N93-26953

NUCLEAR ENGINE SYSTEM SIMULATION (NESS) VERSION 2.0

- OVERVIEW -

22 JANUARY 1992

PRESENTED BY:
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PRESENTED AT:
1992 NUCLEAR PROPULSION - TECHNICAL INTERCHANGE MEETING
NASA LEWIS RESEARCH CENTER
SANDUSKY, OH

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TOPICS

- BACKGROUND
- FEATURES
- COMPARISONS
- CONCLUDING REMARKS

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BACKGROUND

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NUCLEAR THERMAL PROPULSION (NTP) ENGINE SYSTEM ANALYSIS PROGRAM DEVELOPMENT
- Overall Objective -

- Develop a Stand-alone, Versatile NTP Engine System Preliminary Design Analysis Program (Tool) to Support Ongoing and Future SEI Engine System and Vehicle Design Efforts

  - Perform Meaningful (Accurate), Preliminary Design Analysis - Tank to Nozzle
  - Have Flexibility:
    -- To Handle a Wide Range of Design Options to Support Preliminary Design Activities
    -- To Be Easily Upgraded in Terms of Analysis Capability
  - Be Available to the SEI Community, Possibly as an Industry Standard
  - Be Done Promptly and Efficiently
  - Initial Effort:
    -- Focused on NERVA/NERVA Derivative, Solid-Core NTP Systems
    -- Based on Upgrading SAIC's NTP ELES Design Code by Incorporating Westinghouse's ENABLER Reactor and Internal Shield Models

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NUCLEAR THERMAL PROPULSION (NTP) ENGINE SYSTEM ANALYSIS PROGRAM DEVELOPMENT

- Observations -

- No NTP-Specific Code is Commonly Available for Use in SEI Propulsion and Vehicle Design Studies
  - Versatile, Verified NTP Analysis Design Tool Could Be of Great Use to the Community
- It Is Envisioned That NESS Is One Key Element in Developing a Robust (Industry Standard Type) Analysis Capability (Design Workstation) to Support NTP Development Into the 21st Century
  - Enhancements in Terms of Additional Technology/Design Options and/or Analysis Capabilities Possible With the NTP ELES Model

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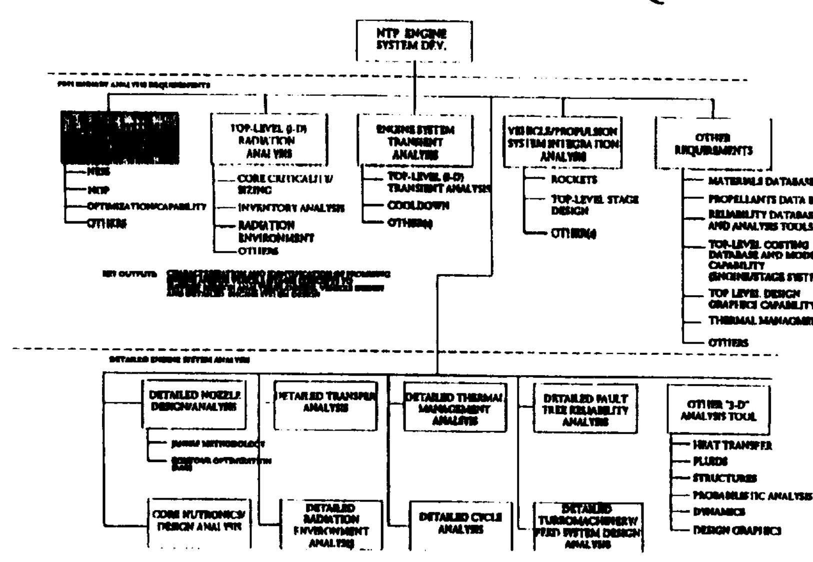
NUCLEAR THERMAL PROPULSION ENGINE DEVELOPMENT ANALYSIS CAPABILITY REQUIREMENTS



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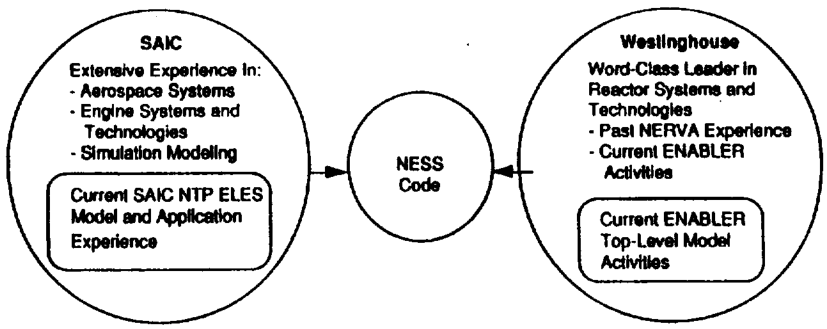
TEAM RESOURCES USED TO SUPPORT NESS DEVELOPMENT



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EXPANDED LIQUID ENGINE SIMULATION (ELES) COMPUTER MODEL
- Background -

- Its Major Objective is to Conduct Preliminary System Design Analysis of Liquid Rocket Systems and Vehicles
- Delivered by Aerojet in the Early 1980's (1981-1984) Under Sponsorship by the Air Force Rocket Propulsion Laboratory (Now Phillips Laboratory)
  - Over $1.2 Million Spent by the Air Force in Its Development
  - Available Through the Air Force
- ELES Has Been Well Distributed and Accepted Within the Propulsion Community for Preliminary Liquid Propulsion System Design Analysis
- ELES Draws on Past Experience and Knowledge From Aerojet and Others
  - Encompasses Aerojet Vast Engineering Base and Expertise in Liquid Propulsion
    -- In-house Experience Included in the Model
  - Has Legacy to Experts Active in the Community

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EXPANDED LIQUID ENGINE SIMULATION (ELES) COMPUTER MODEL (Cont.)

- Background -

- ELES Model Uses Mechanistic as Well as Empirical Models of Components/Subsystems
- The Model Is Well Structured, User Friendly, Easily Modified, and Documented
- A High Degree of Verification has Been Done on the ELES Code

> - ELES Is a Comprehensive Industry Type, Standard Code Available to Perform Preliminary Steady-State Liquid Propulsion Design Analysis
>   - A key Starting Point in Initial NTP Engine System Development

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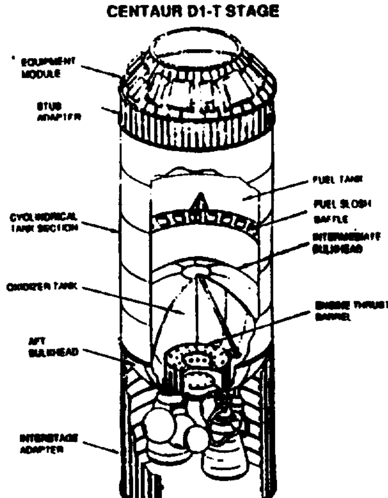
ELES VERIFICATION EXAMPLES

- N-II DELTA (DELTA 2ND STAGE)
- TRANSTAR (TITAN 3RD STAGE)
- CENTAUR/RL-10 DT-1 STAGE
- SPACE SHUTTLE MAIN ENGINE

CENTAUR/RL-10 D1-T VERIFICATION SUMMARY

	ACTUAL	CALC	ACTUAL/CALC
Turbine Pressure Ratio	1.337	1.299	1.029
Regen Jacket ΔT	416	503	0.83
Ox Pump Outlet Pressure	597	604	0.99
Fuel Pump Outlet Pressure	990	954	1.04
Engine System	605	634.9	1.05
TPA Weight	76.1	80.6	0.94
Stage Dry Weight	4046	3952	1.02
Stage Burnout Weight	4602	4364	1.05
Stage Length	360	357.3	1.01
Engine Performance	444	444.6	1.00

CENTAUR D1-T STAGE



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NESS PROGRAM DEVELOPMENT EVOLUTION

FY 1989-90
INITIAL SAIC
NTP-ELES DEVELOPMENT

FY 1991
NESS-VERSION 1.0
- ENABLER I ENGINE
SYSTEM

FY 1992
NESS-VERSION 2.0
- ENABLER II ENGINE
SYSTEM

FY 1993
NESS PUBLIC RELEASE
THROUGH COSMIC
- PC and Vax Versions

- Extensive Anchor/Verification of the Program Performed For Each Development Phase
- BETA Versions of NESS - Versions 1&2 Are Successfully in Operation At NASA Lewis

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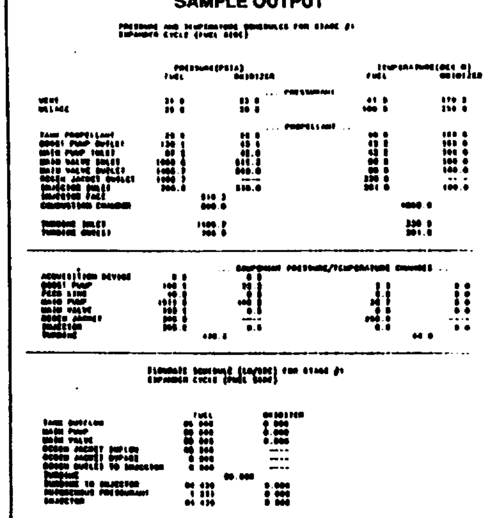
PAST NTP ELES ANALYSIS CODE MODIFICATIONS AND VERIFICATIONS

- ELES-NTP Version Developed and Verified
  - Modifications Performed
    - Incorporation of H_2 and CO Property Tables
    - Monopropellant Turbopump-fed System Modifications
    - Reactor Weight and Dimension Correlations Added
    - Off-Design Engine Operation Capability
  - Verification Conducted
    - Rocketdyne Performance and Weight Data
    - Westinghouse NERVA Data
    - Compared with NASA 90-Day Study Input
  - Much Developed Under SAIC In-House Fund Sponsorship

SAMPLE OUTPUT



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GENERAL NTP ENGINE SYSTEM FEATURES MODELED BY NESS

- **Incorporates a Near-Term Solid-Core NERVA/ NERVA-Derivative Reactor Designs**
  - Westinghouse ENABLER I&II NTP Reactor Designs
  - Strong Westinghouse R-1 Reactor Design Legacy

- **Incorporates State-of-the-Art Propulsion System Technologies and Design Practices**

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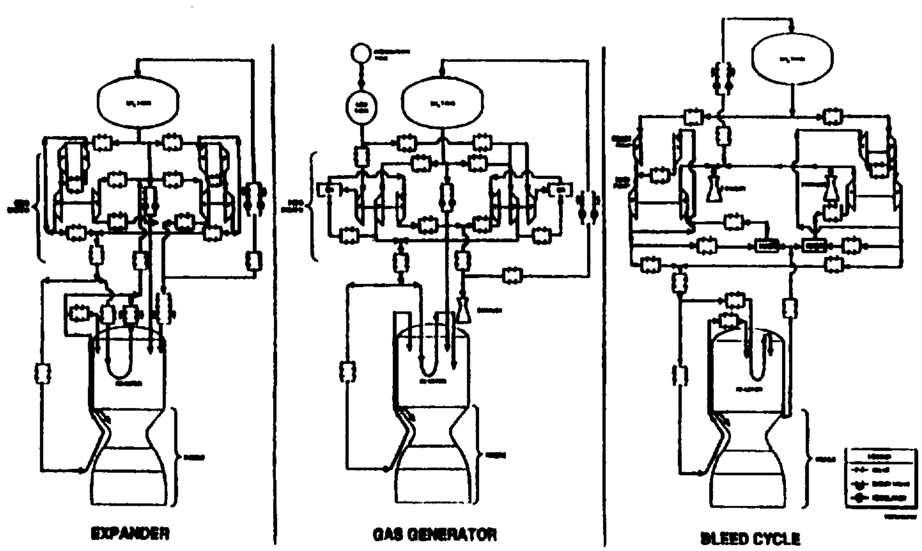
REPRESENTATIVE NTP EXPANDER, GAS GENERATOR, AND BLEED ENGINE SYSTEM CYCLES MODELED BY NESS



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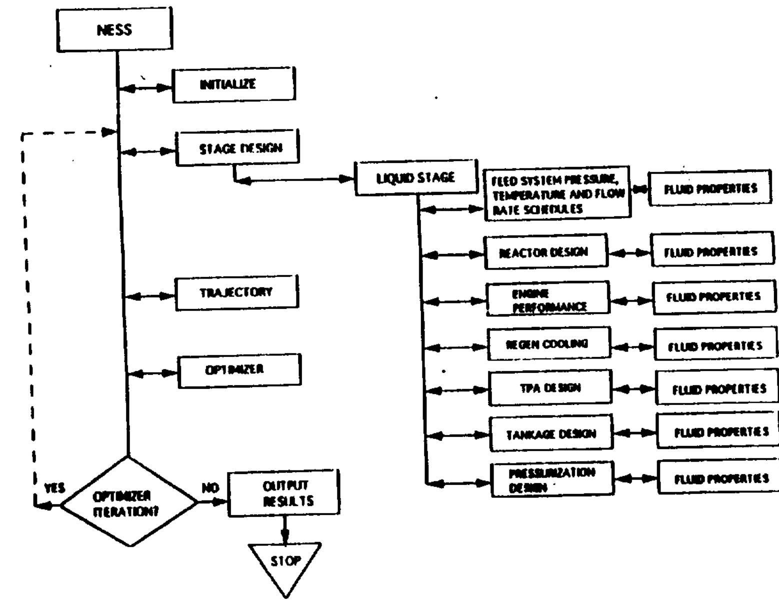
NESS PROGRAM OVERVIEW



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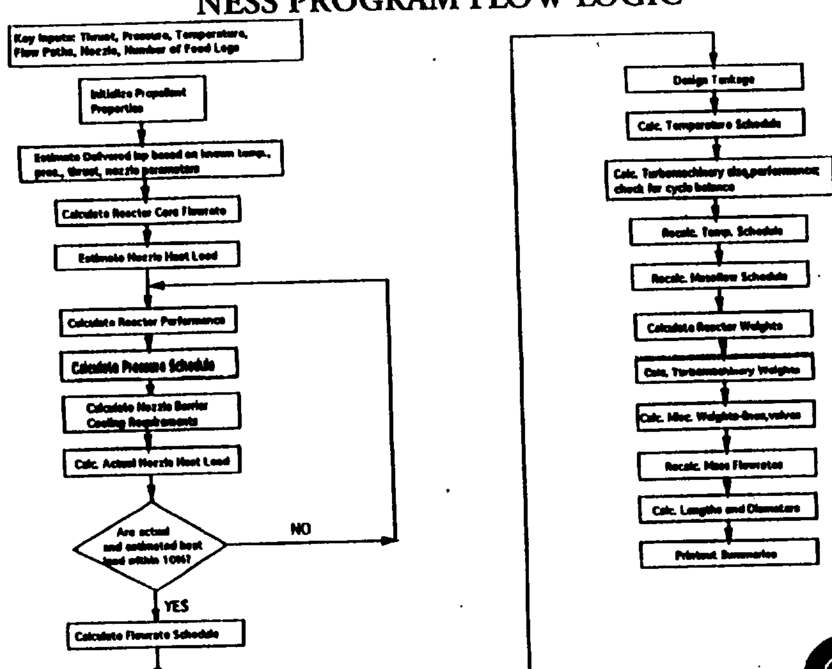
NESS PROGRAM FLOW LOGIC



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TOP-LEVEL KEY NESS FLAGS AND INPUT VARIABLES

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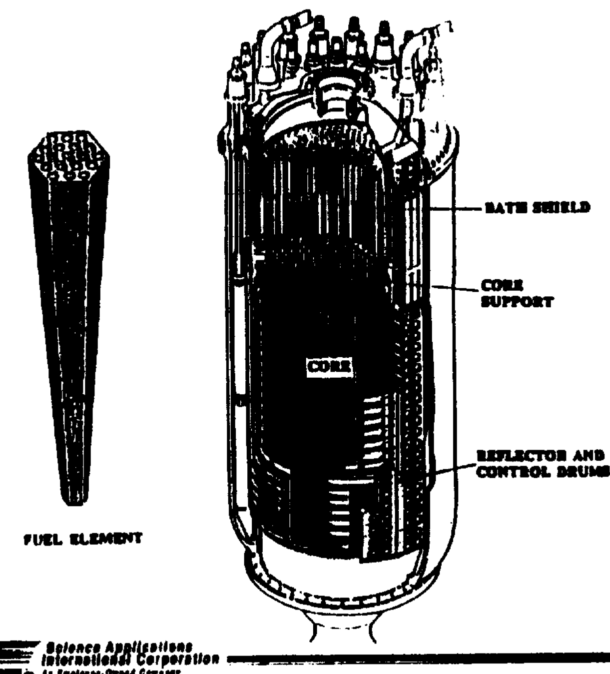
ENABLER (NERVA TYPE) NUCLEAR THERMAL ROCKET ENGINE



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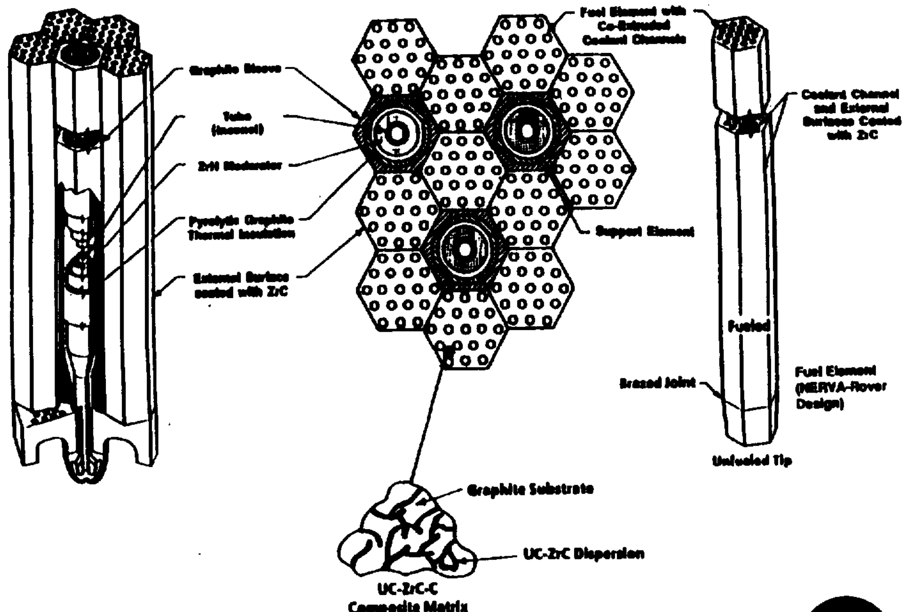
PRISMATIC FUEL ELEMENTS AND SUPPORTS



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REACTOR FUELD AND SUPPORT ELEMENT PARAMETERS

Fuel Element Composition	Graphite	Composite	Carbide
Temperature Range (°K)	2200-2500	2500-2900	2900-3300
Fuel	Coated Particle	UC . ZrC Solid Solution and Carbon	(U,Zr) C Solid Solution
Coating	ZrC	ZrC	—
Unfueled Support Element Composition	Graphite	ZrC-Graphite Composite	ZrC
Unfueled Element Coating	ZrC	ZrC	—

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REACTOR PARAMETERS AS A FUNCTION OF THRUST LEVEL

Thrust (lbf)	15,000	25,000	>50,000
Reactor Power Range	275-400	460-670	920-6700
Fuel and Support Element Length (inch)	35	35	52
Pressure Vessel Length (inch)	82.6	84	101.6
Fuel Element Power (MW)	0.629	0.808	1.20
Relative Fuel Element Power Density	0.778	1.0	1.0
Ratio of Fuel Elements (N) to Support Elements	2:1	3:1	6:1

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INTERNAL SHIELD SIZING

- Sized to Meet Radiation Leakage Requirements Established for the NERVA Program
- Radiation Leakage Limits at a Plane 63 Inches Forward of the Core Center

Type of Radiation	Radiation Leakage Limits Within Pressure Vessel Outside Radius
Gamma Carbon KERMA Rate	1.8×10^7 Rad(c)/hr
Fast Neutron Flux	2.0×10^{12} n/cm^2-sec
Intermediate Neutron Flux	3.0×10^{12} n/cm^2-sec, $0.4\ \text{eV} \leq En \leq 1.0\ \text{MeV}$
Thermal Neutron Flux	6.0×10^{11} n/cm^2-sec $En < 0.4$ ev

- Materials and Thickness
  - For Thrust Level ≥ 50,000 lbf
    - -- 12.5 Inches of Borated Aluminum Titanium Hydrid (BATH)
    - -- 1.3 Inches Lead
  - For Thrust Levels < 50,000 lbf, BATH and Lead Thickness Slightly Reduced Due to Lower Core Power Density

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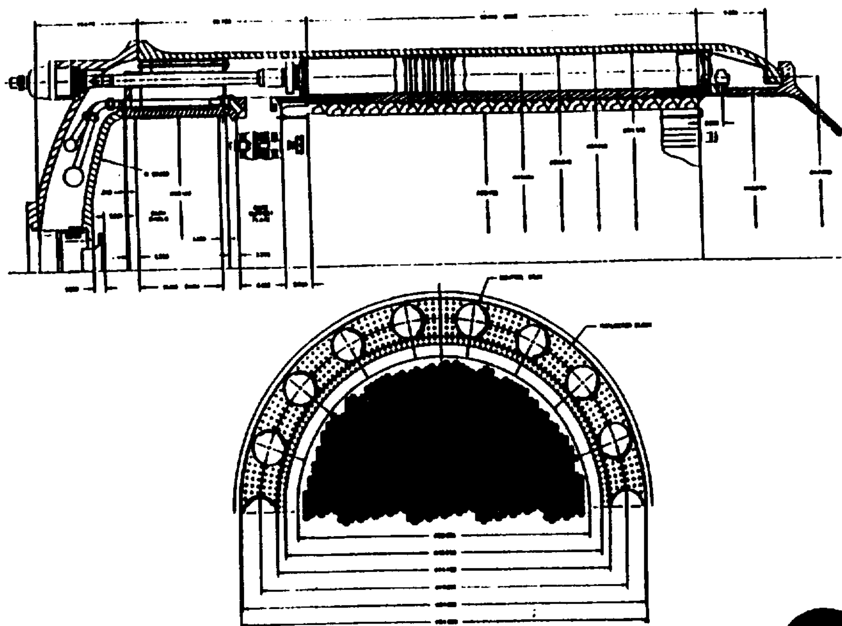
LAYOUT DRAWING OF THE R-1 REACTOR



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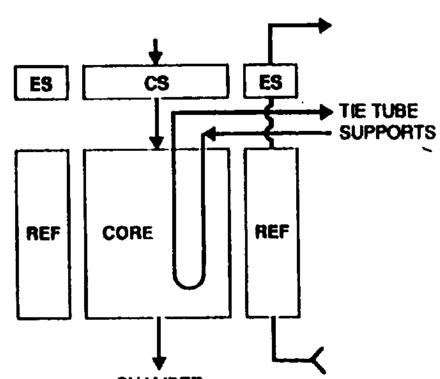
REACTOR THERMAL MODEL

HEAT GENERATION	
Core	~1,500 MW
Tie Tubes	3-7%
Reflector	1-2%
Central Shield	~0.2%
Ext. Shield	~0.03%

COMPONENT BLOCK DIAGRAM



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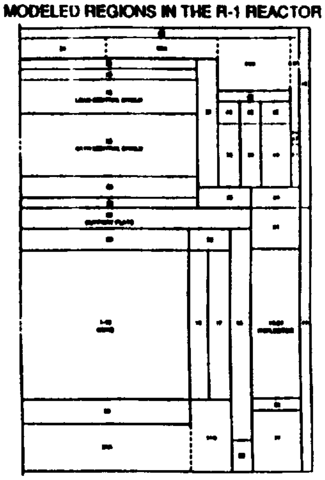
REACTOR WEIGHT MODEL

- Based On R-1 Engine Design
- 53 Reactor Regions Itemized
- Masses Adjusted With Changes In Core Size

MODELED REGIONS IN THE R-1 REACTOR



REACTOR WEIGHT MODEL REGIONS (EXAMPLE)

REGION NUMBER	REGION DESCRIPTION	MATERIAL
1 - 15	Core	Fueled Element Unfueled Element Pyro Sleeve A-286 SS-304 Hydrogen
16	Core Periphery	Graphite-G Pyrofoil ZrC (80% Dense) TZM Moly Hydrogen
17	Lateral Support	P03 Graphite ZTA Graphite Pyrofoil Hydrogen
18	Structure	P03 Graphite Al-6061 A-286 Hydrogen

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NON-NUCLEAR AUXILIARY COMPONENT WEIGHTS

- **Updated Weight Correlations Incorporated for the Following Auxiliary Components:**
  - Instrumentation
  - Pneumatic Supply System
  - Reactor Cooldown Assembly
  - Thrust Structure

- **Based on Past Work by TRW (1965) Which Developed Detailed Weight Correlations for Such Components Based on Evolving NERVA Designs**
  - Updated to Take Into Account Advances In Technology and Design Practices

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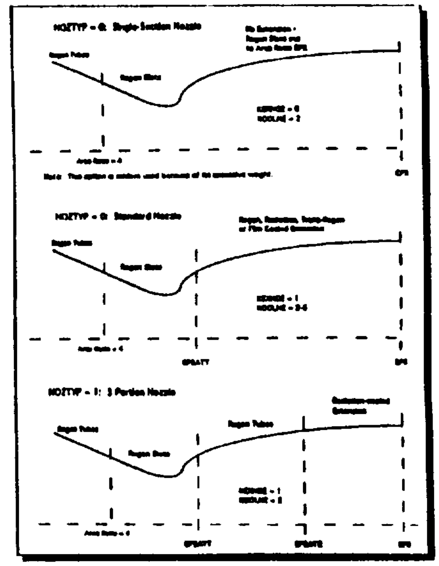
NESS NOZZLE DESIGN OPTIONS

- **STATE-OF-THE-ART NOZZLE DESIGN OPTIONS AVAILABLE**
  - **Regenerative Cooled Slotted-Tube Construction, Radiation Cooled Extension**
  - **Initialized With Up-to-Date Materials**
  - **Capable of Analyzing Nonconventional Nozzle Designs**
  - **Translating and/or Gimbaling Nozzles Possible**



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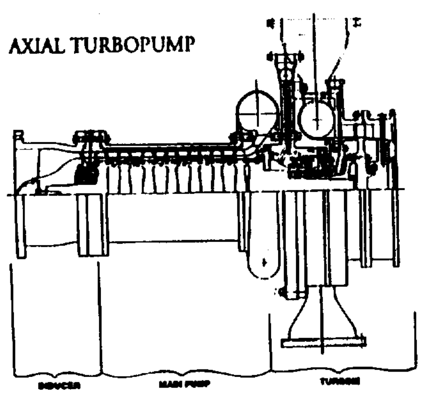
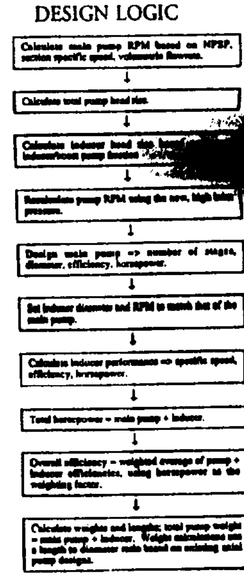
AXIAL TURBOPUMP DESIGN MODULE DEVELOPED AND INTEGRATED INTO NESS VERSION 2.0

AXIAL TURBOPUMP



- Design Correlations Draw on Past Axial Turbopump Decisions and Test
  - Liquid Rocket Engine Axial Flow Turbopumps, NASA SP-8125, April 1978
- Axial Trabopump Weight Model Anchored on:
  - Recent Rocketdyne Design Studies
  - Past Cermet NTP System Design Study

DESIGN LOGIC



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MAJOR NESS ENGINE SYSTEM ENGINEERING DESCRIPTION AREAS

- System Pressure, Temperature and Mass Flow Schedule
- Turbopump Design and Operation
- Nozzle Peformance Losses
- Regenitatively Cooled Nozzle Design
- Reactor Subsystem Design and Operation

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TYPICAL ENGINE SYSTEM DESIGN SUMMARY

ENGINE SUMMARY

EXPANDER CYCLE				
ENABLER II				
CENTRIFUGAL PUMPS				
THRUST LEVEL =	75000.0	lbf	333000.0	N
CHAMBER PRESSURE =	1000.0	psia	[illegible]	kPa
CHAMBER TEMPERATURE =	[illegible]	deg R	2700.0	deg K
NOZZLE EXIT AREA RATIO =	200.0		200.0	
NUMBER OF FEED LEGS =	2		2	
TOTAL PROPELLANT FLOWRATE =	83.1	lbm/s	37.7	kg/s
REACTOR				
COMPOSITE FUEL				
FUEL SCALING FACTOR	0.07		0.07	
REACTOR WEIGHT	[illegible]	lbm	[illegible]	kg
SHIELD WEIGHT	2424.3	lbm	[illegible]	kg
PRESSURE VESSEL DIA.	[illegible]	in	114.7	cm
PRESSURE VESSEL LENGTH	87.0	in	221.0	cm
CORE PROPELLANT MASS FLOW	80.7	lbm/sec	36.6	kg/sec
NOZZLE				
CONVERGING NOZZLE WEIGHT	[illegible]	lbm	76.0	kg
NOZZLE EXTENSION WEIGHT	[illegible]	lbm	27.0	kg
SECOND NOZZLE EXTENSION WEIGHT	226.1	lbm	102.6	kg
TOTAL NOZZLE WEIGHT	[illegible]	lbm	[illegible]	kg
AREA RATIO	200.0		200.0	
THROAT DIAMETER	[illegible]	in	19.0	cm
EXIT DIAMETER	106.0	in	[illegible]	cm
NOZZLE LENGTH	[illegible]	in	416.1	cm
DELIVERED VACUUM ISP	[illegible]	sec	[illegible]	N-sec/kg
DELIVERED THRUST	75000.0	lbf	333000.0	N
TURBOPUMP ASSEMBLY (TOTAL FOR ALL FEED LEGS)				
MAIN PROP. TURBOPUMP WT	406.6	lbm	184.4	kg
PROPELLANT BOOST PUMP WT	84.4	lbm	38.3	kg
MAIN OX PUMP WEIGHT	0.0	lbm	0.0	kg
TPA IGNITION WEIGHT	30.9	lbm	14.0	kg
BLEED LINE/VALVE WEIGHT	0.0	lbm	0.0	kg

MISC. HARDWARE WEIGHTS				
THRUST MOUNT	1670.0	lbm	[illegible]	kg
SUPPORT HARDWARE	[illegible]	lbm	276.4	kg
ENGINE LINES	[illegible]	lbm	97.9	kg
MAIN VALVE	382.0	lbm	173.0	kg
GIMBAL + POWER SUPPLY	302.0	lbm	137.3	kg
MARGIN (2.0%)	83.1	lbm	37.7	kg
TOTAL NONNUCLEAR WEIGHT	4236.1	lbm	1921.1	kg
TOTAL ENGINE SYSTEM				
TOTAL ENGINE WEIGHT	[illegible]	lbm	[illegible]	kg
TOTAL ENGINE WEIGHT WITHOUT SHIELD	10387.3	lbm	[illegible]	kg
THRUST/WEIGHT RATIO WITH SHIELD	[illegible]	lbf/lbm	57.4	N/kg
THRUST/WEIGHT RATIO WITHOUT SHIELD	7.2	lbf/lbm	[illegible]	N/kg
REACTOR SAFETY ROD WT.-LAUNCH ONLY	310.9	lbm	141.0	kg
TOTAL ENGINE LAUNCH WEIGHT	[illegible]	lbm	[illegible]	kg
TOTAL ENGINE LAUNCH WT. W/O SHIELD	[illegible]	lbm	[illegible]	kg
PUMP-OUT CONDITIONS				
PUMP-OUT THRUST	[illegible]	lbf	[illegible]	N
PUMP-OUT CHAMBER PRESSURE	800.0	psia	[illegible]	kPa
PUMP-OUT ISP	[illegible]	sec	[illegible]	N-sec/kg
PUMP-OUT CHAMBER TEMPERATURE	[illegible]	deg R	2700.0	deg K
OVERALL DIMENSIONS				
OVERALL ENGINE LENGTH =	340.0	in	[illegible]	cm
OVERALL ENGINE DIAMETER =	106.0	in	[illegible]	cm

Note: In Addition to Normal Flight Design/Operating Conditions Presented Pump Out Operating and Launch Weight Parameters are Given.

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SAMPLE DESIGN CASE SUMMARY

Case No./ Parameter	1	2	3	4	5	6	7	8
Cycle Type	Expander	Expander	Bleed	Gas Generator	Expander	Bleed	Gas Generator	Expander
Thrust Level (lbf/N)	75,000/ 333,600	75,000/ 333,600	75,000/ 333,600	75,000/ 333,600	75,000/ 333,600	35,000/ 155,700	250,000/ 1,112,000	75,000/ 333,600
Reactor Type	ENABLER I	ENABLER II	ENABLER II	ENABLER II	ENABLER II	ENABLER I	ENABLER I	ENABLER I
Reactor Fuel Type	Composite	Composite	Composite	Composite	Carbide	Composite	Composite	Composite
Chamber Pressure (psia/KPa)	1,000/ 6,895	500/ 3,348	500/ 3,348	500/ 3,348	1,000/ 6,895	500/ 3,348	500/ 3,348	1,000/ 6,895
Chamber Temperature (°R/°K)	4,860/ 2,700	4,860/ 2,700	4,860/ 2,700	4,860/ 2,700	5,580/ 3,100	4,860/ 2,700	4,860/ 2,700	4,860/ 2,700
Nozzle Area Ratio	500:1	200:1	200:1	200:1	500:1	200:1	200:1	500:1
No. of Propellant Feed Legs	2	2	2	2	2	1	3	2
Turbopump Type	Centrifugal	Centrifugal	Centrifugal	Centrifugal	Axial	Centrifugal	Axial	Axial
Reactor Fuel Scaling Factor	1.00	0.67	0.67	0.67	0.67	0.67	1.00	1.00

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NESS VERSION 2.0 OPERATING ENVIRONMENT

- Well Organized Worksheet to Initialize Your Design Are Provided
- Uses Improved Name List Input File
  - Each Input Variable is Defined
- Operates on VMS/VAX System
  - Over 30,000 Lines of Code
- Personal Computer Compatible Version is Available
  - Requirements
    - 486-33 MHz Computer
    - 6 MB RAM
    - 80 MB Hard Drive
    - Leheay Fortran with Extended Memory Required

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NESS PROGRAM USER'S GUIDE

Science Applications International Corporation

No. 205 079
Copy No. _

Nuclear Engine System Simulation (NESS)

Volume I — Program User's Guide

Contract No. NAS3-25809

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Cleveland OH 44135

Prepared by

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SAIC

CONTENTS

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COMPARISIONS

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CYCLE PARAMETER COMPARISON*
- 75,000 lbf, ENABLER I, Expander Cycle -

Parameter	Rocketdyne	SAIC - ELES NTP	SAIC NESS
Total Flowrate (kg/s)	36.7	36.9	37.27
Pump Discharge Pres. (psia)	1,544	1,538.3	2,298.3
Turbine Flowrate, % Pump	50	50	50
Turbine Inlet Temp. (°K)	555.6	555.3	622.3
Turbine Inlet Pres. (psia)	1,412	1,416.8	1,969.0
Turbine Pressure Ratio	1.25	1.295	1.739
Reactor Inlet Pres. (psia)	1,130	1,255.4	1,132.1
Reactor Power, (MW)	1,645	-	1,587
Reactor Core Flowrate (kg/s)	36.7	36.9	36.2
Nozzle Chamber Temp (°K)	2,700	2,700	2,700
Nozzle Chamber Pres. (psia)	1,000	1,000	1,000
Nozzle Exit Diameter (m)	4.15	4.15	4.22
Nozzle Expansion Ratio	500	500	500
Specific Impulse-Vac (sec)	923	922.8	912.9
Pump Speed (rpm)	37,500	34,913	40,583

* Rocketdyne uses their Mark 25 type axial turbopump (4 stages); SAIC ELES-NTP used a single-stage centrifugal pump; SAIC NESS, Sample Case No. 8, uses a 5-stage axial pump.

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ENGINE SUBSYSTEM WEIGHT COMPARISON*
- 75,000 lbf, ENABLER I, Expander Cycle -

Parameter	Rocketdyne	SAIC ELES-NTP	SAIC NESS
Specific Impulse - Vac (sec)	923	922.8	912.9
Reactor (kg)	5,824	5,823	4,783
Internal Shield (kg)	—	1,523	1,108
Nozzle Assembly (kg)	440	421	535
Turbopump Assembly (kg)	304	104	221
Nonnuclear Support Hardware (kg) - Lines, Valves, Actuators, Instrumentation Thrust Structure	1,815	1,264	1,493

* Rocketdyne uses their Mark 25 type axial turbopump (4 stages); SAIC ELES-NTP used a single-stage centrifugal pump; SAIC NESS, Sample Case No. 8, uses a 5-stage axial pump.

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EFFECT OF WALL TEMPERATURE ON PERFORMANCE*

Wall Temperature (°R)	Barrier Temperature (°R)	Isp (Sec.)	Fuel Film Cooling Fraction
1460	1630	912.9	0.03
1800	2106	915.9	0.03
2000	2429	917.5	0.02
2400	2892	919.4	0.02
2800	3418	921.2	0.02
3000	3651	921.9	0.02
3200	3864	922.4	0.02

* Core Temperature = 4860°R (2700°k)

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DESIGN CASE COMPARISION OBSERVATIONS

- NESS Design Exhibits 1% Lower Peformance Than Other Designs
  - NESS Model More Accurately Predicts Nozzle Cooling Losses-Upstream Film Cooling Required to Meet Maximum Wall Temperature Requirements
- Integrated Reactor/Engine System Design Effects Accounted for in the NESS Design
  - Sized to Take Into Account Heat Captured by the Coolant Before It Enters the Reactor
  - Corresponds to Some Difference in Cycle Pressures, Temperatures, and Turbopump Operating Parameters
- Other Weight Differences From Improvements in NESS Weight Correlations
  - 3-Section Nozzle Design
  - Non-Nuclear Auxiliary Components
  - Update H_2 Properties

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CONCLUDING REMARKS

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CONCLUDING REMARKS

- The NESS Preliminary (ENABLER I&II) Design Analysis Program Characterizes a Complete Near-Term Solid-Core NTP Engine System in Terms of Performance, Weight, Size, and Key Operating Parameters for the Overall System and Its Associated Subsystem
  - Incorporates Numerous State-of-the-Art Engine System Technology Design Options and Design Functions Unique to NTP Systems
  - Extensively Verfied and Documented
- The NESS Program is Deemed Accurate to Support Future Preliminary Engine and Vehicle System Design and Mission Analysis Studies
  - NESS Has Been Successfully Operated and Checked Out at NASA Lewis
- Future Recommendations:
  - Incorporate Other NTP Reactor Types
    - -- Particle Bed
    - -- Pellet Bed
    - -- Low Pressure
    - -- Wire Core
    - -- In situ Propellant Based Reactor Designs
  - Incorporate a Radiative Heating Model
  - Update the Material Library
  - Upgrade the NESS Performance Prediction Module

- NESS Devleopment Is One of Many Key First Steps Required to Support NTP Development
- It Is Envisioned that NESS Will Be One Key Element of an Advanced NTP Engine System Design Workstation

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