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REON

SACRAMENTO PLANT

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TO

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

SYSTEMS ANALYSIS PROCEDURES
AND TECHNIQUES

MASTER

APRIL 1965

CONTRACT SNP-1

NERVA PROGRAM

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REPORT NO. RN-S-0212
SYSTEMS ANALYSIS PROCEDURES
AND TECHNIQUES

ROCKET ENGINE OPERATIONS - NUCLEAR

CONTRACT SNP-1 APRIL 1965 NERVA PROGRAM

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ABSTRACT

Systems Analysis Procedures and techniques used by the Systems Analysis and Control Division, REON, for supplying studies for such projects as NRX-A, CFDTS, NRX/EST and XE engines are explained. The function and organizational relationships are shown for both internal and external communications. A review is included on the types of analytical support investigations performed. In addition, the various programs developed are reviewed along with projected uses for these programs.

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1.0 SUMMARY

The Systems Analysis function of the Systems Analysis and Control Division, REON, is to insure the proper integration of the various engine components and assist in defining component criteria. This function is performed for such projects as NRX-A, CFDTIS, NRX/EST and XE. Three departments comprise the Systems Analysis and Control Division; however, this report will be concerned with the activity of the Systems Analysis function and will not cover functional responsibilities or activities for Control Systems.

In order to perform the functional responsibilities analytical models that describe the various NERVA systems are developed. These are used to investigate the static and transient performance of the engines and the necessary test facilities. From these analytical investigations, component performance in the system is evaluated and the various interactions between components are studied. In addition, operational support is provided for each test system. The functional responsibilities are implemented on a staff level to other participants of the NERVA program such as project engineering, component development, staff engineering, engineering support, safety division, Nevada Test Operation and WANL.

The various types of engineering analysis are described under the classification of:

1. Steady-state and tolerance studies in order to evaluate component performance in a system.
2. Constraints to define safe operating regimes for the engine system.
3. Parametric transient studies to define transient performance of system components and to determine operating procedures to safely satisfy test objectives.
4. Control Systems Analysis to aid in the design of the control system.
5. Detailed transient investigations of regions that may result in possible hazardous operation for any component in the system.
6. Pretest predictions of test plan for the experimental test.

1.0, Summary (cont.)

7. Test evaluation to assist in determining whether the test are proceeding satisfactorily or a modified plan should be instituted.

Data analysis activities are discussed and include:

1. Evaluation of test in detail.
2. Independent audit of test data.
3. Investigation of various alternate explanations of the system performance.
4. Program upgrading for better engineering analysis of future systems.

Programs developed for engineering analysis, both analog and digital, are summarized. These include steady-state and transient. Major programs are:

1. Component Program (1108) for detailed analyses of certain components in the system under investigation for steady-state conditions.

2. Nuclear Engine Analysis Program (12034), a steady-state program having a better balance of components, for engine systems analysis.

3. Analog Simulation Program for transient analysis where frequencies up to 20 cycles per second are important.

4. Transient engine program (12013), ^{rough out?} a digital transient program, with a single channel representation of major system components.

5. Nuclear Engine Transient Analysis Program (12039), ~~rough out?~~ a digital program under development with multi-channel capability for representing engine components.

For data analysis, in addition to the above programs, the following programs are available:

1. Digital Simulation Program-364, (12042) for detailed heat transfer and hydrodynamic performance.

2. Data reduction programs to statistically edit and smooth raw data.

The use of the above programs is explained using the NRX/EST as a typical systems analysis investigation.

Facilities available for analytical studies include an IBM 7094 digital computer and two Comcor 5000 and an EAI 231R analog computers.

2.0 FUNCTION

The REON Systems Analysis and Control Division is responsible for performing system analysis and integration studies for the purpose of insuring proper engine integration and assisting in defining component criteria. Component interfaces are studied insofar as both steady-state performance and dynamic interaction are concerned. The system analysis effort assists in developing component, assembly, planning and test specifications. In addition, it evaluates the results of systems test to determine actual performance and to upgrade appropriate computer models.

Activity to accomplish the System Analysis function is to:

1. Develop complete mathematical models that describe the performance of various NERVA engine systems (including NRX-A, CFDTs, XE-Engine, and upgraded NERVA Engine systems). Both linear and non-linear mathematical techniques, which coupled with digital and analog computer programs, are used to analyze the static and dynamic performance of these systems.
2. Analyze each system's static and dynamic performance as it is coupled with either the nuclear or non-nuclear test facilities. Analytical results are presented, though the appropriate project group, prior to each test in order to assist with the test planning.
3. Upgrade the mathematical models for the various NERVA engine systems as operational data become available from component, subsystem and system tests. This includes an operational data file of test results for each component, subsystem and system analyzed.
4. Review and evaluate all test data received from all sources in the nuclear rocket projects as it relates to system performance.
5. Indicate the need for (but not the details of) redesign of components or subsystems as required because of any observed constraints that would prohibit achievement of system performance.

2.0, Function (cont.)

6. Conduct engine parametric studies for all operational regimes. These include engine operations at design conditions, and during startup and cooldown transient cycles. Static and dynamic tolerances and their effects on the design of engine systems are evaluated. Preliminary design criteria, as evolved from these system analyses, are used in revising component development specifications, e.g. control and instrumentation development.

7. Analyze all test plans and standard operating procedures as related to NERVA system development. The scope will include: (1) cumulative system static and dynamic error analysis, (2) compatibility of controls and instrumentation with test goals, (3) support to the Safety Division for dynamic studies of malfunction criteria, and (4) assist in the preparation of measurement and diagnostic instrumentation requirements for data analysis.

8. Monitor all component design modifications and corresponding analyses to insure that both component design changes and component analyses are included in future system analysis models.

3.0 ORGANIZATIONAL AND FUNCTIONAL RESPONSIBILITIES

3.1 Systems Analysis Organization

The Systems Analysis and Control Division reports directly to the office of the REON Program Manager. Systems Analysis activities are divided into two departments - Performance Analysis, Control and Data Analysis. Each department contains two sections. The functional responsibility of the sections is summarized in Figure 3.1.1.

3.2 Relations to NERVA Program

The REON Systems Analysis and Control Division will implement the effort described above by assisting in the work on a staff level of the following NERVA program participants.

1. Project Engineering
 - a. NRX-A
 - b. CFDTs
 - c. XE-Engine
 - d. NES
 2. Component Development
 - a. Thrust chamber assembly
 - b. Propellant feed system (including TPA)
 - c. Engineering Support
 3. Engineering Support
 - a. Sacramento test facilities
 - b. Nevada test facilities (excluding NES)
 - c. Data handling
-

Figure 3.1.1

Systems Analysis Organization

3.2, Relations to NERVA Program

4. Safety Division
 - a. All test facilities - nuclear and non-nuclear
 - b. Engine design criteria
 - c. AEC reactor test requirements
5. Staff Engineering
 - a. Nuclear heating
 - b. Heat transfer
 - c. Applied research
 - d. Stress
 - e. Materials properties
6. Nevada Test Operation
 - a. ETS-1 facility requirements
 - b. ETS-1 data handling
 - c. Test Cell "A" data acquisition system
7. WANL
 - a. Nuclear components
 - b. Reactor design and test
 - c. Controls Analysis

Wherever possible, one man from the Systems Analysis and Control Division is assigned as prime contact for each of the seven technical work areas listed above in accordance with the level of effort required for that particular area. Coordination of all remaining tasks are assigned to one department within the Systems Analysis and Control Division.

3.3 Communications

Systems Analysis personnel are members of the various working design teams such as the CFDTS, NRX/EST, and XE engine design teams. Participation includes:

3.3, Communications (cont.)

1. Preliminary design
2. Detail design
3. Test plan and test specification
4. Measurements list
5. Data analysis

For preliminary design, steady-state and transients analyses are made on a variety of possible system configurations. Information is fed between Systems Analysis, components and projects groups in order to establish a system that will meet the engine criteria at a minimum cost in time and money. Knowledge of individual components must be integrated into an overall system to ensure that all aspects of the design are being considered. Thus, close cooperation is required between each of the groups involved in the design. Contributions from System Analysis are part of the System and Component design criteria, preliminary Measurements Requirements List and preliminary system test plan for the preliminary design.

Following the establishment of a preliminary design, detailed design efforts begin. The objective is to develop the final system and component design criteria, measurements requirements list and test plan and specification. During the final design phase, analyses of steady-state performance and the effects of tolerance variations are carefully investigated. Possible design changes are analyzed in the system to ensure that changes or modifications in one area are being considered throughout the engine system. In addition, the known constraints in the engine are identified. Also transient analysis is performed on startup, full power, shutdown and cooldown. As part of this, detailed studies are made on the control system that lead to the control system component specifications.

The test plan is generated to define the manner the test will meet the original design and data objectives. Transient analysis is used to establish safe operational profiles to ensure that the test plan is realistic. Steady-state analysis is used to provide the design groups with data for the various power operating levels during a test.

3.3, Communications (cont.)

The measurements list is used to establish the instruments required to measure test performance. The system and each component must be evaluated to ensure that the maximum amount of knowledge can be obtained from the test. Systems Analysis is a major contributor to the Measurements Requirements List.

Data analysis includes the review of the test results immediately after each experimental plan, followed by a detailed evaluation of the data. Because of the detailed analytical work that has been previously performed, Systems Analysis personnel are principal contributors to determining how successful the tests series are proceeding. After completion of the test series, a detailed evaluation of the test data is made in order to ensure that as much information as possible is obtained.

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4.0 ENGINEERING ANALYSIS

Various types of engineering analysis are performed to meet the requirements discussed above:

4.1 Steady-State and Tolerance Studies

Steady-state analyses are made to show the performance of each component in a system at a given operating point under the assumption that the system is stable and in equilibrium. The steady-state points provide a means of evaluating the actual operating conditions in the engine. Such questions as: What is the turbopump speed at full power? How much diluent bleed is required for a given turbine inlet temperature? What is the reactor flow rate? ... are answered for project and component designers. Figure 4.1.1 is a representative presentation of the results. It will be noted that the hardware identification as to parts and system schematic are provided along with fluid performance data.

As better component data become available through analysis and tests, the results are entered into the analysis. The effects on all other parts of the system are then evaluated and projects alerted if deficiencies appear. For instance, the reactor component design staff may be able to reduce the core pressure drop. However, a reduced pressure drop may result in inadequate pressure for the diluent bleed. Thus, the question of reducing reactor core pressure drop must be evaluated in terms of total systems performance as well as reactor component design problems.

Tolerance studies are performed to indicate critical components. Small deviations from design specifications can result in major changes in operation. Tolerance studies attempt to identify critical components and ensure adequate performance margins to achieve test objectives. An example of such an item is the hot bleed system. Changes in turbopump performance or reactor pressure drop have a major effect on the ability of the diluent bleed system to provide adequate flow to the turbine.

OVERALL ENGINE THRUST, lb	54,147
MAIN THRUST CHAMBER THRUST, lb	52,309
TURBINE EXHAUST NOZZLE THRUST, lb	1,838
OVERALL ENGINE SPECIFIC IMPULSE, sec	721
CHAMBER SPECIFIC IMPULSE, sec	747
TURBINE NOZZLE SPECIFIC IMPULSE, sec	353
TURBINE POWER CONTROL VALVE POSITION, deg	36.5
AMBIENT PRESSURE, psia	1.25
REACTOR POWER LEVEL, M.W.	1,117
TURBOPUMP POWER, M.W.	4.2
PUMP EFFICIENCY, %	69.7
TURBINE EFFICIENCY, % (Total/Static Pressure)	47.5
NPSP, psi	12.8
TURBOPUMP SHAFT SPEED, rpm	21,745
NOZZLE EXPANSION RATIO	10.1
TURBINE EXHAUST NOZZLE AREA RATIO	4.1

PROGRAM CODE 12034

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4.0, Engineering Analysis (cont.)

4.2 Constraints

An extension to the steady-state analysis, operating regimes are investigated to determine what are safe operating areas and what areas are unsafe. A safe area is defined as one in which all components operate within their capability. Since the boundaries are defined by static means, it is possible that during a transient, other regions can be traversed without a component failure. Also, transient limits may exist on components that must not be violated to operate satisfactorily. Figure 4.2.1 is a typical constraint map for static operation. By indicating the operating conditions, it is possible to determine the components that must be redesigned first if higher performance is desired.

4.3 Parametric Transient Studies

It is not enough to investigate a given steady-state point since even though a cycle balance is achieved, the system may be unstable and never achieve the so-called equilibrium condition. The first transient studies are parametric to investigate what are safe areas for operation and how to remain within the transient limitations established by the component designers. Once it is established that the system can operate safely at design conditions, methods to achieve startup and shut down of the engine must be determined. There are many possible methods to startup, accelerate to full power, shut down and cool down the engine system. Sample results are shown in Figure 4.3.1 from a start up study of the X-Engine.

The parametric transient studies provide the first opportunity to understand the component performance, not as a number of individual elements but, as an integrated unit that will perform the functions of an engine system.

4.4 Control Systems Analysis

In order to design the necessary control system for engine operation, it is necessary to understand the transient behavior of the engine. Control systems are designed to regulate the changing of operating conditions in a safe, pre-determined manner. Once a desired engine operating level is reached, the control system must maintain the desired level. The control system depends on the dynamics of every other component in the system.

T_c

Figure 4.2.1
Typical Constraint Map

Figure 4.3.1
Parametric Transient Studies

4.4, Control Systems Analysis (cont.)

The procedure followed in designing the control system is to perform a linear analysis around selected operating points. Once a preliminary system design appears to meet the engine control requirements, a non-linear investigation must be made. This is usually performed by simulation - the engine and control system are modeled on an analog computer and the performance under conditions such as startup, full power, shutdown and during a failure investigated in detail.

Part of the simulation of the engine and control system is an opportunity to evaluate the inclusion of a man in the control system. Since a man is an integral part or component of the control systems and he operates in actual time, it is necessary to have a model of the system that operates in actual time. In addition to including a man in the control systems analysis, hardware components such as actuators can be tied into the simulation. This provides a means of operating the hardware under a realistic duty cycle and to evaluate the adequacy of the component performance model.

4.5 Detailed Transient Studies

Operations that result in performance in regions that may be hazardous for any of the components in the system must be investigated in detail to ensure that no unsafe conditions will exist. Regions that fall into this category are startup, shutdown, and cooldown. Also, emergency type conditions often require detailed transient analysis.

In order to perform detailed studies, a multi-channel model of the various components is required. Such problems as the effects of manufacturing tolerance variations can then be analyzed. Or another example of an analysis that may be required is a investigation of what would occur if the pump discharge line bursts.

The detailed analyses by their nature are expensive to run. Previous analytical work is used to minimize the number and scope of this type of investigation.

4.0, Engineering Analysis (cont.)

4.6 Pretest Predictions

When the system has progressed to the point of design freeze and when ramps for the experimental plan have been specified, a pretest prediction is provided to the project group. Because changes in components or operations are continuously occurring, the pre-test predictions are published one month prior to test to be as current as possible. This is designed to ensure that the final test plan can be safely performed on the engine and the resulting data will be useful. Component test data are substituted for design data in order to reflect as much as possible the actual hardware performance. Figure 4.6.1 is an example of pretest predictions for CFDTs.

By the time of the pre-test predictions report previous analysis should have established the procedures to meet the test objectives in a safe manner. Therefore, an elaborate program for pre-test predictions is not required. The selected test profiles are the only ones usually included in the pre-test predictions report.

4.7 Test Evaluation

On each engine system, a series of tests are planned. Before proceeding from one test to the next, the data from the previous test are evaluated. From this evaluation, the decision to continue testing and whether to follow the established test plan or a modified test plan must be made. Systems analysis personnel are either members of the Test Review Board or are on hand for consulting purposes in making these decisions to proceed or alter the test plans.

The test data are examined and systems performance evaluated. Techniques include the use of hand or computer calculations to determine the correctness of data measurements, review of instrumentation and data acquisition system performance and the experience of knowledge acquired from the many detailed analytical investigations previously performed.

Figure 4.6.1

Pretest Predictions for CFDTS

5.0 DATA ANALYSIS

A detailed test data analysis is performed following each systems test. The objective of the analysis is to provide an independent audit of the test data, an evaluation of the test, and a means of program improvement. The data analysis effort starts after the 48 hour report is available and CALCOMP plots are released. The Data Analysis personnel, make preparations for the test prior to the actual runs.

The purpose of separating the data analysis effort from the engineering or performance analysis is to avoid trying to prove that what was done before the test was "right". Where more than one interpretation of an event is possible, it is highly desirable to consider all possible interpretations on their respective merits. Also, the separate data analysis effort provides time outside of the normal tasks to sit back and consider what had occurred.

5.1 Evaluation of Test

Once the tests are completed and CALCOMP plots such as in Figure 5.1.1 are available, a detailed evaluation of the data is made. Each data channel must be evaluated for quality of data. This requires a review of all logs or notes made on the particular channel to determine if there is a known reason to suspect its performance, a check against other instruments that are supposed to be measuring the same thing or can be correlated with the measurement and a computer program check to determine if the data are consistent with previous tests. It is important in evaluating the test data not to select channels in a biased manner nor fail to reject channels that are suspected because they appear to prove a conclusion.

In the test system, duplications of instrumentation is purposely provided on some key measurements. In addition, in such items as pressure measurements, differential pressure drops are often made across major components. Therefore, the inter-relations between measurements can be used as a correlation. In addition, statistical methods can be used to evaluate channels in regions where several measurements are made. Using statistical techniques, certain channels may be suspected and eliminated and a confidence level for the measurements developed.

Figure 5.1.1
CALCOMP Plot

5.1, Evaluation of Test (cont.)

The computer programs provide a tool in the evaluation of the measurements. Since the programs have been checked against previous components, Kiwi and NRX-A tests, performance that is different must be reviewed with suspicion. This is not a reason to reject a measurement but it provides a sound reason for further investigation.

Along with the measurements evaluation, detailed studies are being made on the whole system and major portions of particular interest. Transient studies of the power ramp provide an understanding of the performance of the various components and the time constants in the system. Such questions as the effects of two-phase flow, flow asymmetries in components having parallel channels, actual heat transfer correlations are investigated in order to provide an idea of their importance and contribute knowledge for subsequent tests.

5.2 Independent Audit

A major function of the data analysis effort is to make an independent analysis of the data. A minimum of pre-conceived ideas makes it possible to look for more than one explanation to the test data. Also, by being allowed adequate time for analysis after the test - approximately four months - it is possible to make an orderly evaluation of all aspects of the data. If the data were analyzed only by personnel involved in the pre-test and analyses during the test, valuable information might be over-looked.

5.3 Program Improvement

The knowledge learned from each test constitutes feedback into the system in order to better predict and understand future tests and to improve component design. In the area of Systems Analysis a major part of the feedback is in improving the analytical programs used in the performance analysis preceding the test. Better heat transfer and pressure drop representations will result from the data analysis. In addition, the adequacy of the representation of two-phase flow, the requirement for parallel channel engine model and many other important questions are answered.

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6.0 PROGRAMS DEVELOPED

Several digital and analog analytical programs have been developed to fulfill the engineering and data analysis requirements. The combination of economy of operation, availability and different functional requirements results in the ruling out of one general program to perform all operations. Programs are subdivided into the categories in which they are mainly used. In many cases the use is often more general. Table 6.0.1 shows the planned usage of the programs. More details will be covered in Section 7.0.

6.1 Steady-State Programs

At present, a component design and engine steady-state program are in operation. These programs are being mated into one program. The component design program, Program 1108, was developed to look in detail at certain components such as the diluent bleed system as to how the component would behave in the overall system. A simplified engine model was used with the component. This was the first operational steady-state engine program. The Nuclear Engine Analysis Program was developed to investigate the overall engine under steady-state conditions in more detail and with a better balance of components effects on system behavior. It is an operational program but lacks some of the details on particular components that are in the 1108. In addition, it lacks some of the input options that make a program flexible to handle many different situations. Once the two programs are combined, the present form of each will be dropped.

6.1.1 Component Program 1108

The 1108 program is reported in NERVA Engine Balance Steady-State Program, Report 8209-64-9, March 3, 1964*. The program computes a parametric performance schedule of the engine for either a desired chamber temperature,

* Copies of reports thus designated may be obtained from Department 7471, REON.

6.1.1 Component Program 1108 (cont.)

or the chamber temperature resulting from a given core power. Input is required to describe the physical characteristics of the system such as turbine power control valve setting, pressure drop loss coefficients, and the ratio of energy absorbed in the reflector to energy absorbed in the core. The ability to vary the physical characteristics of the system lend a greater flexibility to the program.

The hot bleed port and nozzle tube are detailed programs on the components. These are incorporated into the 1108 program as subroutines. Documents on these programs are Reports 8209-64-2 and 8209-64-5.

The program begins by calculating the pressure head increase across the pump using the given inlet temperature and pressure and an "initial guess" of the pump discharge pressure. The net positive suction pressure is calculated for given inlet pressure and the pump speed is solved for by iteration. The pump work is found, and is set equal to the turbine work. Assuming temperature into and the pressure ratio across the turbine, the turbine flow rate is calculated. The pressure at the turbine inlet nozzle is calculated, and the pressure at the roll nozzle is found by calculating the pressure drop across the turbine and the roll lines. The roll nozzle is assumed choked, and the flow is calculated at its throat. The pressure ratio across the turbine is varied until the flow through the roll nozzle is equal to the flow through the turbine. The pressure drop and temperature change across the nozzle tubes are calculated by the nozzle tube subroutine. If core power is input the temperature out of shield one and the chamber temperature are calculated; if chamber temperature is input the core power, the power absorbed in the reflector, and the temperature out of the shield from the reflector to the dome is found by iterating on the energy absorbed in the reflector. The pressure drop across the reflector and shield to the dome is calculated. If the diluent flow is to be extracted from the dome it is subtracted from the system flow. The pressure drop across the core and shield from the dome to the core is calculated. The pressures and temperatures of both the chamber and the diluent extraction point are inputted into the hot bleed port subroutine, and hot flow, diluent flow, turbine

PROJECTS AND PROGRAMS

<u>PROGRAM CODE</u>	<u>PROJECT</u>	<u>USE</u>
Component Program (1108)	NRX-A NRX/EST	Design Data Establish Performance Operating Points Review and Recommend Changes in Test Plans Data Analysis
Nuclear Engine Analysis Program (1203 ⁴)	NRX/EST XE Advanced Concepts	Establish Performance Operating Points Prepare Constraint Maps Review and Recommend Changes in Test Plans Analyze Measurement Requirements Pre-test Predictions Data Analysis
NERVA Engine Transient Program (12013)	NRX-A CFDTS NRX/EST XE Advanced Concepts	Startup Calculations Shutdown Predictions Cooldown and Emergency Cooldown Computations Preparing Measurements List Data Analysis Pre-test Predictions
Analog Engine Program	CFDTS NRX/EST XE Advanced Concepts	Startup Analysis Shutdown Analysis Cooldown Analysis Control System Analysis Hardware Tie-in Operator Trainees Pre-test Predictions
Nuclear Engine Transient Analysis (12039)	NRX/EST XE Advanced Concepts	Detailed Transient Studies Data Analysis Configuration Studies

Table 6.0.1

PROJECTS AND PROGRAMS (Continued)

<u>PROGRAM CODE</u>	<u>PROJECT</u>	<u>USE</u>
Digital Simulation Program-36 ⁴ (12042)	NRX-A CFDTS NRX/EST XE Advanced Concepts	Data Analysis Transient NRX-A Program Analyze Instrumentation Readings Upgrade Mathematical Models
Analog-to-Digital Data Analysis	NRX-A CFDTS NRX/EST XE	Process Narrow Band Data (N-2) Evaluate Data Quality Detects Spurious Signals Noise Level Count
Statistical Edit and Smooth Program	NRX-A CFDTS NRX/EST XE	Edits N-3 Data Smoothing of Data for 36 ⁴ Input Identify Trends and Missing Data

Table 6.0.1 (Cont.)

6.1.1 Component Program 1108 (cont.)

inlet temperature, and the pressure at the exit of the jacketed line are calculated. The diluent flow previously extracted from the system is compared to the cold flow calculated in the hot bleed port; the diluent flow extracted is adjusted until they are equal. The flow through the main nozzle is calculated by assuming that the main nozzle is choked; the nozzle flow is compared with the flow through the reactor minus the hot bleed port hot flow. The ratio of turbine speed to turbine flow is varied until the nozzle flows are equal. The initial turbine inlet temperature is compared to the temperature calculated in the hot bleed port subroutine; the initial turbine inlet temperature is adjusted until the inlet temperatures are equal. Finally, the turbine flow rate is compared to the total flow rate in the hot bleed port; and the pressure out of the pump is varied until the turbine flows are equal. After all the iterative loops are closed, the exit Mach number from both main and roll nozzle are calculated; thrust and specific impulse are found.

6.1.2 Nuclear Engine Analysis Program (12034)

This is an IBM 709⁴ digital computer program which simulates the steady-state operation of the NERVA hot bleed engine over the full operational range of chamber pressures and temperatures. It is documented in Nuclear Engine Analysis Program, Vol. I, II and III, of REON Report No. RN-S-0171, December 1964. The program contains subroutines which simulate the characteristics of the major components. It computes the energy balances for all engine components and for the entire engine as required to satisfy a demanded chamber pressure and temperature and thereby defines the component relationship to system operation. The program output consists of data such as the turbine inlet temperature, turbine flow rate, hot bleed flow rate, turbopump speed, pump specific speed, turbine power control valve position, nuclear power, engine thrust and specific impulse, plus temperatures, pressures and flow rates throughout the system.

Included in the program are hydrogen properties subroutines which provide a complete representation of its thermodynamic and transport properties.

6.1.2 Nuclear Engine Analysis Program (12034) (cont.)

The program begins to compute the system energy balance by assuming a pump discharge pressure and reactor power and then computing the pump power required. The turbine inlet flow rate and temperature required to drive the pump are obtained. The heat addition, pressure drop, and flow distribution in the nozzle, reflector, shield and core are then computed. If the core exit pressure and temperature do not agree with the demanded chamber pressure and temperature, the assumed pump discharge pressure and reactor power are changed and the computation repeated until agreement is reached. When the calculation has converged, significant engine system performance characteristics are defined.

The detail included in the program is as follows: in the nozzle, 10 axial computation increments in the nozzle and 6 axial computational increments in the parallel nozzle skirt are allowed. In the reflector, up to 7 different types of parallel flow channels may be computed. Each flow channel consists of 10 computational increments. In the shield, up to 5 types of flow channels of 10 computational increments each are provided. In the reactor core, there may be up to 5 types of fuel element flow channels and 3 types of tie-rod flow channels, each consisting of 12 computational increments. Each tie-rod model may consist of as many as 15 concentric annular segments. The turbine inlet line heat exchanger may be split into as many computational increments as desired, 5 to 10 being the usual number used.

Figure 6.1.2.1 shows a typical steady-state output from this program. The program is operational and being used for engine systems analysis.

6.2 Performance Analysis

Several transient analysis programs are used to evaluate the performance of the engine systems. Where high frequencies are important such as in the evaluation of the control system, the analog simulation is used. More detailed

OVERALL ENGINE THRUST	THT	=	53080.012	LBF
MAIN THRUST CHAMBER THRUST	THC	=	51589.743	LBF
TURBINE EXHAUST NOZZLE THRUST AXIAL	TH17	=	1450.269	LBF
OVERALL ENGINE SPECIFIC IMPULSE	XISNET	=	705.937	LBF-SEC/LBM
CHAMBER SPECIFIC IMPULSE	XISC	=	737.040	LBF-SEC/LBM
TURBINE NOZZLE SPECIFIC IMPULSE	XIS17	=	286.865	LBF-SEC/LBM
TURBINE POWER CONTROL VALVE POSITION	EETA	=	36.491	DEG
AMBIENT PRESSURE	PA	=	1.250	PSIA
NUCLEAR POWER	XNP	=	1117.385	MEGAWATTS
TURBOPUMP POWER	POWER	=	4.247	MEGAWATTS
PUMP EFFICIENCY	ETAP	=	0.697	
TURBINE EFFICIENCY (T-S)	ET	=	0.475	
TURBINE EFFICIENCY (T-T)	ET	=	0.658	
NET POSITIVE SUCTION PRESSURE	NPSP	=	12.830	PSIA
TURBOPUMP SHAFT SPEED	N	=	21745.433	RPM
TANK VAPOR PRESSURE	PVAP	=	15.064	PSIA
MAIN NOZZLE EFFICIENCY	ETANC	=	0.560	
MAIN CHAMBER COEFFICIENT	CFC	=	1.652	
TURBINE PRESSURE RATIO	P16/P17	=	6.568	
TURBOPUMP POWER	POWER	=	37588711.500	IN-LB/SEC
TURBINE BLADE TIP SPEED	V	=	11.239	FT/SEC
TURBINE ISENTROPIC SQUIETING VELOCITY	CO	=	9103.967	FT/SEC
NET POSITIVE SUCTION HEAD	NPSH	=	416.640	FT
PUMP SPECIFIC SPEED	NS	=	852.929	
PUMP FLOW RATE	WD1	=	75.191	LB/SEC
PUMP CAPACITY	Q1	=	7612.539	GAL/MIN
PUMP HEAD RISE	H1D2	=	29037.541	FT
VALVE COEFFICIENT	F	=	35.010	

TC= 4090.0 DEG R PC= 550.0 PSI WC= 70.00 LB/SEC

STATION NUMBER	W LB/SEC	P PSI	T DEG R
0	75.19	40.0	36.5
1	75.19	40.0	36.5
2	75.19	27.9	36.6
3	75.19	922.1	48.6
4	75.19	905.0	48.8
5	75.19	733.9	138.2
6	71.19	692.2	212.3
7	71.19	683.2	217.3
8	71.19	550.0	4090.0
9	70.00	550.0	4090.0
10	4.01	692.2	212.3
11	4.01	660.0	274.9
12	1.19	550.0	4090.0
13	5.20	549.3	1230.1
14	5.20	548.9	1143.1
15	5.20	547.3	1143.1
16	5.20	369.8	1143.1
17	5.20	56.3	916.4
18	5.20	49.6	916.4
19	0.	692.2	212.3

Figure 6.1.2.1
Typical Steady State Output

6.2 Performance Analysis (cont.)

studies such as the investigation of distributed effects on material temperatures during a startup utilize the Transient Engine Simulation Program. Being developed is a more detailed digital program that will include parallel flow passages to investigate such items as flow asymmetries or single tube failures in the Nuclear Engine Transient Analysis Program.

6.2.1 Analog Simulation Program

This analog program was developed over the past year. It replaces an earlier model limited to transients in the power range. It was developed specifically to compute transients starting from conditions of zero flow, zero speed, and zero power into and through the power region. The details of the program are reported in REON Reports RN-S-0091, Basic Analog Model for NERVA Engine, May 1964, and RN-S-0202, Basic Analog Model for X-E, EST and CFDTS Turbopump and TPCV, February 1965. In so doing, it better describes the propellant phase change, the property change of materials and propellant, the system geometry, and turbopump characteristics to the degree that these effect the dynamics of the system flow and heat transfer. The upgraded analog engine program used approximately 340 amplifiers plus associated non-linear equipment as compared to the earlier but still existing model which used 120 amplifiers plus associated non-linear equipment.

The reactor assembly, nozzle and pump are distributed between 16 nodes for heat transfer. Internal flow is described in 2 paths through the nozzle, 3 paths through the reflector, and 2 paths through the core. The feed system includes the description of diluent bleed and the TPCV flow and pressure drop relationships. The heat transfer during pump chilldown is also included in the feed system description. The pump has variable head curve characteristics for low speed operation.

Hydrogen properties are input for a range between 40 and 5000°R on temperature, and 0 to 1000 psia pressure. The operating range of the model is capable of zero to full power operation.

6.2.1 Analog Simulation Program

In addition, a detailed representation of the control system is included in the analog model.

6.2.2 Transient Engine Simulation Program (12013)

The Transient Engine Simulation Program referred to as the Rough-Cut Program is designed to predict the transient operation of the NERVA Rocket Engine with minimum run time on the computer; however, the mathematical model is flexible enough to determine the thermal and hydrodynamic characteristics of a wide range of monofluid flow systems. The description of the engine appears in RN-S-0114, Transient Engine Simulation Program, August 1964. Therefore, while the logical order of solution is tied into the NERVA engine, it is also applicable to other systems.

The Transient Engine Simulation Program is a finite difference, explicit solution, digital computer program that calculates solid temperature, liquid temperature, and pressure distribution as functions of distance and time throughout the engine system. Separate analyses of the turbopump, hot-bleed port, reflector, shield, core, nozzle, and various tanks and lines are combined to represent the transient performance of the complete engine. The turbopump assembly model consists primarily of an energy balance, including an energy storage term to account for the angular energy of the rotating machinery.

The analytical representation of the reflector, shield and core (identified as parts in the program) is a one-fluid channel, finite-difference energy balance. The single-channel representation allows computation simplicity and improves computing speed but necessitates utilization of several unique analysis techniques. The flow channels in the various components are of different size and shape and thus require incorporation of a "void fraction" in the heat transfer analysis. The void fraction, when used properly, quite satisfactorily simulates the heat transfer of a many-channeled heat exchanger with a one-channel representation. However, this method destroys the hydrodynamic characteristics.

6.2.2 Transient Engine Simulation Program (12013)

The fluid-pressure distribution is obtained by analyzing the various flow channels and calculating a bulk friction factor for use with the one-channel representation. This method has been tested for nuclear power engine cases and with test data for liquid, cold gas, and ambient gas flows; good results have been obtained in all cases for both heat transfer and pressure drop characteristics.

The nozzle, being a counter-current heat exchanger, is not adaptable to the basic model used for the reflector, shield and core. Therefore, a model was developed treating the nozzle as a single-pass counter-current heat exchanger. The tubes are divided into finite distance increments for pressure-drop and heat transfer calculations. Calculations are made for flow, heat transfer coefficients, unique metal conductivities, and exit, entrance and turning pressure losses. Heat transfer areas, wetted perimeter, and pressure-loss coefficients are required as input.

From NRX-A1, a series of flow tests with zero reactor power, good agreement was demonstrated under ambient, cold-gaseous and liquid hydrogen conditions for the reflector, shield and core. The nozzle-tube representations were originally developed for a nuclear transient run where the largest heat addition to the nozzle coolant is from the core exit gases; on these tests the largest heat addition was from the nozzle tube jacket. The nozzle portion of the program was, therefore, revised to reflect heat storage as a result of the information from the NRX-A1 test.

In NRX-A2, a full power reactor test, the power ramp from startup to full flow has been computed without program changes. The rapid transients in the test provided a good check on the program performance over a large range.

6.0 Programs Developed (cont.)

6.2.3 Nuclear Engine Transient Analysis Program (12039)

The Nuclear Engine Transient Analysis Program simulates the low frequency transient operation of the NERVA engine, NRX reactor test and cold flow development test systems over the full operational range of temperatures and pressures. Documents include RN-S-0154, Preliminary Advanced Engine Studies (NERVA II), December 1964 (Appendix (A)) and a more complete report to be issued in April, RN-S-0207, Nuclear Engine Transient Analysis Program. The program assumes a closed loop system in which all parameters are determined by a pair of demanded parameters for any particular time. The pairs of demanded parameters versus time which may be used in the program include chamber pressure and temperature, chamber pressure and power level, turbine power control valve position and chamber temperature, and turbine power control valve position and power level. The program includes subroutines which simulate the operation of each component, including the turbopump, nozzle, reflector, shield, core and the parts of the turbopump loop, including the turbine inlet line heat exchanger. The program solution is by relaxation methods for the heat transfer loop and by a network iteration method for the pressure-flow loop. The program begins a computation, at any time step, by reading the pair of demanded parameters, such as chamber pressure and temperature. The heat transfer loop is then relaxed to a solution by changing the nuclear power level until the demanded chamber temperature is reached. The pressure-flow loop is relaxed until the turbine power control valve setting and the pump discharge pressure are those required to supply the necessary flow rate for the demanded chamber pressure. The heat transfer loop and the pressure-flow loop are then recomputed and the iteration process is continued until convergence is reached. The nozzle includes up to 20 axial increments for flow on the coolant side. The calculation includes the effects of two-phase heat transfer and allows for flow choking at the point of greatest restriction in the nozzle coolant tubes. Multiple channels are allowed in the reflector, shield, and core and for each channel up to 10 axial increments may be calculated. Thermal capacitance is included for each node in the nozzle, reflector, shield and core. Flow choking is allowed at the inlet and exits of each of these components. Flow capacitance is provided at each plenum between components. The pump is simulated by the inclusion of a complete pump map which links the parameters of NPSP, head rise, flow rate and turbopump speed. The

6.2.3, Nuclear Engine Transient Analysis Program (12039)

turbine is simulated by a curve relating turbine efficiency and turbopump speed. The storage of energy by the TPA is included by computation of the effect of the rotational momentum of the turbopump.

6.3 Data Analysis

Data Analysis utilizes the steady-state and transient programs described above. In addition, a more detailed computer program is under development in order to model in great detail any component of interest during a transient. This program has been designed to minimize the number of assumptions in order to understand any unusual occurrences during a test. In addition, several special programs for data handling have been developed.

6.3.1 Digital Simulation Program (12042)

A general purpose digital program has been developed for detailed transient heat transfer analysis and hydrodynamic performance behavior. Details are reported in RN-S-0047, a Digital Program for Simulation of Nuclear Powered Rocket Engines (Computer Job No. 364), September 1964. When completed, as an engine system, it will be capable of handling many parallel engine channels. The system being simulated is described as part of the data input so that changes in configuration or emphasis of detail in modeling could be done without reprogramming. At the current level of program development and computer limitations, the system being simulated may have the following characteristics:

- (1) Up to 300 thermal nodes, each representing a location in a solid part of the model. These nodes will be associated either with mass and heat capacity or with surface area.
- (2) Up to 500 conduction and/or radiation connections between thermal nodes can be accommodated.

6.3.1, Digital Simulation Program (12042)

- (3) Up to 100 flow nodes representing the propellant or coolant.
There must be either one or two surface thermal nodes for each flow node.
- (4) Up to 25 dissimilar propellant flow paths (branches) in parallel, all starting at a common flow node and rejoining at another flow node.
- (5) Up to 50 nozzle hot-gas flow nodes.
- (6) Two modes of heat generation, which for nuclear powered rockets would represent energy transfer by neutron and gamma radiation, respectively. For experimental studies using electrical heating, it would represent the latter.

The system being simulated is represented by a complicated system of highly interrelated non-linear partial differential equations. To keep the cost of performing the calculations with currently available digital computers from becoming prohibitive, empirical equations were developed for the properties of hydrogen and for more economical representation of two-dimensional, axially asymmetric, supersonic flow in the nozzle. These equations represent the desired functional behavior with an accuracy which is more than adequate.

The major assumptions made are as follows:

- (1) The program will be used only at low frequencies where the acoustical and mechanical transient effects are insignificant.
- (2) The steady-state heat transfer and isothermal friction factor correlations used are valid for single phase flow.

6.3.1, Digital Simulation Program (12042)

- (3) The Hendricks, Graham, Hsu and Medeiros heat transfer correlation for two-phase flow is valid.
- (4) The momentum and energy equations are based upon homogeneous two-phase flow using a friction factor based upon a curve fit of experiments with different Reynold's numbers and roughness factors.

6.3.2 Data Reduction Programs

Several programs were developed specifically for data processing. These programs are reported in RN-S-0146, Data Analysis Techniques, October 1964. The first of these programs is the Statistical Edit and Smooth Program. This program was written to use NERVA N-3 data tape as input to: (1) identify missing time values; (2) identify and correct outlying (erroneous observations); and (3) identify significant shifts in the trend of the data. Editing of data values is performed by fitting a third-degree polynomial to 40 data points and extrapolating the polynomial one point advanced in time, estimating the standard deviation of the extrapolated point, and comparing the observed and extrapolated values on a statistical basis. Smoothing of the data is provided by evaluating the polynomial near its midpoint at a point corresponding to a desired output time. This assures that corresponding smoothed values for all channels will be for identical times. The program then advances one data point and repeats its process. Finally, the program produces a tape for input to the 364 data analysis activity.

The program has a low cut-off frequency of 1 cps based on 40 points/sec to exclude noise.

The NRX-A1 data was smoother than anticipated and this program was not used. After this program was developed, it became apparent that a program was needed to analyze the narrow band data for frequency content above 1 cps. For this reason, the second program was developed and is called The Analog-to-Digital

6.3.2, Data Reduction Programs (cont.)

Data Analysis (ADDA) Program. This program processes the narrow band NERVA test data, in the form in which it comes directly from analog-to-digital conversion (N-2 tapes), to provide measures of data mean and variance for a grouping of 40 data samples.

The program also performs a Fourier analysis of the grouping for frequency content. The output is a summary of:

- (a) Frequency content
- (b) Discarded data
- (c) Intermittent multiplex failures
- (d) Inherent noise in data system.

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7.0 PROJECT ANALYSIS

In order to show how the analytical programs are used, the NRX/EST will be cited as an example of a Systems Analysis job. The CFDTS or XE-Engine analysis proceeds in a similar manner.

First, in order to establish the engine performance capability, the design point is computed using the steady-state digital program. This computes pressures, temperatures and flow rates through the major system components. In addition, such quantities as thrust, specific impulse, valve angle, and turbopump efficiencies are determined. After establishing the design point, a steady-state operating constraint map is made by computing points for various temperatures and pressures until a component constraint is violated. These maps become part of the engine test specification.

After establishing design conditions, the analog engine program is used to study startup, full power and shutdown characteristics. This program includes proposed engine control systems for the NRX/EST so that an integrated systems analysis can be accomplished considering such parameter variations as tank pressure, TPCV opening rates, back pressure, temperature and pressure programming.

Also, while the analog program is being used to establish normal operating conditions, the digital NERVA engine transient program (12013) is being used to establish emergency cooldown requirements. This program provides a more detailed representation of engine components but does not include the engine control systems. The cooldown is more readily handled on the digital program because the properties for hydrogen, helium and nitrogen are incorporated into the digital program whereas the analog engine program is set up with hydrogen properties only.

In addition, the digital and analog analysis are used to complement each other by providing a means of checking results. The choice of whether a study is performed by the analog or digital programs depends both on the availability of personnel and computers and the type of study.

7.0, Project Analysis (cont.)

Pretest predictions will probably be performed using the NERVA Engine Transient Program. This program has been verified with component, Kiwi, NRX-A data for the nozzle, reflector, shield and reactor. It is being used for the pretest predictions for CFDTS because of its operational status. CFDTS data will provide a means of verifying the low speed performance of the program.

Data analysis after the NRX/EST test will undoubtedly utilize several programs. At this point, both the NERVA Engine Transient and Digital Simulation Programs will probably be used. The first will make it possible to verify the pretest predictions which will most likely be for a slightly different ramp than is actually run in the test. The Digital Simulation Program will probably be used for detailed analysis of certain components or flow phenomena from the test. If a multi-channel program is required to analyze the test data, this program if checked out in its engine format or the Nuclear Engine Transient Analysis Program will be used.

Table 7.1 shows a summary of the programs currently planned. Results of analysis is reported in numerous memorandums as well as the following documents:

CFDTS

- RN-S-0150 - Preliminary CFDTS Systems Analysis, September 1964
- RN-S-0148 - Test Plan for Cold Flow Development Test System, September 1964
(major contributor)
- RN-S-0213 - CFDTS Pretest Predictions, April 1965

NRX/EST

- RN-S-0160 - NRX/EST Status Presentation, October 7, 1964 (major contributor)

NRX-A

- RN-S-0115 - Data Analysis Report on NRX-A1 Tests, July 1964
- RN-S-0208 - NRX-A2 Data Analysis, April 1965

XEngine

- RN-DR-0200 - Preliminary Specification, NERVA X-Engine, September 1965
(contributor)
- RN-TM-0206 - Performance Limitations of XE-Engine, 17 March 1965
- 7471:M2068 - (Memo) Emergency Cooldown Analysis Report, 21 December 1964

7.0, Project Analysis (cont.)

CFDTS/NRX/EST/NRX-A/XE

- RN-S-0173 - NERVA Technical Review Meeting, Volume I, December 1964
(contributor)

PROGRAMS BEING USED FOR GIVEN PROJECTS

<u>Engineering Analysis</u>	<u>NRX-A</u>	<u>CFDTS</u>	<u>NRX/EST</u>	<u>XE</u>	<u>Requirements</u>
1. Steady State and Tolerance Studies	1108	-	1108 12034	1108 12034	Economical. Detailed components for integration. Parallel channels only if components limits are involved.
2. Constraint	1108	-	12034	1108 12034	
3. Parameters Transient Studies	-	Analog 12013	Analog 12013	Analog 12013	Single channel. Economical to operate. Change configuration conveniently. Large number of reasonable assumptions.
4. Control System Analysis	-	Analog	Analog	Analog	Frequencies to 20 cps; many run economically; low accuracy on components; large number of reasonable assumptions.
5. Detailed Transient Analysis	-	12013	12013	12013 12039 or 12042	Detailed component representation. Parallel channels. Easy of input. Check previous analysis.
6. Pretest Predictions	12015*	12013 Analog	12013 Analog	Depends on Programs Available	Use component acceptance data. Detail depends on 3, 4, and 5 above. Rapid turn around.
7. Test Evaluation (DRAGON)	12015* 1108	12013	12013	Depends on Programs Available	
<u>Data Analysis</u>	12015* 12039 12042	12013 12042	12013 12042	12013 12042	Detailed multichannel model. Program checked by all previous tests for measurement evaluation. Program to verify performance analysis codes.

* NRX-A version of 12013 Program

Table 7.1

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8.0 DESCRIPTION OF FACILITIES

8.1 Digital Computer Facilities

A central digital computer facility is maintained in the Sacramento Plant. This includes the most modern computers available. At present, an IBM 7094 computer is devoted exclusively to scientific and engineering problems. In addition, two IBM 7044 computers are used for business applications with extra time available for engineering problems.

The IBM 7094 is an ultra high-speed digital computer capable of solving the most advanced problems encountered in aerospace technology. It utilizes 32,768 "words" of magnetic core storage; each word contains 36 binary bits which are roughly equivalent to 10.5 decimal digits. Any of these words can be brought into the working registers in 2.18 microseconds, which means that the computer can perform more than 220,000 operations every second. Data can be transferred up to 90,000 characters per second between the computer and magnetic tape. A single role of magnetic tape can hold almost 4,000,000 words of information.

8.2 Analog Computation Facilities

With the delivery of two new Comcor Computers in May 1965, a large well-equipped analog facility will be available for Systems Analysis and control studies in the REON Computation Laboratory, Sacramento. This facility will include the two new Comcor 5000 computers and one Electronic Associates 231R console. The capacity will be 340 computing amplifiers, 138 solid-state quarter-square multipliers (with amplifiers), 60 variable diode function generators (with amplifiers) and 490 potentiometers (450 are servo-set). In addition, 4 Brush recorders are available for recording analytical results. An automatic input-output unit is available in order to servo-set the potentiometers from paper tape. This facilitates problem change-over and checkout on each of the computer consoles. An important aspect of the facility is that the major portion of the equipment (Comcor 5000 computers) are completely solid state for minimum maintenance and maximum availability for solving large systems problems.

8.2 Analog Computation Facilities (cont.)

Hardware laboratories are located in the same area making it possible to tie control components such as actuators and electronic equipment into the analog computers. This tie-in capability is used for preliminary hardware checkout and operator familiarization prior to shipment to the test facility.

A major use of the analog facility is the design of the Test Stand Control System. The analog computers are used to simulate the XE-engine and test stand controls with voltmeters on a console providing a mockup of the display system. An operator can manipulate the demand switches on the console and monitor the system response. The analog computer provides the dynamic representation in actual or real time for the operator.