curve shown in Figure 35 and manufacturers' data for the valves used. This friction factor, together with manufacturers data for the proposed 12-in. security valves, was used to determine the flow impedance for the proposed modified transfer line. The results of this analysis are shown in Figure 36. The flow resistance of the line $(\frac{K}{A^2})$ was 0.00875 in.^{-4} .

Based on the flow impedance values shown in Figures 35 and 36 the capability of both the present system and the proposed modified system to fulfill the requirements established by the Criteria for Conceptual Study, ETS-1 Modification for 75K NERVA, dated 8 March 1968, was evaluated. In addition, the capability of either system to achieve a steady-state run with the 75K engine in which all of the propellant stored in V-3801 and V-5001 is consumed was evaluated. This criterion appears to be of interest because it represents a maximum-duration test in which all available propellant is consumed.

Figure 35 - Topping Flow Rate vs Differential Pressure between V-3801 and V-5001

Figure 36 - Topping Flow Rate vs Differential Pressure

This evaluation was based on the following ground rules:

- a A maximum operating pressure in V-3801 of 100 psia
- b A minimum liquid level in V-5001 of 10%
- c Steady-state flow to the engine from V-5001
- d Normal operating procedure for loading propellant

V-3801 would be filled to the 90% level prior to propellant fill and chill of V-5001 and V-5002. V-5001 and V-5002 and the associated lines would then be chilled and filled from V-3801 and the test would be initiated without refilling V-3801. It is estimated from facility test data that V-3801 would contain a maximum of 94,414 lb of propellant at the start of a test and V-5001 would contain 40,900 lb.

Topping would be initiated when the liquid level in V-5001 reached 80%. Based on the predicted start transient shown in Criteria for Conceptual Study, ETS-1 Modification for 75K NERVA, 1562 lb of LH_2 would be consumed in reaching a steady-state flow of 91 lb/sec, providing approximately 72 seconds to ensure normal operation of the engine and feed system prior to reaching the 80% liquid level in V-5001.

The capability of the present and the modified system to supply LH_2 for a steady-state run consuming 90,200 lb of propellant is shown in Figure 37. With the modified system the V-5001 tank pressure is limited only by the maximum operating pressure limit of the tank, and the topping system is adequate even at an engine flow rate of 110 lb/sec. Figure 37 also indicates that the present system is extremely marginal for the accommodation of 75K engine testing. For example, at the engine design flow

Figure 37 - Capability of Topping System for a Steady-State Run
Consuming 90,200 lb

rate of 91 lb/sec the V-5001 run tank pressure must be less than 49 psia to obtain the required topping; at 100 lb/sec flow rate the run tank pressure must be less than 38 psia.

The capability of the present and the modified system to perform a maximum duration steady-state test is shown in Figure 38. Again the modified system is capable of operation at any run tank pressure up to the operating pressure limit and any engine flow rate up to 100 lb/sec. In contrast, at 91 lb/sec the present system would be limited to a run tank pressure of less than 29.5 psia.

(b) NPSP vs Temperature, Pressure, and Liquid Level With and Without Topping

Plots of NPSP versus pump inlet flow rate based on the LH_2 vapor pressure data of Figure 39 for an 80% and 20% V-5001 propellant tank level were constructed for various LH_2 tank pressures (24, 26, 30, 35 and 40 psia) and pump inlet temperatures (35°, 37°, 38°, 40° and 41°R). The curves shown in Figure 40 are based on the latest calculated flow resistance of the propellant supply line from the LH_2 run tank to the pump inlet, which includes the modified PSV inlet adapter for the 75K NERVA engine system. The curves show the effect of temperature and tank pressure on NPSP for steady-state engine operation without topping. For example, if the pump inlet flow rate is 90 lb/sec and the fluid temperature at the pump inlet is 38°R, the run tank pressure must be 24 psia or more to provide a positive NPSP at the pump.

Figure 41 presents curves that show the effect of temperature and pressure with tank topping. The curves have been based on FEP-III-2 topping test data and include the effect of transfer line on pump inlet temperature rise on NPSP during the transfer of LH_2 from V-3801 to the engine pump inlet.

Figure 38 - Capability of Topping System to Utilize all Available Propellant During a Steady-State Run

Figure 39 - Hydrogen Vapor Pressure vs Temperature

Figure 40 - NPSP Map for Various Tank Pressures and Pump-Inlet Temperatures

Figure 41 - NPSP vs Pump Inlet Temperature

FEP-III-2 test data showed that the total temperature rise from V-3801 to V-5001 with the existing 3-LH-6 transfer line to PCV-750 is 2.4°R for a series of seven topping tests. With the LH_2 transfer line change for the 75K mod system, the temperature rise at the pump inlet is predicted to be 1.95°R .

Figure 41 indicates that for a flow rate of 91 lb/sec with an NPSP of zero, the predicted pump inlet temperature and tank pressure are 38.05°R and 24 psia, respectively. The V-3801, 10% tank level, however, should be set at 36°R and held constant. This can be accomplished by venting the V-3801 LH_2 storage tank to atmospheric conditions until the 10% level temperatures remains stable. From Figure 41, venting the V-3801 tank to atmospheric conditions (12.8 psia) would result in a temperature of 35.7°R .

(c) Temperature Rise in Transfer Line

During FEP-III-2 the propellant feed system was operated for approximately 4960 seconds and the maximum measured fluid temperature in the PSL was 41.3°R . The initial unpressurized liquid temperature in V-3801 was 38.25°R and seven periods of topping or V-5001 refill were experienced with a total accumulated time of about 895 seconds. Based on this test data, the fluid temperature at the pump inlet can be kept sufficiently cold during run tank topping to satisfy the 75K engine test requirements.

The predicted LH_2 transfer line steady-state temperature rise between V-3801 (TT-402) and V-5001 (TT-044) as a function of LH_2 flow rate is shown in Figure 42.

The curve is based on FEP-III-2 V-3801 to V-5001 tank topping test data. The temperature rise in the transfer line during the FEP-III-2 tests resulted in a ΔT of 1.05°R . The topping flowrate and system (3-LH-6 transfer line) pressure drop was 75 lb/sec and 80 psi,

Figure 42 - Topping Flow Rate vs Temperature Rise (V-3801 to V-5001)

respectively. Using the test data, an equivalent heat gain due to friction and piping system heat leak was obtained for the 75K modified system. This heat gain was used to construct the curve shown in Figure 42.

Figure 42 shows that for high flow rates the temperature rise is due mainly to friction. For the lower flow rates the inverse is true. For flow rates between 30 to 60 lb/sec there is relatively little temperature rise.

(d) Effect of Rate of Change in Liquid Level on NPSP

The effect of V-5001 liquid level on NPSP was investigated to determine if it would be realistic to closely match topping flow to engine flow if there would be a future requirement for engine tests at constant NPSP.

Based on a V-5001 tank internal diameter of 257 in. and a propellant density of 4.4 lb/ft³ or .002546 lb/in.³, the nomograph presented in Figure 43 was constructed from the data listed below, showing the rate of change in liquid head (or NPSP) contributable to the mass flow into or out of V-5001.

<u>lb/sec</u>	<u>in.³/sec</u>	<u>V-5001 Liquid Level Rate of Change, in./sec</u>	<u>Rate of Change In V-5001 Liquid Head, psi/sec</u>
0	0	0	0
25	9819	0.1893	0.00048
50	19638	0.3786	0.00096
75	29458	0.5679	0.00144
100	39276	0.7572	0.00192

Figure 43 - Rate of Change in the Liquid Head

The results shown in Figure 43 indicate that even with a gross difference between engine flow and topping flow, the rate of change due to liquid head in V-5001 is negligible compared with possible changes in V-5001 pressure (± 0.5 psi), or pump inlet LH₂ temperature relative to control of pump NPSP. For example, at an engine flow of 80 lb/sec with topping at 10 lb/sec the liquid head change rate is only -0.0012 psi/sec. It was therefore concluded that no practical requirement exists for maintaining the liquid level in V-5001 constant during engine testing.

(e) Determination of Steady-State Conditions
During Topping

During the topping, the attainment of steady-state in the modified topping line will be established by monitoring the following ETS-1 facility parameters. These are the same channels that were monitored during a series of seven topping tests conducted during the FEP-III-2 tests, except for TT-044, which is assumed to be located in the modified system as it is now in the present 3-LH-6 system.

- TT-402 - 10% V-3801 LH₂ storage tank temperature, °R.
- TT-044 - LH₂ transfer line temperature, upstream of V-5001 run tank fill entrance, °R (to be added in new system).
- PT-68 - V-3801 LH₂ storage tank ullage pressure, psia.
- PT-99 - V-5001 LH₂ run tank ullage pressure, psia.

TT-402 is the measurement of fluid temperature into the 7-LH-12HV and 3-LH-6LV LH₂ transfer line from V-3801 to V-5001. TT-044 is the temperature at the downstream end of the above line. These two

measurements will be used to determine any heat leak into the transfer line. Steady-state temperature conditions will exist when the temperature at the entrance to V-5001 run tank (TT-044) remains constant.

The V-3801 and V-5001 tank pressures, PT-068 and PT-099 will be monitored to determine that the ullage tank pressures are constant prior to and during topping. The V-3801 to V-5001 flow resistance has been calculated for the new transfer line configuration based on FEP-III-2 test data so flow rate can be planned for and achieved by selection of the tank pressures. The pressures in both tanks are regulated by the tank ullage pressurization systems. No flow meter is needed in the transfer line for monitoring during the tests. Flow rates will be determined by the V-3801 to V-5001 pressure differential.

Additional parameters will be monitored to determine engine inlet conditions prior to and during the topping. These parameters are pump inlet temperatures and pressures. Also, NPSP will be computed on-line and monitored in the Test Diagnostic Center.

(4) Transient Operation

(a) Response Characteristics of V-5001 Pressurization System

The adequacy of the V-5001 pressurization system to maintain pressure control during rapid transients of engine flow and topping flow was demonstrated during FEP-III-2 conducted 24 March 1967. Data from selected portions of this test are shown in Figures 44 through 47 to illustrate the controlling capability of the system.

Figure 44 - Initiation and Termination of Topping

Figure 45 - Initiation of Topping

Figure 46 - Termination of Topping and V-5001 Outflow

Figure 47 - Termination of V-5001 Outflow with Topping

Figure 44 shows the action of the PCV-165 control valve and the run tank pressure during initiation and termination of topping with a small ullage in the V-5001 tank. During this time period the outflow from V-5001 was 83 lb/sec. It may be seen from this figure that the V-5001 pressure was maintained within 0.5 psia during both initiation and termination of topping.

Figure 45 presents data for initiation of topping with a large ullage value (i.e., low liquid level) present in V-5001. Again the V-5001 pressure is constant within 1 psia. For this time period the outflow from V-5001 was approximately 77 lb/sec when a topping flow rate of about 67 lb/sec was established. The large motions of PCV-165 shown prior to the range time 50825 were caused by increases in tank pressure demand.

Figure 46 shows the V-5001 pressurization characteristics during termination of topping, followed by termination of V-5001 outflow and subsequent venting of the run tank. Termination of the topping flow caused PCV-165 to open from about 50% to about 70% in order to maintain the tank pressure and then close fully after the V-5001 outflow was terminated. Subsequent full opening of the vent valve PCV-180 caused the tank pressure to decrease at approximately 1.5 psi/sec.

Figure 47 presents the case in which the V-5001 outflow is rapidly terminated while topping flow continues with subsequent increase in the V-5001 liquid level. Although the topping flow rate was high (approximately 77 lb/sec) PCV-180 moved only to the 22% open position in order to maintain V-5001 pressure within 1 psi. This shows that the V-5001 automatic vent valve PCV-180 is capable of preventing overpressurization of the tank in the event of an emergency shutdown of the engine while run tank topping is in process.

(b) Engine Startup

Run tank topping will not be initiated when the V-5001 liquid level is greater than 80% or following engine startup until the engine system has operated at a steady-state condition long enough to verify that the run tank pressurization system is operating in a normal manner.

(c) Engine Steady-State Operation and Flow Ramps

The data presented in Figures 44 through 47 show that run tank topping may be initiated and terminated at any time during engine operation without affecting engine operation. Evaluation of past and future nuclear engine tests shows that, in general, two types of tests can be expected for the 75K engine:

1 Steady-state tests in which the engine is held at constant conditions for a prolonged period of time;

2 Mapping tests in which the chamber temperature and pressure (and consequently engine flow) are frequently varied.

Run tank topping for the first of these types has already been discussed. For mapping tests, it would be possible to vary the topping rate or to intermittently top the tank; however, it appears unlikely that such a procedure would be required. A review of the mapping tests planned for XE-1 tests shows that, due to the large volume of the V-5001 tank, it is likely that any mapping tests conducted on the 75K engine could be accommodated by a single period of topping at a constant topping flow rate. To illustrate this capability, an example of a mapping test for a 75K engine is shown in Figure 48. This is a rather extreme example since the test includes a period of high flow rate both at start and shutdown with a

Figure 48 - Example of 75K Mapping Test with Propellant Topping

total propellant consumption of 82,000 lb of LH_2 in 1600 sec. It was further decided to determine if the topping requirements could be met at the topping flow rate of 50 lb/sec, corresponding to minimum temperature increase in the transfer line (Figure 42). The results of this example are shown in Figure 48. The topping requirements can easily be satisfied by a single period of topping at a constant flow rate of 50 lb/sec while still maintaining the liquid level in V-5001 between 36% and 73% with a 22% shutdown margin.

(d) Normal Engine Shutdown

In general, topping will be terminated prior to initiation of a scheduled normal engine shutdown, since the propellant consumed during a shutdown is small. In any case, the demands on the propellant feed control system would be less stringent during a normal engine shutdown than during the emergency shutdown, discussed below, because the rate of change in propellant outflow from V-5001 is lower.

(e) Emergency Shutdown

The worst case for an emergency engine shutdown, relative to the propellant feed system, is for the shutdown to occur when topping is at the maximum flow rate, with the V-5001 tank pressure at the maximum operating limit and minimum ullage present in V-5001. Under these conditions, two requirements must be satisfied:

- 1 The V-5001 tank must not be over-pressurized.
- 2 Topping flow must be terminated prior to overflowing the V-5001 tank with LH_2 .

For the operating conditions previously established these worst-case conditions correspond to a V-5001 liquid level of 80% and a V-5001 tank pressure of 60 psia. The maximum topping flow rate for these conditions (Figure 36) is 95.5 lb/sec.

The ullage volume of V-5001, corresponding to a liquid level of 80%, is 2892 ft^3 . Assuming a LH_2 density of 4.4 lb/ft^3 the volumetric topping flow rate is $21.7 \text{ ft}^3/\text{sec}$. For the V-5001 pressure to reach the operational limit of 65 psia, the ullage must be reduced to $\frac{60}{65} (2892) = 2669 \text{ ft}^3$ with no venting of the pressurizing gas. This is a reduction in ullage volume of $2892 - 2669 = 223 \text{ ft}^3$. Therefore, at the topping flow rate of $21.7 \text{ ft}^3/\text{sec}$ it would require 10.3 sec for the V-5001 tank pressure to reach 65 psia if the outflow from V-5001 were stopped instantaneously. Extrapolation of the pressure control valve action, shown in Figure 47, shows that the vent valve PCV-180 would have opened to 100% within 10.4 sec of first closing motion of PCV-165 had it continued to open at its maximum slew rate. Therefore, it is apparent that the control system is more than adequate to prevent over-pressurization of V-5001 for this worst case. In addition, V-5001 was proof-tested to 82 psig and is further protected by relief valve 50-RV-66 set to relieve at 55 psig with a burst disc in parallel designed to rupture at 65 psig. In addition, rapid venting may be accomplished by opening RSV-390, a 12-in. valve with $C_v \approx 2900$. Since it would require 48 sec for V-5001 pressure to reach 94 psia at constant topping flow and no venting, sufficient time for manually opening RSV-390 is available if needed.

For an ullage volume of 2892 ft^3 and a topping flow of $21.7 \text{ ft}^3/\text{sec}$, there is $\frac{2892}{21.7} \approx 133.3 \text{ sec}$ available for closing the security valves in the propellant topping line, to prevent overflowing V-5001 with LH_2 .

(5) Analysis of Water Hammer Effects

A simplistic analysis was made of the maximum pressure spike conditions for the proposed 75K LH_2 topping line due to water hammer.

The analysis showed that if the valve is closed in 0.28 sec or less, a pressure rise of 425 psid will occur. Due to the simplifying assumptions the accuracy of this number has not been determined. The value may not necessarily be conservative. In addition to maximum pressure considerations the probability of large pressure gradients at bends must be considered.

To analyze longer closing times would require the use of a computer program. Such analysis would, however, not account for two-dimensional effects in bends (17 total) or reflections in area reducers (2 total). It is not believed that such an analysis would give adequate information to relate closing time and structural design.

A simple analogy to a water hammer recorded in XECF-EP-II in a LN_2 line was made. On this test a 50 psid overpressure was noted for a valve closing time of 4 seconds. Through analogous comparisons of variables, it was estimated that during 100 lb/sec LH_2 flow in the 75K modified line a condition 50% to 75% as severe would result for the same closing time. As with the other calculations, the accuracy has not been determined, and values may not be conservative.

As 120 seconds is the minimum time required for valve closing, it is recommended that the valve be dampened so the maximum accidental closing rate is 10 seconds. In addition, as a part of normal facility testing, a determination should be made of the quickest closing time in which water hammer is noticeable. A proposed plan is to close the transfer line valves in 30 seconds the first time topping is required and to reduce the closing time by about 5 seconds during each succeeding test until fluid hammer is first noticeable.

d. Summary

The results of this investigation show that the present propellant transfer system must be considered marginal for the requirements of the 75K NERVA engine tests. Incorporation of the modifications to the propellant transfer line described in RD-DR-0150 will provide a system more than adequate for the 75K engine tests. It is recommended that propellant topping be manually controlled by adjustment of V-3801 pressure and by shutoff valves in the propellant transfer line. Flow tests conducted with the present system have demonstrated that the run tank pressurization system is adequate to allow initiation and termination of topping with less than 1 psi variation in tank pressure. The most rapid response time required for the suggested mode of operation is that in the event of an emergency shutdown at maximum V-5001 liquid level and 100 lb/sec topping flow, the propellant line shutoff valves must be closed in less than 123 sec to avoid overflow of V-5001. This is considered to be more than adequate time for operator action.

The most significant effect of topping on engine performance is increase in propellant feed temperature. This effect can be minimized by obtaining a minimum V-3801 liquid temperature at test initiation, and by maintaining a high vacuum in the propellant transfer line jacket.

11. Parametric Study of the Full-Flow Engine Cycle

a. Scope

This study report presents a parametric analysis of three versions of the full-flow cycle 75K NERVA engine, with an evaluation of the performance of each cycle.

b. Functional and Technical Requirements

Reactor changes make a topping cycle NERVA engine feasible and practical. As a consequence, Aerojet should design topping cycle versions of the NERVA engine and compare them with the best bleed cycle engine. A topping cycle engine will provide a specific impulse of 846 sec with a 70:1 nozzle area ratio. This is 23 sec more than the corresponding bleed cycle engine. (Reference: AGC Interoffice Memo (Official Use Only) J. H. Beveridge to W. D. Stinnett, dated 29 April 1968, subject: NERVA Engine Cycle.)

Updated estimates of energy input obtainable from the nozzle, the reflector, and the stem coolant passages, indicate the feasibility of a topping cycle. It was agreed that AGC/WEC would study this matter further and would make system analyses covering the entire engine operating map. (Reference: SNPO-C Letter dated 17 June 1968, R. W. Schroeder to S. A. Varga, subject: NERVA Engine Task Force Meeting of June 13-14, 1968.)

c. Approaches and Significant Characteristics

(1) Three methods of engine pressure control were selected for study:

(a) Throttling valve--a control valve is placed in series with the turbine (Figure 49)

Figure 49 - Throttle Valve

- (b) Turbine bypass--a controllable flow path is provided that bypasses the turbine (Figure 50) and
- (c) Variable area turbine--engine pressure control is maintained by varying the turbine inlet nozzle area (Figure 51).

(2) Throttling Valve

A flow schematic of the throttling valve system is shown on Figure 49. A steady-state summary of design point operating conditions is shown on Figure 52. Two performance maps were made for the full-flow engine cycle with the throttling valve. The first (Figure 53) was made with the engine described on the steady-state summary (Figure 52) and the other (Figure 54) with the reflector and structural support performance perturbed.

The performance map contains lines of constant valve factor, pump discharge pressure, turbine inlet pressure, turbine inlet temperature, and turbopump speed.

The valve factor is plotted instead of valve position lines, since the control valve is not designed and its operating characteristics are not known. Valve factor is inversely proportional to valve angle, with a zero valve factor equivalent to a wide-open valve with no pressure drop. The factor increases as the valve closes, with infinity being equivalent to a closed valve. The valve factor is calculated from the equation:

$$\text{Valve Factor} = \rho (\Delta P)(1000)/\dot{w}^2$$

where: ρ = density at the valve

ΔP = pressure drop across the valve

$\dot{w}$ = flow rate through the valve

The constant valve factor lines starting at 1000°R show a decrease in chamber pressure with a rise in temperature to approximately

Figure 50 - Turbine Bypass

Figure 51 - Variable Area Turbine

$P_c = 450 \text{ psia}$, $T_c = 4500^\circ\text{R}$

	<u>Pressure (psia)</u>	<u>Temperature (°R)</u>	<u>Flow Rate (lb/sec)</u>
Tank	30	40	86.8
Pump Outlet	1645	50	86.8
Struc. Support Outlet	1374	287	23.6
Turbine Inlet	864	301	86.3
Turbine Outlet	611	277	86.3
Chamber	450	4500	86.8

Valve Drop = 510 psid
 Madsen Factor = 0.02
 Turbopump Speed = 28,748 rpm
 Specific Impulse = 847 sec

Figure 52 - Full-Flow Engine Cycle Throttling Valve System Design Point Summary

Figure 53 - Full Power Throttling Valve, Engine Performance Map

Figure 54 - Variable Area Turbine, Engine Performance Map

1800°R, with the larger factors having the greatest decrease, and a progressively smaller decrease in pressure as the valve factors decrease. Above 1800°R the lines show an increase in chamber pressure with an increase in temperature. This performance characteristic is directly attributable to the fact that the unchoked turbine is in the main flow stream and the pressure drop through the core determines the back pressure at the turbine exit. This, in turn, affects the pressure ratio across the turbine and for this particular turbopump assembly, the 1800° to 2000°R range is the most critical, with a minimum pressure ratio at this temperature range. During startup this would have an important effect on the start ramp. If the ramp attempts to follow an increasing pressure and temperature line, the throttling valve would start in a nearly closed position, then rapidly transverse toward the open position as the chamber temperature goes toward 1800°R. At that point a constant valve position line could be followed to the maximum chamber temperature line.

Also during startup the pump discharge pressure remains constant as the chamber temperature and pressure are increased to the 1800 to 2000°R range. Above that the pump discharge pressure is directly proportional to the chamber pressure. At low chamber pressures and chamber temperatures above 2000°R, the pump discharge pressure goes up with increase in temperature, without a corresponding increase in chamber pressure. This is in the region of a nearly closed valve, resulting in an extremely high pressure rise and entropy gain.

As indicated on the map (Figure 53), the turbine inlet temperature follows the chamber temperature. This phenomenon is expected, since the heat gain to the fluid through the components upstream of the turbine is a direct function of the reactor power.

Conversely to the turbine inlet temperature, the inlet pressure is a function mainly of the chamber pressure, and as pointed out previously, the unchoked turbine pressure states are determined by the chamber conditions, core pressure drop, and turbopump operating characteristics.

The pump stall line on each of the operating maps was calculated from the turbopump performance characteristics. For the full-power throttling system, this line is relatively far to the right compared with the other system designs. This is due to the fact that the addition of the valve in the flow stream tends to increase the system entropy gain while increasing the pump head for any particular flow rate. This limits the operation of this system to the right of the stall line on the map.

The following is a partial list of typical characteristics related to a NERVA engine with a throttling valve control system:

(a) Inherently, this is the least efficient of the three types of controls studied. The throttling valve increases the pressure drop through the system, thereby generating entropy. All of the parameters studied are significantly higher in value at the full power operation point than the other two cycles.

(b) The pump stall line limiting operation in the low chamber pressure, high chamber temperature region is much more restrictive on throttling than the other methods of control.

(c) Poor transient start characteristics are expected because of the feedback control of the core flow parameters. At the temperature range from 1000 to 2200°R it can be observed as a reverse necking of the valve factor lines. During a transient start a rapid change in valve position would be required to maintain a smooth transition to full power. During a start transient the valve must be cycled open-close-open; this type of control would tend to complicate the engine controller.

(d) At the design point, chamber temperature and pressure of 4500°R and 450 psia, the valve factor has a value of 0.02. Assuming a wide-open valve would have a valve factor of approximately zero, a chamber

pressure of 607 psia could be reached regardless of other engine limits. This results in an engine control margin of 157 psia at 4500°R.

(3) Turbine Bypass

The bypass engine system (Figure 50) features control by regulating turbine flow. This enables the system to operate at lower pressures than the throttling valve system, since no additional resistance was inserted into the flow stream. The engine system described by the design point steady-state summary on Figure 55 was mapped and is shown on Figure 56. The most apparent difference between the two systems is that the pump stall line is much farther to the left on the map for the bypass than for the throttling valve. This provides a much wider range of operation for the system.

Generally, the constant state lines follow the same general direction as those on the full-power throttling valve system. Lines of constant bypass fraction were calculated that look similar to the valve factor lines on the turbine throttle valve. The turbopump speed lines are increased smoothly with increases in chamber pressure, and show little effect of the chamber temperature except in the lower temperature, higher pressure chamber conditions. Compared to the throttling valve system, much less turbine work is required for similar chamber conditions.

The following is a partial list of typical characteristics related to a NERVA engine with a turbine bypass control system:

(a) This is a more complicated flow design than the throttling valve system, but is more efficient due to less entropy generation.

(b) This system has a broad range of operation, with less than one-half the total flow required by the turbine for full-power operation.

$$P_c = 450 \text{ psia}, T_c = 4500^\circ\text{R}$$

	<u>Pressure (psia)</u>	<u>Temperature (°R)</u>	<u>Flow Rate (lb/sec)</u>
Tank	30	40	86.8
Pump Outlet	1142	47.4	86.8
Struc. Support Outlet	811	306	21.2
Turbine Inlet	811	295	71.4
Turbine Outlet	611.6	275	71.4
Chamber	450	4500	86.8

Bypass Flow Fraction = 0.174

Turbopump Speed = 24,153 rpm

Specific Impulse = 847 sec

Figure 55 - Full-Flow Engine Cycle Turbine Bypass System Design
Point Summary

Figure 56 - Bypass Valve, Engine Performance Map

(c) Of the study designs, the bypass version is least affected by the core flow characteristics, which results in good transient start characteristics.

(d) Pump discharge pressure is 1142 psia at the design point compared with 1645 psia for the throttling valve--a decrease of 503 psia.

(e) At the design point, chamber temperature and pressure of 4500°R and 450 psia, the bypass fraction is 0.174. If all of the pump flow is permitted to flow through the turbine, i.e., bypass fraction of 0.0, a chamber pressure of 606 psia can be reached. This results in an engine control margin of 156 psia at the design chamber temperature of 4500°R.

(4) Variable Area Turbine

The control of the variable area turbine configuration is achieved by changing the pressure ratio across the turbine, which regulates the turbine work and pump head. This pressure ratio is varied by changing the turbine inlet nozzle flow area. The engine system described by the design point steady-state summary on Figure 57 was mapped and is shown on Figure 53.

Similar to the bypass system, the pump stall line allows for operation well to the left on the map. At any given turbine inlet area, the increase in core power results in an increase in chamber pressure and temperature at approximately an equal rate. This is in exception to the map region below 1400°R chamber temperature where the pressure has a decreasing slope. In this area, a rapid reduction of turbine area would be necessary to provide a smooth start transient.

The following is a partial list of typical characteristics related to a NERVA engine with a variable inlet area turbine:

$$P_c = 450 \text{ psia}, T_c = 4500^\circ\text{R}$$

	<u>Pressure (psia)</u>	<u>Temperature (°R)</u>	<u>Flow Rate (lb/sec)</u>
Tank	30	40	86.8
Pump Outlet	1027	47.2	86.8
Struc. Support Outlet	795	349	21.1
Turbine Inlet	795	295	86.5
Turbine Outlet	611.6	280	86.5
Chamber	450	4500	86.8

$$\text{Turbine Inlet Flow Area} = 13.41 \text{ in.}^2$$

$$\text{Turbopump Speed} = 24,117 \text{ rpm}$$

$$\text{Specific Impulse} = 847 \text{ sec}$$

Figure 57 - Full-Flow Engine Cycle Variable Turbine Inlet Nozzle
System Design Point Summary

(a) The pump discharge pressure at the design point is 1027 psia. It is 115 psia lower than the bypass system and 618 psia lower than the throttling valve system. The decrease in pump discharge pressure is indicative of a greater overall engine efficiency.

(b) This is the most efficient of the candidate designs, as the inlet area may be programmed to maintain the desired chamber pressure without introducing entropy losses throughout the system.

(c) Start transient should be smooth, requiring a minimum variation of the turbine inlet throat area.

(d) Largest operational range over complete chamber temperature-pressure map.

(e) The control margin for this system is not as easily defined as the other systems. Chamber pressure is plotted as a function of turbine inlet area on Figure 58. At the design point of 450 psia, the required turbine inlet area is 13.4 in.². Decreasing this area by 9.5% gives a control margin equal to that obtained by the bypass system. To transverse the entire operating map to a maximum $P_c = 680$ psia, a variation of turbine inlet area of 45% is needed. The maximum chamber pressure attainable is then a function of turbine design considerations.

(5) Engine System Sensitivity

To determine the engine system sensitivity to component variation the structural support, core and reflector pressure drop, and the reflector and structural support nuclear power fraction were perturbed. These parameters were chosen to enable variation of conditions upstream and downstream of the turbine.

Figure 58 - Variable Area Turbine Full-Flow Engine System Turbine Inlet Area vs Chamber Pressure

For each system considered, the control variable was plotted versus percent change in reflector and structural support loss coefficient (Figure 59), core loss coefficient (Figure 60), and reflector and structural support nuclear power fraction (Figure 61).

For a variation of the indicated component function of 80% around the design point, the control parameter variations are as follows:

CONTROL PARAMETER VARIATION
IN
PERCENT OF DESIGN VALUES
vs
+40% VARIATION IN COMPONENT BEHAVIOR

<u>System</u>	<u>Core K/A²</u>	<u>Reflector and Structural Support K/A²</u>	<u>Reflector and Structural Support Power</u>
Throttling Valve	0.630	0.204	0.766
Turbine Bypass	0.598	0.244	0.795
Variable Area Turbine	0.229	0.029	0.245

To further illustrate the effect of parameter variation on engine system characteristics, an operating map of the throttling system was compiled with the reflector and structural support nuclear power fraction decreased by 30% and pressure drop coefficients for these components increased by 30%. (Figure 62). The control margin in this case was reduced from 157 psia to 94 psia at 4500°R chamber temperature. This is a reduction of 40%. However, this system, which has the most dependence on component variation, has more than sufficient control margin to obtain the required design conditions.

Figure 59 - Vary Reflector and Structural Support Power Fraction

Figure 60 - Vary Core K/A^2

Figure 61 - Vary Reflector and Structural Support K/A^2

Figure 62 - Throttling Valve, Engine Performance Map

d. Comparison Matrix of Design Approaches

	<u>Throttle Valve</u>	<u>Bypass System</u>	<u>Variable Area Turbine</u>
1. Control margin above 450 psia at 4500°R	157 psia	156 psid	230 psid at least. To be determined by component design consideration.
2. Startup ability	Poor	Good	Excellent
3. Controllability	Poor	Poor	Good
4. Overall engine efficiency as indicated by pump discharge pressure at $T_C = 4500^\circ R$ and $P_C = 450$ psia	1645 psia	1142 psia	1027 psia
5. Percent variance in control param- eters for $\pm 40\%$ variance in reflector and structural support loss coefficient.	20.4%	24.4%	2.9%
6. Percent variance in control param- eters for a $\pm 40\%$ variance in core loss coefficient.	63%	59.8%	22.9%
7. Percent variance in control param- eters for a $\pm 40\%$ variance in reflector and structural support nuclear power fraction.	76.6%	79.5%	24.5%

e. Conclusions and Recommendations

(1) The engine cycle appears feasible even if one considers the largest variations from nominal that are predicted in pressure drops heat generation and heat transfer.

(2) Results show that predicted steady-state performance is satisfactory. However, transient computer runs should be made to describe startup, normal shutdown, emergency shutdown, and other transient operating engine conditions. This would be done with detailed component data in order that critical areas may be defined and investigated.

(3) The variation in percent from design operating conditions of the core, reflector, and structural support are shown on the three sensitivity plots. These plots show the change in control factor, a full-power operating condition, as a function of the respective changes.

Because the variable area turbine is designed to operate at the most optimum performance level under the entire range of engine operating conditions, it is least affected by system design changes.

B. REACTOR SYSTEMS ANALYSIS

1. Determination of Steady-State Operating Summary of 75K NERVA R-Test Article at 100% and 60% Power

a. Scope

This study was made to provide a summary of pertinent system parameters for a NERVA R-test article operating at 100% and 60% of rated power level.

b. Functional and Technical Design Requirements

In accordance with NERVA Program Requirements Document, dated 5 June 1968, page 2, Performance Requirements at Rated Conditions:

Minimum Mixed Mean Chamber Inlet Temp., $T_c = 4500^\circ\text{R}$
Nominal Chamber Pressure, $P_c = 450 \text{ psia}$

c. Approaches and Significant Characteristics

Steady-state points were established through the use of the NERVA engine transient analysis digital computer program. The system was balanced to give the desired chamber temperature and pressure. Complete documentation of the computer program capabilities is presented in Report No. RN-S-0432, Transient Engine Simulation Program (FORTRAN IV).

d. Results

The results of this effort are documented in Figures 63 and 64.

Engine: $P_c = 450$; $T_c = 4464$; Thrust = 59,170 lb; Impulse = 680 sec;
 Power Level = 1550 Mw; $P_a = 12.7$ psia; $\frac{A_E}{A_T} = 12:1$
 Turbopump: None

<u>State Point</u> <u>Description</u>	<u>Flow</u> <u>(lb/sec)</u>	<u>(PS) Pressure (PO)</u>		<u>Temp.</u> <u>(°R)</u>
		<u>Static</u> <u>(psia)</u>	<u>Total</u> <u>(psia)</u>	
Engine Interface	91.0		891	53.3
Bolt Coolant	3.0		887	53.3
Struc. Support Outlet	23.7		638	273
Struct. Bypass Outlet	5.0		638	53.3
Skirt Inlet	59.3		887	53.3
Skirt Outlet	59.3		877	85.1
Nozzle Inlet	59.3		877	85.1
Nozzle Outlet	59.3		693	221
Reflector Inlet	59.4		693	215
Reflector Outlet	59.4		649	325
Periph. Shield Outlet	59.4		638	335
Support Plate Inlet	88.1		638	302
Central Shield Inlet	88.1		629	308
Core Inlet	88.1		617	313
Core Outlet	88.1		450	4501
Nozzle Chamber	86.8		450	4464
Diluent Bleed Inlet	2.89		693	215
Hot Bleed	1.31		450	4473
Turbine Inlet (Simulated)	4.20		327	1660

Figure 63 - R-Test Article Steady-State Summary 100% Power

Engine: $P_c = 270$; $T_c = 4457$; Thrust = 29,580 lb; Impulse = 568 sec;
 Power Level = 930 Mw; $P_a = 12.7$ psia; $\frac{A_E}{A_T} = 12:1$
 Turbopump: None

State Point Description	Flow (lb/sec)	(PS) Pressure (PO)		Temp. (°R)
		Static (psia)	Total (psia)	
Engine Interface	54.3		523	48
Bolt Coolant	3.0		526	48
Struc. Support Outlet	15.3		392	232
Struc. Bypass Outlet	3.2		392	48
Skirt Inlet	32.8		526	48
Skirt Outlet	32.8		523	76
Nozzle Inlet	32.8		523	76
Nozzle Outlet	32.8		424	245
Reflector Inlet	34.1		424	232
Reflector Outlet	34.1		398	355
Periph. Shield Outlet	34.1		392	365
Support Plate Inlet	52.6		392	318
Central Shield Inlet	52.6		386	324
Core Inlet	52.6		378	329
Core Outlet	52.6		270	4500
Nozzle Chamber	52.1		270	4457
Diluent Bleed Inlet	1.73		424	232
Hot Bleed	0.49		270	4473
Turbine Inlet (Simulated)				

Figure 64 - R-Test Article Steady-State Summary 60% Power

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2. Determination of Effect of Core Peripheral Bypass Flow on
Core Exit Temperature for NR Test Article

a. Scope

This study was conducted to determine the core exit gas temperature required to maintain a mixed mean nozzle chamber temperature of 4500°R given a core lateral support leakage flow of 1.33 lb/sec at 1500°R exit temperature.

b. Functional and Technical Design Requirements

In accordance with NERVA Program Requirements Document, dated 5 June 1968, page 2, Performance Requirements at Rated Conditions:

Minimum mixed mean chamber inlet temperature, $T_c = 4500^\circ\text{R}$

c. Approaches and Significant Characteristics

An energy balance on the core, assuming an inlet pressure of 618 psia and temperature of 325°R, was made at flow rates from 0 to 5 lb/sec to determine the core exit gas temperature required to maintain 4500°R mixed mean nozzle chamber temperature. The analysis was made by assuming that the energy of the gas in the nozzle chamber was equal to the sum of the energy in the lateral support flow plus the energy of the core flow. Figure 65 shows the variation in core exit gas temperature as a function of bypass flow rate at the conditions specified.

d. Results

An energy balance on the core, assuming an inlet pressure of 618 psia and a temperature of 325°R, showed that a core exit temperature of 4539°R would be required to maintain a mixed mean exit temperature of 4500°R.

Figure 65 - Core Exit Temperature Required to Maintain Mixed Mean Exit Temperature of 4500°R vs Core Bypass Flow Rate