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WANL-TME-2753
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DATA ITEM S-31

**THERMAL AND FLUID FLOW
ANALYSIS REPORT (U)**

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THERMAL AND FLUID FLOW
ANALYSIS REPORT (U)

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ABSTRACT

Thermal and fluid flow analyses are presented to document the detailed analyses conducted to derive and establish the performance and design requirements for the Nuclear Subsystem and its Engineering Critical Components. This Data Item establishes and substantiates the appropriate parameters of the selected design and provides the source for steady state and transient data used in the detail thermal and structural analyses.

This Data Item report gives a summary of the applicable specifications relevant to the thermal design, a description and derivation of the analytical models and methods, the maturity of the input data, the validity of the analytical methods, and the interpretation and analysis of the resulting steady state and transient data.

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1.0 INTRODUCTION

1.1 PURPOSE OF REPORT

The purpose of this report is to document the thermal and fluid flow analysis of the Nuclear Subsystem (NSS) and its Engineering Critical Components (ECC) of the NERVA Engine. The NSS Assembly is described as the Contract End Item (CEI) of the NERVA Engine, 75K, Full Flow and listed as a subsystem in the detail Engine Specification CP-90290. This report constitutes the primary source of all steady state and transient thermal and fluid flow data. The detailed thermal and fluid flow analysis was conducted for the following purposes:

1. To derive and establish the performance and design requirements for the NERVA NSS and the ECC components.
2. To substantiate appropriate parameters of the subject design.
3. To provide the source of steady state and transient environment conditions for both thermal and structural evaluation of the ECC components

This report substantiates the selected design and reflects the ensuing design iterations throughout the life cycle of items 1 through 3 above.

The following detailed information is contained in this report for the NSS and the ECC components:

1. Correlation between the appropriate analysis and the requirements listed in the Detailed Specification.
2. Description and derivation of the analytical procedures and the analytical models. The methods of analysis are justified for application and the source of special or unusual methods are included and justified.
3. Presentation of special factors or correlations upon which the results are based such as the reference run profile, material thermophysical properties, heat transfer correlations, and radiation heating rates.
4. Development and the evaluation of uncertainties in material properties, method of analysis and operating environment are included for each analysis. In addition, the results of component and full scale testing are presented wherever possible to validate the methods of analysis.

5. Evaluation of the environmental condition at the start of life, during life, and end of life for the following phases of engine operations: Normal mode (startup, throttled, rated and shutdown), malfunction mode (single TPA operating) and growth mode. Both startup and shutdown chamber temperature ramps were run for $+175^{\circ}\text{R}/\text{sec}$ and $-175^{\circ}\text{R}/\text{sec}$ (Spec. extreme ramp rate) for a composite and graphite core to demonstrate the more critical nature of one condition over another and to provide adequate data to other disciplines (Structural Design, Reactor Mechanical Design) to complete their respective verification of the selected design.

6. Presentation of tabulated values and curves of fluid characteristics: temperatures, pressures, pressure losses and flow rates with respective uncertainty limits to provide a comprehensive justification of the design.

1.2 CONTENTS OF REPORT

Thermal and fluid flow data are presented for the NSS in Chapter 2 and for the following ECCs:

1. Support Plate and Plena, ECC677561, (Chapter 6)
2. Internal Shield, ECC677562, (Chapter 7)
3. Reflector Assembly, ECC677559, (Chapter 8)
4. Control Drum Drive Assembly, ECC677585, (Chapter 9)
5. Structural Support Coolant Valve Assembly, ECC 677576 (Chapter 10.2)
6. Nuclear Subsystem Instrumentation, ECC677565, (Chapter 11)

Thermal and fluid flow data for the following ECCs are not presented because these ECCs are reported in Trade Studies being prepared for NSS PDR in the appropriate S-54 Data Items.

1. Fuel Element, ECC677566, (Chapter 3)
2. Cluster Hardware, ECC677558, (Chapter 4)
3. Core Periphery, ECC677564, (Chapter 5)
4. The Lateral Support portion of the Reflector Assembly, ECC677559, (Chapter 8)

In general, this Data Item contains the following information for the NSS and each ECC:

1. Description of the component
2. Summary of results and conclusions
3. The applicable requirements and the compatibility of the thermal performance with the NSS specification
4. The method of analysis which includes:
 - a) A description of the analytical procedures employed
 - b) A description and the derivation of the analytical models used
 - c) The maturity of the input data upon which the results are based
 - d) A discussion of the validity of the analysis, including comparisons with experimental results and the derivation of the statistical distribution of uncertainties in the thermal and fluid flow data.
5. The results, analysis, and the interpretation of data which contain time-history plots of pertinent thermal and fluid flow parameters for the NSS and detailed steady state and transient temperature distributions for the ECC components.
6. A list of references and supporting documents.

2.0 NUCLEAR SUBSYSTEM ASSEMBLY

2.1 INTRODUCTION

This Chapter describes the results of the thermal analysis for the NSS Assembly of the NERVA Engine. The NSS is designed to supply a nominal 1510 MW power with a propellant flow rate of 91.2 pounds per sec. at a thrust chamber inlet temperature of 4250°R and pressure of 450 psia. The Performance Requirements of the NSS are given in NSS Specification document No. CP-677555A (Reference 1).

The NSS consists of reactor components designated Engineering Critical Components (ECC) in the CEI. The organization level of each ECC relative to the NSS is illustrated on NERVA Engine Specification Tree ST-1, Rev. G.

This Chapter will present for both a composite and graphite core, (Reference 2), the calculated boundary conditions for the normal and single turbopump malfunction modes consistent with Figure 2, NERVA Engine Operational Phases of the NSS Specification, CP-677555A. Time plots for the normal mode phases of the major NSS thermal and fluid parameters (power, flow, plenum pressures, and plenum temperatures) are presented, (Reference 3). The plenum conditions define the transient and steady state boundary conditions used in the detail analysis of each ECC to determine the effects of various operational phases on the reactor design.

2.1.1 Description of Nuclear Subsystem

The following general design features are given in CP-677555A for the NSS:

"3.3.1. General Design Features

The NSS consists of a hydrogen cooled, graphite

moderated, intermediate neutron energy reactor and its associated reactivity control devices consisting of neutron absorbing control drums with their actuation system and the Structural Support Coolant Assembly."

Supplemental descriptive information follows:

The reactor includes a core, reflector, core support plate and associated piping and internal shield. The core contains fuel element clusters. Each cluster, except for the irregular clusters in the periphery, consists of six fueled elements surrounding a central unfueled element. A counterflow support stem passes through each central element to the support plate. The support stems carry the core pressure drop load to the core support plate and also accommodate a varying hydrogen inventory for core reactivity control.

The core support plate transmits the core pressure drop load to the reflector and also incorporates plenums for support stem hydrogen feed, exhaust, and bypass.

The reflector surrounds the core and as its name implies, reflects neutrons into the core to sustain reactivity. Eighteen control drums are contained in the reflector. Each control drum has a neutron absorbing plate covering approximately 120 degrees of its external surface. Synchronous rotation of the control drums provides the means to establish reactor criticality. A lateral support system is also housed in the reflector. This supplies radial restraint for the core, acting through the core periphery which consists of thermal insulation and flow barriers, backed up by filler strips to round the core into a cylindrical shape for interfacing with the lateral support.

An internal shield which provides radiation protection for engine components and NSS instrumentation completes the major components of the reactor.

2.2 SUMMARY OF RESULTS AND CONCLUSIONS

Thermal analyses have been performed for the Nuclear Subsystem (NSS) of the Reference Design, Drawing No. 939J740, with both a composite and a graphite core design. The results demonstrate that the NSS thermal and fluid flow performance meet the requirements defined in the NSS Specification. The results of these analyses also provide steady-state and transient environments for detailed thermal analyses of the various ECC reported in this Data Item and other S-54 Data Item Trade Studies for "C" type components.

The TNT-II code and model were used to calculate the thermal and fluid environments. For the TNT-II code the NSS assembly is modeled with 348 solid material nodes, 32 flow channels and 16 plena. The material nodes and the complex flow system of the coolant channels, both series and parallel, are modeled in this program. The non-nuclear components, i.e., nozzle and turbopump assembly, used in the TNT-II are consistent with those modeled in the July 1, 1970 PAM.

The steady-state conditions analyzed were: normal mode rated, throttle hold, growth mode and malfunction mode, single turbopump operation. Transient startup and shutdown were analyzed using the "Reference Profiles" developed in the S-001 Data Item. The chamber temperature ramp rates in the thrust buildup and temperature retreat phases of the startup and shutdown profiles are the extreme ramp of $+175^{\circ}\text{R}/\text{sec}$ and -175°R respectively.

The Monte Carlo analyses were performed at steady-state operating conditions for the purpose of estimating the variation of thermal and hydraulic parameters at the conclusion of the engine qualification program. The Monte Carlo method is essentially a computer experiment which simulates the building and testing of a number of engines. Thirty engines simulated by the TNT-II model were used for the analysis. Thirty random sets of TNT-II input were prepared using the standard deviations of 162 independent model parameters and a random number table. The results of the 30 TNT-II computer cases were then statistically processed to determine the sample standard deviation and one sided tolerance limits with 99% proportion and 95% confidence level for the thermal

and hydraulic parameters computed by TNT-II. These results are presented on the environmental drawings.

The calculated NSS environments at the above mentioned steady-state operating conditions and at key points during the startup and shutdown transients for start of life and end of life are shown on the NSS Thermal and Fluid Environment Drawing, Figures 2-1B to 2-1G. The steady-state environment calculated by the TNT-II for both composite and graphite core designs are consistent with the state points at the various steady-state conditions established in the July 1, 1970 meeting, but reflect the latest NSS reference design modeled for the TNT-II calculation.

Comparison of the plena conditions at the NSS and engine interface state points shown in Figures 2-1B to 2-1G with those tabulated in the NSS Specification, show that the interface state points and uncertainties agree well within 10 psi on pressure, 15°R on temperature and 0.7 lb/sec on flow rate.

At start of life rated conditions the calculated hot critical drum angle of the NSS with a composite core is 46.8 degrees and that with a graphite core 58.2 degrees. These drum angles are the "orifice angles" of the reactor for the two core designs. The corresponding cold to hot NSS reactivity swing are \$1.08 and \$0.75. At end of life the NSS feedback reactivity insertion by stem flow adjustment was considered to be \$1.00 to compensate for corrosion loss. The additional \$0.11 due to fuel burnup, was not included in the analysis. The NSS feedback reactivity requirement at EOL throttled condition for the composite core is then, \$2.08 and that for the graphite core \$1.75. The support stem assembly (SSA) can supply a stem flow of 15.7 lb/sec (nominal value) with a wide open SSCV at the EOL throttled condition providing a NSS feedback reactivity of \$2.42 for a composite core, and 15.2 lb/sec and \$1.75 respectively for a graphite core. This indicates that on a nominal basis with both core designs the SSA can supply the \$1.00 reactivity insertion by stem flow adjustment alone for operation from SOL rated condition to EOL throttled condition.

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However, with the upper uncertainty limit of the stem flow taken into consideration, a slight drum motion is required to meet the EOL throttled condition.

The results of this thermal analysis at EOL throttled condition also indicate that the average peripheral region fuel elements fission power factor is reduced about 3 percent for both the composite and graphite core design due to the change of hydrogen content in the core and reflector relative to that at rated SOL condition. This indicates that slight outward drum motion at EOL throttled condition is desirable to flatten the core edge power.

Due to the difference in the radiation heating rates between the composite and the graphite core design on the NSS components, the core inlet temperature and the core pressure drop for the composite core are 281°R and 168 psi as compared to the 292°R and 170 psi for the graphite core design at SOL rated condition. The reactor pressure drop (pressure drop from reflector inlet to chamber) is 685 psi for the composite core as compared to 677 psi for the graphite core design at SOL rated condition. The highest reactor pressure drop occurs, however, at the malfunction mode of a single turbopump operation at SOL (80 percent power) with a composite core. The reactor pressure drop is 798 psi with a 99/95 percent upper limit uncertainty of ± 21 psi, resulting in a maximum pressure drop of 819 psi.

The uncertainty analysis results obtained from the three core region TNT-II model indicate that the maximum radial variation of the fuel exit temperature is 117°R which is within the specified limit of $\pm 150^{\circ}\text{R}$. Also, the results indicate that the minimum reflector and pressure vessel annulus flow is 6.3 lb/sec at EOL rated condition which is greater than the minimum pressure vessel annulus flow requirement of 6.2 lb/sec.

During the thrust buildup phase of the startup with the extreme chamber temperature ramp of $175^{\circ}\text{R}/\text{sec}$, the chamber pressure ramp from the initiation of the thrust buildup to the throttle point is linear at 13 psi/sec for all cases. After the throttle point the pressure ramp rate was 50 psi/sec as specified. The maximum rate of the liner tube and stem material temperature increase is about $30^{\circ}\text{R}/\text{sec}$. The liner tube and stem temperature operating limits were not exceeded at any time during the thrust buildup. The maximum temperature difference between the average fuel temperature and central element average temperature computed by the TNT-II model during the thrust buildup is about 300°R for both core designs.

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(U) During the throttling phase of the shutdown operation, the chamber pressure ramp rate was the specified ramp rate of -50 psi/sec. During the temperature retreat phase of the shutdown with the extreme chamber temperature ramp rate of $-175^{\circ}\text{R}/\text{sec}$, the maximum chamber pressure ramp rate was -75 psi/sec. The reactor flow rate decreased rapidly initially during the temperature retreat, but increased gradually afterwards in order to maintain the demand chamber ramp of $-175^{\circ}\text{R}/\text{sec}$. The flow reversal peak occurs at the end of the temperature retreat phase of the shutdown.

The reversal of propellant flow results in a reversal of feedback reactivity. However, the minimum NSS shutdown reactivity for all the cases analyzed was greater than $-\$0.90$, assuring the capability to achieve reactor shutdown.

(CRD) The maximum liner tube and stem material temperatures increased rapidly during the early phase of the temperature retreat, decreased toward the end of the temperature retreat, but increased again during the early phase of pump tailoff phase of the shutdown. This occurred for both the composite and graphite core. The maximum liner tube material temperature for both core designs is about 1430°R and the maximum stem material temperature for both core designs is about 1100°R . These maximum temperatures are less than the respective cooldown limits of 1450°R and 1500°R .

(U) The maximum temperature difference between the average central element temperature and the average fuel temperature computed by the TNT-II model during the shutdown profile analyzed are about 180°R for both core designs.

2.3 APPLICABLE REQUIREMENTS AND COMPATIBILITY OF THERMAL PERFORMANCE WITH THE NSS SPECIFICATION

The applicable requirements and design conditions stated in this Section are specified in Reference 1, Section 3.0, issued on September 28, 1970.

*"3.1.1.1.1. Operational Modes - The NSS shall be capable of operation within the following modes:

- (a) Normal Mode
- (b) Malfunction Mode
 - (1) Single Turbopump Operation
 - (2) Component Malfunction Mode
- (c) Emergency Modes"

In this chapter, only a modified normal mode (See Section 2.4.3.1) and the steady state Malfunction Mode, Single Turbopump Operation, will be reported in this Data Item Report for the NSS PDR, (Reference 7).

"3.1.1.1.2. Rated Performance - The NSS performance rating is based on the capability of steady state operation identified by the following:

- (a) Nominal thermal power 1510 Mw
- (b) Mixed mean chamber inlet stagnation temperature (Nominal + 2.326 σ , including a controllability tolerance of tbd) $4250^{\circ}\text{R} \pm 40^{\circ}\text{R}$
- (c) Nominal chamber stagnation pressure 450 psia
- (d) Nominal chamber flow rate 91.2 lb/sec
- (e) Normal Mode Endurance-- 600 minutes at rated temperature (accumulated in up to 60 cycles of varying duration up to 60 minutes maximum per cycle). "

The NSS design parameters and environment at steady state rated operation is reported in Sections 2.5.1.1 and 2.5.2.1 and satisfy the rated performance requirements stated in Section 3.1.1.1.2., (a) through (d).

* Section extracted directly from NSS Specification.

"3.1.1.1.5.1.2 Startup Operations - Startup operations consist of temperature conditioning, nuclear startup, bootstrap and thrust buildup. Startup begins at the receipt of a command signal to initiate propellant flow or nuclear startup and is completed when rated performance has been achieved within specified controllability limits."

The analysis in this chapter will commence with a modified Temperature Conditioning subsequent to the Nuclear Startup. There will be no thermal evaluation of Nuclear Startup. The startup profile used for design data are those considered "Reference Profiles" at the time of initiation of thermal and fluid flow analyses on the selected NSS design for this Data Item, (Reference 8). The thermal conditioning and bootstrap phases were provided to establish initial conditions for the detailed thrust buildup analysis.

"3.1.1.1.5.1.2.2. Bootstrap - Bootstrap operation consists of the establishment of powered pump operation using the heat energy available within the engine system. Bootstrap is initiated at the completion of Temperature Conditioning and Nuclear Startup and propellant flow is admitted to the turbine. It is terminated with the initiation of Thrust Buildup which is coincident with the achievement of chamber conditions of (tbd). "

The reference profile used during the Bootstrap operation shows that the initiation of Thrust Buildup is coincident with the achievement of chamber conditions of 60 psia and 1130°R. (Refer to Section 2.4.3.1).

"3.1.1.1.5.1.2.3. Thrust Buildup - Following Bootstrap, a programmed increase in chamber temperature and pressure is initiated and completed at the attainment of Steady State Operations.

The NSS shall be capable of rates of change of temperature and pressures consistent with the following rates of change of chamber temperature and pressure.

- (a) $150 \pm 25^{\circ}\text{R}/\text{sec}$ for $1100^{\circ}\text{R} \leq T_c \leq 4250^{\circ}\text{R}$
- (b) $50 \pm 10 \text{ psi}/\text{sec}$ for $293 \text{ psia} \leq p_c \leq 450 \text{ psia}$

During this phase, the control drum shut-down capability shall not be less than .50.25; and the mixed mean chamber inlet temperatures shall not exceed (tbd)°R. "

The present evaluation of the Thrust Buildup operation given in Section 2.5 indicates that the above rates of change of chamber temperature and pressure, 3.1.1.1.5.1.2.3. (a) and (b) were satisfied. For the reference startup profile reported in this Data Item, a $175^{\circ}\text{R}/\text{sec}$ rate change of chamber temperature was used. This rate is the $+25^{\circ}\text{R}$ extreme condition on chamber temperature ramp. Perfect controllers on T_c , P_c and the SSCV position were assumed in the reference profiles (i.e., the demand schedule on the control parameters such as T_c and P_c were the same as actual or "measured" values).

"3.1.1.1.5.1.3. Steady State Operation - Steady state is initiated by the attainment of specified conditions of chamber temperature and pressure and is terminated by receipt of a command signal to begin retreat from this point. The NSS shall be capable of the operation specified in 3.1.1.1.2. (Rated Performance)."

The NSS rated performance is evaluated in Sections 2.5.1.1 and 2.5.2.1 which show that the NSS attains the performance requirements.

"3.1.1.1.5.1.3.1. Core Temperature Profile - Based on a preselected fixed drum operation at rated performance, the NSS shall be capable of limiting the radial and azimuthal variations in core exit gas temperatures during rated performance operation to $\pm 150^{\circ}\text{R}$ with respect to the instantaneous average core exit gas temperature. (This requirement shall not apply to the lateral support and core periphery flow). As an aid in achieving the above, the NSS shall be designed such that reactivity adjustment requirements at rated operations can be satisfied by adjustments in the support stem assembly (SSA) flow rate equivalent to ± 2.00 as a minimum. "

The evaluation of fuel element exit gas temperatures in Sections 2.5.1.1 and 2.5.2.1 in this Data Item report and Reference 9 indicates that radial and azimuthal variations in core exit gas temperatures during rated performance operation is expected to be within $\pm 150^{\circ}\text{R}$ with respect to the instantaneous average core exit gas temperature. The NSS reactivity adjustment requirements at rated operations can

be satisfied by adjustments in the support stem assembly flow rate equivalent to a \$2.00 minimum.

"3.1.1.1.5.1.4 Shutdown Operations - Shutdown Operations consist of Throttling, Throttle Hold, Temperature Retreat, and Pump Tailoff. Shutdown is initiated by a command signal to depart from steady state conditions and is completed upon termination of powered pump operation. During these operations, the control drums shall be commanded to the position to provide maximum reactivity shutdown. The NSS shall be capable of providing the dynamic reactivity to reduce thermal power from steady state operation when satisfying the following requirements. "

The shutdown reference profile analyzed was terminated at 65 psia chamber pressure for the composite core and at 80 psia for the graphite core. The corresponding chamber temperature was 1800°R for each core. This profile takes the shutdown into the pump tail off phase, but does not take it fully to the end of pump tailoff.

"3.1.1.1.5.1.4.1. Throttling - Throttling consists of a ramp down in chamber pressure at rated temperature. The throttling phase is initiated by a command signal to depart from steady state operation and is terminated when the throttle point is reached. The NSS shall be capable of rates of change of pressure consistent with a chamber pressure transient of -50 ± 10 psi/sec for $293 \text{ psia} \leq P_c \leq 450 \text{ psia}$, and shall be capable of reactivity adjustments consistent with maintaining rated chamber temperature within $\pm (tbd)^\circ\text{R}$ during the transient. So far as possible, the reactivity adjustment shall be effected by changes in structural support flow. "

The shutdown reference profile assumed perfect control. Therefore, the rate of chamber pressure change for $293 \text{ psia} \leq P_c \leq 450 \text{ psia}$ was maintained at 50 psi/sec, while the chamber temperature remained constant at 4250°R. The SSCV was adjusted to maintain essentially constant drum angle during the pressure transient for both the SOL and EOL shutdowns. (Refer to Sections 2.5.1.2 and 2.5.2.2.).

"3.1.1.1.5.1.4.2. Throttle Hold - The NSS shall be capable of a throttle hold identified by a nominal chamber pressure of 293 psia and a mixed mean chamber inlet temperature of $4250^{\circ}\text{R} + 40^{\circ}\text{R}$ (2.326 σ). While at the operating point, the NSS shall be capable of satisfying the pressure, temperature, and flow requirements shown on Tables 3* and 4*. The throttle hold phase is initiated when the throttle point is reached and is terminated by a command signal to depart from rated temperature. The temperature controllability requirements of Paragraphs 3.1.1.1.5.1.3.1 (Core Temperature Profile) and 3.1.1.1.5.1.3. (Temperature Controllability) shall also apply during the Throttle Hold with the loss of core reactivity of \$1.20.

The maximum duration for single throttle hold operations shall not exceed (tbd) seconds; and the throttle hold shall be limited to chamber pressures greater than (tbd) psia. "

Sections 2.5.1.1 and 2.5.2.1 show that the NSS can operate at the throttle hold conditions of a nominal chamber pressure of 293 psia, a mixed mean chamber inlet temperature of $4250^{\circ}\text{R} \pm 40^{\circ}\text{R}$ (2.326 σ) assuming perfect controllers. The throttle hold duration in the shutdown reference profile is 40 seconds at a chamber pressure of 293 psia. The throttle hold considered for design boundary conditions for the ECC detailed design was a steady state condition at $T_c = 4250^{\circ}\text{R}$ and $P_c = 293$ psia.

The reactivity adjustment at the EOL Throttle Hold condition is capable to insert \$1.00 reactivity to account for corrosion loss. The amount of \$0.11 for fuel burnup (Reference 10) at EOL is not considered in the present analysis.

"3.1.1.1.5.1.4.3. Temperature Retreat - Following the throttle hold phase, a programmed decrease in chamber temperature and pressure is initiated and is completed when pump tailoff is initiated.

The NSS shall be capable of rates of change of temperature and pressures consistent with the

*These Tables contain flow characteristics data.

following rates of change of chamber temperature and pressure:

$$(a) -150 \pm 25^{\circ}\text{R/sec for } (tbd)^{\circ}\text{R} \leq T_c \leq 4250^{\circ}\text{R}$$

$$(b) (tbd) \pm (tbd) \text{ psi/sec for } (tbd) \text{ psia} \leq P_c \leq 293 \text{ psia}''$$

Following the Throttle Hold phase, the NSS environment included the following rates of change of chamber temperature and pressure:

$$(a) 175^{\circ}\text{R/sec for } 1800^{\circ}\text{R} \leq T_c \leq 4250^{\circ}\text{R}$$

$$(b) 75 \pm 5 \text{ psi/sec for } 130 \text{ psi} \leq P_c \leq 293 \text{ psia}$$

These conditions are illustrated on Figures 2-43 and 2-47 in Sections 2.5.1.1,

As noted, the pressure transient during this phase of Temperature Retreat exceeds the $-50 \text{ psi/sec} \pm 10 \text{ psi/sec}$ specification value during the Throttling phase of shutdown.

"3.1.1.1.5.1.4.4. Pump Tailoff - The pump tailoff phase is that portion of shutdown between the end of Temperature Retreat and the termination of powered pump operation. The NSS shall have a shutdown reactivity capability of (tbd) \$. This phase shall be completed within (tbd) seconds. "

During the pump tailoff of the shutdown reference profile, the pump tailoff was terminated before the tank pressure of 30 psia was reached. (Refer to Sections 2.5.1.2. and 2.5.2.2). During the pump tailoff, the NSS has a shutdown reactivity capability of at least \$1.85.

"3.1.1.1.5.1.5. Cooldown Operations - Cooldown is initiated upon completion of shutdown and is completed upon final termination of propellant flow or the receipt of a command signal for restart; (i.e., prestart and cooldown may overlap). "

Cooldown operations are not included in this Data End Item Report, but are reported in the Systems Analysis Summary Report, Reference 6.

"3.1.1.1.5.2. Malfunction Modes - The NSS shall be capable of meeting the following performance requirements when operating under the following malfunction conditions. The NSS shall be capable of direct transition to the malfunction modes during any phase of NSS operations. "

The single turbopump operation mode is the only malfunction mode considered in this issue of the S-031 Data End Item Report, (Reference 7).

"3.1.1.1.5.2.1. Single Turbopump Operation Mode - The NSS shall be capable of operating with one Propellant Feed Subsystem (PFS) leg inoperative. The NSS requirements differ from the Normal Mode only in propellant pressures and temperatures within the NSS. The phases of the Single Turbopump Operation are identical to those of the Normal Mode with the following exceptions:

(a) During Steady State Operations, the NSS shall be capable of satisfying the pressure, temperature, and flow requirements shown on Tables 5* and 6*.

(b) During Throttle Hold, the NSS shall be capable of satisfying the pressure, temperature, and flow requirements shown on Tables 7* and 8*.

During steady state single turbopump operation, the NSS thermal and fluid environment satisfies the pressure, temperature and flow requirements of 80% thrust at full temperature. Figures 2-1B through 2-1F summarize the thermal and fluid parameters satisfying the requirements of 80% thrust.

During throttle hold single turbopump operation, the NSS environment satisfies the pressure, temperature, and flow requirements of 65% power at rated temperature. Figures 2-1B through 2-1F summarize the thermal and fluid parameters satisfying this requirement for 65% power.

"3.3.1.1.7. Growth Characteristics - The NSS design shall incorporate such features as necessary (exclusive of fuel elements) to allow growth, to operate at a nominal mixed mean chamber temperature of 4500°R at 450 psia pressure. NSS performance shall be shown in Table 13* and 14*. The NSS shall have the capability to operate at this condition for a minimum of 120 minutes accumulated into multiple cycles, up to 12, of varying duration up to 60 minutes. "

The thermal and fluid environment for the growth mode operation is discussed in Sections 2.5.1.1 and 2.5.1.2 and shown in Figure 2-1G.

*These Tables contain flow characteristics data.

2.4 METHOD OF ANALYSIS (DESIGN PRACTICES)

To perform thermal analyses for the NSS Assembly and the detailed analyses of the ECC, inputs, e.g. heat generation rates, material properties, run profiles etc., are required from other WANL engineering disciplines. The results from the thermal analyses are used as boundary conditions for Structural Design. The flow of data between the various engineering disciplines is interrelated. The thermal analysis procedures and techniques presented in this document are, therefore, part of the overall framework of Design Engineering Analysis Procedures.

In the first subsection of this section, the overall Design Engineering Analysis Procedures and Design Practices are presented. The Thermal Design procedure is then described. In the subsequent subsections, the modeling of the NSS and the calculational procedures and the method of calculating the uncertainties for the thermal environments at steady state operating conditions are discussed.

2.4.1 Analytical Procedures

The purpose of this section is to describe (1) the overall framework of Nuclear, Thermal, and Structural Design Analyses (2) the relationship of Thermal computations to this overall framework and (3) the procedures by which Thermal results are obtained.

2.4.1.1 Overall Design Engineering Procedures

Figure 2-2 displays the flowchart of Nuclear, Thermal and Structural Analyses. In this figure, and in all subsequent figures describing analytical procedures, the following symbolism is employed:

- 1) An inverted trapezoid (shorter baseline on the bottom) denotes an input of information.
- 2) An upright trapezoid (shorter baseline at the top) denotes an output of information.
- 3) A rectangular block represents an operation.

- 4) All functions have a number in the upper right hand corner which identifies the function on any subsequent flowchart.
- 5) When the operations performed for a given function are expanded into several subfunctions, the base identification number will remain the same and suffix numbers identifying the subfunctions will be added (i.e., the subfunctions for block 11 will be numbered 11-1, 11-2, etc.).
- 6) When a specific function is performed by an existing operational computer code, the name of the computer code will appear at the bottom of the function block.

The procedure for performing Nuclear, Thermal, and Structural Analyses has been broken down into four steps which are as follows:

- Step 1. The first step consists of developing or obtaining the data necessary to define the engineering model of the NSS from the NSS and/or component drawings.
- Step 2. The second step consists of translating the information in the engineering model of the NSS or NSS components into the analysis models required to perform Nuclear, Thermal, and Structural Analyses.
- Step 3. The third step consists of employing the NSS analysis models developed in Step 2, to obtain nuclear, thermal and structural results for the NSS.
- Step 4. The fourth step consists of employing the NSS component analysis models developed in Step 2 and the computational results obtained in Step 3 to obtain detailed thermal and structural results for component analyses and reporting the results of thermal and structural analyses. Note that the nuclear analysis is performed only on the NSS as a whole and no component nuclear analysis is performed. This step also consists of (1) comparing analytical and experimental results to obtain uncertainties in the calculational technique, and (2) employing experimental or other reference information to improve the analytical model or technique.

A brief description of each step follows.

Figure 2-2 shows that Step 1 consists of the following inputs of information:

- 1) Block 1 is NSS and or component drawings.
- 2) Block 2 is the bill of materials defining the type, quantity and composition of individual parts.
- 3) Block 3 is material properties information which includes the nominal value and standard deviation for each property.
- 4) Block 4 is the run profile, state points, and engine component data information.
- 5) Block 5 consists of optional input data for off design conditions which can be employed in (a) Monte Carlo analyses of the NSS to evaluate failure mode probabilities, or (b) malfunction analyses to evaluate Failure Mode Effects and Criticality Analyses (FMECA).

The information from Blocks 1 through 5 is combined together to generate the engineering model of the NSS in Block 7. This procedure is expected to be automated. A computer description of each component and the bill of materials would be handled by the Weights and Moments of Inertia (WAMI) code to generate the weights, center of gravity, and moments of inertia for each component (Block 6). The WAMI code would also act as the file manager for the majority of the information in the engineering model and would provide the information needed to generate analysis models. The Nuclear, Thermal and Stress (NUTS) code handles the material properties information and provides the information in a format which is directly useable by the design computation codes. Codes, such as the Design Performance Reliability (DPR) code, are being developed which will automatically generate probability of failure mechanism information of the core via the Monte Carlo technique to evaluate propagation of errors (NRP 605).

Step 2 in the Nuclear, Thermal, and Structural analyses consists of developing the analysis models required by each discipline (Blocks 8, 9, and 10) from the information contained in the common engineering data bank (Block 7). This procedure may also be automated with the Nuclear Analytical Model (NAM), Thermal Analytical Model (TAM),

and Stress Analytical Model (SAM) codes in order to make the optimum utilization of manpower and avoid duplication of effort. The NAM, TAM, and SAM codes are currently only names which may apply to several computer codes, some of which are already in existence, used to generate an analytical model.

Step 3 in the Nuclear, Thermal, and Structural Analyses consists of performing the analysis related to the NSS as a whole. The nuclear analysis model developed in Block 8 is employed to perform the nuclear radiation calculations in Block 11. In addition, in order to perform the nuclear computations the region average temperatures and hydrogen densities are required (Block 12) from the thermal analyses. However, note that the thermal analyses, both for the NSS and components (Blocks 13 and 19), require heating rates, fission distribution, and reactivity coefficients in order to be performed (Block 15). Therefore, as can be seen from Figure 2-2, the nuclear and thermal computations form a closed loop which require some iteration in order to obtain nuclear and thermal data.

The thermal calculations for the NSS (Block 13) employ the thermal analysis models (Block 9) and nuclear information (Block 15) to generate thermal data for the NSS and thermal-flow boundary conditions (Block 16), which are used in the thermal calculations for components (Block 19), and in the stress calculations for both the NSS (Block 14), and components (Block 21). The stress calculations for the NSS employ the stress analysis models (Block 10) and the thermal-flow boundary conditions (Block 16) to generate the stress data for the NSS, and the loads and displacement boundary conditions (Block 17) which are used in the stress calculations for components (Block 21).

Step 4 in the nuclear, thermal and structural analyses consists of the following three phases:

- 1) Thermal and stress calculations are performed on a component level (Note that nuclear calculations are not performed on a component level).
- 2) Analytical and experimental results are compared to derive uncertainties or experimental results or other reference information are employed to improve the analytical model or technique (Block 18). This function provides feedback to the second step of this procedure.

3) Nuclear, thermal and stress computations are reported in the appropriate data item. In addition, the results of off-design condition calculations for Monte Carlo analyses to aid in the evaluation of failure mode probabilities and/or malfunction analyses to evaluate FMECA's which have been obtained by essentially the same calculational technique are reported.

The thermal calculations for component analysis (Block 19) employ the thermal analysis models (Block 9), the nuclear information (Block 15), and the thermal-flow boundary conditions from the NSS computations (Block 16) to generate thermal data for the components and the thermal boundary conditions (Block 20) for the components. The stress calculations for component analysis (Block 21) employ the stress analytical model (Block 10), the thermal-flow boundary conditions from the NSS and component analyses (Block 16 and 20), and the loads and displacement boundary conditions from the NSS computations (Block 17) to generate the stress data for the components. Radiation level information is also provided to Thermal and Structural Design to modify radiation sensitive property data in the analyses.

2.4.1.2 Thermal Design Procedure (Design Practice)

The thermal design procedure consists of first, generating the analytical models (Block 9 of Figure 2-2, Step 2 in the overall framework); second, the overall NSS Thermal Calculations (Block 13 of Figure 2-2, Step 3 in the overall framework); and third, the Component Thermal Calculations (Block 19 of Figure 2-2, Step 4 in the overall framework). The details of Block 9, 13 and 19 and their relationships with the overall analysis procedure are described below.

a) Generation of the thermal analytical models (Block 9).

Figure 2-3 shows the general procedure for developing the analyses models. The models required are two- or three-dimensional finite difference models which can be generated either by the computer codes, W-MESHER (Reference 11) or AUTOTEM (Reference 12), or manually. The procedure is as follows: The given geometry (Block 1 input) is first divided into

a finite number of nodal points or cells. The volumes of the nodes, connection lengths and the interface areas between two adjacent nodes and the heat transfer surface area of the surface nodes are the major part of the input data required to describe the model. These input data can be calculated by the computer using the W-MESHER or the AUTOTEM code automatically. For more complex models which are beyond the present capability of the above codes, manual preparation of the model is required. To assist the manual preparation of a complex model, an electronic digitizer can be utilized (Block 9-1), if it is available. To use the digitizer, the user first draws the geometry and the desired nodal pattern to scale. The digitizer can record the overall contour of the geometry and the coordinates of the vertices of each node. The output of the digitizer is a deck of cards or a magnetic tape which becomes input to the W-MESHER or AUTOTEM. With these card input the volumes of nodes, connection lengths, interface area between adjacent nodes, etc. can be calculated. For the present time, the model used for TNT-II analysis, to be described in Section 2.4.2, of the NSS assembly (Block 9-2) was prepared manually without the digitizer because of the complexity of the NSS assembly. Each of the components in the NSS assembly was represented by a gross finite difference model consisting of internal nodes, flow channels and plena. For the detailed analyses of the components, such as reflector blocks, control drum, fuel elements, support plate, shields and cluster hardware, the models possess great details. Some of these models were prepared by W-MESHER and AUTOTEM using either manual or digitizer developed geometry data, and others were prepared manually.

The input to the modeling is the complete common engineering data (Block 7) which consists of all the input requirements shown in Block 1 through 5 of Figure 2-2. The list of the independent parameters and the estimates of their standard deviation (Block 18) are also required when uncertainty analysis is to be performed.

b) NSS level thermal calculations (Block 13).

Figure 2-4 shows the general procedure to calculate the Step 3 NSS performance. The input data required are the NSS analysis model (Block 9) as discussed previously and the heat generation rates, fission

distribution and reactivity coefficients input from Nuclear Design (Block 15). The NSS thermal and fluid flow environment is calculated by the TNT-II code (Block 13-1). The thermal environment uncertainty calculations are also performed by the TNT-II code to obtain N samples for each of the NSS environmental (dependent) parameters by a Monte Carlo or random sampling technique which will be discussed in Section 2.4.4. The output of the TNT-II code is the complete thermal and hydraulic environments of the NSS. Blocks 12 and 16 show the boundary conditions output required by Nuclear Design and Structural Design respectively. With the thermal environments computed in Block 13-1, a core corrosion and reliability analysis can be performed by the planned DPR code (Block 13-2). This code is being developed and hence no results from this block will be presented in this Data Item Report. However, subroutines which will be incorporated in the DPR code are being used and the results reported in Reference 9.

c) Component Thermal Calculations (Block 19)

Figure 2-5 shows the general procedure to perform components thermal analysis. The input data requirements are shown by the blocks 9, 15, 16, and 19-1. The detailed heat conduction, fluid flow and corrosion calculations are performed by the computer codes shown in Block 19-2. A brief description of each of these codes follows in the next paragraph. Blocks 20 and 23 of this figure show the output and the reporting of the individual calculations. The results of the analyses can be used to compare with experiments, if available; and to check the validity of the assumptions made for the analyses (Block 18 of Figure 2-2). The final analysis from the operation in Block 18 may provide better analysis methods and/or models and better estimates of uncertainty parameters for further design analysis.

A brief description of each of the heat conduction, fluid flow and corrosion analysis codes used by Thermal Design designated on Block 19-2 follows:

a. TAP-A* (Reference 13)

The TAP-A computer program is used to solve transient and steady state heat transfer problems in a multi-dimensional system having arbitrary geometric configurations,

* Operating instructions have been issued in "Thermal Design Computer Code Manual."

boundary conditions, initial conditions, heat generation and temperature dependent physical properties. The program has the capability to consider the following modes of heat transfer and boundary conditions: internal conduction and radiation, free and forced convection, radiation to and from external surfaces, time dependent surface temperatures and surface heat fluxes and time dependent external boundary (environmental) temperatures.

b. MCAP* (Reference 14)

The MCAP computer program is used to calculate the fluid and material hot spot temperatures in a heat generating solid that is cooled internally by parallel flow passages arranged in a uniform pattern. The flow passages within the heat generating solid are treated as isolated channels with no channel to channel radial heat conduction and no axial conduction within the heat generating solid. The program has the flexibility to use various parameters, such as film heat transfer correlations, materials, cooling system configurations (circular passages in equilateral - triangular array, square array, flat plates, concentric cylinders), and various cooling fluids. Features of this code include the following options: (1) flow balancing in parallel channels; (2) adjustment of power; and (3) determination of channel diameters or entrance coefficients to meet specified exit conditions. A step change in pressure may be introduced at an intermediate axial distance. The pressure drop through a heat exchanger may be determined for a given flow rate or the flow rate may be determined for a specified pressure drop. Internal heat generation rate is specified for each channel and may vary axially. Channel diameter may vary axially in the parallel flow channels.

c. TRACK II* (Reference 15)

The TRACK II computer program is used to perform transient and steady-state thermal analyses of heat generating solids of arbitrary geometry which are cooled by fluid flowing through multiple parallel or series channels. The hydraulic and heat convection calculations are coupled with finite element heat conduction calculations to determine coolant conditions and detailed material temperature distributions of the solid in a single

* Operating instructions have been issued in "Thermal Design Computer Code Manual."

computation. A key feature of the program is the versatility of the flow network. Two independent groups of coolant channels are permitted and the channels may be arranged in series and parallel combinations. Additional features include an option for interface conduction between components which are modeled separately and a method to accommodate the effect of fast neutron fluence on the material thermal conductivity and thus on component temperature distribution variations with run time (i.e., fluence level).

d. ICAP*

The ICAP computer program is used to calculate the flow rate, pressure distribution, surface regression distribution caused by the graphite - hydrogen chemical reaction, and weight loss in various types of narrow flow channels having graphite walls with hydrogen flowing between them. It is applicable at thermal conditions which lead to reactions involving C, H₂, CH₄, and C₂H₂. Presently, only the laminar flow regime is treated by the program. The fluid bulk and wall axial temperature distributions must be specified because no heat transfer computations are performed by the program. For these reasons, ICAP is best suited for analysis of the flow and corrosion either in channels where the fluid and wall temperature distributions are not strongly related to the flow rate, or in channels where these temperature distributions can be computed by other means.

e. AUTOTEM* (Reference 12)

The AUTOTEM computer code is used for automating the procedure of modeling and obtaining temperature distributions for a given two-dimensional irregular body with a geometry description, such as engineering drawing information, as input. This code meshes the solid geometry into a nodal system as required by the TAP-A heat conduction code. The nodal system, as generated, is plotted on the SC 4020 data plotter for visual inspection. From the calculated nodal temperatures, isotherms can be plotted for specified temperature values.

* Operating instructions have been issued in "Thermal Design Computer Code Manual".

This program can handle any two dimensional (constant in the third dimension) or axial symmetrical body consisting of a single material. Time dependent internal heat generation, temperature dependent material thermal properties, and time dependent boundary conditions can be considered.

f. W-MESHER (Reference 11)

The W-MESHER computer code is an improved version of AUTOTEM. This code is capable of handling a more complex two dimensional figure than AUTOTEM and can also mesh a figure that is composed of more than one material. The nodes which form the mesh network are analytically described in the printed, punched and plotted output. The punched output is used in the TAP-A heat conduction code.

g. TNT-II

The TNT-II computer code is used to perform a coupled transient and steady state thermal, hydraulic and nuclear analysis of the NERVA engine including the NSS component detailed models and the non-NSS components. This code is used to calculate the engine state points and NSS thermal fluid environments. The details of this code are discussed in Section 2.4.2.

h. TAP-B

The TAP-B computer code is a modified TNT-II code that is used to perform only a coupled fluid flow and heat conduction calculation without the nuclear computations. This code can handle many parallel and series flow networks inside a heat conducting solid body as well as a counter flow system. This code is similar to the TRACK II code except that a three-dimensional heat conduction model is required to represent the solid body and that methods for handling the iterations between fluid and conduction calculations have been improved.

i. LOWERE* (Reference 16)

The LOWERE code was developed to predict the corrosion weight loss distribution of the fuel coolant channel, the associated loss in reactivity, and the resultant drum angle changes. The two major modes considered in calculating carbon weight loss in the fuel element bore were midband and hot end corrosion. Semi-empirical relationships were derived for corrosion weight loss calculations from fuel element corrosion experimental results and reactor tests.

j. Core Corrosion and Reliability

The Core Corrosion and Reliability code is used to calculate** failure probabilities for the core complement of fuel elements. The failure modes considered are: (1) probability of reactivity loss due to corrosion exceeding defined limit, (2) probability of the incremental corrosion weight loss (grams per inch) in one or more elements exceeding a predetermined limit, and (3) probability of maximum material temperatures in one or more fuel elements exceeding a predetermined limit. Probability distribution functions need not be normal and can be specified by any cumulative distribution. The effects of changes in nominal core temperatures due to corrosion, fission product poisoning, fuel burnup, support stem flow, and control drum position are accounted for. The mathematics of combining the probabilities considers the fact that some of the uncertainties affect single elements, some affect entire groups of elements in the core, and others affect the entire core.

k. MCARLO

The MCARLO code is used to automate the Monte Carlo sampling method for use with the TNT-II program. The MCARLO code consists of two programs. The first program prepares TNT-II input for all calculations using the nominal TNT-II input deck, the estimated standard deviations of the selected independent TNT-II parameters, and the

** Description applies to final version of the completed program.

* Operating instructions have been issued in "Thermal Design Computer Code Manual."

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random multiplication factors for those selected parameters. The second program processes the TNT-II results to obtain mean values, sample standard deviations, and tolerance limits for any computed parameters.

The following computer codes have been registered as indicated by PMD No. 8, Rev. A, Controlling NERVA CDC 6600 Computer Production Codes: MCAP, AUTOTEMP and TAP-A.

2.4.2 Analytical Model

The analysis model used by the TNT-II code to calculate the steady state and transient NSS thermal and fluid environment is described in this section.

2.4.2.1 Justification

Performance analyses for all the previous NRX-A reactors had been calculated using a computer model and the thermal-nuclear-transient (TNT) code (Reference 17). In this original TNT the reactor and engine components, such as reflector, shield, support plate, core tie rod, pressure vessel, nozzle, pump (for XE and NRX/EST) were represented in the model. Pre-test predictions and post-test data analysis were performed by the TNT code. The calculated reactor plena conditions showed good agreement with test data, see Reference 18. The TNT-II code was developed to analyze NERVA reactor NSS performance. The TNT-II code is in general similar to the original TNT code but possesses many improvements in modeling technique and calculational methods. The major improvements are as follows:

- (1) The components material temperatures are computed by a finite difference nodal network. Radial heat transfer from reactor center line to pressure vessel annulus and axial heat transfer within a component are considered.
- (2) A coupled fluid flow and heat conduction solution is obtained by solving the equations for conservation of mass, momentum, and energy for both transient and steady state calculations.
- (3) Improved neutron and delayed precursors calculational procedure is utilized
- (4) The calculational models are specified with program input and are not built into the program as was done with TNT. This allows for flexibility of design changes, since this only necessitates changing of the calculational model.

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(U) With the past experience of good agreements between NRX-A test data and calculated results using the original TNT code and the above major improvements, the use of the TNT-II code to calculate the NSS thermal and fluid environment is justified.

(CRD) 2.4.2.2 Description of TNT-II Model (U)

(U) The TNT-II model flow system is divided into 32 flow channels and 16 plena. The component material temperatures are represented by 348 internal nodes. The overall schematic diagram of the models is shown in Figure 2-6. The channel and plena arrangement is shown in Figure 2-7. The NSS components from core station 0 to 52 inches including the pressure vessel are divided into nine (9) equal layers as shown in the figures. The heating rates in every region of the NSS are obtained from the preliminary data issued by Radiation and Shielding Design in Reference 19.

(CRD) The core is divided into three (3) regions. The central region is from the core center to a radius of 11.60 inches consisting of 738 fuel elements and 123 central elements. The fuel to central element ratio is 6 to 1 representing 123 regular clusters. The mid-region is from radius 11.60 inches to 17.23 inches consisting of 870 fuel and 168 central elements. The fuel to central element ratio is 5.2 to 1. The peripheral region is from radius 17.23 inches to the O.D. of the core. This region consists of 270 fueled elements and 58 central elements. The fuel to central element ratio is 4.65 to 1. The peripheral region occupies an area of about 2.5 fuel elements wide. The purpose of dividing the core into three (3) regions is to provide a reasonable representation of the radial variation of the core temperature without overtaxing the computer memory requirement and computational time on the computer. The detailed relative radial distribution of heating in the fuel elements is shown in Figure 2 of Reference 19. After dividing the core into three regions as discussed above, the heating rates of the fuel elements in each region were averaged and normalized to unity. The resulting average power factors at the central, mid and peripheral core regions for the fuel elements are 1.058, 1.01 and 0.817, respectively. Following the same procedure the average power factors of the unfueled components in these three (3) regions were calculated to be 1.196, 0.965 and 0.686, respectively.

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(CRD) The core components in the three (3) core regions are modeled the same way, as shown in Figure 2-6. The fuel and the central elements are each represented by one radial layer and the pyrosleeve by three (3) radial layers. The hydrogen gap (0.0045 inches) between the O.D. of the pyrosleeve and the liner tube is incorporated into the inner layer of the pyrosleeve nodes. The equivalent thermal conductivities and specific heat for the two (2) equivalent layers are shown in Figures 2-8 and 2-9. The liner tube is represented by one radial layer.

(CRD) The support stem node is a composite node consisting of a Uniloy A-286 stem, hydrogen gap (0.003 inches), shim material and stainless steel shim tube. The equivalent thermal conductivity and specific heat of the stem nodes are shown in Figures 2-10 and 2-11. It was assumed that for a normal built reactor, one-third of the shim material would be TaC and the other two-thirds ZrC (Reference 10). The total heating rate of the shim material used in the model consists of one-third of the heating from TaC and the other two-thirds from ZrC. This total heating is homogenized in all of the stem nodes of the core in the model. In each core region the fuel coolant flow and the support stem coolant flow first pass and second pass are each represented by one channel. Each of these channels have the total flow area and heat transfer surface area in the region. The support stem flow channels are orificed at the turn-around for normal mode rated operating conditions so that the axial average material temperature of the support stems across the core radius are approximately uniform.

(CRD) The orificing of the stem flow was performed by using a detailed cluster model. The procedure of orificing was as follows: Since the materials at the center of the core (the 000 cluster) have the highest relative power factors, the stem coolant flow in this one cluster was not orificed. The first step was to calculate the overall pressure drop of the stem assembly at this center cluster by specifying the design stem exit pressure and adjusting the stem flow, so that the maximum liner tube temperature of this cluster was about the

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nominal design limit of 1190°R (Reference 20). Applying the pressure drop thus calculated for the stem at the center cluster to those at the three core regions of the TNT-II model and by trial and error the flow impedances at the turnaround could be determined to restrict the stem flow at each of these cluster models, so that the axial average stem material temperatures at the three models are about the same as that at the center cluster. These impedances are the orifices used in the TNT-II calculations. As mentioned above the stem channels were orificed for the rated operating conditions instead of for optimum performance during cooldown operation in order to maximize the reactivity insertion of the stems.

(CRD) The core periphery insulation wrapper with a total radial thickness of 0.275 inches consists of 0.260 inches of ZrC (50% dense) and two layers of TZM Molybdenum (0.003 inches each) with a layer of grafoil (0.009) sandwiched in between. The wrapper is represented also by composite nodes. The equivalent thermal conductivity and specific heat are shown in Figures 2-12 and 2-13.

(CRD) The filler strips are represented by a uniform cylinder surrounding the core having the actual number of cooling holes. The thickness of the cylinder is the average thickness of the strips.

(U) The lateral support seal system (LSS) is represented by a homogeneous cylinder whose total volume is the solid material volume of the seal segments. The coolant channel lengths in the model is, however, the actual length of the seal segments which are 27.56 inches instead of 52 inches. The plena between seals are disregarded. The filler strip and LSS channels were orificed to obtain the required flow rates at rated performance as calculated from TNT-II. Therefore, they are not directly representative of that computed from the detailed analysis. However, a normalized correction obtained from the detailed analysis pressure distribution can be applied to the TNT-II computations and the resulting LSS pressure distribution is in good agreement with the detailed calculations (Reference 21).

(U) The reflector is divided into four sections: Outer reflector segment, inner reflector

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segment, the aluminum structure and the control drum assembly as shown in Figure 2-6. The dividing line between the outer and the inner segments is the control drum center line circle. The cooling holes in the outer reflector segment, the inner reflector segment, and the aluminum structure are each represented by a flow channel. In the control drum assembly the drum bore annulus is represented by one flow channel and the internal cooling holes, the annulus gap, and the vane annulus are lumped into another flow channel. Each section is cooled by convection along the cooling channel within that section and the annulus channel bordering the section. Radial heat conduction between these sections is considered in the following manner: The outer reflector segment is connected to the inner reflector segment; the inner reflector is connected in turn to the aluminum structure; the aluminum structure is connected to the core periphery LSS system, and the control drum assembly is connected to the outer and inner reflector through convection heat transfer along the drum bore annulus only.

For the peripheral and the central shields the model is shown in Figure 2-6 and each shield consists of six (6) homogeneous layers. The top layer (forward end) is aluminum representing part of the aluminum structure, the second is lead, the third, fourth and fifth layers are BATH, and the bottom layer (aft end) is aluminum representing the aft structure. The flow holes in each of the shields are lumped into one flow channel which accommodates the total coolant flow through the shield and the total heat transfer area. The flow area in the peripheral shield flow channel also includes the control drum drive shaft annulus. The flow impedance across the shields are set to give the same pressure drops defined by preliminary detailed flow analysis of the shields.

The support plate model consists of three (3) axial layers. Each layer is represented by one material node. The top layer (forward end) is cooled by the SSA (Support Stem Assembly) feed inlet channel, the middle layer is cooled by the mixing and discharge channel and the bottom layer (aft end) is cooled by the SSA bypass flow channel. The length of

the channel is 10 inches long which is approximately half of the radius of the support plate. The flow area in each channel is the average flow passage area at the mid-radius of the support plate and is 14.966 in^2 . Since the total radial inward flow of the SSA coolant decreases as flow is being bled off the stems along the radius, an effective heat transfer surface area must be used to account for the flow variation and the complexity of the flow passage geometry. The feed channel effective heat transfer surface area used in the TNT-II model was determined as the area which resulted in the same total heat pickup in the feed channel as calculated by preliminary detailed analysis of the support plate. The results of the preliminary analysis is shown in Reference 22. In this reference the total heat pickup in the feed channel was calculated to be 0.30 MW at the rated SOL condition and 0.47 MW at EOL throttled condition for the graphite core. The surface area required to account for this amount of heat pickup in the TNT-II model is 1140 in^2 . The surface area for the mixing and discharge channel is 3300 in^2 and for the bypass channel is 1140 in^2 . Besides the heat pickup along the feed channel, there is additional heat pickup from the stem hanger hardware located at the entrance to the stem flow. This amounts to 0.155 MW at rated performance. This energy is added to the internal heat generation rate of the stem material nodes.

The nozzle model used for TNT-II calculation is shown in Figure 2-6. This is a simplified model from the engine calculational model used by Aerojet Nuclear System Company (ANSC) (Reference 23). The channel inlet and outlet loss coefficients were adjusted to provide as close as possible the same nozzle exit pressure and temperature at all operating conditions as is indicated in Reference 6. The Turbopump Assembly (TPA) equations used in the model were obtained from Reference 4.

The details of the TNT-II model hydraulic and conduction data are shown in Tables 2-1 to 2-6. The drawing numbers and ECC numbers for the components modeled are tabulated in Reference 24. Tables 2-1 and 2-2 show the hydraulic input data for the NSS

flow system. Tables 2-3 to 2-5 show the heat conduction nodal data for all the components in the model. The volumes and axial length of the nodes, the connecting lengths and the interface areas between adjacent nodes and surface nodal connections are shown in the tables. Table 2-6 shows the hydraulic data for the simplified nozzle model used in the TNT-II code.

2.4.3 Maturity of Input Data

This section describes the major input data besides the analysis models required to perform the TNT-II NSS performance calculations and the maturity of these input data.

2.4.3.1 Startup and Shutdown Profiles

As shown in Block 4 of Figure 2-2 the run profile is input to the NSS analysis in the Step 1 of the analysis procedure. Figure 2-14 shows the NERVA Engine Operational Phases for the normal mode operation as indicated in the NSS Requirement Specification CP-677555A (Reference 1). The portion of the profile indicated by A-B in this figure is the as run "Reference Profile" input for the NSS startup and shutdown analyses reported in this Data Item and shown in more detail in Figure 2-15. These startup and shutdown profiles were developed in Reference 6 as the analysis profiles for the NSS and component design PDR Analyses. These profiles only cover the three main portions of a complete operating cycle, i.e. startup, steady state rated operation and shutdown. The Pre-startup Operations, Nuclear Startup, Cooldown, Post Operations and Coast Operations are not included for analysis in this issue of S-031 Data Item.

The startup profile consists of 25 seconds of a modified Temperature Conditioning, seven seconds of Bootstrap and 21 seconds of Thrust Buildup. These Temperature Conditioning and Bootstrap profiles were considered in order to obtain transient boundary condition input to the Thrust Buildup phase of the startup. The time scale for startup was selected in a way such that at time = 0 sec, the pump shutoff valve (PSOV), is opened to initiate propellant flow. Prior to time equal to 0 sec, a dry autostart was assumed such that a thermal power of

4 MW was achieved and the integrated power did not affect the NSS assembly temperatures. At this time all material and fluid temperatures were assumed to be 532°R . The power of 4 MW was maintained by drum control during the first 25 seconds of Temperature Conditioning. The Bootstrap procedure which follows, was tailored to provide approximately $P_c = 60$ psia and $T_c = 1130^{\circ}\text{R}$ at the end of the Bootstrap.

During the Thrust Buildup a chamber temperature ramp of 175°R/sec was used. This T_c ramp of 175°R/sec equals to the nominal startup ramp of 150°R/sec specified in the NSS Requirement Specification CP-677555A plus an uncertainty of 25°R/sec . This represents the specification extreme on the ramp parameter for the NSS assembly and was used so that material stresses under the extreme transient conditions could be evaluated. The rate of chamber pressure increase during the period from the initiation of Thrust Buildup to the throttling point was linear with time (from $P_c = 60$ to 293 psia in 18 seconds, see Figure 2-15). From the throttling point to rated condition, the chamber pressure ramp was the specified nominal rate of 50 psi/sec. These chamber pressure rates were specified in the TNT-II startup calculation as one of the control parameters. Control drum control on T_c during Thrust Buildup, Throttle and Rated operations was chosen as another control parameter. An open loop control on SSCV travel as a function of chamber pressure was assumed with the intent of minimizing drum motion. Figure 2-16 shows the variation of the SSCV position with P_c for SOL and EOL transients and Figure 2-17 shows the relationship between SSCV travel in per cent and the loss coefficients of the SSCV used in the TNT-II code for the composite core. Figure 2-18 and 2-19 show the corresponding curves for graphite core.

Table 2-7 outlines the startup and shutdown procedure in more detail. The open loop SSCV control profiles for startup and shutdown, as shown in Figures 2-16 and 2-18, are assumed to be linear with the chamber pressure P_c . This linear relationship was based on the maturity of input data at the time the startup and shutdown studies were initiated.

The NSS startup computations were performed up to 60 seconds after the initiation of the startup profile. Consequently, all the time plots for the calculated NSS startup thermal conditions presented in Section 2.5 are from time = 0 seconds to 60 seconds.

In steady state operations, steady state computations were performed and are reported in Section 2.5.

The shutdown profile consists of Throttling from chamber pressure 450 psia to 293 psia with a P_c ramp of 50 psi/sec at full chamber temperature of 4250°R and no drum motion. Following the Throttling, the Throttle Hold period was 40 seconds, and then followed by Temperature Retreat with the utilization of drum movement. At the initiation of Temperature Retreat, the SSCV was stepped to its minimum flow position (0% travel) and remained in this position for the rest of the shutdown operation. The control drum roll-in rate was assumed to be at its maximum rate of 10°/sec. The chamber temperature ramp rate was also the specification extreme rate of 175°R/sec. The chamber temperature was decreased to 1800°R and is held at 1800°R during the Pump Tailoff operation. The end of Pump Tailoff occurs when the engine system inlet pressure equals the propellant tank pressure of 30 psia. The time scale selected in the as run "Reference Profile" for the initiation of shutdown was 600 seconds as shown in the bottom time scale of Figure 2-15. This designates that the neutron and delayed precursors used for the shutdown calculations were for 10 minutes at rated chamber temperature and power. The zero time is, therefore, the time at the beginning of the 10 minutes operation at rated condition as shown on the bottom time scale of Figure 2-15. The shutdown calculations were continued to 80 seconds after the initiation of shutdown, which is at the early stage of the Pump Tailoff operation. Consequently, all the time plots for the calculated NSS thermal shutdown conditions presented in Section 2.5 are from 600 seconds to 680 seconds.

The typical run profiles for a 10 and a 60 minutes duration of normal mode operation as specified in the NSS Specification No. CP-677555A are shown on Figure 2-20. The as run 10 minutes duration differs from the typical profile, Figure 2-20A, by 56 seconds; and therefore, the neutron and delayed precursors used in the analysis are slightly different from the typical profile. The effect of the difference in the precursors used to start the

shutdown transient computations is insignificant. Figure 2-20B shows a typical cycle with a maximum duration of 60 minutes at rated chamber temperature and power. This cycle was not analyzed in this issue of the Data Item. It is presented here to show how these cycles are defined. When integrated dose of irradiation for a maximum duration cycle is discussed, the fluence accumulated over 60 minutes at rated chamber temperature and power is implied.

2.4.3.2 Material Property Input

The material thermal properties used for the TNT-II performance and detailed component analyses are obtained from a material file which is maintained on a magnetic tape for thermal code utilization. The thermal property data on this tape are obtained, in turn, from the WANL Materials Department. This tape is updated periodically when additional data are received. The PDS numbers, source of data, and other pertinent information concerning the properties are included in issued documentation (Reference 25). The material property input to Thermal Design are shown in the overall calculation flow chart, Block 2, of Figure 2-2. The data for each material stored on the tape are density at room temperature, nominal thermal conductivity, and specific heat as a function of temperature. For many materials, the estimated one sigma variation at different temperatures and non-irradiated and irradiated thermal conductivity at one or more irradiation doses are on tape. At the present time, the one sigma variation and irradiated data are available for the materials used in the NSS major components of the Reference Design. Access to the library tape is obtained by specifying the material number which is assigned to a material at the time the data for the material is stored on the tape. For those materials which the one sigma variation and irradiation data are not available, a message is provided to the user that indicates that only nominal values are stored for that material. For the composite nodes such as the cluster hardware support stem which consists of the stem, hydrogen gap, shim material, and shim tube, equivalent thermal conductivity and specific heat must be used in the calculation. These special

properties are input to the computer code by punched cards. An example of the equivalent thermal conductivity is shown in Figure 2-8.

2.4.3.3 Hydrogen Properties

The hydrogen fluid used for the NSS thermal analysis and the component detailed analyses was assumed to be 100% para hydrogen as recommended in Reference 26. The National Bureau of Standards (NBS) para hydrogen property subroutines (Reference 27) were used by all thermal analysis codes except for one investigation in the reflector assembly, see Chapter 8, which used the equilibrium hydrogen properties to compare the effect of hydrogen properties on the reflector performance. A general discussion of the para to ortho conversion and its effect on the NSS is presented in Reference 6.

2.4.3.4 Heating Rates and Nuclear Data Input

The heating rates and nuclear data input to the TNT-II calculations are shown in Block 15 on the Design Engineering overall analysis flow chart, Figure 2-2. The heating rates in each component of the NSS are obtained from the results of preliminary analysis performed by Nuclear and Radiation Design and reported in Reference 19. The detailed heating rates reported in the reference are for a graphite core reactor. A table of multipliers is given to convert the heating rates to a composite core reactor. The comparison of the preliminary heating rates and those issued in the Radiation and Shielding Analysis Report (Reference 28) is discussed in Reference 29.

The TNT-II nuclear calculation input is as follows (Reference 30):

1) Drum Worth

The drum reactivity variation employed in this analysis for this NSS Reference Design is based on a \$4.50* drum span with a cold critical shutdown margin of \$1.85.

* Reference 10 indicates that the reference design reflector thickness and drum design provides greater \$4.50 (\$5.40 for the composite and \$5.35 for the graphite core). This added drum span provides operational flexibility.

The impressed reactivity by control drums calculated in TNT-II is

$$\Delta \rho_I = \Delta \rho_D (1 + F_\theta) \quad (1)$$

In this equation, $\Delta \rho_D$, is the drum reactivity variation with drum motion and is defined as

$$\Delta \rho_D = \$0.40 - \$2.25 \cos \theta \quad (2)$$

This corresponds to a cold critical angle of $79^\circ 46'$ (rounded off to 80°).

The variable F_θ in equation (1) is the fractional change in drum worth determined by the following equation:

$$F_\theta = \left[0.001078 M_S + 0.01165 M_B + 0.004913 M_R \right] \left[1 - 0.05341 M_T \right] + (0.0001335 \Delta T) \left[1 + 0.3978 M_T (1 - 0.05341 M_T) \right] \quad (3)$$

where

M_S = Filler strip and seal region hydrogen content (lbs)

M_B = Aluminum structure hydrogen content (lbs)

M_R = Reflector hydrogen content (lbs)

M_T = $M_S + M_B + M_R$

ΔT = Be temperature change from $532.8^\circ R$

2) Feedback Reactivity

The feedback reactivity is a function of core and reflector temperatures and hydrogen contents. The net feedback reactivity calculated in TNT-II is:

$$\Delta \rho_F = \Delta \rho_C + \Delta \rho_R^0 - F_\theta (6.28 - \rho_{cc}) \quad (4a)$$

$$= \Delta \rho_{CT} + \Delta \rho_{CF} + \Delta \rho_R^0 - F_\theta (6.28 - \rho_{cc}) \quad (4b)$$

The terms in the equation are computed as follows:

$$\Delta \rho_{CT} = \text{Core temperature worth} = (A) (T_c - 532.8) \quad (5)$$

where $A = -0.000763 \text{ } \$/^\circ R$ for composite core and $-0.000886 \text{ } \$/^\circ R$ for graphite core

T_c = Average core material temperature, $^{\circ}\text{R}$

Core hydrogen worth is computed for each radial core region separately by integrating the axial density distributions with the hydrogen worth profile given below. Since the hydrogen is worth more at the central region than at the peripheral region of the core, the feedback reactivity due to core hydrogen is weighted radially. These weighted results are summed to obtain the total core hydrogen worth ($\Delta \rho_{CF}$). The equation for computing core hydrogen worth is:

$$\Delta \rho_{CF} = \sum_{i=1}^3 \left\{ \sum_{j=0}^I [M(X) W(X)]_j \right\} C_i \quad (6)$$

where $M(X)$ = Mass of hydrogen at core station i in the j^{th} core region, lb.
 $W(X)$ = Axial hydrogen worth in core station i , $\$/\text{lb}$.
 I = Length of core channels, including fuel and support stem channels, inch.
 C_i = Weighting factors in the j^{th} core region; these are 1.327, 0.857 and 0.592 for the TNT-II central, mid and peripheral regions respectively (Reference 10).

The axial distribution of the hydrogen worth $W(X)$ is tabulated below:

	X	$W(X)$	
	Station (in)	Worth ($\$/\text{Kgm}$)	= ($\$/\text{lb}$)
Inlet	0	0.188	0.085
	4	1.99	0.903
	8	4.14	1.87
	12	5.80	2.63
	16	7.45	3.38
	20	8.55	3.88
	24	9.00	4.08
	28	8.74	3.96
	32	7.88	3.57
	36	6.15	2.79
	40	4.73	2.15
	44	2.57	1.17
	48	1.31	0.59
	52	0.134	0.061
Outlet			

The feedback reactivity due to the reflector temperature and hydrogen content (without control vane) is computed by the following equation:

$$\Delta \rho_R^0 = \left[0.7354 M_S + 0.7053 M_B + 0.061 M_R \right] \left[1 - 0.06235 M_T \right] + (0.0007617 \Delta T) \left[1 + 0.4421 M_T (1 - 0.04657 M_T) \right] \quad (7)$$

where M_S , M_B , M_R and ΔT are defined as above.

The variable ρ_{cc} is the cold critical shutdown margin; for the present design $\rho_{cc} = 1.85$.

3) Excess Reactivity*

The excess reactivity is the sum of the control drum impressed reactivity and the feedback reactivity summarized in the following equation:

$$\Delta \rho_{EX} = \Delta \rho_D (1 + F_\theta) + \Delta \rho_c + \Delta \rho_R^0 - F_\theta (6.28 - \rho_{cc}) \quad (8)$$

In Equation (8) the first term on the right hand side of the equation is the drum impressed reactivity and the following three terms are the net feedback reactivity discussed above.

4) Core Radial Fission Power Perturbation from Normal SOL Rated Condition

In all the TNT-II calculations analyzed for this Data Item, the effect of core radial fission power distribution perturbation on core material temperatures was taken into consideration. The perturbation is a function of control drums position, NSS component material temperatures and hydrogen content. Since the NSS is designed to have the capability to compensate the feedback reactivity loss by support stem flow with minimum drum motion during steady state operations, the distribution at the nominal start of life rated condition was chosen as the reference distribution and the core is to be orificed at this condition. The equations to determine the fractional power change at each of the three (3) core regions modeled in TNT-II are obtained from the preliminary analysis results from Reference 31 as shown below:

*The mathematical definition of excess reactivity is discussed in Reference 10. In TNT-II calculation, it is expressed by Eq (8) and is to be interpreted as the NSS reactivity or maneuver reactivity.

$$\left(\frac{P}{P_{\text{SOL}}}\right)_i = \left[\frac{1 + F_{1,i} (H_c - 1)}{1 + F_{1,i} (H_c^* - 1)} \right] \left[\frac{1 + F_{2,i} (H_s - 0.2)}{1 + F_{2,i} (H_s^* - 0.2)} \right] \left[\frac{1 + F_{3,i} (H_R - 1.0)}{1 + F_{3,i} (H_R^* - 1.0)} \right] * \\ * \left[\frac{1 + F_{4,i} (T_c - 2880)}{1 + F_{4,i} (T_c^* - 2880)} \right] \left[\frac{1 + F_{5,i} (T_R - 139.5)}{1 + F_{5,i} (T_R^* - 139.5)} \right] \left[\frac{1 + F_{6,i} (4.48 - \rho)}{1 + F_{6,i} (4.48 - \rho^*)} \right] \quad (9)$$

The nomenclature and the values of the constants shown in the above equations are:

- P = Relative fission power factor for the i^{th} core region.
 H_c = Core hydrogen content, lb.
 H_s = LSS and filler strip hydrogen content, lb.
 H_R = Reflector and aluminum structure hydrogen content, lb.
 T_c = Average core material temperature, $^{\circ}\text{R}$
 T_R = Average Be reflector material temperature, $^{\circ}\text{R}$
 ρ = Drum worth to removal, \$

The (*) values are those at SOL conditions.

- F_1 = fractional power change per lb. increase in core H_2 content
 F_2 = fractional power change per lb. increase in LSS and filler strip H_2 content
 F_3 = Fractional power change per lb. increase in reflector and aluminum structure H_2 content
 F_4 = Fractional power change per $^{\circ}\text{R}$ increase in average core temperature
 F_5 = Fractional power change per $^{\circ}\text{R}$ increase in average Be reflector temperature
 F_6 = Fractional power change per dollar of outward drum rotation
 i = i^{th} core region, central, mid or peripheral

	CORE REGION		
	Central	Middle	Peripheral
F_1	+0.00884	-0.00279	-0.01542
F_2	-0.0173	-0.0094	+0.0823
F_3	-0.00348	-0.0027	+0.01919
F_4	-9.5×10^{-7}	$+4.62 \times 10^{-6}$	-1.294×10^{-5}
F_5	-4.3×10^{-6}	$+2.0 \times 10^{-6}$	$+5.3 \times 10^{-6}$
F_6	-0.0269	-0.0040	+0.0555

2.4.3.5 Heat Transfer Coefficients and Friction Factor Correlations

The heat transfer correlations used in TNT-II calculations are:

1) McCarthy and Wolf Correlation: (Reference 32):

$$H = (0.025) (Re)_b^{0.8} (Pr)_b^{0.4} \left(\frac{T_b}{T_w} \right)^{0.55} \left(\frac{k_b}{D} \right) \quad (10)$$

This correlation is used in the flow channels of the reflector, shields, support plate and pipes. The symbols used in this and the following equations are explained in the table of nomenclature at the end of this subsection,

2) ANSC correlation for Nozzle cooling tubes (Reference 33):

$$H = (C_i) \left((Re)_b \frac{\rho_f}{\rho_b} \right)^{0.8} (Pr)_b^{0.4} \left(\frac{k_f}{D} \right) [1 + 0.01457] \left(\frac{\mu_w}{\mu_b} \right) \left(\frac{\rho_b}{\rho_w} \right) \quad (11)$$

The constant C_i depends on the location of the nozzle tube (See Table 2-6).

3) Simplified Petukhov correlation (Reference 34):

$$H = (0.0212) (Re)_b^{0.8} (Pr)_b^{0.4} \left(\frac{k_b}{D} \right) \left(\frac{T_b}{T_w} \right)^c \quad (12)$$

where $C = 0.135 + 0.005548 \left(\frac{X}{D} \right)$, for $X/D > 75.0$

or $C = 0.55$, for $X/D < 75.0$

This correlation is used for the support stem flow channels.

4) Fuel Channels correlation (Reference 35):

for $X < 8.0$ inches

$$H = (0.0212) (Re)_b^{0.8} (Pr)_b^{0.4} \left(\frac{k_b}{D} \right) \left(\frac{T_b}{T_w} \right)^c \quad (13)$$

where C is a function of length to diameter ratio as follows:

X/D	C
0	0.125
10.	0.190
20.	0.245
30.	0.300
40.	0.350
50.	0.410
60.	0.460
70.	0.500
80.	0.520
90. and up	0.530

for $8.0 \leq X \leq 26$ inches

$$H = \left[0.0212 + 0.0002111 (X-8) \right] (Re)_b^{0.8} (Pr)_b^{0.4} \left(\frac{k_b}{D} \right) \left(\frac{T_b}{T_w} \right)^{0.55} \quad (14)$$

for $x \geq 26.0$ inches

$$H = 0.025 (Re)_b^{0.8} (Pr)_b^{0.4} \left(\frac{k_b}{D} \right) \left(\frac{T_b}{T_w} \right)^{0.55} \quad (15)$$

In two phase regions, the film coefficient is corrected by the following multiplier (Reference 36):

$$H_2 = H_1 * \text{EXP} \left[-0.185 - 0.251 \log_e X - 0.00767 (\log_e X)^2 \right] \quad (16)$$

where X is the quality and H_1 is the film coefficient computed from one of the above equations.

The Friction Factor Correlations (Reference 37) used in TNT-II Calculations are:

1) For turbulent flow: $R_{ew} > 3000$, where the Reynolds Number (based on channel wall temperature) is defined as:

$$R_{ew} = \left(\frac{GD}{\mu} \right) \left(\frac{T_b}{T_w} \right) \quad (17)$$

a) If surface roughness, $\epsilon = 0$ (smooth channel), the turbulent friction factor is:

$$f_t = \left(0.0014 + \frac{0.125}{R_{ew}^{0.32}} \right) \sqrt{\frac{T_b}{T_w}} \quad (18)$$

*

b) If surface roughness is not zero, $\epsilon \neq 0$, the turbulent friction factor is calculated from the following series of computations:

$$f_a = \left(0.0014 + \frac{0.125}{A^{0.32}} \right), \text{ where } A = \frac{495.0}{\epsilon^{1.138}} \quad (19)$$

$$f_b = \left(0.0014 + \frac{0.125}{B^{0.32}} \right), \text{ where } B = \frac{A}{20} \quad (20)$$

if $R_{ew} > A$, set R_{ew} equal to A , then compute the following:

$$P = \frac{R_{ew}}{A}, \quad Q = 0.3 - 0.1 \times P, \quad (21)$$

$$\text{and} \quad Y = (f_b - f_a) (P)^Q \quad (22)$$

then the turbulent friction factor is

$$f_t = \left\{ \frac{1.0}{2.28 + 4.0 \log_{10} \left[\frac{1.0}{\epsilon + \frac{4.675}{R_{ew} \sqrt{f'}}} \right]} \right\}^2 \quad (23)$$

$$\text{where} \quad f' = \left(0.0014 + \frac{0.125}{R_{ew}^{0.32}} \right) \sqrt{\frac{T_b}{T_w}} + Y \quad (24)$$

2) For laminar flow: $R_{ew} < 2000$, the laminar friction factor is

$$f_l = \frac{16.0}{R_{ew}} \quad (25)$$

3) For transition flow: $2000 < R_{ew} < 3000$, the friction factor is

$$f_s = f_t Y + f_l (1 - Y) \quad (26)$$

where $Y = \frac{R_{ew} - 2000}{1000} \quad (27)$

The nomenclature of the symbols in the heat transfer and friction factor equations are as follows:

- D = Hydraulic diameter, inch
- G = Fluid mass flow rate, lb/sec - in²
- H = Heat transfer film coefficient, Btu/sec - in² - °R
- k = Thermal conductivity of fluid, Btu/sec - in - °R
- N_u = Nusselt No. = HD/k
- Pr = Prandtl No. = C_pμ/k
- R_e = Reynolds No. = GD/μ
- T = Fluid Temperature, °R
- X = Distance from entrance of channel, inch
- μ = Absolute viscosity, lb/in - sec
- ρ = Fluid density, lb/in³

Subscripts designate the condition at which the fluid properties are to be evaluated:

- b = bulk l = laminar
- w = wall
- f = film

2.4.3.6 Non-NSS Components Input

The non-NSS components input, namely the nozzle model data and the TPA operating characteristics, are obtained from ANSC. The nozzle model used in TNT-II as

shown in Figure 2-6 is a simplified model from the ANSC model given in Reference 23. The TPA operating characteristic equations and tables are obtained from Reference 4. These non-nuclear component models are consistent with those incorporated in the PAM model described in the Data Item S-001, Reference 6 .

2.4.4 Validity of Analysis

2.4.4.1 Applicable Test Results from the NRX Test Series

For the evaluation of the system performance of the NRX series of tests the TNT computer code was used. The TNT-II code used for performance analysis throughout this chapter is in general similar to the original TNT code, but possesses many improvements in modeling techniques and calculational methods. These improvements are listed in Section 2.4.2.1. Reference is made in the following paragraph to typical NRX test results comparing measured performance data with the calculated performance data to reflect on the validity of the present analytical model.

For purposes of illustration, several transients in the NRX-A6 test series (Reference 18) were selected for comparison with predictions. All calculations were performed using the pre-test NRX-A6 reactor model and the test data inputs of flow and power. The analytical model represented reactor and engine components (reflector, shield, support plate, pressure vessel, nozzle, pump) similar to NSS components being evaluated in this report. Typical results comparing measurements with predictions are given in Figure 2-21, for plena temperatures and pressures. The calculated reactor plena conditions exhibited good agreement with the test data.

Improvements have been made to the modeling techniques and to calculational methods in the TNT-II code which have not been verified with test data. However, it is expected, based on the comparisons shown in Figure 2-21, that the TNT-II results will provide good agreement substantiating that the TNT-II code is a valid means of evaluating the NSS performance.

2.4.4.2 Uncertainty Analysis

The uncertainty analysis performed for the NSS thermal and fluid parameters reported in this section is by a Monte Carlo random sampling method. The purpose of the Monte Carlo uncertainty analysis is to estimate the variations of the NSS thermal and fluid parameters simulated by the TNT-II model described in Section 2.4.2 at the completion of the NERVA engine qualification program. These estimated variations were input to (1) detailed thermal and hydraulic uncertainty analyses presented in the following ECC chapters of this report and (2) structural uncertainty analyses to obtain load, stress and displacement distributions presented in Reference 38. The results of these uncertainty analysis consist of the sample standard deviation and tolerance limits for NSS parameters applicable at the completion of the engine qualification program; therefore, the results presented in this section do not include any non random errors or biases that could be in the current computer models.

This section is organized into four subsections: a. Substantiation of the Monte Carlo Method, b. Description of the Monte Carlo Method, c. Input Uncertainties, and d. Results of the Monte Carlo Analysis.

a. Substantiation of the Monte Carlo Method

Reference 39 describes the use of the Monte Carlo method and gives substantiation for its use. The Monte Carlo method was utilized for uncertainty analysis because it was the only method that was found to be practical for problems of this magnitude which do not have closed form solutions. Other uncertainty analysis methods included: (1) The Taylor's Series Expansion* and (2) The Algebra of Normal Functions were found to be impractical, since they require closed form solutions.

A sample thermal-stress problem described in Reference 39 was used to check-out the Monte Carlo method. The sample problem consisted of a thick walled hollow cylinder with internal heat generation and convective heat exchange on both inner and outer surfaces.

*This method is also sometimes referred to as the Propagation of Error Method.

A closed solution was obtained for the maximum thermal stress. Ten of the parameters were randomly varied for each calculation and 4000 maximum stresses were computed. Samples of 20 stresses each were drawn from this simulated population and were used to compute the tolerance limits of the maximum thermal stress. These tolerance limits which define the location of a certain proportion of the population with a specified confidence level were compared against the simulated population and good agreement was found. In addition, the calculated stresses were found to follow a normal distribution.

b. Description of the Monte Carlo Method

The Monte Carlo method is essentially a computer experiment which simulates the testing of a number of engines. Thirty engines simulated by the TNT-II model were used for this analysis. The simulated testing was done with the TNT-II computer program. Thirty random sets of TNT-II input were prepared using the standard deviations of the important model parameters (independent parameters such as heating rates, flow areas, heat transfer coefficients and material thermal conductivities that define the TNT-II model) and a random number table. The random input were generated using the design nominal value as the mean for each independent parameter. These thirty sets of TNT-II model input may be considered as the analytical models corresponding to thirty actual engines constructed from the same set of drawings. The TNT-II program was then used to calculate the operating characteristics of the thirty simulated engines. The results of these calculations consisted of 30 values of all dependent parameters generated by TNT-II such as fluid and material temperatures, fluid pressures and flow rates. In the final step each parameter was statistically analyzed to determine the sample standard deviation and tolerance limits. The various steps of the Monte Carlo method as outlined in this paragraph are described below in more detail:

Step 1 Uncertainties for Independent Parameter

The first step of the Monte Carlo Method consisted of the selection of the one standard deviations for all important independent parameters of the TNT-II equations and reference model. The 162 selected parameters with the estimated one standard deviations

at the completion of the qualification program are given in Section c. These parameters were then catalogued into groups consisting of one independent parameter or several independent parameters that were determined to be mutually dependent. The grouping of independent parameters with mutually dependent behavior is necessary in order to correctly simulate the NSS in Monte Carlo analysis. A total of 116 groups consisting of one or more parameters were obtained. Relative index numbers from 1 to 116 were assigned to these groups for use in Step 3 of the Monte Carlo Method.

Step 2 Random Number Multiplication Factors

A random number table and the assumption that all independent parameters selected in Step 1 follow a Gaussian distribution were used to determine the random number multiplication factors. The CDC 6600 computer subroutine, RANF, was used to generate a table of 20,000 random numbers between zero and one. RANF uses the mathematical method described in Reference 40. For this analysis, it was assumed that all selected independent parameters would vary according to a Gaussian distribution between the limits of -4 to $+4$ sigma. Mathematically, the cumulative distribution function for a standard normal variable was used to transform the random numbers obtained from RANF to random multiplication factors between -4 and $+4$ sigma. The following equation was used for this transformation:

$$N = F(M) = \int_{-4}^M f(x) dx$$

where,

N = Random Number

$F(M)$ = Cumulative Distribution Function

$f(x)$ = Density Function for Standard Normal Variable

M = Random Multiplication Factor Corresponding to Random Number N .

This transformation is graphically illustrated by a plot of the cumulative distribution function shown on Figure 2-22. The random Number (N) is entered on the ordinate of the figure and

is used to find the corresponding random multiplication factor (M) on the abscissa. In this example, the random number with a numerical value of approximately 0.74 yields a random multiplication factor of approximately 0.6. Using this procedure, the table of 20,000 random numbers obtained with RANF was transformed to 20,000 corresponding random multiplication factors. These random multiplication factors are used in the next step to obtain TNT-II input for all random cases.

Step 3 TNT-II Input for Random Cases

The standard deviations selected in Step 1, the random multiplication factors obtained in Step 2, and the nominal input values of the TNT-II model were used to compute input for thirty random TNT-II models. Figure 2-23 illustrates the procedure that was used to select the random number multipliers for each set of TNT-II input. The first column shows the storage locations of the 20,000 random multiplication factors which were computed in Step 2. The relative index numbers assigned to the TNT-II and RATS (Reference 38) independent input parameters are shown in column 2. The RATS program uses the TNT-II results to compute load and stress distributions on the NSS level. The selection of the relative index numbers for each independent parameter or groups of independent parameters that were mutually dependent was described in Step 1. The starting location on the random multiplication factor table was randomly selected and this location occurred at the 145th position. The random multiplication factor corresponding to location 145 was used with the first independent TNT-II input parameter to determine the input value for the first random Monte Carlo calculation. Six hundred random multiplication factors were made available to prepare input for each TNT-II and RATS calculation. Of these 600 random multiplication factors, the first 200 were available for TNT-II and the next 400 for RATS. Only 116 of the 200 available random multiplication factors were required for each TNT-II calculation. These 116 random multiplication factors required to determine the input values for the first random TNT-II calculation were obtained from locations 145 through 260. The random multiplication factors in location 261 through 344 which had been assigned to TNT-II were

not required. Locations 345 through 744 were assigned to the input values for the first RATS calculation. Random multiplication factors to determine input for the second TNT-II calculation were obtained from locations 745 through 860. This process was repeated in increments of 600 to determine random multiplication factors for thirty sets of randomly selected TNT-II and RATS input parameters. Section c describes the equations that were used to determine the random TNT-II input values using the random multiplication factors, the standard deviation values and the nominal model input values.

Step 4 TNT-II Calculations

For each steady state operating condition, 31 TNT-II calculations were performed. The first calculation was the nominal case without any variations followed by thirty calculations with the randomly selected input. The results of these thirty-one calculations were stored on tape for input to statistical analysis.

The controlled parameters for each steady state operating condition were chamber temperature, chamber pressure, and control drum position. A control drum position demand of 46.8 degrees corresponding to the orifice angle was used for the composite core calculations at rated and throttled hold conditions. The TNT-II program adjusts the SSCV position (or loss coefficient) to obtain the necessary feedback reactivity to maintain zero excess reactivity. In case the reactivity feedback requirement cannot be achieved through SSA flow, the TNT-II program sets the SSCV at the full open position (minimum loss coefficient) and then positions the control drum bank to achieve zero excess reactivity.

Step 5 Statistical Analysis

The results of the thirty-one calculations (the nominal calculations followed by thirty calculations with random input) were used to compute the sample standard deviation and tolerance limits for the TNT-II output parameters. The following equation was used to determine the sample standard deviation for each parameter:

$$S = \sqrt{\frac{\sum_{i=1}^N (Y_N - Y_i)^2}{N}} \quad (2)$$

where,

S = The one standard deviation for any TNT-II output parameter.

Y_N = Nominal value of TNT-II output parameter

Y_i = Value of TNT-II output parameter for one of the N random calculations

N = Number of random calculations. A value of N equal to thirty was used for this analysis.

Tolerance limits were determined with the following equation:

$$U = K * S \quad (3)$$

where,

U = Uncertainty of a dependent TNT-II parameter for the proportion and confidence level corresponding to the K factor

K = Tolerance factor obtained from Reference 42

S = Sample standard deviation of the dependent TNT-II parameter.

The K factor was selected to give one-sided tolerance limit of 99 percent proportion of the population at 95 percent confidence. This corresponds to a numerical K value of 3.064 according to Table III of Reference 42. One sided tolerance limits mean that either only the upper uncertainty limit (nominal value plus uncertainty limit) or the lower uncertainty limit (nominal value minus uncertainty) are applicable at one time. Both limits do not apply simultaneously.

Tolerance limits define the location of a proportion of the population. In this case, the population is defined as all engines that can be manufactured from a set of drawings and specifications. Tolerance limits are used to define either the upper or the lower limit of any parameter. SNPO-C-I describes the use of tolerance limits to define either the upper or the lower limit of any parameter. The following example is given to describe the interpretation

of one sided tolerance limit. Assume that a certain parameter has a nominal value of 200 and an uncertainty value of 30 corresponding to a one-sided 99 percent proportion at 95 percent confidence. The resulting upper limit of this parameter with the probability of 99 percent proportions at 95 percent confidence is $200 + 30$ or 230. The interpretation of this tolerance limit is as follows: If 100 samples containing 100 engines each are randomly selected from the total population of engines, then in 95 of the 100 samples, 99 engines out of 100 in each sample will have values of this parameter less than 230.

c. Input Uncertainties

This section gives the one standard deviation uncertainties of the TNT-II calculational and model parameters varied in the Monte Carlo uncertainty analysis. The estimated independent parameter uncertainties after the completion of the NERVA engine qualification program were used for this analysis. Therefore, these uncertainties do not account for any non-random errors in the reference design TNT-II model and equations. These uncertainties will be referred to as the "post engine qualification" uncertainties in this report. These uncertainties may also be referred to as "flight type uncertainties".

The one standard deviation values in this section were estimated on the basis of engineering judgement using: (1) the experience obtained from previous test data, (2) the expected dimensional tolerances, and (3) design specifications. Since the uncertainties were estimated, they may be considered to be based on population statistics; or infinitive degrees of freedom.

Three different calculational procedures were used to determine the new parameter values (the values for each random case) from the nominal parameter value and the corresponding one standard deviation value. Procedure 1 was used for the internal nuclear heat generation parameters, Procedure 2 was used for channel loss coefficients, and Procedure 3 was used for all other parameters.

Procedure 1

The following two equations were used for the internal nuclear heat generation parameters:

Case 1, Positive Multiplication Factor (M)

$$X = X_N * (1 + M * \sigma)$$

Case 2, Negative Multiplication Factor (M)

$$X = X_N * (1 + |M| * \sigma)$$

where,

X = New Value of parameter

X_N = Nominal value of parameter

M = Random multiplication factor corresponding to a Gaussian distribution between the limits of -4 and +4 sigma

σ = One standard deviation value in fraction of nominal parameter value

Procedure 2

The following equation was used for channel inlet and exit loss coefficients. This special procedure was required to assure the independent application of the channel flow area and loss coefficient uncertainties:

$$C = C_N * (1 + M * \sigma) * \left(\frac{A}{A_N} \right)^2$$

where,

C = New value of loss coefficient

C_N = Nominal value of loss coefficient

M = Random multiplication factor corresponding to a Gaussian distribution between the limits of -4 and +4 sigma

σ = One standard deviation of loss coefficient in fraction of nominal

A = New value of channel area as determined by Procedure 3

A_N = Nominal value of channel area

Procedure 3

The following equation was used for all parameters except internal nuclear heat generation and channel loss coefficient:

$$X = X_N * (1 + M * \sigma)$$

where,

X = New value of parameter

X_N = Nominal value of parameter

σ = One standard deviation of uncertainty in fraction of nominal value of parameter

M = Random multiplication factor corresponding to a Gaussian distribution between -4 and +4 sigma

The following subsections, (1) through (6), present the input one standard deviations and describe the application of the uncertainties to the Monte Carlo analysis:

(1) Thermal and Hydraulic Parameters

Table 2-8 gives the one standard deviation for channel area, inlet and exit loss coefficients, heat transfer coefficients, and friction factors for each of the NSS channels of the TNT-II model. For convenience, the table is organized by ECC number. In the Monte Carlo analysis, dependent behavior is accounted for by using the same random number index for dependent parameters. The following notes describe the parameters on Table 2-8 which were assumed to be dependent:

- (a) All channels shown on the same line in Table 2-8 were assumed to have dependent thermal and hydraulic parameters. For example, the area of channels 15, 16, and 17 are assumed to be dependent and the same random number index was assigned to the channel area uncertainty of all three channels.
- (b) For each channel, the heat transfer coefficient and friction factor uncertainties were assumed to be dependent. The same random number was therefore assigned to both the heat transfer coefficient and friction factor uncertainties of each channel.

- (c) The heat transfer coefficient and friction factors of the support plate feed and bypass channels were assumed to be dependent; and were therefore, assigned to the same random number index. This same characteristic was assumed for the peripheral shield and shield-PV annulus channels.

The lateral support channel was handled in a different manner. Zero uncertainties were used for inlet and exit loss coefficient and the hydraulic diameter. A 4.3 per cent one standard deviation uncertainty was assigned to the lateral support area. Separate random number indices were assigned to (1) the stations 0 through 3, (2) stations 4 through 6, and (3) stations 7 through 9 of the lateral support channel.

(2) Internal Nuclear Power

Table 2-9 gives the one standard deviation value of internal nuclear power for the components of the TNT-II model. The group numbers on Table 2-9 indicates those components for which the internal nuclear power were assumed to vary in a dependent manner. In addition, the following specialized calculation procedures were used to apply these uncertainties for the Monte Carlo analysis to the following component groupings:

- (a) Central, Mid, and Peripheral Fuel-The uncertainty of the total power generated in all fuel elements is very nearly zero. A power increase in the central fuel region would be accompanied by a power decrease in the peripheral fuel region. This characteristic is simulated by arbitrarily assigning a negative power generation uncertainty to the central fuel region, a zero uncertainty to the mid region, and a positive uncertainty to the peripheral region. The sign of the random number multiplier will then determine the direction of the power change in the central and peripheral regions.
- (b) Unfueled Element, Pyrographite Insulation, and Support Stem Assembly for all Core Regions - The variation in internal nuclear power of these components is assumed to be dependent; i.e., the same random number index is assigned to each of these components. In addition, the change in internal power for these components is expected to be dependent on the variation in fuel power generation. This characteristic is handled as follows: The total uncertainty (the one standard deviation value multiplied

by the random number multiplier) of the non-fuel component is added algebraically to the total uncertainty of the corresponding fuel region.

- (c) Filler Strips, Core Insulation, Lateral Support, Outer Foil, Aluminum Structure, Beryllium Reflector, and Pressure Vessel - The variations in internal nuclear power of these components is assumed to be dependent, i.e., the same random number index is assigned to these components. In addition, the change in internal power for these components is expected to be dependent on the power in the peripheral fuel region. This characteristic is handled for each of these components as follows: The total uncertainty (the one standard deviation value multiplied by the random number multiplier) is added algebraically to the total uncertainty of the peripheral fuel region.

(3) Material Thermal Conductivity

One standard deviation uncertainties were assigned to all materials, and wherever possible, the values specified on the Thermal Material Property tape (Reference 25) were used. For materials without specified uncertainties, the one standard deviations were estimated to be equal to 10 per cent of the nominal value.

(4) Nuclear Design Parameters

The following one standard deviation uncertainties were used for the nuclear parameters:

<u>Description of Parameter</u>	<u>One Standard Deviation- %*</u> <u>(Post Engine Qualification)</u>
Core Material Temperature Reactivity Feedback	4
Core Hydrogen Reactivity Feedback	1
Total Reflector Reactivity Feedback	4
Control Drum Worth	2

The void volume of the lateral support is a factor in the calculation of total reflector reactivity feedback. The one standard deviation of this volume was estimated to be 2 percent.

*Percent of nominal value

(5) Control Parameters

The following one standard deviations were used for the three engine control parameters: nozzle chamber temperature, pressure, and control drum bank position.

<u>Description of Parameter</u>	<u>One Standard Deviation (Post Engine Qualification)</u>
Nozzle Chamber Temperature	17.3°R
Nozzle Chamber Pressure	2 psi
Control Drum Position	0.128 degree

These uncertainties include both control system and measurement uncertainties. The nozzle chamber temperature and pressure uncertainties were obtained from Reference 41. The control drum position uncertainty corresponds to the design specifications.

(6) Engine Subsystem Parameters

The one standard deviations for engine subsystem parameters are given in Table 2-10. The uncertainties for group No. 1 parameters were specified directly by Reference 41, Group No. 2 parameters were not obtained directly from Reference 41, but they were selected to match the one standard deviations of nozzle tube pressure drop and temperature rise given in this reference.

d. Results of Monte Carlo Analysis

The results of two sets of Monte Carlo uncertainty analyses are presented in this report. The first set of results was obtained with the TNT-II model and the second with the PAM model. The first set of results was obtained with the TNT-II model using the procedure described in Section 6 and the uncertainty values given in Section c for the following three operating conditions:

Case 1. Composite Core, Rated Performance, Start of Life, Normal Mode

Case 2. Composite Core, Steady State Performance, Start of Life, Single Turbo-Pump Operation

Case 3. Composite Core, Throttle Hold Performance, End of Life, Normal Mode

Cases 1 and 2 were analyzed since these represent critical design conditions. Case 3 was analyzed to estimate the probability of requiring control drum motion for this operating condition. Monte Carlo analysis with the TNT-II model was limited to these essential cases in order to minimize computer costs. Each of these cases required between 90 and 140 minutes of CDC-6600 computer time.

Tables 2-11 through 2-13 present some of the significant results from these three Monte Carlo analysis. The results consist of the nominal value and the one standard deviation for the state point parameters listed on the NSS Thermal and Fluid Environment, Figures 2-1B to 2-1G in Section 2.2. The nominal values are obtained directly from Figures 2-1B to 2-1G. The uncertainties listed in Section 2.2 were obtained from the sample standard deviations given in Tables 2-11 through 2-13 using equation (3) of Section b. The use of these uncertainty analysis were for the detailed thermal and structural analyses. Both of these major uses required the detail available with TNT-II model and could not be satisfied with the PAM model which was used for the second set of uncertainty analyses.

As mentioned previously, Case 3 the "Composite Core, Throttled Hold Performance, End of Life, Normal Mode" was analyzed to estimate the probability of achieving this operating condition at the orifice control drum bank position. This operating condition is the one most likely to require additional reactivity insertion by a change in control drum bank position. The logic that was used for TNT-II calculation is described in Section b. Briefly, each TNT-II calculation requires convergence to the specified chamber temperature and pressure and to the 46.8 degree orifice control drum bank position. These three control parameters were randomly selected for each random case. Additional logic is incorporated in the TNT-II program to change the control drum bank position if the specified position

cannot be achieved by a wide open SSCV. Examination of the results of the 30 random TNT-II calculations showed that 28 calculations did not require any change in the orifice control drum bank position. The remaining two calculations required outward control drum bank position changes of 7.4 and 7.8 degrees respectively. Therefore, on the basis of these results, a preliminary estimate of the probability that this operating condition can be achieved at the orifice control drum bank position is 28/30 or 93 per cent.

Uncertainties for eight additional operating conditions were determined by normalizing the uncertainties given in Reference 6. These uncertainties were computed by Monte Carlo analysis with the PAM model. This normalization was justified by the following two factors:

- (1) The TNT-II model is a considerably more detailed representation of the NSS compared to the PAM model.
- (2) The TNT-II model of the NSS represents the latest reference design; the PAM model represents the July 1 reference design.

The following equation was used to normalize the tolerance limits computed by PAM:

$$t = \left(\frac{t_m^*}{t_p^*} \right) (t_p)$$

where,

t = Normalized tolerance limit for any parameter at the operation conditions corresponding to t_p^* .

t_m^* = Tolerance limit of the same parameter calculated with the TNT-II model at the operating condition selected for normalization.

t_p^* = Tolerance limit of the same parameter calculated with the PAM model at the operating condition selected for normalizing

t_p = Tolerance limit of the same parameter calculated with the PAM model.

Table 2-15 defines the correspondence between the operating conditions used to compute the normalizing factors and the operating conditions that were normalized. The TNT-II and PAM one sample standard deviations for the three cases that were used to compute normalizing factors are given in Tables 2-15 through 2-17. The sample standard deviation based on 30 random calculations are given in these tables; however the actual tolerance limits were used for the correction. The uncertainties obtained from the PAM results are presented in Figures 2-1 B through 2-1G. The following state point conditions were not normalized since these are not separately modeled by PAM:

1. Filler Strip Outlet
2. Lateral Support Outlet
3. Central, Mid, and Peripheral Fuel Outlet

2.5 RESULTS, ANALYSIS, AND INTERPRETATION

This section presents the results, analysis and interpretation on the composite and graphite cores, thermal and fluid environments of the NSS assembly at various steady state and transient operating conditions. The startup and shutdown profiles analyzed are described in Section 2.4.3.1. The term "start of life" (SOL) is used to designate that portion of a first cycle of operation, including the startup, 10 minutes of steady state at rated conditions, and the shutdown phases of the cycle. The term "end of life" (EOL) is used to designate that portion of the last cycle of 10 minutes rated condition run including the last normal startup and shutdown after 60 cycles and 600 minutes at rated chamber temperature. At the last cycle of operation the reactivity loss of the core due to corrosion has been accumulated to a specified maximum value of \$1.00. The reactivity loss of \$0.11 due to fuel burnup at EOL throttled condition (Reference 10) is not considered in this analysis. The startup operation at the first cycle is, therefore, called the SOL startup. The 10 minutes at rated conditions is called the SOL steady state operation and the shutdown operation is called the SOL shutdown. Similarly, the startup, rated operation, and shutdown at the last cycle is called the EOL startup, EOL rated operation, and EOL shutdown.

The analysis results on thermal and fluid environment for the composite and graphite core designs are presented for:

- a. Normal mode operation, start of life (SOL) (includes startup, steady state rated, throttled hold, and shutdown).
- b. Normal mode operation, end of life (EOL) (includes startup, steady state rated and throttle hold, and shutdown).
- c. Malfunction mode operation, single turbopump start of life (SOL) (includes steady state at 80 percent thrust and throttle hold).
- d. Malfunction mode operation, single turbopump, end of life (EOL) (includes steady state at 80 percent thrust and throttle hold).
- e. Growth mode operation at $T_c = 4500^{\circ}\text{R}$ and $P_c = 450\text{psi}$, start of life (SOL) (Steady State).
- f. Growth mode operation at $T_c = 4500^{\circ}\text{R}$ and $P_c = 450\text{ psi}$, end of life (EOL). (Steady State).

The calculated plena conditions, i.e. flow rate, pressures and temperatures of the NSS at the above mentioned operating points are shown in the NSS Thermal and Fluid Environment Drawing (No. 939J746), Figures 2-1B to 2-1G. Figure 2-1A shows the schematic diagram of the NSS and the locations at which the plena conditions were calculated and presented in this Data Item. On the above figures the nominal values of the plena conditions and the uncertainties for 11 of the 20 steady state points are shown. The 11 steady state cases for which the uncertainties were analyzed are discussed in Section 2.4.4.2. The details of the results, analysis and interpretation of the thermal and fluid environment are presented in the following subsections.

2.5.1 Composite Core

2.5.1.1 Steady State Performance

a. Steady State Rated Performance at SOL

At steady state operations, the Support Stem Assembly (SSA) is designed to supply the required feedback reactivity insertion to compensate the reactivity loss due to corrosion by stem flow adjustment. The SSA flow rate adjustment is obtained by controlling the position (i.e., the flow impedance) of the SSCV. At SOL, the reactivity loss of the core due to corrosion is zero.

The initial position of the SSCV at rated operation is determined in the following manner. The SSCV is first adjusted at its minimum position such that the maximum material temperature of the cluster hardware liner tube is at its limiting operating temperature of 1190°R (Reference 20). The minimum SSCV position is defined as the 0% travel position of the SSCV and the wide open SSCV position as the 100% travel position. The support stem flow rate thus determined at the 0% travel is defined as the minimum stem flow rate and represents the spec extreme condition on this parameter. For a composite core design, the minimum stem flow rate was calculated to be 5.3 lb/sec giving a total reactor feedback reactivity of \$.63. This \$.63 represents the minimum cold to hot reactivity swing of the reactor at SOL. From past analysis and experience, the best estimate of the uncertainty in cold to hot reactivity swing was \$.35 and the uncertainty of the SSCV controllability was another \$.10, giving a total uncertainty of \$.45. To account for this uncertainty the nominal SOL operating point is chosen to be the point where the feedback reactivity is \$1.08 ($\$.63 + \$.45 = \1.08) by increasing the SSCV travel to admit more hydrogen into the core. The calculated nominal support stem flow rate at this nominal SOL point is 7.1 lb/sec corresponding to a SSCV travel of 13.5%. The increase of the support stem flow from 5.3 to 7.1 lb/sec to account for the estimated feedback reactivity uncertainty of \$.45 is 1.8 lb/sec. The NSS thermal and fluid environment for the composite core at this nominal SOL steady state condition is shown on Figure 2-1C Event E. For this Event E, the plena condition uncertainties with the one sided 99/95% maximum and minimum tolerance limits are also shown. The 99/95% tolerance limits have been defined and discussed in Section 2.4.4.2. It is noted that the calculated maximum 99/95% uncertainty limit for the support stem flow at this nominal SOL is also 1.8 lb/sec as shown on location 2 of the Figure (Event E). This calculation verifies that the initial estimate of \$.45 of cold to hot swing uncertainty in setting the SSCV above the minimum flow travel is ascertained and is applicable for this reference reactor design.

The calculated control drums position at the nominal SOL condition is 46.8°. This angle is the hot critical drum angle of the NSS and is the orificed drum angle for this reference design with the composite core.

The calculated nominal reflector, core and reactor pressure drops are 61, 168, and 685 psid respectively. The nominal pressure drop of the SSA is 41 psi. From the Structural Support Coolant Assembly (SSCA) inlet to the stem flow inlet plenum the pressure drop is 241 psi, of which about 239 psi is the pressure drop across the SSCV.

The reflector and pressure vessel annulus is orificed to give a flow rate of 7.0 lbs/sec at SOL rated conditions to assure that the annulus flow would not be less than the minimum extreme value of 6.2 lb/sec at other operating conditions, namely at end of life, as agreed to in Reference 43. The minimum pressure vessel annulus flow at EOL rated condition is discussed in the next subsection.

As shown in Figure 2-1B the 99/95% tolerance limits uncertainties of the fuel channel exit gas temperatures are $\pm 99^{\circ}\text{R}$ for the core central region, $\pm 107^{\circ}\text{R}$ for the core mid region and $\pm 187^{\circ}\text{R}$ for the core peripheral region. The flow weighted average fuel channel exit temperature is, however, 4301°R with a 99/95% tolerance limit of $\pm 65^{\circ}\text{R}$. If the upper limit of the uncertainties were applied to these temperatures, the corresponding maximum fuel exit temperatures are 4408°R , 4409°R and 4483°R . The upper limit of the average fuel exit temperature is 4366°R . The maximum radial variation of the fuel exit temperature is therefore, $4483 - 4366 = 117^{\circ}\text{R}$ which is within the limit of $\pm 150^{\circ}\text{R}$ specified in the NSS Specification, Reference 1. It should be noted, however, that this radial temperature variation is based on the Step3, NSS level TNT-11 calculations. For a detailed discussion on core radial exit temperature variation and uncertainty, the Step 4 component analysis is reported in the Fuel Element Trade Study, Reference 9.

b. Steady State Rated Performance At EOL

At EOL, the reactor is assumed to have operated 60 cycles with a total of 600 minutes at rated chamber temperature. The reactivity loss of the core due to corrosion has accumulated to the specified value of \$1.00. The SSCV is opened further to admit more hydrogen in the support stems to compensate for this loss, so that the operating hot critical control drum position remains unchanged. Since the nominal feedback reactivity at nominal SOL is \$1.08, the required feedback reactivity at nominal EOL is \$2.08 ($\$1.08 + \$1.00 = \2.08). The support stem flow rate required to provide this feedback reactivity was

calculated to be 10.9 lb/sec. This flow corresponds to a SSCV travel of 34.35%. The NSS thermal and fluid environments at nominal EOL is shown in Figure 2-1C.

The nominal reflector, core and reactor pressure drops are 58, 168, and 679 psi respectively.

The nominal reflector and pressure vessel annulus flow rate is 6.7 lb/sec and the lower 99/95% tolerance limit of stem flow rate is 0.44 lb/sec (see location 9 of Figure 2-1C, Event E) resulting in a minimum annulus flow of 6.26 lb/sec. The 6.26 lb/sec is slightly higher than the minimum extreme of 6.2 lb/sec as requested by ANSC per Reference 43.

c. Throttle Hold at SOL

For the reactor shutdown, the reactor is throttled from a chamber pressure of 450 psia to 293 psia with a P_c ramp rate of -50 psi/sec at rated chamber temperature of 4250°R. The Throttle Hold continues for 40 seconds before Temperature Retreat begins. The shutdown profile used for the analysis is discussed in Section 2.4.3.1. For the NSS nominal thermal and fluid environments at the SOL Throttle Hold condition, a steady state TNT-11 calculation was performed. The results are shown in Figure 2-1B, (Event F). For this calculation the SSCV travel was adjusted to provide the required total reactivity feedback of \$1.08 (i.e., the same total feedback reactivity as at SOL rated condition). The calculated nominal support stem flow rate is 10.2 lb/sec.

The nominal reflector, core, and reactor pressure drops are 39, 120, and 394 psi respectively.

The details of the calculated nominal thermal results during the SOL Throttle Hold are also presented in Section 2.5.1.2b where SOL shutdown transient is discussed. In the Throttling and Throttle Hold transient calculation (to be discussed in Section 2.5.1.2) the control drum angle was held constant as indicated in Section 2.4.3.1. Only the effect on core radial power distribution due to the change of hydrogen content was considered. The fractional change of the radial fission power distribution relative to the nominal SOL condition during the SOL Throttle Hold is shown in Figure 2-57 (from time = 603 to 643 seconds). The curves on the figure show that the relative fission power factors at the core central and mid regions increase about 0.4%, but that at the core peripheral region decreases about 2%.

These changes are due to the change of hydrogen content only. In order to maintain a flat radial power distribution, therefore, some control drum motion may be required to offset the effect of the change in hydrogen content in the core and reflector. The requirement of holding the drum position constant during the throttling and throttle hold may require re-examination. A discussion of the reactor neutronics on this effect and its implication on control modes is presented in Reference 10. The ramification on the NSS thermal performance with drum motion to offset the effect of change of hydrogen content during steady state operations, both SOL and EOL, are not included in this issue of Data Item.

d. Throttle Hold at EOL

The steady state thermal and fluid environment at the EOL Throttle Hold was also obtained by a steady state TNT-II calculation similar to the SOL, except that a \$1.00 reactivity loss due to corrosion was specified in the calculation. The feedback reactivity specified was \$2.08 in the TNT-II input. The NSS thermal and fluid environment is shown in Figure 2-1C (Event F).

The Monte Carlo uncertainty calculations were performed for this operating point. As shown in the figure the calculated nominal support stem flow is 14.1 lb/sec and the 99/95% tolerance limits for the support stem flow rate is ± 2.0 lb/sec. This means that a maximum support stem flow with 95% confidence of 16.1 lb/sec ($14.1 + 2.0$) is required to obtain an EOL Throttle Hold feedback reactivity of \$2.08. A TNT-II calculation was also performed with a wide-open SSCV (100% travel) and the nominal input parameters for the EOL Throttle Hold operating point. The calculated nominal support stem flow rate is 15.7 lb/sec, (Computer run 158 10/2/70).^{*} This nominal stem flow rate with the wide open SSCV is slightly lower than the maximum flow rate computed and discussed above. This indicates that the NSS on a nominal basis has more than the required reactivity swing to operate from nominal SOL rated condition to nominal EOL throttled condition by stem flow adjustment, However, within the 99/95% upper tolerance limit uncertainty of the stem flow, the NSS can still meet the required reactivity swing with about 7 to 8° of drum motion. The details of the calculated thermal results during the EOL Throttle Hold are also presented in Section 2.5.1.2D where EOL shutdown transient is discussed.

^{*}To insure traceability, all computer runs throughout this text and on all figures will be referenced with a sequence run number and the data of the run.

Similarly as discussed for SOL conditions, the curves showing the fractional changes of the core radial fission power distribution at the EOL Throttle Hold are shown in Figure 2-90 (from time = 603 to 643 seconds). The relative power factors at the core central region and at the mid region increase about 0.8 and 0.2% respectively, but that at the core peripheral region decreases about 3% as compared to the 2% at SOL Throttle Hold. The power factor perturbation is more pronounced at EOL than at SOL because of the added stem flow at EOL, and again drum movement may be required to flatten the power profile.

e. Feedback Reactivity Insertion Capability

From the previously discussed steady state calculations, the feedback reactivity insertion capability of the SSA with a composite core can be summarized as follows. At the nominal SOL rated condition the nominal stem flow is 7.1 lb/sec providing a feedback reactivity of \$1.08 as shown on Figure 2-24. The 99/95% tolerance limits uncertainty on the stem flow is ± 1.8 lb/sec. At the nominal EOL throttled condition, the nominal stem flow is 14.1 lb/sec providing a feedback reactivity of \$2.08 with \$1.00 reactivity compensation for corrosion loss. The 99/95% tolerance limits uncertainty on the stem flow at this throttled condition is ± 2.0 lb/sec. However, among the 30 random cases Monte Carlo calculations, in two cases the stem flow could not supply the required \$2.08 reactivity with wide open SSCV. On a nominal basis with a wide open SSCV, the nominal stem flow is 15.7 lb/sec providing a feedback reactivity of \$2.43. This implies that the reactivity insertion capability of this reference design with a composite core is sufficient to supply the swing requirement on a nominal basis. There is a 7 percent (2 out of 30 cases) probability that drum motion is required to supply the required feedback reactivity at EOL throttled condition.

f. Start of Life and End of Life Growth Mode Operations

As specified in the NSS Requirements Specifications, No. CP-677555A, Section 3.3.1.17 Reference 1, the NSS design shall be able to operate at a nominal chamber temperature and pressure of 4500°R and 450 psia respectively, to allow for growth exclusive of fuel elements. The steady state nominal thermal and fluid environment for SOL and EOL operations at the growth mode condition were calculated and shown in Figure 2-1 G. The calculated stem flow at SOL is 7.7 lb/sec and at EOL 11.8 lb/sec which are within the capability of reactivity insertion of the present SSA design.

The reflector, core, and reactor pressure drops are similar in magnitude to that of the nominal conditions. Since the fuel element performance is excluded in the Requirements Specification, from the thermal environments shown in the figure, it can be concluded that the other NSS components are considered adequate from a thermal and fluid flow standpoint to operate at the growth mode operations.

2.5.1.2 Transient

a. Start of Life Startup Performance

The startup profile analyzed in this Data Item is shown in Figure 2-15 and discussed in Section 2.4.3.1.

Figures 2-25 to 2-32 show the time plots of the calculated NSS nominal chamber temperature, flow rates, power, plenum pressure and plenum temperature during the startup. The NSS attains rated temperature and flow at time = 53 sec, but the calculation were continued to time = 60 sec only. At 60 seconds the reactor has not yet reached its steady state condition. For steady state thermal environments the steady state values are shown on Figure 2-1 B. The justification for terminating the calculation at 60 seconds is that the worst thermal conditions during the startup transient have passed. The boundary conditions up to 60 seconds are sufficient for component analyses.

As shown from these Figures the chamber temperature and pressure during the startup are those demanded in the control reference profile. Figures 2-33 to 2-35 show the cluster hardware support stem and liner tube material temperatures and the stem coolant temperatures. The stem and liner tube material temperatures are far below the nominal operating limits of 1040°R and 1190°R respectively (Reference 20). Figures 2-36 and 2-37 show the control drum position, the feedback, impressed and the excess* reactivities. The nominal cold critical control drum position is 80°. The control drum angle dropped slightly initially but returned to 80° as the temperature conditioning proceeds. During the Bootstrap the drums were rolled out to provide the increasing power requirement. During the Thrust Buildup, because the SSCV is gradually opened to admit more support stem flow, the control drums are rolled in as shown in the latter portion of the Figure 2-36 until rated operating

*The feedback, impressed and excess reactivities, are defined in Section 2.4.3.3.

conditions are reached. At rated conditions the drum position is calculated to be 46.8° for the composite core design. The minimum control drum angle calculated during Thrust Buildup is 34° (See Figure 2-36) and the corresponding impressed reactivity is $\$1.40$ (Figure 2-37). This indicates a minimum control drum shutdown capability of $\$0.45$ ($\$1.85 - 1.40 = \0.45) which exceeds the $\$0.25$ minimum specified in the NSS Requirement Specification, Reference 1.

Figure 2-38 shows the change of the core radial fission power distribution relative to the distribution at the nominal SOL rated condition during the startup. As discussed in Section 2.4.3.3.4 and the previous two sections, the core radial region power factor perturbation is a function of the hydrogen content in the core and reflector and core drum position. During the startup, the power factor for the core mid region remains relatively constant and unchanged. The power factor for the core peripheral region is perturbed as much as $+10\%$ and the maximum occurs during the Bootstrap phase of the profile. On the other hand, the power factor for the core central region is perturbed about -4.5% . During startup, the central region fuel elements tend to operate hotter than the peripheral region fuel elements because of the heat loss to the core periphery from the peripheral fuel elements and also due to the redistribution of flow because of the orifice characteristics, see Reference 9. This redistribution of core radial power factor would tend to reduce the temperature difference between the central fuel element temperature and the peripheral fuel element temperature. The changes in radial power fractions should approach unity as the nominal SOL steady is reached. This is verified in Figure 2-38 after time equal to 55 sec.

Figure 2-39 shows the trends in the temperature difference between the core central region average fuel temperatures and the core peripheral region average fuel temperatures computed using the TNT-II model at the nine axial stations represented in the model. It should be noted that this figure and the subsequent figures discussed in the following sections only show the trends in fuel element temperature differences during the transient. The detailed temperature distribution across a fuel element and the temperature difference between fuel and central element

temperatures are treated in Step 4 component detailed analyses and are to be reported in Fuel Element Trade Study, Reference 9. The maximum temperature difference is about 260°R which occurs at the hot end during the Thrust Buildup phase of startup. The curves in this Figure are labeled 1 through 9 designating the nine stations modeled in TNT-II (See Figure 2-6). The legends at the bottom of this Figure however, only explain the station numbers for curves 1, 3, 5, 7, and 9, because of space limitation. The even numbered curves which are not explained in the legends, are located mid-way between the odd numbered stations. This practice is used throughout this Chapter for Figures similar to this one. It is interesting to observe from this Figure that the temperature differences change sign twice during the transient because of heat conduction out of the core periphery and changes in fuel element flow distribution. The differences diminish rapidly as rated design condition SOL is approached.

Figures 2-40 to 2-42 show the trends of the temperature differences between the fuel element average temperature and the central element average temperature in the three core regions. The maximum difference is about 215°R (obtained from the gross TNT-II model) occurring at the core central region. These differences are much higher than the rated condition steady state values as shown by the rapidly decreasing values at times after 50 seconds.

Figure 2-43 shows the trends in the temperature difference between the average peripheral fuel temperature and the average filler strip temperatures at the nine axial stations. The maximum differences at each of the stations are not much higher than their corresponding full power steady state values.

b. Start of Life Shutdown Performance

The shutdown profile analyzed is shown in Figure 2-15 and discussed in Section 2.4.3.1. The time scale for the as run shutdown profile is shown at the bottom scale of the figure. The time of initiation of shutdown is 600 seconds signifying that the NSS has operated 600 seconds at rated conditions. The calculation terminated at 80 seconds after the initiation of the shutdown procedure. At this time the engine is at its early stage of the pump tailoff run. The NSS system inlet pressure is about 80 psia for a composite core. The remaining portion of the pump tailoff and subsequent cooldown operation will not be included in this Data Item. Information on cooldown analysis is presented in Data Item S-001 (Reference 6).

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(U) Figures 2-44 through 2-51 show the calculated nominal plena thermal conditions during the first 80 seconds of the shutdown. During Throttling and the Throttle hold, the chamber temperature and pressure are the demanded conditions (i. e., perfect control assumed). The detailed thermal and fluid environments at the steady state Throttle Hold is shown in Figure 2-1B, Event F. For the Temperature Retreat, the calculated T_c ramp closely approximates that demanded in this profile. The chamber pressure decrease was at a very high rate of about 75 psi/sec during the first two seconds as shown in Figure 2-48 (at time between 643 and 645 seconds). In order to maintain the high chamber temperature decrease ramp the flow increases rapidly during the temperature retreat. A fast temperature retreat which results in a flow rate increase is undesirable because of the accompanied increase in excess reactivity. This condition is shown in Figures 2-45 and 2-56 from time 645 seconds to 656 seconds. The extreme reference profile used at this maturity of design analysis may be marginal when all uncertainties are considered. Other shutdown profile studies have been made subsequent to the "reference profiles" and are discussed in Reference 6 .

(CRD) Figures 2-52 to 2-54 show the cluster hardware support stem, liner tube and stem fluid temperatures. The maximum stem temperature continues to increase, but levels off at 680 seconds (See Figure 2-52). The maximum liner tube temperature reaches the maximum level of 1400°R at about 650 sec (See Figure 2-53). This is still below the liner tube nominal operating material temperature limit of 1500°R during cooldown operation (Reference 20). This indicates that the cluster hardware support stem and liner tube temperatures do not exceed the operating limits for a temperature retreat ramp rate up to $-175^{\circ}\text{R}/\text{sec}$.

(U) Figure 2-55 shows the control drums position during shutdown. The control drum motion during the Throttling phase was slight. This indicates that the SSCV control profile (See Figure 2-16 .) assumed was reasonable. The open loop SSCV control profile could be further improved to minimize the drum motion. Figure 2-56 shows the feedback, impressed and the excess reactivities during the shutdown.

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During the Temperature Retreat the shutdown reactivity increases to \$2.45 but subsequently reduces to \$0.90 (from time = 643 to 657 seconds). This reversal is due to the up surge of flow rate to maintain the $-175^{\circ}\text{R}/\text{sec}$ chamber temperature rate. During the early phase of the Pump Tailoff the shutdown reactivity increases to \$2.10 at time = 680 seconds. This indicates that the shutdown reactivity capability of the NSS at this time is at least \$2.10.

Figure 2-57 shows the change of the core radial fission power distribution relative to the nominal distribution at SOL rated condition. The peripheral region fuel element power factor is reduced about 2 per cent during the Throttling and the Throttle Hold. This change is entirely due to the hydrogen content in the core and the reflector, since no drum motion was assumed. After the Temperature Retreat the peripheral fuel elements power factor is reduced by more than four percent.

Figure 2-58 shows the trends in the temperature difference between the central region average fuel temperature and the peripheral region average fuel temperature at the nine axial stations. The maximum difference is about 560°R (obtained by the gross TNT-II model) which occurs at the aft end of the elements at the time the chamber temperature is at about 1800°R . At station 26 the difference is about 300°R . These radial temperature differences only occur for a very short period of time and diminish rapidly as Pump Tailoff operation continues. Figures 2-59 to 2-61 show the trends in the temperature differences between the average fuel element and the average central element temperature at the three core regions. The maximum difference is about 180°R which occurs at the end of the Temperature Retreat phase of the shutdown. The magnitude of the difference is not much higher than that at the rated operating condition. The steady state and transient temperature differences between the fuel element and the unfueled central element are covered in more detail in Step 4 component analysis in the Fuel Element Trade Study (Reference 9).

Figure 2-62 shows the trends in the temperature difference between the average peripheral fuel temperature and the average filler strip temperature at the nine axial stations.

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Because the filler strips are of the cold strip design and are cooled by a coolant flow, the temperature difference during the shutdown procedure is always less than the steady state value at rated condition.

c. End of Life Startup Performance

The EOL startup profile is the same as the SOL startup profile except that a reactivity loss of \$1.00 was specified in the calculation. The SSCV control profile is shown by the upper curve of Figure 2-16. The slope of this curve is steeper than that for the SOL transient (lower curve of Figure 2-16) because the SSCV must be opened faster to admit more hydrogen into the core. For the initial boundary conditions used for the EOL startup calculation, the initial material temperatures of the NSS were assumed to be at the same temperatures of 532°R as in the SOL startup calculation, since the exact engine duty cycle is not defined at this time. The material thermal properties used in the calculation were the same as those in the SOL startup calculation assuming that the reactor had been shut down long enough between sequential cycles, so that there was no change in properties due to irradiation. Also it was assumed that there was no fission products buildup and only the reactivity loss due to corrosion was considered.

Figures 2-63 to 2-70 show the chamber temperatures, flow rates, power, plenum pressure and plenum temperature plots. These plots are similar to those shown for the SOL startup except for the support stem flow rate. The maximum stem flow is 15 lb/sec as compared to 12 lb/sec for the SOL startup which occurs at the throttle point during the Thrust Buildup phase. When full power conditions are reached at 53 seconds, the stem flow reduces to 11.1 lb/sec as compared to 7.1 lb/sec for the SOL case. Figures 2-71 to 2-73 show the cluster hardware support stem, liner tube material and the SSA coolant temperatures. The maximum liner tube temperature is about 660°R as compared to the maximum tube temperature of 920°R during the SOL startup because of the higher stem flow.

Figures 2-74 and 2-75 show the control drum position and the feedback, impressed, and the excess reactivities. With an initial feedback reactivity of \$1.00 to account for the reactivity loss due to corrosion, the cold critical control drum position is about 106° . The initial feedback reactivity as shown in Figure 2-75 is \$-1.00 as specified. The impressed reactivity at time 0 sec. is about \$1.00, resulting in an excess reactivity of about zero. The feedback reactivity increases rapidly during the Thrust Buildup phase because of the rapid opening of the SSCV. Figure 2-76 shows the change of the core radial power factor distribution due to the change of hydrogen content in core and the control drum position. The peripheral region power factor increases as much as 16 per cent, while the central region power factor reduces as much as 7 per cent, both occur at the bootstrap phase of the startup. The trends of temperature differences between the average central region fuel element and the average peripheral fuel element and between the fuel and the central elements at the three core regions are similar in magnitude as the SOL case. Therefore, the time plots of these temperature differences were not presented.

d. End of Life Shutdown Performance

The EOL shutdown profile analyzed is also the same as the SOL shutdown except that a reactivity loss of \$1.00 was specified in the EOL shutdown calculation. The SSCV control profile during the EOL shutdown is shown by the upper curve of Figure 2-16.

Figures 2-77 to 2-84 show the plena chamber temperature, flow rate, power, plenum pressures and plenum temperatures plots. These plots are also similar to those shown for the SOL shutdown except for the stem flow rate and the power reversal after the control drum was completely rolled in. The stem flow rate as shown in Figure 2-78 during the Throttled Hold is about 14.0 lb/sec as compared to the 10 lb/sec for the SOL shutdown case, (Figure 2-45) because of the difference in the SSCV control profile. The power as shown in Figure 2-79 increased less after the control drum was completely rolled in at time after 650 seconds than in the SOL shutdown case because of the additional \$1.00 shutdown reactivity.

Because of this smaller reversal in power, the flow rate reversal was also less in the EOL shutdown case, consequently, the stem and liner tube temperatures are about 100°R higher (at time = 680 seconds on the figures) in the EOL case than in the SOL case. These temperatures are, however, still lower than the stem and liner tube nominal operating limits during cooldown operation, Reference 20. Figure 2-88 shows the control drum position during shutdown. The drums were rolled in about 6° during the throttling phase but gradually returned to the hot critical angle of 46.8° before temperature retreat began. Figure 2-89 shows the calculated nominal feedback, impressed and excess reactivities during the shutdown profile. As in the SOL shutdown, the shutdown reactivity increased to more than $\$3.50$, then decreased to $\$2.20$ (from time = 643 to 657 seconds), and increased again to more than $\$3.20$ at time = 680 seconds. Figure 2-90 shows the change of the core radial fission power distribution relative to the distribution at nominal SOL rated condition. The comparison of the perturbation at the three core region during the throttle hold between SOL and EOL was discussed previously in Section 2.5.1.1. C and D.

2.5.1.3 Single TPA Operating Mode

a. Start of Life and End of Life Single TPA Operation Performance

The TNT-II calculations for single TPA malfunction operation were performed at steady state conditions only. With a single TPA operating, the NSS operates at 80 per cent power at the rated chamber temperature of 4250°R , chamber pressure of 360 psia, and flow rate of 72.9 lb/sec. The thermal and fluid environments for the SOL and EOL steady state conditions are shown in Figure 2-1F. As shown in the figure, the support stem flow rates at the nominal SOL and EOL single TPA operations are slightly higher than the corresponding flow rates at the nominal SOL and EOL cases.

At both SOL and EOL, the reflector and core pressure drops for the single TPA operation are less but the reactor overall pressure drops are higher than the corresponding nominal operation with both TPA operating. The reactor pressure drop at SOL is 798 psi and at EOL, 791 psi. These reactor pressure drops are about 112 psi higher than those at the

nominal cases. The upper limit of the 99/95% tolerance limits in the reactor pressure drop at SOL is 21 psi, resulting in a upper limit of 819 psi. This upper limit of 819 psi is the highest reactor pressure drop value under all the operating conditions analyzed. The effects of this high reactor pressure drop on the reflector segments, and aluminum structure are discussed in Chapter 8 and Reference 44.

b. Start of Life and End of Life Single TPA Operations at Throttled Condition Performance

At steady state throttled conditions with single TPA operating, the NSS still operates at 65 per cent power as in nominal operation at throttled conditions. With the single TPA at throttled condition, the reflector and core pressure drops are less but the reactor pressure drop is higher at both SOL and EOL conditions as compared to that at the corresponding normal operation as in the case discussed in (a). The SOL reactor pressure drop is 563 psi and the EOL reactor pressure drop is 557 psi. The magnitudes are considerably less than those at the 80 per cent power single TPA condition discussed in (a). The thermal and fluid environments for the SOL and EOL single TPA operations at throttled condition are shown in Figure 2-1F.

2.5.2 Graphite Core

2.5.2.1 Steady State Performance

a. Steady State Rated Performance at SOL

The determination of the support stem flow rate for the minimum stem flow condition and for the nominal SOL rated condition is the same for the graphite core design as for the composite core design as discussed in Section 2.5.1. The minimum stem flow rate, which results in the maximum operating allowable liner tube material temperature of 1190°R , was calculated to be 5.8 lb/sec providing a total feedback reactivity of $\$0.30$. This compares to the $\$0.63$ at the minimum stem flow condition for the composite core. The reduction of the feedback reactivity for the graphite core is due to the higher core temperature reactivity coefficient effect and the smaller hydrogen worth in the core. In addition, the graphite core internal heating rates of the fuel elements are lower but that of the unfueled components are higher. This lowers the hydrogen density in the core coolant channels appreciably. Adding

the \$0.45 uncertainty to the \$0.30 at the minimum stem flow condition to obtain the reactivity requirement at the nominal SOL rated condition, the stem flow necessary to provide the \$0.75 (\$0.45 + \$0.30) of nominal feedback reactivity was calculated to be 7.8 lb/sec. corresponding to a SSCV travel of 14 per cent. The calculated NSS thermal and fluid environment at the nominal SOL rated condition is shown in Figure 2-1D, Event E. The calculated control drum position was 58.2°. This drum position is the hot critical drum angle and is assumed to be the orifice angle for this reference design with a graphite core as compared to the hot critical angle of 46.8° for the composite core design.

The calculated nominal reflector, core and reactor pressure drops are 62, 170 and 677 psi respectively. The reflector pressure drop is similar in magnitude as for the composite core but the core pressure drop is about 1 psi higher because of higher core inlet temperature. The reactor overall pressure drop is 8 psi lower than that for the composite core because of higher turbine inlet temperature. The work required by the turbine is, therefore, less for the graphite core design, resulting in lower pump discharge pressure.

The pressure vessel annulus flow is 6.9 lb/sec similar to that for the composite core.

b. Steady State Rated Performance at EOL

For the EOL rated performance calculation, a \$1.00 corrosion reactivity loss was specified in the calculation while the control drum position remained unchanged. The calculated NSS thermal and fluid environment is shown in Figure 2-1E, Event E. The calculated support stem flow to provide feedback reactivity of \$1.75 (\$0.75+\$1.00) was 11.9 lb/sec.

The nominal reflector, core and reactor pressure drops are 59, 170 and 670 psi respectively. Similar to the SOL conditions previously discussed, the nominal core pressure drop is about 1 psi higher and the reactor pressure drop is about 9 psi lower than that for the composite core design.

c. Throttle Hold at SOL

For the SOL Throttle Hold during SOL shutdown the feedback reactivity requirement is \$0.75, the same as the SOL rated condition. A steady state TNT-II calculation was performed

by specifying the required reactivity. The NSS nominal thermal and fluid environment for this condition is shown in Figure 2-1D, Event F. The stem flow rate necessary to provide this reactivity without drum motion was calculated to be 10.9 lb/sec.

The nominal reflector, core and reactor pressure drops are 40, 121 and 391 psi respectively.

d. Throttle Hold at EOL

For the EOL Throttle Hold during the EOL shutdown, the feedback reactivity requirement is \$1.75. A steady state TNT-II calculation was performed by specifying the required reactivity. The NSS nominal thermal and fluid environment is shown in Figure 2-1E, Event F. The nominal stem flow rate necessary to provide this reactivity was calculated to be 15.2 lb/sec. However, to obtain this 15.2 lb/sec of flow rate, the SSCV was at the wide open position. This indicates that with the wide open SSCV the NSS has just enough capability to supply the nominal stem coolant flow to compensate for the required \$1.00 corrosion reactivity loss from the normal mode SOL rated conditions to EOL at throttled condition. The 99/95% tolerance limits on the stem flow as shown in the Figure is ± 2.0 lb/sec, the upper limit in stem flow required to supply this reactivity swing is then 17.2 lb/sec ($15.2 + 2.0 = 17.2$) which is beyond the capability of the present SSA with the graphite core design. However, with drum motion, the reactivity insertion requirement at EOL throttled conditions still can be met.

The calculated nominal reflector, core, and reactor pressure drops are 36, 121 and 385 psi respectively.

e. Feedback Reactivity Insertion Capability

From the previously discussed steady state calculations the feedback reactivity insertion capability of the NSS with a graphite core can be summarized as follows. For the nominal SOL rated condition the nominal stem flow is 7.8 lb/sec providing a feedback reactivity of \$0.75 ($0.30 + .45$ uncertainty) and for the nominal EOL throttled condition the nominal stem flow is 15.2 lb/sec with a wide open SSCV providing the maximum feedback reactivity of \$1.75, see Figure 2-91. The design, therefore, has the capability to insert the required \$1.00 corrosion reactivity on the normal basis; there is no margin to account for any

uncertainties. Drum motion may be required at EOL throttled condition to account for the 99/95% tolerance limits uncertainties.

f. Start of Life and End of Life Growth Mode Operations

Similar to the composite core design, the steady state NSS nominal thermal and fluid environment for the growth mode operations at chamber temperature of 4500°R were calculated for the SOL and EOL conditions and are shown in Figure 2-1 G. The calculated nominal stem flow rates were 8.3 lb/sec for SOL and 12.9 lb/sec for EOL which are within the capability of reactivity insertion of the present SSA design with a graphite core. Excluding the fuel element performance at $T_c = 4500^{\circ}\text{R}$, the other NSS components are considered adequate to operate at the growth mode operations as in the composite core design case.

2.5.2.2 Transient

a. Start of Life Startup Performance

The startup profile analyzed for the graphite core is the same as that for the composite core previously discussed and described in Section 2.4.3.1. The open loop SSCV control profiles for startup and shutdown and the relationship between the SSCV travel in percent versus the loss coefficient used in the TNT-II code are shown in Figures 2-18 and 2-19 . These profiles are slightly different from those for the composite core due to differences in heating rates of the NSS components and the feedback reactivity. The wide open (100 percent travel) SSCV loss coefficient of 31 is, however, the same for both composite and graphite core designs.

Figures 2-92 to 2-102 show the corresponding time plots of the NSS nominal plena conditions, power and support stem and liner tube temperatures for the graphite core as those for the composite core. Figure 2-103 shows the control drum position during the startup. The drum angle increases to as high as 96° during the Bootstrap phase and reduces to as low as 49.5° during the Thrust Buildup phase of the startup, but gradually approaches the calculated steady state nominal hot critical angle of 58.2° . Figure 2-104 shows the feedback, impressed and excess reactivities during the startup. The minimum impressed reactivity is $\$1.06$ during the startup which occurs at about 53 seconds after the initiation of the startup. This indicates

that a minimum shutdown reactivity of \$0.79 ($\$1.85 - \$1.06 = \0.79) is available and is greater than the requirement of at least \$0.25 as specified in the NSS Requirement Specification, Reference 1.

Figure 2-105 shows the change of the core radial fission power distribution relative to the distribution at the nominal SOL rated condition. The perturbations at the three (3) core regions are similar to those for the composite core. The core average material temperature differences, such as the difference between the average fuel and central element temperatures at the three core regions, and the difference between the average central region fuel temperature and the average peripheral region fuel temperature are similar in magnitude as for the composite core design. The time plots are not included here. The details in core transient temperatures will be discussed in the Trade Study for Fuel Elements Reference 9.

b. Start of Life Shutdown Performance

The shutdown profile analyzed for the graphite core is also the same as that for the composite core and described in Section 2.4.3.1. The open loop SSCV control profile is shown by the lower curve of Figure 2-18.

Figures 2-106 to 2-116 show the NSS nominal plena conditions power and support stem and liner tube temperatures. These conditions are similar to those for the composite core. Figure 2-117 shows the control drum position during the shutdown. The drum motion is slight during the Throttling and returned to the hot critical angle of 58.2° toward the end of the Throttle Hold. Figure 2-118 shows the feedback, impressed and excess reactivities during the shutdown. During the Temperature Retreat phase the minimum shutdown reactivity was about \$1.10 (at time = 657 seconds) and during the early stage of the Pump Tailoff phase analyzed the shutdown reactivity increases to more than \$2.30 as compared to \$2.10 for the composite core. The drum reactivity insertion from hot critical to completely in position is about \$1.00 for the graphite core as compared to about \$0.70 for the composite core because of the larger

hot critical angle for the graphite core. Figure 2-119 shows the change of the core radial fission power distribution relative to the distribution at the normal SOL rated condition. The perturbations are similar to those for the composite core.

c. End of Life Startup Performance

The calculation for the EOL startup performance was similar to that for the composite core calculation. Figures 2-120 to 2-130 show the NSS nominal plena conditions, power and support stem and liner tube temperatures during the startup. Figure 2-131 shows the control drum position during the startup. The drums were rolled out to 123° during the Bootstrap to supply demanded power, then rolled back in to 40° toward the end of the Thrust Buildup phase of the startup. The drums were finally rolled out again and approached the steady state nominal value of 58.2° (hot critical angle). Figure 2-132 shows the feedback, impressed and excess reactivities during the startup. Corresponding to the minimum drum angle of 40° , the impressed reactivity of the drum is -1.33 (at time = 53 seconds) resulting in a minimum available shutdown reactivity of 0.52 as compared to the 0.79 during the SOL startup for the graphite core design. Figure 2-133 shows the change of the core radial fission power distribution relative to the distribution at nominal SOL rated condition. The peripheral region fuel element relative power factor perturbation was as much as $+13.5$ percent during the Bootstrap phase of the startup.

d. End of Life Shutdown Performance

The EOL shutdown profile analyzed was the same as that for the composite core. Figures 2-134 to 2-146 show the NSS nominal plena conditions, power and support stem and liner tube temperatures during the shutdown. These figures show the same NSS performances as for the composite core except the difference in behavior due to a difference in hot critical angle for the graphite core (58.2°). The available shutdown reactivity during the Temperature Retreat and the early stage of the Pump Tailoff analyzed is about 0.10 more

for the graphite core than for the composite core design. The perturbations of the core radial fission power factors, as shown in Figure 2-147, are of the same magnitude as for the composite core. The discussion of possible flattening of radial power profile by drum motion at EOL for the composite core, Section 2.5.1.1.d, applies in this case also.

2.5.2.3 Single TPA Operating Mode

a. Start of Life and End of Life Single TPA Operation Performance

As for the composite core design, the TNT-II calculations for graphite core single TPA operation were performed for steady state conditions at 80 per cent power. The calculated nominal thermal and fluid environments are shown in Figure 2-1F. The calculated nominal support stem flows are 8.1 lb/sec for SOL and 12.1 lb/sec for EOL which are slightly higher than the corresponding flow rates at nominal rated conditions.

The reflector and core pressure drops are 40 and 143 psi respectively for SOL and 38 and 143 for EOL. These results are similar to the composite core operating with a single TPA. The reactor pressure drop is 784 for SOL and 777 psi for EOL as compared to 798 and 791 psi for the composite core because of a higher turbine inlet temperature for the graphite core design.

b. Start of Life and End of Life Single TPA Operation at Throttled Condition

For the throttled condition at single TPA operation, the reactor still operates at 65 per cent power as for the nominal throttled condition. Steady state TNT-II calculations were performed, and the calculated nominal thermal and fluid environments are shown in Figure 2-1F. The nominal stem flow rates are 9.2 lb/sec for SOL and 13.0 lb/sec for EOL which are both less than those at the corresponding nominal throttled condition especially at EOL. At nominal EOL throttled operation the stem flow rate is 15.2 lb/sec with a wide open SSCV with no margin to account for uncertainties; however, with the single TPA, there is a margin of $15.2 - 13.0 = 2.2$ lb/sec. The reactor pressure drops are 555 psi for SOL and 548 for EOL as compared to 391 and 385 at the nominal throttled operating condition.

2.5.3 Space Soak Effects

For extended storage times in space without power (space soak), a thermal model of the NSS was analyzed, Reference 45, to determine the maximum steady state equilibrium temperatures in the major components of the NSS. The details of this analysis are presented in Reference 6.

2.6 REFERENCES

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TABLE 2-1
TNT-II MODEL HYDRAULIC DATA

Flow Channel Description	Channel Number	Channel Length, (in)	Hydraulic Diameter, (in)	Flow Area, (in ²)	Flow Nodes		Loss Coefficients	
					From	To	Inlet	Exit
Pipe from Pump to Tee	1	20.0	4.75	35.44	1	1	0.175	1.6
Pipe from Tee to Nozzle Inlet	2	277.75	4.75	17.72	2	2	2.0	0.0
Support Stem Feed Line	3	10.0	0.562	14.966	197	197	3924. *	0.0
Support Stem Bypass Line	4	10.0	0.562	14.966	198	198	10700. **	102. ***
Main Nozzle	5	83.61	0.557	63.94	4	19	32.	0.895
Aluminum Structure	7	52.0	0.200	17.108	139	147	6.5	4.67
Inner Reflector Segment	8	52.0	0.125	7.1835	148	156	0.115	0.427
Outer Reflector Segment	9	52.0	0.125	3.8259	157	165	0.87	0.417
Pressure Vessel Annulus	10	52.0	0.512 ****	43.635	166	174	488.34	47.8
Control Drum	11	52.0	0.0531	17.758	179	187	2.4	1.69
Control Drum Gap	12	52.0	0.150	18.385	188	196	54.5	158.0
Core Central Region Support Stem Feed First Pass	15	59.25	0.249	5.9895	34	43	2.73	11.8

NOTE:

*Support stem feed line inlet loss coefficient includes the SSCV impedance and the pipe loss from tee to support plate O.D. The loss coefficients for various steady state operating conditions and core design is shown in Table 2-2.

**The SSA bypass line inlet loss coefficient includes the flow impedance of the bypass fixed orifice and line loss from SSBO to pressure vessel dome penetration.

***The SSA bypass line exit loss coefficient includes the line loss from pressure vessel dome penetration to support plate O.D.

****Hot dimension at rated full power condition.

TABLE 2-1 (CONT'D)

Flow Channel Description	Channel Number	Channel Length, (in)	Hydraulic Diameter, (in)	Flow Area, (in ²)	Flow Nodes		Loss Coefficients	
					From	To	Inlet	Exit
Core Mid Region Support Stem Feed First Pass	16	59.25	0.249	8.1808	75	84	2.73	21.4
Core Peripheral Region Support Stem Feed First Pass	17	59.25	0.249	2.8243	96	105	2.73	35.2
Core Central Region Support Stem 2nd Pass	18	60.53	0.257	17.43	44	54	0.0	0.1
Core Mid Region Support Stem 2nd Pass	19	60.53	0.257	23.4	85	95	0.0	0.1
Core Peripheral Region Support Stem 2nd Pass	20	60.53	0.257	8.23	106	116	0.0	0.1
SSA Mixing and Discharge	21	10.0	0.562	44.897	199	199	4.84	0.0
Peripheral Shield	22	13.6	0.167	43.885	209	214	0.376	0.1
Top of PV and Peripheral Shield	23	11.5	0.512 ****	43.635	175	178	9.34	-0.51
Pipe from Dome End to Turbine	24	73.9	7.188	40.58	215	215	0.68	0.0
Pipe from Turbine to Central Shield	25	69.5	7.188	40.58	216	216	0.95	1.1
Central Shield	26	13.6	0.188	98.018	200	205	1.22	0.0
Support Plate	27	6.0	0.4375	79.688	206	208	1.5	-0.1

****Hot dimension at rated full power condition.

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TABLE 2- 1 (CONT'D)

Flow Channel Description	Channel Number	Channel Length, (in)	Hydraulic Diameter, (in)	Flow Area, (in ²)	Flow Nodes From	Flow Nodes To	Loss Coefficients Inlet	Loss Coefficients Exit
Core Central Region	28	53.28	0.095	99.39	58	64	41.9	-0.2
Core Mid Region Fuel	29	53.28	0.095	117.2	65	74	61.0	-0.2
Core Peripheral Region Fuel	30	53.28	0.095	36.36	117	126	186.0	-0.2
Filler Strip	31	52.0	0.110	1.6546	219	227	1.5	0.5
Lateral Support	32	27.56	0.0958	2.4652	130	138	225.	0.5

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~~RESTRICTED DATA~~
1954

~~Astronautical~~
Laboratory

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TABLE 2-2
SSCV LOSS COEFFICIENTS AT VARIOUS STEADY STATE OPERATING
CONDITIONS AND CORE DESIGNS

	<u>Composite Core</u>	<u>Graphite Core</u>
Rated Condition, Minimum Stem Flow	3924	3211
Rated Condition, Nominal SOL	2070	1652
Rated Condition, Nominal EOL	737	579
Throttled at 65% Power, SOL	320	231
Throttled at 65% Power, EOL	76	32
Throttled at 80% Thrust, SOL (Single TPA)	995	825
Throttled at 80% Thrust, EOL (Single TPA)	348	266
Throttled at 65% Power, SOL (Single TPA)	361	289
Throttled at 65% Power, EOL (Single TPA)	100	58
Growth Mode, $T_c = 4500^\circ R$, SOL	1658	1397
Growth Mode, $T_c = 4500^\circ R$, EOL	572	431

NOTE:

The loss coefficient is based on the channel flow area of 14.966 in^2 . These coefficients include the SSCV impedance and feed line losses from pump discharge line (PDL) tee to support plate periphery.

~~CONFIDENTIAL~~
~~RESTRICTED DATA~~
1954

TABLE 2-3
RADIAL CONDUCTION NODAL DESCRIPTION

<u>Conduction Between</u>		A-Node		B-Node		Length in	Length in	Area
Item A	Item B	From	To	From	To	A, (in)	B, (in)	Area/Node, (in ²)
Outer Reflector Segment	Inner Reflector Segment	289	297	276	284	1.21	1.13	889.4
Inner Reflector Segment	Aluminum Structure	276	284	267	275	1.776	0.5	807.6
Aluminum Structure	Outer Wrapper	267	275	258	266	0.5	0.015	767.7
Outer Wrapper	Lateral Support System	258	266	249	257	0.015	0.3	585.1
Lateral Support System	Filler Strips	249	257	240	248	0.05	0.1	701.1
Filler Strips	Composite Insulation	240	248	231	239	0.2537	0.32	874.5
<u>Peripheral Core</u>								
Composite Insulation	Fuel Elements	231	239	222	230	0.0775	0.125	864.6
Fuel Elements	Unfueled Elements	222	230	213	221	0.04	0.067	876.41
Unfueled Element	Pyro Insulator - 3	213	221	204	212	0.053	0.0093	552.79
Pyro Insulator - 3	Pyro Insulator - 2	204	212	195	203	0.0089	0.00936	514.79
Pyro Insulator - 2	Pyro Insulator - 1	195	203	186	194	0.00866	0.0093	475.86
Pyro Insulator - 1	Support Stem Liner	186	194	177	185	0.00893	0.00506	437.0
Support Stem Liner	Support Stem	185		175		3.15	0.875	1.1217
<u>Mid Core</u>								
Fuel Element	Unfueled Element	101	109	110	118	0.04	0.067	2538.4
Unfueled Element	Pyro Insulator - 3	110	118	119	127	0.053	0.0093	1601.0
Pyro Insulator - 3	Pyro Insulator - 2	119	127	128	136	0.0089	0.00936	1491.0

TABLE 2-3 (CONT'D)

<u>Conduction Between</u>								
Item A	Item B	A-Node From To		B-Node From To		Length in A, (in)	Length in B, (in)	Area Area/Node, (in ²)
Pyro Insulator - 2	Pyro Insulator - 1	128	136	137	145	0.00866	0.0093	1378.4
Pyro Insulator - 1	Support Stem Liner	137	145	147	155	0.00893	0.005062	1265.75
Support Stem Liner	Support Stem	155		165		3.15	0.875	3.213
<u>Central Core</u>								
Support Stem	Support Stem Liner	45		55		0.875	3.15	2.3302
Support Stem Liner	Pyro Insulator - 1	47	55	56	64	0.005062	0.00893	926.74
Pyro Insulator - 1	Pyro Insulator - 2	56	64	65	73	0.0093	0.00866	1009.2
Pyro Insulator - 2	Pyro Insulator - 3	65	73	74	82	0.00936	0.0089	1091.7
Pyro Insulator - 3	Unfueled Element	74	82	83	91	0.0093	0.053	1172.2
Unfueled Element	Fueled Element	83	91	92	100	0.067	0.04	1858.5
Central Fuel	Mid Fuel	92	100	101	109	5.26	1.83	214.8
Mid Fuel	Peripheral Fuel	101	109	222	230	2.11	0.995	308.5

TABLE 2-4
AXIAL CONDUCTION NODAL DESCRIPTIONS

Item	Node From	Number Thru	Material Description	Material Index Number	Number of Items	Total Volume Per Node, (in ³)	Axial Length, (in)	Axial Conduction Area Total/Node (in ²)
Pressure Vessel	298	310:						
	298	301	Aluminum	3	1	996	8.0	124.5
	302	310	Aluminum	3	1	719	5.77778	124.5
Central Shield	323	328:						
	323		Aluminum	3	1	218.46	0.2	1092.29
	324		Lead	69	1	1420.	1.3	1092.29
	325	327	BATH	10	1	4042.	3.7	1092.29
	328		Aluminum	3	1	1092.3	1.0	1092.29
Peripheral Shield	332	337:						
	332		Aluminum	3	1	610.3	0.75	1016.63
	333		Lead	69	1	1266.6	1.3	974.3
	334	336	BATH	10	1	2906.4	3.7	974.3
	337		Aluminum	3	1	203.3	0.2	1016.63
Support Plate	329	331:						
	329	331	Aluminum	3	1	1437.4	2.0	718.7
Aluminum Liner	285	288:						18.838
	285		Aluminum	3	1	24.49	1.3	18.838
	286	288	Aluminum	3	1	69.70	3.7	18.838
Outer Reflector	289	297:						
	289	297	Beryllium	4	1	1389.3	5.77778	404.48
Inner Reflector	276	284:						
	276	284	Beryllium	4	1	1058.1	5.77778	331.3

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TABLE 2 - 4 (CONT'D)

Item	Node From	Number Thru	Material Description	Material Index Number	Number of Items	Total Volume Per Node, (in ³)	Axial Length, (in)	Axial Conduction Area Total/Node (in ²)
Aluminum Structure	267	275:						
	267	275	Aluminum	3	1	767.5	5.77778	149.941
Control Drum	311	319:						
	311	319	Beryllium	4	18	1452.6	5.77778	251.408
Outer Foil	258	266:	Laminated					
	258	266	Bonded Grafoil	29	1	23.01	5.77778	3.983
Lateral Support System	249	257:						
	249	251	ZTA Graphite	17	1	62.215	5.77778	No Axial Conduction
	252	254	ZTA Graphite	17	1	62.215	5.77778	No Axial Conduction
	255	256	ZTA Graphite	17	1	62.215	5.77778	No Axial Conduction
	257		ZTA Graphite	17	1	62.215	5.77778	No Axial Conduction
Filler Strips	240	248:						
	240	248	Graphite G	18	1	329.18	5.77778	61.28
Core Wrapper Insulation	231	239:						
	231	233	Bonded Grafoil	29	1	238.77	5.77778	41.15
	234	239	ZrC, 50% Dense	92	1	238.77	5.77778	41.15
<u>Core Peripheral Region</u>								
Fuel Elements	222	230:						
	222	230	Composite Fuel*	65	270	557.97	5.77778	96.57

* For graphite core design, the fuel material is loaded graphite, number 28.

TABLE 2 - 4 (CONT'D)

Item	Node From	Number Thru	Material Description	Material Index Number	Number of Items	Total Volume Per Node, (in ³)	Axial Length, (in)	Axial Conduction Area Total/Node (in ²)
Unfueled Elements	213	221:						
	213	220	Composite Unfueled***	58	58	92.605	5.77778	16.01
	221		Composite Unfueled	58	58	106.23	6.62778	16.01
*Pyro Insulation - 1	186	194:						
	186	193	Pyrolytic Sleeve	9	58	6.36	5.77778	1.4616
	194		Pyrolytic Sleeve	9	58	7.296	6.62778	1.4616
Pyro Insulation - 2	195	203:						
	195	202	Pyrolytic Sleeve	9	58	9.0715	5.77778	1.5857
	203		Pyrolytic Sleeve	9	58	10.406	6.62778	1.5857
Pyro Insulation - 3	204	212:						
	204	211	Pyrolytic Sleeve	9	58	8.27725	5.77778	1.6646
	212		Pyrolytic Sleeve	9	58	9.49496	6.62778	1.6646
Support Stem Liner	176	185:						
	176		Uniloy - A - 286	54	58	6.9971	6.4	1.0927
	177	184	Uniloy - A - 286	54	58	6.3168	5.77778	1.0927
	185		Uniloy - A - 286	54	58	7.2462	6.62778	1.0927
** Support Stem	166	175:						
	166		Uniloy - A - 286	54	58	7.7507	6.4	1.3578
	167		Uniloy - A - 286	54	58	6.9971	5.77778	1.3578
	175	174	Uniloy - A - 286	54	58	8.0265	6.62778	1.3578
<u>Core Mid Region</u>								
Fuel Elements	101	109:						
	101	109	Composite Fuel	65	870	1797.9	5.77778	311.173

*An equivalent Grafoil sleeve thermal conductivity was used which includes the hydrogen gap.

**An equivalent thermal conductivity is used for the Support Stem, H₂ gap, shim material and shim tube.

***For graphite core design, the unfueled central element is AXM graphite, Number 33.

TABLE 2 - 4 (CONT'D)

Item	Node From	Number Thru	Material Description	Material Index Number	Number of Items	Total Volume Per Node, (in ³)	Axial Length, (in)	Axial Conduction Area Total/Node (in ²)
Unfueled Elements	110	118:						
	110	117	Composite Unfueled	58	168	268.23	5.77778	46.368
	118		Composite Unfueled	58	168	307.70	6.62778	46.368
*Pyro Insulation - 3	119	127:						
	119	126	Pyrolytic Sleeve	9	168	23.975	5.77778	4.8216
	127		Pyrolytic Sleeve	9	168	27.503	6.62778	4.8216
Pyro Insulation - 2	128	136:						
	128	135	Pyrolytic Sleeve	9	168	26.276	5.77778	4.5931
	136		Pyrolytic Sleeve	9	168	30.142	6.62778	4.5931
*Pyro Insulation - 1	137	145:						
	137	144	Pyrolytic Sleeve	9	168	18.426	5.77778	4.2336
	145		Pyrolytic Sleeve	9	168	21.137	6.62778	4.2336
Support Stem Liner	146	155:						
	146		Uniloy - A - 286	54	168	20.268	6.4	4.1651
	147	154	Uniloy - A - 286	54	168	18.297	5.77778	3.1651
	155		Uniloy - A - 286	54	168	20.989	6.62778	3.1651
**Support Stem	156	165:						
	156		Uniloy - A - 286	54	168	22.45	6.4	3.9329
	157	164	Uniloy - A - 286	54	168	20.268	5.77778	3.9329
	165		Uniloy - A - 286	54	168	23.249	6.62778	3.9329

*An equivalent Grafoil sleeve thermal conductivity was used which includes the hydrogen gap.

**An equivalent thermal conductivity is used for the Support Stem, H₂ gap, shim material and shim tube.

TABLE 2-- 4 (CONT' D)

Item	Node From	Number Thru	Material Description	Material Index Number	Number of Items	Total Volume Per Node, (in ³)	Axial Length, (in)	Axial Conduction Area Total/Node (in ²)
<u>Core Central Region</u>								
Fuel Elements	92 92	100: 100	Composite Fuel	65	738	1525. 1	5. 77778	263. 959
Unfueled Elements	83 83 91	91: 90	Composite Unfueler ¹ Composite Unfueled	58 58	123 123	196. 39 225. 28	5. 77778 6. 62778	33. 952 33. 952
*Pyro Insulation - 1	56 56 64	64: 63	Pyrolytic Sleeve Pyrolytic Sleeve	9 9	123 123	13. 491 15. 475	5. 77778 6. 62778	3. 0996 3. 0996
Pyro Insulation - 2	65 65 73	73: 72	Pyrolytic Sleeve Pyrolytic Sleeve	9 9	123 123	19. 238 22. 207	5. 77778 6. 62778	3. 3628 3. 3628
*Pyro Insulation - 3	74 74 82	82: 31	Pyrolytic Sleeve Pyrolytic Sleeve	9 9	123 123	17. 553 20. 136	5. 77778 6. 62778	3. 5301 3. 5301
Support Stem Liner	46 46 47 55	55: 54	Uniloy - A - 286 Uniloy - A - 286 Uniloy - A - 286	54 54 54	123 123 123	14. 839 13. 396 15. 367	6. 4 5. 77778 6. 62778	2. 3173 2. 3173 2. 3173
**Support Stem	36 36 37 45	45: 44	Uniloy - A - 286 Uniloy - A - 286 Uniloy - A - 286	54 54 54	123 123 123	16. 437 14. 839 17. 022	6. 4 5. 77778 6. 62778	2. 8795 2. 8795 2. 8795

*An equivalent Grafoil sleeve thermal conductivity was used which includes the hydrogen gap.

**An equivalent thermal conductivity is used for the Support Stem, H₂ gap, shim material and shim tube.

TABLE 2-5
INTERNAL TO SURFACE NODAL CONNECTIONS

Description of Components	Internal Nodes From	Internal Nodes To	Surface Nodes From	Surface Nodes To	Conduction Length, (in)	Surface Area Area/Node, (in ²)
Pressure Vessel to Annulus Side	298	310	3226	3238	0.36	986
Outer Reflector to PV Annulus Side	289	297	3217	3225	0.3	980.
Outer Reflector To Internal Coolant Holes	289	297	3204	3212	0.3	1552.
Outer Reflector to Control Drum Bore Annulus	289	297	3266	3274	0.1	737.
Control Drum to Control Drum Bore Annulus	311	319	3248	3256	0.05	1441.
Control Drum to Control Drum Coolant Holes	311	319	3239	3247	0.05	3380
Inner Reflector to Control Drum Bore Annulus	276	284	3257	3265	0.01	737.
Inner Reflector to Internal Coolant Holes	276	284	3195	3203	0.01	
Aluminum Structure to Coolant Holes	267	275	3186	3194	0.01	1895.
Lateral Support to Coolant Holes	249	251	3177	3179	0.005	315.
	252	254	3180	3182	0.005	221.
	255	256	3183	3184	0.005	243
	257		3185		0.005	70.
Filler Strips to Coolant Holes	240	248	3168	3176	0.061	348
<u>Core Peripheral Region</u>						
a. Fuel to Coolant Holes	222	230	3159	3167	0.02075	8846
b. Support Stem Liner to Support Stem 2nd Pass	176		3149		0.00975	449
	177	184	3150	3157	0.00975	405
	185		3158		0.00975	465
c. Support Stem to Support Stem 2nd Pass	166		3139		0.01414	353
	167	174	3148	3147	0.01414	319
	175		3148		0.01414	366

TABLE 2-5 (CONT'D)

Description of Components	Internal From	Nodes To	Surface From	Nodes To	Conduction Length (in)	Surface Area Area/Node (in ²)
d. Support Stem to Support Stem 1st Pass	166 167 175	174	3129 3130 3138	3137	0.01282 0.01282 0.01282	290 262 301
<u>Core Mid Region</u>						
a. Fuel to Coolant Holes	101	109	3090	3098	0.02075	28501.
b. Support Stem Liner to Support Stem 2nd Pass	146 147 155	154	3099 3100 3108	3107	0.00975 0.00975 0.00975	1300 1174 1347
c. Support Stem to Support Stem 2nd Pass	156 157 165	164	3109 3110 3118	3117	0.01414 0.01414 0.01414	1023 924 1060
d. Support Stem to Support Stem 1st Pass	156 157 165	164	3119 3120 3128	3127	0.01282 0.01282 0.01282	841 759 871
<u>Core Central Region</u>						
a. Fuel to Coolant Holes	92	100	3081	3089	0.02075	24177.
b. Support Stem Liner to Support Stem 2nd Pass	46 47 55	54	3295 3296 3304	3303	0.00975 0.00975 0.00975	952. 860. 986
c. Support Stem to Support Stem 2nd Pass	36 37 45	44	3052 3063 3071	3070	0.01414 0.01414 0.01414	749 677 776

TABLE 2-5 (CONT'D)

Description of Components	Internal Nodes		Surface Nodes		Conduction Length (in)	Surface Area Area/Node (in ²)
	From	To	From	To		
d. Support Stem to Support Stem 1st Pass	36		3052		0.01282	616
	37	44	3053	3060	0.01282	556
	45		3061		0.01282	638
Peripheral Shield to Coolant Holes	332		3287		0.286	491
	333		3288		0.286	1129
	334	336	3289	3291	0.286	2962
	337		3292		0.286	849
Central Shield to Coolant Holes	323		3278		0.10	466
	324		3279		0.175	3030
	325	327	3280	3282	0.175	8624
	328		3283		0.175	2331
Support Plate to Coolant Holes	329	333	3284	3286	0.1	1477
Support Plate to Support Stem FEED	329		3275		0.2	1140
Support Plate to Support Stem Mixing Chamber	330		3276		0.2	3300
Support Plate to Support Stem Bypass	331		3277		0.2	1140
Peripheral Shield to Pressure Vessel Annulus	285		3213		0.06	442.8
	286	288	3214	3216	0.05564	627.7

TABLE 2-6
MAIN NOZZLE HYDRAULIC DATA, (REFERENCE 22)

Flow Node	Developed Length From Tube Inlet-(in)	Flow Area-(in ²)	Hydraulic Diameter-(in)	Effective Surface Area-(in ²)	CL*	CG*	Tube Thickness-(in)
	0**	63.94	0.557				
4				1633.89****	0.0177	0.05	0.028
	10, 15***	65.66	0.581				
5				1461.67	0.0177	0.0495	0.026
	20.92	54.00	0.528				
6				1084.60	0.0177	0.0435	0.023
	31.0	40.61	0.452				
7				590.65	0.0177	0.035	0.020
	38.22	28.08	0.366				
8				371.002	0.0177	0.0258	0.018
	44.39	19.66	0.283				
9				94.19	0.0177	0.0202	0.016
	46.42	17.06	0.253				
10				92.259	0.0177	0.0173	0.014
	48.76	14.26	0.219				

NOTES:

* CG is the coefficient in the simplified Bartz equation for hot gas side heat transfer film correlation, and CL is the coefficient for the cooling tube side heat transfer film correlation.

** Inlet dimension of node.

*** Outlet dimension of node.

****Average dimension within node.

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TABLE 2-6 (CONT'D)

Flow Node	Developed Length From Tube Inlet-(in)	Flow Area-(in ²)	Hydraulic Diameter-(in)	Effective Surface Area-(in ²)	CL*	CG*	Tube Thickness-(in)
	48.76	14.26	0.219				
11				67.807	0.0288	0.0256	0.013
	50.65	7.776	0.186				
12				40.57	0.0295	0.0325	0.013
	51.75	7.776	0.190				
13				91.785	0.0263	0.0310	0.014
	53.95	14.47	0.251				
14				224.12	0.0177	0.0255	0.015
	58.05	21.82	0.326				
15				477.03	0.0177	0.0310	0.016
	64.21	29.16	0.388				
16				412.89	0.0177	0.0460	0.017
	68.33	28.51	0.263				
17				681.83	0.0177	0.0644	0.0175
	74.01	19.87	0.225				
18				630.48	0.0177	0.0846	0.020
	78.81	19.44	0.224				
19				633.344	0.0177	0.875	0.022
	83.61	19.44	0.224				

NOTES:

*CG is the coefficient in the simplified Bartz equation for hot gas side heat transfer film correlation, and CL is the coefficient for the coating tube side heat transfer film correlation.

**Inlet dimension of node.

***Outlet dimension of node.

****Average dimension within node.

TABLE 2-7
DESCRIPTION OF STARTUP AND SHUTDOWN PROCEDURE*
FOR EXTREME "REFERENCE PROFILES" AVAILABLE AT INITIATION OF DESIGN ANALYSES FOR NSS PDR

a. Startup			
PHASE	TIME - SECS	CONDITIONS	CONTROL MODE
Autostart	0	$P_c = 0$ $T_c = 519$ Power = 0 - 4 MW	A dry autostart was assumed such that 4 MW is achieved and the integrated power did not affect material temperatures.
Modified Temperature Conditioning	0 - 25	$P_c = 0 - 2.85$ psia $T_c = 519^\circ\text{R} - 525^\circ\text{R}$ Power = 4 MW (Constant)	Drum control on power to maintain 4 MW. SSCV held at minimum position. Pump Shutoff Valve (PSOV) opened at $t = 0$ seconds.
Bootstrap	25 - 32	$P_c = 2.85 - 60$ psia $T_c = 525 - 1130^\circ\text{R}$ Power = 4 - 132 MW	Open loop profile on power such that the power increases on a 1.6 second period for 7 seconds from an initial power of 4 MW. Pressure was increased exponentially from 2.85 to 60 psia.
Thrust Buildup			
a. Ramp to Rated Temperature	32 - 50 sec	$P_c = 60 - 292.5$ psia $T_c = 1130 - 4250^\circ\text{R}$	Drum control of T_c for a T_c ramp demand of $175^\circ\text{R}/\text{sec}$ ($150^\circ\text{R}/\text{sec} + 25^\circ\text{R}/\text{sec}$). Open loop profile on SSCV (See Note). Linear increase in P_c .
b. Ramp to Rated Pressure	50 - 53 sec	$P_c = 292.5 - 450$ psia $T_c = 4250^\circ\text{R}$ (constant)	Drum control of T_c for a constant T_c demand (4250°R) and a P_c ramp of $+50$ psia/sec. Open loop profile on SSCV (See Note).
Rated Operation	53 - 60 sec	$P_c = 450$ psia $T_c = 4250^\circ\text{R}$	Drum control of T_c for a constant T_c demand and a constant P_c . SSCV position held constant (See Note).
b. Shutdown			
Throttle	600-603.15	$P_c = 450 - 292.5$ $T_c = 4250^\circ\text{R}$ (constant)	Drum control on T_c for a constant T_c demand (4250°R) and P_c ramp of -50 psia/sec. Open loop profile on SSCV (See Note). Rated operation for 10 minutes was assumed prior to $t = 600$ seconds.
Throttle Hold	603.15-643.15	$P_c = 292.5$ $T_c = 4250$	Drum control on T_c for a constant T_c demand and a constant P_c of 292.5. SSCV position constant (See Note).
Temperature Retreat	643.15-680.0	$P_c = 292.5$ - Calculated $T_c = 4250 - 1800^\circ\text{R}$	Open loop ramp on drums at $-10^\circ/\text{sec}$ to 0° . SSCV stepped to minimum position (0% travel). T_c demand ramp of $-175^\circ/\text{sec}$ to 1800°R and held.

NOTE: See Figure 2-16 for composite core and Figure 2-18 for graphite core.

*Reference 6. ()

Table 2-8
NSS Hydraulic and Thermal Channel Uncertainties for TNT-II Model

ECC SPECIFICATION		TNT-II MODEL CHANNEL		ONE STANDARD DEVIATION (Post Engine Qualification), % OF NOM.				
NO.	TITLE	CHANNEL NO.	CHANNEL NAME	AREA	CL _{IN}	CL _{OUT}	H(1)	f(1)
677558	Cluster Hardware	15,16,17	SS Pass 1	0.1	3.33	3.33	10.	3.33
		18,19,20	SS Pass 2	0.1	3.33	3.33	10.	3.33
677559	Reflector Assembly	10	PV Annulus	10.0	3.33	3.33	10.	3.33
		8, 9	Inner and Outer Refl.	1.0	3.33	3.33	10.	3.33
		11	Control	1.0	3.33	3.33	10.	3.33
		12	Drum Bore Gap	1.0	3.33	3.33	10.	3.33
		7	Aluminum Structure	.66	3.33	3.33	10.	3.33
		32	Lateral Support	(5)	(5)	(5)	10.	3.33
677561	Support Plate and Plena	21	SP Mixing Chamber	2.0	5.0	5.0	10.	10
		27	SP Axial Flow	1.0	3.33	3.33	10.	3.33
		3	SP Feed	2.0	(4)	5.0	10. ⁽³⁾	10 ⁽³⁾
		4	SP Bypass	2.0	3.33	5.0	10. ⁽³⁾	10 ⁽³⁾
677562	Internal Shield	22	Peripheral Shield	2.0	3.33	3.33	10. ⁽²⁾	3.33 ⁽²⁾
		23	Shield-PV Annulus	4.0	3.33	3.33	10. ⁽²⁾	3.33 ⁽²⁾
		26	Central Shield	2.0	3.33	3.33	10.	3.33
677564	Core Periphery	31	Filler Strips	2.0	3.33	3.33	10.	3.33
677566	Fuel Elements	28,29,30	Central Mid and Peripheral Fuel	0.1	0.5	0.5	3.33	1.

- (1) For each channel, the heat transfer coefficient (H) and the friction factor (f) one standard deviations are assumed to be dependent; i.e., for Monte Carlo analysis the same random number index will be used for both (H) and (f).
- (2) The heat transfer coefficients and friction factors for channels 12 and 13 are assumed to be dependent.
- (3) The heat transfer coefficients and friction factors for channels 3 and 6 are assumed to be dependent.
- (4) This loss coefficient represents the SSCV. Zero uncertainty is assumed since the SSCV will be controlled to maintain constant control drum bank position.
- (5) The special treatment of these parameters is described in the text.

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~~1954~~

Table 2-9
Nuclear Power Uncertainties

<u>Group No.</u>	<u>Component</u>	<u>One Standard Deviation %*</u> <u>(Post Engine Qualification)</u>
1	Fuel, Central Region	0.7
2	Unfueled Element, Central Region	5.
2	Pyrographite Insulation, Central Region	5.
2	Support Stem Assembly, " "	3.5
1	Fuel, Mid Region	0
2	Unfueled Element, Mid Region	5.
2	Pyrographite Insulation, " "	5.
2	Support Stem Assembly, " "	3.5
1	Fuel, Peripheral Region	1.2
2	Unfueled Element, Peripheral Region	5.
2	Pyrographite Insulation, " "	5.
2	Support Stem Assembly, " "	3.5
3	Filler Strips and Core Wrapper	5.
3	Lateral Support and Outer Foil	5.
3	Aluminum Structure	3.5
3	Inner Be Reflector	5.5
3	Outer Be Reflector	5.5
3	Pressure Vessel	6.
4	Control Drum and Vane	5.5
5	Support Plate	6.
6	Central Shield	9
7	Peripheral Shield	12

*Percent of nominal value.

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Table 2-10
Engine Subsystem Uncertainties

<u>Group</u>	<u>Parameter</u>	<u>One Standard Deviation (Post Engine Qualification)</u>
1	Turbine Efficiency	0.73%**
1	Pump Efficiency	0.34%
1	Nozzle Throat Area	0.062%
1	Turbine Nozzle Area	0.8%
1	Bearing Coolant Flow	0.09 lb/sec
1	Tank Pressure	1.3 psi
1	Tank Enthalpy	1.44 btu/lb
2	Nozzle Tube Area	1.0%
2	Nozzle Tube Inlet Loss Coefficient	4.0%
2	Nozzle Tube Exit Loss Coefficient	4.0%
2	Nozzle Tube Friction Factor	4.0%
2	Nozzle Tube Film Coefficient	3.0%
2	Nozzle Tube Hot Side Film Coefficient	3.0%

* Uncertainties for Group No. 1 parameters were directly specified by ANSC. Uncertainties for Group No. 2 parameters were estimated to match the nozzle tube ΔT and ΔP uncertainties specified by ANSC.

** Percent of nominal value.

TABLE 2-11
NOMINAL VALUE WITH ONE STANDARD DEVIATION***
BASED ON 30 CALCULATIONS FOR COMPOSITE CORE
RATED PERFORMANCE, START OF LIFE, NORMAL MODE

	<u>Location Description</u>	<u>W - LB/SEC</u>	<u>P - PSIA</u>	<u>T - °R</u>
1**	Pump Outlet (Each)	45.6/0.32***	1363/12.4	58/0.55
2*	SSCA Inlet	7.1/0.58	1356/12.4	58/0.55
3	SSA Inlet Plenum	7.1/0.58	1115/9.8	72/1.2
4	SSA Feed Inlet Line at P/V Dome	7.1/0.58	1116/9.8	60/0.51
5*	SSA Bypass Line at P/V Dome	3.2/0.067	1074/7.1	60/0.51
6	SSA Outlet After Mixing	10.3/0.60	1074/7.1	542/19.3
7*	Reflector Inlet Plenum	80.9/0.71	1135/7.6	192/3.4
8	Reflector Outlet	73.9/0.61	1074/7.0	262/4.8
9	Reflector Pressure Vessel Annulus Outlet	7.0/0.15	1074/7.1	242/5.1
10	Peripheral Shield Inlet Plenum	91.2/0.46	1074/7.1	290/5.1
11	Peripheral Shield Outlet	66.5/0.67	1064/7.0	292/5.1
12	Peripheral Shield P/V Annulus Outlet	24.7/0.56	1064/7.0	293/5.1
13*	NSS Exit to Turbine	91.2/0.46	1064/7.0	292/5.1
14*	NSS Inlet From Turbine	91.2/0.46	667/3.2	273/4.9
15	Central Shield Inlet Plenum	91.2/0.46	640/2.9	273/4.9
16	Support Plate Inlet Plenum	91.2/0.46	630/2.9	276/4.8
17	Core Inlet Plenum	91.2/0.46	618/2.7	281/4.8
18	Core Central Region Fuel Channel Outlet	37.1/0.21	450/1.8	4309/32.

*NSS and engine interface state point.

**Engine data include for reference only.

***The one standard deviation represents the estimated variations after the completion of the engine qualification program. These standard deviations do not account for any possible non-random errors in the TNT-II model (including all equations and input parameters) of the reference design which would cause biases in the nominal values of these parameters.

TABLE 2-11 (Continued)

	<u>Location Description</u>	<u>W - LB/SEC</u>	<u>P - PSIA</u>	<u>T - °R</u>
19	Core Mid Region Fuel Channel Outlet	41.8/0.28	450/1.8	4302/35.
20	Core Peripheral Region Fuel Channel Outlet	10.3/0.074	450/1.8	4300/60.
21	Filler Strip Channel Outlet	1.4/0.066	450/1.8	1298/72.
22	Lateral Support Channel Outlet	0.6/0.22	450/1.8	1404/77.
23*	Core Outlet Chamber	91.2/0.46	450/1.8	4250/19.1
	Calculation Run Reference		160, 10/14/70	

*NSS and engine interface state point.

TABLE 2-12

NOMINAL VALUE WITH ONE STANDARD DEVIATION***
 BASED ON 30 CALCULATIONS FOR COMPOSITE CORE,
 STEADY STATE PERFORMANCE, START OF LIFE, SINGLE TURBOPUMP OPERATION

	<u>Location Description</u>	<u>W - LB/SEC</u>	<u>P - PSIA</u>	<u>T - °R</u>
1**	Pump Outlet (Each)	73.1/0.31***	1310/10.4	60/0.53
2*	SSCA Inlet	7.5/0.56	1293/10.2	60/0.53
3	SSA Inlet Plenum	7.5/0.56	1160/9.2	74/1.2
4	SSA Feed Inlet Line at P/V Dome	7.5/0.56	1162/9.2	61/0.51
5*	SSA Bypass Line at P/V Dome	2.5/0.053	1122/8.1	62/0.50
6	SSA Outlet After Mixing	10.0/0.57	1118/8.1	537/18.2
7*	Reflector Inlet Plenum	63.0/0.67	1158/8.2	205/3.5
8	Reflector Outlet	57.5/0.59	1118/8.1	281/5.3
9	Reflector Pressure Vessel Annulus Outlet	5.5/0.13	1118/8.1	257/5.1
10	Peripheral Shield Inlet Plenum	73.1/0.44	1118/8.1	312/5.7
11	Peripheral Shield Outlet	53.1/0.58	1111/8.1	313/5.7
12	Peripheral Shield P/V Annulus Outlet	20.0/0.45	1111/8.1	315/5.7
13*	NSS Exit to Turbine	73.1/0.44	1111/8.1	314/5.7
14*	NSS Inlet From Turbine	72.9/0.44	543/3.0	294/5.5
15	Central Shield Inlet Plenum	72.9/0.44	520/2.8	294/5.4
16	Support Plate Inlet Plenum	72.9/0.44	511/2.8	297/5.4

*NSS and engine interface state point.

**Engine data included for reference only.

***The one standard deviation represents the estimated variations after the completion of the engine qualification program. These standard deviations do not account for any possible non-random errors in the TNT-II model (including all equations and input parameters) of the reference design which would cause biases in the nominal values of the parameters.

TABLE 2-12 (Continued)

	<u>Location Description</u>	<u>W - LB/SEC</u>	<u>P - PSIA</u>	<u>T - °R</u>
17	Core Inlet Plenum	72.9/0.44	502/2.6	301/5.3
18	Core Central Region Fuel Channel Outlet	29.7/0.19	360/1.9	4303/32
19	Core Mid Region Fuel Channel Outlet	33.4/0.71	360/1.9	4300/27
20	Core Peripheral Region Fuel Channel Outlet	8.2/0.065	360/1.9	4277/53
21	Filler Strip Channel Outlet	1.1/0.050	360/1.9	1384/72
22	Lateral Support Channel Outlet	0.5/0.017	360/1.9	1410/76
23*	Core Outlet Chamber	72.9/0.44	360/1.9	4250/19.1
	Calculation Run Reference		119, 10/31/70	

*NSS and engine interface state point.

TABLE 2-13
 NOMINAL VALUE WITH ONE STANDARD DEVIATION***
 BASED ON 30 CALCULATIONS FOR COMPOSITE CORE,
 THROTTLE HOLD PERFORMANCE, END OF LIFE, NORMAL MODE

	<u>Location Description</u>	<u>W - LB/SEC</u>	<u>P - PSIA</u>	<u>T - °R</u>
1**	Pump Outlet (Each)	29. 6/0. 29***	790/7. 7	51/0. 51
2*	SSCA Inlet	14. 1/0. 67	787/7. 7	51/0. 51
3	SSA Inlet Plenum	14. 1/0. 67	752/11. 6	61/0. 91
4	SSA Feed Inlet Line at P/V Dome	14. 1/0. 67	756/11. 6	51/0. 51
5*	SSA Bypass Line at P/V Dome	2. 3/0. 047	651/5. 0	52/0. 48
6	SSA Outlet After Mixing	16. 3/0. 66	645/5. 0	359/13. 0
7*	Reflector Inlet Plenum	39. 0/0. 70	681/5. 3	225/4. 7
8	Reflector Outlet	35. 1/0. 62	645/4. 9	322/7. 1
9	Reflector Pressure Vessel Annulus Outlet	3. 9/0. 10	645/5. 0	288/6. 4
10	Peripheral Shield Inlet Plenum	59. 2/0. 41	645/5. 0	329/2. 1
11	Peripheral Shield Outlet	42. 8/0. 50	637/4. 9	331/6. 8
12	Peripheral Shield P/V Annulus Outlet	16. 4/0. 38	637/4. 9	333/6. 8
13*	NSS Exit to Turbine	59. 2/0. 41	637/4. 9	331/6. 8
14*	NSS Inlet From Turbine	59. 2/0. 41	449/3. 1	319/6. 3
15	Central Shield Inlet Plenum	59. 2/0. 41	429/2. 9	319/6. 3
16	Support Plate Inlet Plenum	59. 2/0. 41	421/2. 9	322/6. 5

*NSS and engine interface state point.

**Engine data included for reference only.

***The one standard deviation represents the estimated variations after the completion of the engine qualification program. These standard deviations do not account for any possible non-random errors in the TNT-II model (including all equations and input parameters) of the reference design which would cause biases in the nominal values of the parameters.

TABLE 2-13 (Continued)

	<u>Local Description</u>	<u>W - LB/SEC</u>	<u>P - PSIA</u>	<u>T - °R</u>
17	Core Inlet Plenum	59.2/0.41	413/2.7	324/6.5
18	Core Central Region Fuel Channel Outlet	24.1/0.18	293/1.8	4337/32
19	Core Mid Region Fuel Channel Outlet	37.1/0.21	293/1.8	4296/26
20	Core Peripheral Region Fuel Channel Outlet	6.7/0.059	293/1.8	4170/51
21	Filler Strip Channel Outlet	0.9/0.039	293/1.8	1439/72.
22	Lateral Support Channel Outlet	0.4/0.014	293/1.8	1410/74
23*	Core Outlet Chamber	59.2/0.41	293/1.8	4250/19.1
	Calculation Run Reference		118, 10/31/70	

*NSS and engine interface state point.

TABLE 2-14

CORRESPONDENCE BETWEEN OPERATING CONDITIONS USED TO COMPUTE
NORMALIZING FACTORS AND OPERATING CONDITIONS NORMALIZED

Operating Conditions Used to Compute Normalizing Factors	Operating Conditions That Were Normalized
1. Composite Core, Rated Performance, Start of Life, Normal Mode	1.1 Composite Core, Rated Performance, End of Life, Normal Mode 1.2 Graphite Core, Rated Performance, Start of Life, Normal Mode 1.3 Graphite Core, Rated Performance, End of Life, Normal Mode
2. Composite Core, Steady State Performance, Start of Life, Single Turbopump Operation	2.1 Composite Core, Steady State Performance, End of Life, Single Turbopump Operation 2.2 Graphite Core, Steady State Performance, Start of Life, Single Turbopump Operation 2.3 Graphite Core, Steady State Performance, End of Life, Single Turbopump Operation
3. Composite Core, Throttle Hold Performance, End of Life, Normal Mode	3.1 Composite Core, Throttle Hold Performance, Start of Life, Normal Mode 3.2 Graphite Core, Throttle Hold Performance, Start of Life, Normal Mode 3.3 Graphite Core, Throttle Hold Performance, End of Life, Normal Mode

TABLE 2-15

COMPARISON BETWEEN TNT-II AND PAM ONE STANDARD DEVIATION ***
FOR COMPOSITE CORE, RATED PERFORMANCE, START OF LIFE, NORMAL MODE

Location Description	W - LB/SEC		P - PSIA		T - °R	
	TNT-II	PAM	TNT-II	PAM	TNT-II	PAM
1** Pump Outlet (Each)	0.32	0.33	12.4	10.2	0.55	0.66
2* SSICA Inlet	0.58	0.55	12.4	10.2	0.55	0.66
3 SSA Inlet Plenum	0.58	0.55	9.8	8.5	1.2	1.8
4 SSA Feed Inlet Line at P/V Dome	0.58	0.55	9.8	8.5	0.51	0.63
5* SSA by Pass Line at P/V Dome	0.067	0.073	7.1	6.7	0.51	0.61
6 SSA Outlet After Mixing	0.60	0.55	7.1	6.7	19.3	19.6
7* Reflector Inlet Plenum	0.71	0.82	7.6	7.3	3.4	3.4
8 Reflector Outlet	0.61	0.74	7.0	6.7	4.8	5.0
9 Reflector Pressure Vessel Annulus Outlet	0.15	0.17	7.1	6.7	5.1	5.2
10 Peripheral Shield Inlet Plenum	0.46	0.47	7.1	6.7	5.1	6.3
11 Peripheral Shield Outlet	0.67	0.56	7.0	6.7	5.1	6.3
12 Peripheral Shield P/V Annulus Outlet	0.56	0.39	7.0	6.7	5.1	6.3
13* NSS Exit to Turbine	0.46	0.46	7.0	6.7	5.1	6.3
14* NSS Inlet from Turbine	0.46	0.46	3.2	3.7	4.9	6.3
15 Central Shield Inlet Plenum	0.46	0.46	2.9	3.3	4.9	6.3
16 Support Plate Inlet Plenum	0.46	0.46	2.9	3.2	4.8	6.3

TABLE 2-15 (Cont'd)

	Location Description	W - LB/SEC		P - PSIA		T - °R	
		TNT-II	PAM	TNT-II	PAM	TNT-II	PAM
17	Core Inlet Plenum	0.46	0.46	2.7	3.2	4.8	6.3
18	Core Central Region Fuel Channel Outlet	0.21	---	2.0	---	32.	---
19	Core Mid Region Fuel Channel Outlet	0.28	---	2.0	---	35.	---
20	Core Peripheral Region Fuel Channel Outlet	0.074	---	2.0	---	60.	---
21	Filler Strip Channel Outlet	0.066	---	2.0	---	72.	---
22	Lateral Support Channel Outlet	0.22	---	2.0	---	77.	---
23*	Core Outlet Chamber	0.46	0.46	2.0	2.0	17.3	17.3

* NSS and engine interface state point

** Engine data included for reference only

*** The one standard deviation represents the estimated variations after the completion of the engine qualification program. These standard deviations do not account for any possible non random errors in the TNT model (including all equations and input parameters) of the reference design which would cause biases in the nominal values of these parameters.

TABLE 2-16
COMPARISON BETWEEN TNT-II AND PAM ONE STANDARD DEVIATION ***
FOR COMPOSITE CORE, STEADY STATE PERFORMANCE,
START OF LIFE, SINGLE TURBOPUMP OPERATION

Location Description	W - LB/SEC		P - PSIA		T - °R	
	TNT-II	PAM	TNT-II	PAM	TNT-II	PAM
1** Pump Outlet (Each)	0.31	0.32	10.4	12.3	0.53	0.66
2* SSA Inlet	0.56	0.52	10.2	12.1	0.53	0.66
3 SSA Inlet Plenum	0.56	0.52	9.2	9.8	1.2	1.3
4 SSA Feed Inlet Line at P/V Dome	0.56	0.52	9.2	9.8	0.51	0.64
5* SSA by Pass Line at P/V Dome	0.053	0.061	8.1	10.5	0.50	0.62
6 SSA Outlet After Mixing	0.57	0.52	8.1	10.6	18.2	18.5
7* Reflector Inlet Plenum	0.67	0.78	8.2	10.8	3.5	3.9
8 Reflector Outlet	0.59	0.70	8.1	10.6	5.3	5.0
9 Reflector Pressure Vessel Annulus Outlet	0.13	0.14	8.1	10.6	5.1	5.4
10 Peripheral Shield Inlet Plenum	0.44	0.45	8.1	10.6	5.7	6.8
11 Peripheral Shield Outlet	0.58	0.49	8.1	10.6	5.7	6.8
12 Peripheral Shield P/V Annulus Outlet	0.45	0.31	8.1	10.6	5.7	6.8
13* NSS Exit to Turbine	0.44	0.44	8.1	10.6	5.7	6.8
14* NSS Inlet from Turbine	0.44	0.44	3.0	3.5	5.5	6.7
15 Central Shield Inlet Plenum	0.44	0.44	2.8	3.2	5.4	6.6
16 Support Plate Inlet Plenum	0.44	0.44	2.8	3.1	5.4	6.7

TABLE 2-16

	Location Description	W - LB/SEC		P - PSIA		T - °R	
		TNT-II	PAM	TNT-II	PAM	TNT-II	PAM
17	Core Inlet Plenum	0.44	0.44	2.6	3.1	5.3	6.7
18	Core Central Region Fuel Channel Outlet	0.19	---	2.0	---	32.	---
19	Core Mid Region Fuel Channel Outlet	0.71	---	2.0	---	27.	---
20	Core Peripheral Region Fuel Channel Outlet	0.065	---	2.0	---	53.	---
21	Filler Strip Channel Outlet	0.050	---	2.0	---	72.	---
22	Lateral Support Channel Outlet	0.017	---	2.0	---	76.	---
23*	Core Outlet Chamber	0.44	0.44	2.0	2.0	17.3	17.3

* NSS and engine interface state point

** Engine data included for reference only

*** The one standard deviation represents the estimated variations after the completion of the engine qualification program. These standard deviations do not account for any possible non random errors in the TNT model (including all equations and input parameters) of the reference design which would cause biases in the nominal values of these parameters.

TABLE 2-17
COMPARISON BETWEEN TNT-II AND PAM ONE STANDARD DEVIATION ***
FOR COMPOSITE CORE, THROTTLE HOLD PERFORMANCE,
END OF LIFE, NORMAL MODE

	Location Description	W - LB/SEC		P - PSIA		T - °R	
		TNT-II	PAM	TNT-II	PAM	TNT-II	PAM
1**	Pump Outlet (Each)	0.29	0.31	7.7	7.5	0.51	0.61
2*	SSCA Inlet	0.67	0.60	7.7	7.4	0.51	0.61
3	SSA Inlet Plenum	0.67	0.60	11.6	10.7	0.91	0.89
4	SSA Feed Inlet Line at P/V Dome	0.67	0.60	11.6	10.7	0.51	0.62
5*	SSA by Pass Line at P/V Dome	0.047	0.57	5.0	5.5	0.48	0.58
6	SSA Outlet After Mixing	0.66	0.59	5.0	5.4	13.0	14.0
7*	Reflector Inlet Plenum	0.70	0.82	5.3	5.8	4.7	5.8
8	Reflector Outlet	0.62	0.74	4.9	5.3	7.1	7.2
9	Reflector Pressure Vessel Annulus Outlet	0.10	0.11	5.0	5.4	6.4	7.6
10	Peripheral Shield Inlet Plenum	0.41	0.44	5.0	5.4	2.1	7.9
11	Peripheral Shield Outlet	0.50	0.44	4.9	5.4	6.8	7.9
12	Peripheral Shield P/V Annulus Outlet	0.38	0.26	4.9	5.4	6.8	7.9
13*	NSS Exit to Turbine	0.41	0.43	4.9	5.4	6.8	7.9
14*	NSS Inlet from Turbine	0.41	0.43	3.1	3.4	6.3	7.5
15	Central Shield Inlet Plenum	0.41	0.43	2.9	3.1	6.3	7.5
16	Support Plate Inlet Plenum	0.41	0.43	2.9	3.0	6.5	7.5

TABLE 2-17 (Cont'd)

	Location Description	W - LB/SEC		P - PSIA		T - °R	
		TNT-II	PAM	TNT-II	PAM	TNT-II	PAM
17	Core Inlet Plenum	0.41	0.43	2.7	3.0	6.5	7.4
18	Core Central Region Fuel Channel Outlet	0.18	---	2.0	---	32.	---
19	Core Mid Region Fuel Channel Outlet	0.21	---	2.0	---	26.	---
20	Core Peripheral Region Fuel Channel Outlet	0.059	---	2.0	---	51.	---
21	Filler Strip Channel Outlet	0.039	---	2.0	---	72.	---
22	Lateral Support Channel Outlet	0.014	---	2.0	---	74.	---
23*	Core Outlet Chamber	0.41	0.43	2.0	2.0	17.3	17.3

* NSS and engine interface state point

** Engine data included for reference only

*** The one standard deviation represents the estimated variations after the completion of the engine qualification program. These standard deviations do not account for any possible non random errors in the TNT model (including all equations and input parameters) of the reference design which would cause biases in the nominal values of these parameters.

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Figure 2-1A. Thermal and Fluid Environment Drawing (939J746) Sheet 1 of 7,
NSS Plenum Location Number Designation

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EVENTS		TEMPERATURE CONDITIONING WITH FLOW INITIATION 中 央 系 统			INITIATION OF BOOTSTRAP			INITIATION OF THRUST BUILDUP			THROTTLE POINT DURING THRUST BUILDUP			STEADY STATE PERFORMANCE AT RATED CONDITIONS			THROTTLE HOLD PERFORMANCE			TERMINATION OF TEMPERATURE RETREAT			EARLY PERIOD OF PUMP TAILOFF (80 SECONDS AFTER INITIATION OF SHUTDOWN)					
LOCATION DESCRIPTION		A			B			C			D			E			F			G			H					
		W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R			
1*	PUMP OUTLET (EACH)	0.7	30.0	40	0.7	29.9	40	13.6	263	44	29.7	802	51	45.6±1.0	1363±38.1	58±1.7	29.6±0.89	808±24.5	51±1.5	23.6	441	46	4.4	80	41			
2	SSCA INLET	0.2	29.9	41	0.2	29.9	40	1.9	262	44	10.1	799	51	7.1±1.8	1356±38.0	58±1.7	10.2±1.9	805±24.4	51±1.5	2.5	439	46	0.7	80	41			
3	SSA INLET PLENUM	0.2	29.1	41	0.2	29.6	54	1.9	229	53	10.1	721	62	7.1±1.8	1115±30.1	72±3.8	10.2±1.9	718±32.8	63±3.2	2.5	382	60	0.7	76	49			
4	SSA FEED INLET LINE AT P/V DOME	0.2	29.1	41	0.2	29.6	40	1.9	229	44	10.1	729	53	7.1±1.8	1116±30.1	60±1.6	10.2±1.9	729±32.8	52±1.5	2.5	383	47	0.7	76	41			
5*	SSA BYPASS LINE AT P/V DOME	0.07	26.9	40	0.1	27.7	41	1.3	218	45	2.3	651	53	3.2±0.21	1079±21.7	60±1.6	2.4±0.15	693±15.4	53±1.5	1.7	360	47	0.8	63	41			
6	SSA OUTLET AFTER MIXING	0.3	26.4	437	0.3	27.5	405	3.2	217	318	12.4	646	107	10.3±1.8	1074±21.7	542±59.2	12.6±1.9	648±15.3	434±45.8	4.2	358	456	1.5	62	318			
7*	REFLECTOR INLET PLENUM	1.1	27.6	313	1.1	28.8	165	23.9	249	63	46.8	683	209	80.9±2.2	1135±23.1	192±10.3	46.6±2.0	687±16.4	213±12.6	42.8	385	83	6.5	70	101			
8	REFLECTOR OUTLET	1.0	26.4	514	1.0	27.5	526	20.9	217	417	42.9	646	299	73.9±1.9	1074±21.3	262±14.8	42.4±1.8	648±15.3	304±18.7	39.1	358	206	5.7	62	264			
9	REFLECTOR PRESSURE VESSEL ANNULUS OUTLET	0.1	26.4	534	0.1	27.5	503	3.0	217	260	3.9	646	279	7.0±0.46	1074±22.7	242±15.7	4.2±0.31	648±15.3	272±17.1	3.7	358	176	0.8	62	199			
10	PERIPHERAL SHIELD INLET PLENUM	1.3	26.4	514	1.4	27.5	498	27.1	217	386	59.3	646	299	81.2±1.4	1074±22.7	290±15.6	59.2±1.3	648±15.3	328±20.6	46.9	358	206	8.8	62	269			
11	PERIPHERAL SHIELD OUTLET	0.8	26.2	527	1.0	27.2	518	18.9	210	420	42.9	639	299	66.5±2.0	1064±21.5	292±15.6	41.8±1.5	639±15.0	330±20.6	33.4	352	225	6.2	60	265			
12	PERIPHERAL SHIELD P/V ANNULUS OUTLET	0.5	26.2	523	0.4	27.2	517	8.2	210	414	16.3	639	299	24.7±1.7	1064±21.5	293±15.7	16.4±1.1	640±15.0	331±20.7	13.5	352	225	2.6	60	271			
13*	NSS EXIT TO TURBINE	1.3	26.2	526	1.4	27.2	517	27.1	210	418	59.3	639	301	81.2±1.4	1064±21.5	292±15.6	59.2±1.3	640±15.0	330±20.6	47.9	352	225	8.8	60	267			
14*	NSS INLET FROM TURBINE	1.3	9.5	530	1.4	8.9	519	27.2	185	417	59.3	446	289	81.2±1.4	667±9.8	273±15.1	59.2±1.3	449±9.4	317±19.4	47.0	245	219	8.9	50	264			
15	CENTRAL SHIELD INLET PLENUM	1.3	8.7	530	1.4	8.0	519	27.2	140	417	59.3	427	289	81.2±1.4	640±9.0	273±15.0	59.2±1.3	429±8.7	317±19.4	47.0	229	219	8.9	47	264			
16	SUPPORT PLATE INLET PLENUM	1.3	8.1	534	1.4	7.3	530	27.2	132	459	59.3	420	289	81.2±1.4	630±9.0	276±14.8	59.2±1.3	421±8.7	320±19.8	47.0	223	244	6.9	45	260			
17	CORE INLET PLENUM	1.3	7.7	534	1.4	6.8	525	27.2	124	462	59.3	413	293	81.2±1.4	618±8.3	281±14.7	59.2±1.3	413±8.2	323±19.9	47.0	215	250	8.9	44	260			
18	CORE CENTRAL REGION FUEL CHANNEL OUTLET	0.6	5.4	536	0.6	2.7	632	11.6	63	1111	23.9	293	4335	37.1±0.63	450±5.0	430±9.9	24.1 —	293 —	4325 —	20.2	149	1722	3.6	28	1773			
19	CORE MID REGION FUEL CHANNEL OUTLET	0.6	5.4	536	0.6	2.7	618	12.4	63	1077	26.9	293	4346	41.8±0.86	450±5.0	430±10.7	27.1 —	293 —	4302 —	21.5	149	1860	4.1	28	1792			
20	CORE PERIPHERAL REGION FUEL CHANNEL OUTLET	0.1	5.4	534	0.1	2.7	566	2.7	63	929	6.8	293	4136	10.3±0.23	450±5.0	4300±183	6.7 —	293 —	4182 —	4.6	149	2278	1.0	28	1849			
21	FILLER STRIP CHANNEL OUTLET	0.02	5.4	536	0.03	2.7	540	0.4	63	548	1.1	293	924	1.4±0.20	450±5.0	298±22.1	0.9 —	29 —	1436 —	0.5	149	1346	0.1	28	1113			
22	LATERAL SUPPORT CHANNEL OUTLET	0.01	5.4	534	0.01	2.7	535	0.2	63	520	0.5	293	827	0.6±0.066	450±5.0	1404±238	0.4 —	293 —	1405 —	0.2	149	1297	0.05	28	1035			
23*	CORE OUTLET CHAMBER	1.3	5.4	536	1.4	2.7	616	27.2	63	1066	59.3	293	4250	81.2±1.4	450±5.0	4250±40	59.2±1.3	293±5.0	4250±40	47.0	149	1833	8.5	28	1780			
	REACTOR TOTAL THERMAL POWER, MW	4			4			278			1190			1510			978			185			54					
	CONTROL DRUMS POSITION, DEGREES	77.0			80.0			85.0			57.9			46.8			46.8			0.0			0.0					
	FEEDBACK REACTIVITY, \$	0.07			-0.03			0.53			1.13			1.08			1.08			.99			-.33					
	REACTIVITY LOSS, \$	0.00			0.00			0.00			0.00			0.00			0.00			0.00			0.00					
	CALCULATION RUN REFERENCE	82 10/10/70			79 10/3/70			79 10/3/70			79 10/3/70			158 10/2/70 160 10/14/70			158 10/2/70			596 10/10/70			596 10/10/70					

NOTE

* NSS AND ENGINE INTERFACE STATE POINT. ** ENGINE DATA INCLUDED FOR REFERENCE ONLY. *** ONE SIDED UNCERTAINTY LIMIT FOR 99% PROPORTION WITH 95% CONFIDENCE BASED ON 30 RANDOM SAMPLE CASES ARE GIVEN. NOTE EITHER THE UPPER(+) OR THE LOWER(-) UNCERTAINTY APPLIES; BOTH UNCERTAINTIES DO NOT APPLY SIMULTANEOUSLY. (THESE) UNCERTAINTIES REPRESENT THE ESTIMATED VARIATIONS AFTER THE COMPLETION OF THE ENGINE QUALIFICATION PROGRAM.

*** EVENT A IS AT TIME = 1.0 SECONDS AFTER STARTUP. AT TIME = 0 THE NSS ENVIRONMENT WAS ASSUMED AT 532°R.

Figure 2-1B. Thermal and Fluid Environment Data (2-12-70) Set 2 of 7, Composite Core, Start of Life, Normal Mode Operation

EVENTS	TEMPERATURE CONDITIONING WITH FLOW INITIATION ***			INITIATION OF BOOTSTRAP			INITIATION OF THRUST BUILDUP			THROTTLE POINT DURING THRUST BUILDUP			STEADY STATE PERFORMANCE AT RATED CONDITIONS			THROTTLE HOLD PERFORMANCE ***			TERMINATION OF TEMPERATURE RETREAT			EARLY PERIOD OF PUMP TAILOFF (80 SECONDS AFTER INITIATION OF SHUTDOWN)		
	A			B			C			D			E			F			G			H		
LOCATION DESCRIPTION	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R
1* PUMP OUTLET (EACH)	0.7	30.0	40	0.7	30.0	40	13.6	263	44	23.8	783	51	43.6 ± 0.98	1342 ± 36.4	57 ± 1.7	23.6 ± 0.89	790 ± 23.6	51 ± 1.5	17.9	331	45	3.5	65	41
2 SSCA INLET	0.2	29.9	41	0.2	30.0	40	1.9	263	44	14.2	780	51	18.9 ± 2.1	1336 ± 36.4	58 ± 1.7	14.1 ± 2.0	787 ± 23.6	51 ± 1.5	2.1	330	45	0.6	65	41
3 SSA INLET PLENUM	0.2	29.1	41	0.3	29.6	41	1.9	229	53	14.2	744	61	10.9 ± 2.1	1135 ± 31.7	70 ± 3.0	14.1 ± 2.0	752 ± 35.6	61 ± 2.8	2.1	292	60	0.6	62	47
4 SSA FEED INLET LINE AT P/V DOME	0.2	29.2	41	0.2	29.6	40	1.9	229	44	14.2	751	52	10.9 ± 2.1	1137 ± 31.7	59 ± 1.6	14.1 ± 2.0	756 ± 35.6	51 ± 1.6	2.1	293	45	0.6	62	41
5* SSA BYPASS LINE AT P/V DOME	0.1	26.9	40	0.1	27.6	41	1.3	218	45	2.2	649	52	3.2 ± 0.21	1076 ± 20.4	60 ± 1.6	2.3 ± 0.14	651 ± 15.3	52 ± 1.5	1.5	270	45	0.8	50	41
6 SSA OUTLET AFTER MIXING	0.3	26.4	437	0.3	27.5	383	3.2	217	318	16.4	643	333	14.1 ± 2.1	1071 ± 20.8	444 ± 43.8	16.3 ± 2.0	645 ± 15.3	359 ± 38.7	3.6	268	455	1.3	49	307
7* REFLECTOR INLET PLENUM	1.1	27.6	313	1.0	28.8	166	20.9	299	63	42.8	676	221	70.6 ± 2.4	1129 ± 22.3	196 ± 11.8	39.0 ± 2.1	681 ± 16.2	225 ± 14.4	32.1	292	81	5.7	57	109
8 REFLECTOR OUTLET	1.0	26.4	514	0.8	27.5	528	17.9	217	417	39.2	643	297	63.9 ± 2.1	1071 ± 20.5	269 ± 15.7	35.1 ± 1.9	645 ± 15.1	322 ± 21.7	29.2	268	235	5.1	49	294
9 REFLECTOR PRESSURE VESSEL ANNULUS OUTLET	0.1	26.4	534	0.2	27.5	318	3.0	217	260	3.6	643	289	6.7 ± 0.44	1071 ± 20.8	250 ± 16.4	3.9 ± 0.31	645 ± 15.3	288 ± 19.7	2.9	268	189	0.6	49	230
10 PERIPHERAL SHIELD INLET PLENUM	1.3	26.4	514	1.4	27.5	472	27.1	217	386	59.3	643	297	91.2 ± 1.4	1071 ± 20.8	294 ± 15.7	59.2 ± 1.3	645 ± 15.3	329 ± 20.8	35.6	268	295	7.0	49	292
11 PERIPHERAL SHIELD OUTLET	0.8	26.2	527	0.9	27.2	507	18.9	210	420	42.9	636	298	66.5 ± 2.0	1061 ± 20.4	295 ± 15.7	42.8 ± 1.5	637 ± 15.0	331 ± 20.8	25.3	263	255	4.9	48	288
12 PERIPHERAL SHIELD P/V ANNULUS OUTLET	0.5	26.2	523	0.5	27.2	497	8.2	210	414	16.3	636	303	24.7 ± 1.7	1061 ± 20.4	297 ± 15.7	16.4 ± 1.1	637 ± 15.0	333 ± 20.9	10.3	263	255	2.1	48	294
13* NSS EXIT TO TURBINE	1.3	26.2	526	1.4	27.2	504	27.1	210	418	59.3	636	299	91.2 ± 1.4	1061 ± 20.4	296 ± 15.7	59.2 ± 1.3	637 ± 15.0	331 ± 20.8	35.6	263	255	7.0	48	290
14* NSS INLET FROM TURBINE	1.3	9.5	530	1.4	9.0	506	27.2	155	417	59.3	445	288	91.2 ± 1.4	668 ± 9.7	276 ± 15.0	59.2 ± 1.3	449 ± 9.5	319 ± 19.4	35.7	190	251	7.1	41	287
15 CENTRAL SHIELD INLET PLENUM	1.3	8.7	530	1.4	8.1	506	27.2	140	417	59.3	427	288	91.2 ± 1.4	640 ± 9.9	276 ± 14.9	59.2 ± 1.3	429 ± 8.8	319 ± 19.4	35.7	178	251	7.1	38	287
16 SUPPORT PLATE INLET PLENUM	1.3	8.1	534	1.4	7.3	526	27.2	132	459	59.3	420	289	91.2 ± 1.4	630 ± 9.9	279 ± 14.9	59.2 ± 1.3	421 ± 8.8	322 ± 19.9	35.7	172	269	7.1	36	284
17 CORE INLET PLENUM	1.3	7.7	534	1.4	6.8	524	27.2	124	462	59.3	413	291	91.2 ± 1.4	619 ± 8.2	283 ± 14.7	59.2 ± 1.3	413 ± 8.3	324 ± 19.9	35.7	166	273	7.1	35	285
18 CORE CENTRAL REGION FUEL CHANNEL OUTLET	0.6	5.4	536	0.6	2.7	647	11.6	63	1100	23.9	293	4334	37.1 -	450 -	4325 -	24.1 ± 0.54	293 ± 5.0	4337 ± 99	15.4	113	1716	2.9	22	1765
19 CORE MID REGION FUEL CHANNEL OUTLET	0.6	5.4	536	0.7	2.7	635	12.4	63	1075	26.9	293	4342	41.8 -	450 -	4288 -	37.1 ± 0.66	293 ± 5.0	4296 ± 80	16.3	113	1871	3.3	22	1787
20 CORE PERIPHERAL REGION FUEL CHANNEL OUTLET	0.1	5.4	534	0.1	2.7	591	2.0	63	944	6.8	293	4156	10.3 -	450 -	4281 -	6.7 ± 0.18	293 ± 5.0	4170 ± 156	3.4	113	2317	0.8	22	1883
21 FILLER STRIP CHANNEL OUTLET	0.02	5.4	536	0.02	2.7	517	0.4	63	548	1.1	293	934	1.4 -	450 -	1299 -	0.9 ± 0.12	293 ± 5.0	1439 ± 219	0.4	113	1387	0.1	22	1136
22 LATERAL SUPPORT CHANNEL OUTLET	0.01	5.4	534	0.01	2.7	512	0.2	63	520	0.5	293	836	0.6 -	450 -	1404 -	0.4 ± 0.042	293 ± 5.0	1410 ± 226	0.2	113	1305	0.04	22	1054
23* CORE OUTLET CHAMBER	1.3	5.4	536	1.4	2.7	633	27.2	63	1062	59.3	293	4250	91.2 ± 1.4	450 ± 5	4250 ± 40	59.2 ± 1.3	293 ± 5.0	4250 ± 40	35.7	113	1840	7.1	22	1778
REACTOR TOTAL THERMAL POWER, MW	4			4			76			1189			1511			979			104			44		
CONTROL DRUMS POSITION, DEGREES	105.6			105.6			111			56.2			46.8			46.8			0.0			0.0		
FEEDBACK REACTIVITY, \$	-1.07			-1.05			-0.53			1.48			1.08			1.08			-0.35			-1.42		
REACTIVITY LOSS, \$	1.00			1.00			1.00			1.00			1.00			1.00			1.00			1.00		
CALCULATION RUN REFERENCE	82 10/10/70			704 9/29/70			152 10/7/70			152 10/7/70			158 10/2/70			158 10/2/70 118 10/31/70			401 10/13/70			401 10/13/70		

NOTE: * NSS AND ENGINE INTERFACE STATE POINT. ** ENGINE DATA INCLUDED FOR REFERENCE ONLY. *** ONE SIDED UNCERTAINTY LIMIT FOR 99% PROPORTION WITH 95% CONFIDENCE BASED ON 30 RANDOM SAMPLE CASES ARE GIVEN.
 *** EVENT (A) IS AT TIME = 1.0 SECONDS AFTER STARTUP.
 AT TIME = 0 THE NSS ENVIRONMENT WAS ASSUMED AT 532°R.
 NOTE EITHER THE UPPER (+) OR THE LOWER (-) UNCERTAINTY APPLIES; BOTH UNCERTAINTIES DO NOT APPLY SIMULTANEOUSLY.
 THESE UNCERTAINTIES REPRESENT THE ESTIMATED VARIATIONS AFTER THE COMPLETION OF THE ENGINE QUALIFICATION PROGRAM.

Figure 2-1C. Thermal and Fluid Environment Drawing (939J746), Sheet 3 of 7, Composite Core, End of Life, Normal Mode Operation

EVENTS	TEMPERATURE CONDITIONING WITH FLOW INITIATION ***			INITIATION OF BOOTSTRAP			INITIATION OF THRUST BUILDUP			THRUSTLE POINT DURING THRUST BUILDUP			STEADY STATE PERFORMANCE AT RATED CONDITIONS			THRUSTLE HOLD PERFORMANCE			TERMINATION OF TEMPERATURE RETREAT			EARLY PERIOD OF PUMP TAILOFF (80 SECONDS AFTER INITIATION OF SHUTDOWN)		
	A			B			C			D			E			F			G			H		
LOCATION DESCRIPTION	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R
1** PUMP OUTLET (EACH)	0.7	30.0	40	0.7	30.0	40	13.3	259	44	29.8	797	51	45.6 ± 0.98	1352 ± 37.9	58 ± 1.6	29.6 ± 0.88	802 ± 24.9	51 ± 1.5	21.7	401	45	3.6	66.0	41
2 SSCA INLET	0.2	29.9	41	0.2	30.0	40	2.0	259	44	10.6	794	51	7.8 ± 2.0	1346 ± 37.8	58 ± 1.6	10.9 ± 2.1	800 ± 24.8	51 ± 1.5	2.6	400	45	0.6	66.0	41
3 SSA INLET PLENUM	0.2	29.1	41	0.2	29.6	41	2.0	227	53	10.6	726	63	7.8 ± 2.0	1116 ± 40.7	72 ± 3.8	10.9 ± 2.1	735 ± 36.0	63 ± 3.2	2.6	351	60	0.6	33.0	47
4 SSA FEED INLET LINE AT P/V DOME	0.2	29.1	41	0.2	29.6	40	2.0	227	44	10.6	730	52	7.8 ± 2.0	1117 ± 40.7	60 ± 1.5	10.9 ± 2.1	738 ± 36.0	52 ± 1.5	2.6	352	46	0.6	63.4	41
5* SSA BYPASS LINE AT P/V DOME	0.07	26.9	40	0.1	27.6	41	1.3	214	45	2.3	647	52	3.2 ± 0.21	1070 ± 21.1	60 ± 1.5	2.4 ± 0.15	650 ± 13.7	53 ± 1.4	1.6	327	411	0.8	51.0	41
6 SSA OUTLET AFTER MIXING	0.3	26.4	437	0.3	27.5	383	3.3	213	333	12.9	642	421	11.0 ± 2.0	1065 ± 21.1	558 ± 61.4	13.3 ± 2.0	644 ± 15.4	440 ± 43.3	4.2	325	454	1.3	50.2	309
7* REFLECTOR INLET PLENUM	1.1	27.6	313	1.1	28.8	166	23.3	245	63	46.3	678	210	80.3 ± 2.3	1127 ± 23.0	192 ± 11.0	45.9 ± 2.2	684 ± 16.9	215 ± 13.0	38.9	351	82	5.9	57.6	106
8 REFLECTOR OUTLET	1.0	26.4	514	1.0	27.5	528	20.4	213	422	42.4	642	309	73.4 ± 2.0	1065 ± 21.0	269 ± 19.6	41.8 ± 1.9	644 ± 15.7	314 ± 24.9	35.5	325	217	5.2	50.2	277
9 REFLECTOR PRESSURE VESSEL ANNULUS OUTLET	0.1	26.4	534	0.2	27.5	318	2.9	213	262	3.9	642	287	6.9 ± 0.46	1065 ± 21.2	254 ± 22.9	4.1 ± 0.33	644 ± 15.4	287 ± 24.9	3.4	325	186	0.7	50.2	224
10 PERIPHERAL SHIELD INLET PLENUM	1.3	26.4	514	1.4	27.5	472	26.6	213	391	59.3	642	309	91.2 ± 1.4	1065 ± 21.2	300 ± 19.4	59.2 ± 1.3	644 ± 15.4	340 ± 25.0	43.1	325	217	7.2	50.2	279
11 PERIPHERAL SHIELD OUTLET	0.8	26.2	527	0.9	27.2	507	18.6	206	424	42.9	634	310	66.5 ± 2.0	1054 ± 20.8	302 ± 19.5	42.8 ± 1.5	640 ± 14.9	342 ± 25.4	30.6	319	237	5.0	40.7	276
12 PERIPHERAL SHIELD P/V ANNULUS OUTLET	0.5	26.2	523	0.5	27.2	497	8.0	206	418	16.3	634	315	24.8 ± 1.7	1054 ± 20.8	304 ± 19.5	16.4 ± 1.2	640 ± 14.9	344 ± 25.2	12.5	319	237	2.2	48.7	282
13* NSS EXIT TO TURBINE	1.3	26.2	526	1.4	27.2	504	26.6	206	422	59.2	634	311	91.2 ± 1.4	1054 ± 20.8	303 ± 19.5	59.2 ± 1.3	640 ± 14.9	342 ± 25.3	43.1	319	237	7.2	48.7	278
14* NSS INLET FROM TURBINE	1.3	9.5	530	1.4	9.0	506	26.7	154	221	59.3	448	299	91.2 ± 1.4	671 ± 10.6	283 ± 18.6	59.2 ± 1.3	452 ± 10.0	329 ± 25.5	43.2	227	232	7.3	41.4	275
15 CENTRAL SHIELD INLET PLENUM	1.3	8.7	530	1.4	8.1	506	26.7	139	421	59.3	429	299	91.2 ± 1.4	642 ± 9.5	283 ± 18.4	59.2 ± 1.3	431 ± 9.0	329 ± 25.5	43.2	212	233	7.3	38.7	275
16 SUPPORT PLATE INLET PLENUM	1.3	8.1	534	1.4	7.3	526	26.7	130	460	59.3	422	300	91.2 ± 1.4	631 ± 9.4	287 ± 18.3	59.2 ± 1.3	423 ± 8.9	333 ± 24.3	43.2	205	257	7.3	37.4	271
17 CORE INLET PLENUM	1.3	7.7	534	1.4	6.8	525	26.7	123	465	59.3	414	303	91.2 ± 1.4	620 ± 8.6	292 ± 18.1	59.2 ± 1.3	414 ± 8.3	336 ± 24.6	43.2	199	261	7.3	36.2	273
18 CORE CENTRAL REGION FUEL CHANNEL OUTLET	0.6	5.4	536	0.6	2.7	650	11.3	63	1142	23.9	293	4345	37.1 —	450 —	4313 —	24.1 —	293 —	4331 —	18.5	137	1727	3.0	23.2	1795
19 CORE MID REGION FUEL CHANNEL OUTLET	0.6	5.4	536	0.7	2.7	635	12.2	63	1107	26.9	293	4346	41.9 —	450 —	4300 —	27.2 —	293 —	4307 —	19.8	137	1849	3.4	23.2	1791
20 CORE PERIPHERAL REGION FUEL CHANNEL OUTLET	0.1	5.4	534	0.1	2.7	589	2.6	63	967	6.8	293	4109	10.2 —	450 —	4304 —	16.7 —	293 —	4151 —	4.2	137	2258	0.8	23.2	1806
21 FILLER STRIP CHANNEL OUTLET	0.02	5.4	536	0.02	2.7	517	0.4	63	542	1.1	293	921	1.4 —	450 —	1288 —	0.9 —	293 —	1421 —	0.4	137	1356	0.1	23.2	1108
22 LATERAL SUPPORT CHANNEL OUTLET	0.01	5.4	534	0.01	2.7	512	0.2	63	513	0.5	293	830	0.6 —	450 —	1406 —	0.4 —	293 —	1400 —	0.2	137	1305	0.04	23.2	1032
23* CORE OUTLET CHAMBER	1.3	5.4	536	1.4	2.7	634	26.7	63	1096	59.3	293	4250	91.2 ± 1.4	450 ± 5.0	4250 ± 40	59.2 ± 1.3	293 ± 5.0	4250 ± 40	43.2	137	1828	7.3	23.2	1783
REACTOR TOTAL THERMAL POWER, MW	4			4			277			1192			1509			978			158			44		
CONTROL DRUMS POSITION, DEGREES	77.0			80.0			88.1			40.5			58.2			58.2			0.00			0.00		
FEEDBACK REACTIVITY, \$	0.07			-0.05			0.40			0.71			0.75			0.76			0.81			-0.48		
REACTIVITY LOSS, \$	0.00			0.00			0.00			0.00			0.00			0.00			0.00			0.00		
CALCULATION RUN REFERENCE	82 10/10/70			82 10/10/70			82 10/10/70			82 10/10/70			381 9/29/70			381 9/29/70			39 9/30/70			39 9/30/70		

NOTE: * NSS AND ENGINE INTERFACE STATE POINT. ** ENGINE DATA INCLUDED FOR REFERENCE ONLY. *** ONE SIDED UNCERTAINTY LIMIT FOR 99% PROPORTION WITH 95% CONFIDENCE BASED ON 30 RANDOM SAMPLE CASES ARE GIVEN.
 *** EVENT A IS AT TIME = 1.0 SECONDS AFTER STARTUP. AT TIME = 0 THE NSS ENVIRONMENT WAS ASSUMED AT 532°R.
 NOTE EITHER THE UPPER (+) OR THE LOWER (-) UNCERTAINTY APPLIES; BOTH UNCERTAINTIES DO NOT APPLY SIMULTANEOUSLY.
 (THESE) UNCERTAINTIES REPRESENT THE ESTIMATED VARIATIONS AFTER THE COMPLETION OF THE ENGINE QUALIFICATION PROGRAM.

AS RUN REFERENCE PROFILES FOR STARTUP & SHUTDOWN
 CHAMBER TEMPERATURE RAMP RATE DURING THRUST BUILDUP AND TEMPERATURE RETREAT = 17.5°R/SEC.
 CHAMBER PRESSURE RAMP RATE FOR THROTTLING = 50 PSI/SEC

Figure 2-1D. Thermal and Fluid Environment Drawing (939J746), Sheet 4 of 7, Graphite Core, Start of Life, Normal Mode Operation

EVENTS		TEMPERATURE CONDITIONING WITH FLOW INITIATION * * * *			INITIATION OF BOOTSTRAP			INITIATION OF THRUST BUILDUP			THRUSTLE POINT DURING THRUST BUILDUP			STEADY STATE PERFORMANCE AT RATED CONDITIONS			THRUSTLE HOLD PERFORMANCE			TERMINATION OF TEMPERATURE RETREAT			EARLY PERIOD OF PUMP TAILOFF (80 SECONDS AFTER INITIATION OF SHUTDOWN)					
LOCATION DESCRIPTION		A			B			C			D			E			F			G			H					
		W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R			
1*	PUMP OUTLET (EACH)	0.7	30.0	40	0.7	30.0	40	13.3	259	44	29.8	775	51	45.6 ± 0.98	1331 ± 56.7	58 ± 1.6	29.6	784	51	17.8	328	45	3.5	65.0	41			
2	SSCA INLET	0.2	29.9	41	0.2	30.0	40	2.0	258	44	15.1	773	51	11.9 ± 2.4	1324 ± 56.6	58 ± 1.6	15.2	781	51	2.2	327	45	0.6	64.8	41			
3	SSA INLET PLENUM	0.2	29.1	41	0.2	29.6	41	2.0	227	53	15.1	753	60	11.9 ± 2.4	1135 ± 41.6	70 ± 3.0	15.2	764	61	2.2	291	60	0.6	62.5	47			
4	SSA FEED INLET LINE AT P/V DOME	0.2	29.1	41	0.2	29.6	40	2.0	227	44	15.1	761	52	11.9 ± 2.4	1137 ± 41.6	59 ± 1.5	15.2	768	51	2.2	292	45	0.6	62.5	41			
5*	SSA BYPASS LINE AT P/V DOME	0.07	26.9	40	0.1	27.6	41	1.3	214	45	2.2	645	52	3.1 ± 0.21	1067 ± 21.1	60 ± 1.5	2.2	649	52	1.5	267	45	0.8	50.0	41			
6	SSA OUTLET AFTER MIXING	0.3	26.4	437	0.3	27.5	383	3.3	213	333	17.3	638	340	15.0 ± 2.4	1061 ± 21.0	445 ± 46.8	17.4	642	360	3.7	266	461	1.3	49.2	315			
7*	REFLECTOR INLET PLENUM	1.1	27.6	313	1.2	28.8	166	23.4	245	63	41.9	671	224	76.2 ± 2.5	1120 ± 22.7	198 ± 12.1	41.8	678	229	31.6	290	82	5.6	56.8	110			
8	REFLECTOR OUTLET	1.0	26.4	514	1.0	27.5	528	20.4	213	422	38.3	638	307	69.7 ± 2.2	1061 ± 20.8	278 ± 20.8	38.1	642	336	28.7	266	246	5.0	49.2	303			
9	REFLECTOR PRESSURE VESSEL ANNULUS OUTLET	0.1	26.4	534	0.2	27.5	318	3.0	213	262	3.6	638	299	6.6 ± 0.45	1061 ± 21.0	262 ± 24.8	3.7	642	305	2.9	266	201	0.6	49.2	249			
10	PERIPHERAL SHIELD INLET PLENUM	1.3	26.4	514	1.4	27.5	472	26.7	213	391	59.3	638	307	91.2 ± 1.4	1061 ± 21.0	303 ± 19.6	59.2	642	341	35.2	266	246	6.9	49.2	301			
11	PERIPHERAL SHIELD OUTLET	0.8	26.2	527	0.9	27.2	507	18.6	206	424	42.9	631	308	66.5 ± 2.0	1051 ± 20.6	305 ± 19.7	42.8	634	343	24.9	260	264	4.8	47.5	297			
12	PERIPHERAL SHIELD P/V ANNULUS OUTLET	0.5	26.2	523	0.5	27.2	497	8.0	206	418	16.3	631	313	24.8 ± 1.7	1051 ± 20.6	307 ± 19.7	16.4	634	345	10.3	260	264	2.1	47.5	304			
13*	NSS EXIT TO TURBINE	1.3	26.2	526	1.4	27.2	504	26.7	206	422	59.3	631	309	91.2 ± 1.4	1051 ± 20.6	306 ± 19.7	59.2	634	344	35.2	260	264	6.9	47.5	299			
14*	NSS INLET FROM TURBINE	1.3	9.5	530	1.4	9.0	506	26.8	154	420	59.3	447	298	91.2 ± 1.4	672 ± 10.8	287 ± 18.8	59.2	452	331	35.3	189	261	7.0	40.4	296			
15	CENTRAL SHIELD INLET PLENUM	1.3	8.7	530	1.4	8.1	506	26.8	139	420	59.3	429	298	91.2 ± 1.4	643 ± 9.8	287 ± 18.7	59.2	431	331	35.3	177	261	7.0	37.6	296			
16	SUPPORT PLATE INLET PLENUM	1.3	8.1	534	1.4	7.3	526	26.8	130	460	59.3	421	298	91.2 ± 1.4	632 ± 9.7	290 ± 18.6	59.2	423	334	35.3	171	278	7.0	36.1	293			
17	CORE INLET PLENUM	1.3	7.7	534	1.4	6.8	524	26.8	123	465	59.3	414	301	91.2 ± 1.4	620 ± 8.8	294 ± 18.3	59.2	414	337	35.3	165	283	7.0	34.9	295			
18	CORE CENTRAL REGION FUEL CHANNEL OUTLET	0.6	5.4	536	0.6	2.7	647	11.4	63	1129	23.9	293	4353	37.0 —	450 —	4333 —	24.1	293	4346	15.2	112	1726	2.9	21.9	1782			
19	CORE MID REGION FUEL CHANNEL OUTLET	0.6	5.4	536	0.7	2.7	635	12.2	63	1106	27.1	293	4335	41.9 —	450 —	4292 —	27.2	293	4299	16.1	112	1865	3.3	21.9	1787			
20	CORE PERIPHERAL REGION FUEL CHANNEL OUTLET	0.1	5.4	534	0.1	2.7	591	2.6	63	983	6.8	293	4117	10.2 —	450 —	4239 —	6.7	293	4131	3.4	112	2299	0.8	21.9	1846			
21	FILLER STRIP CHANNEL OUTLET	0.02	5.4	536	0.02	2.7	517	0.4	63	523	1.1	293	930	1.4 —	450 —	1280 —	0.9	293	1425	0.3	112	1399	0.1	21.9	1140			
22	LATERAL SUPPORT CHANNEL OUTLET	0.01	5.4	534	0.01	2.7	512	0.2	63	513	0.5	293	839	0.6 —	450 —	1399 —	0.4	293	1407	0.2	112	1322	0.04	21.9	1060			
23*	CORE OUTLET CHAMBER	1.3	5.4	536	1.4	2.7	634	26.8	63	1091	59.3	293	4250	91.2 ± 1.4	450 ± 5.0	4250 ± 40.0	59.2	293	4250	35.3	112	1840	7.0	21.9	1781			
	REACTOR TOTAL THERMAL POWER, MW	4			4			276			1192			1510			978			102			44					
	CONTROL DRUMS POSITION, DEGREES	105.6			105.6			114.4			69.0			58.2			58.2			0.0			0.0					
	FEEDBACK REACTIVITY, \$	-1.07			-1.05			-0.59			0.76			0.75			0.74			-0.43			-1.52					
	REACTIVITY LOSS, \$	1.00			1.00			1.00			1.00			1.00			1.00			1.00			1.00					
	CALCULATION RUN REFERENCE	82 10/10/70			144 10/7/70			144 10/7/70			144 10/7/70			381 9/29/70			381 9/29/70			542 10/9/70			542 10/9/70					

NOTE: * NSS AND ENGINE INTERFACE STATE POINT. ** ENGINE DATA INCLUDED FOR REFERENCE ONLY. *** ONE SIDED UNCERTAINTY LIMIT FOR 99% PROPORTION WITH 95% CONFIDENCE BASED ON 30 RANDOM SAMPLE CASES ARE GIVEN. NOTE EITHER THE UPPER (+) OR THE LOWER (-) UNCERTAINTY APPLIES; BOTH UNCERTAINTIES DO NOT APPLY SIMULTANEOUSLY (THESE) UNCERTAINTIES REPRESENT THE ESTIMATED VARIATIONS AFTER THE COMPLETION OF THE ENGINE QUALIFICATION PROGRAM.

*** EVENT A IS AT TIME = 1.0 SECONDS AFTER STARTUP. AT TIME = 0 THE NSS ENVIRONMENT WAS ASSUMED AT 532°R.

AS RUN REFERENCE PROFILES FOR STARTUP & SHUTDOWN

CHAMBER TEMPERATURE RAMP RATE DURING THRUST BUILDUP AND TEMPERATURE RETREAT = 175°R/sec
CHAMBER PRESSURE RAMP RATE FOR THROTTLING = 50°R/sec

Figure 2-1E. Thermal and Fluid Environment Drawing (939J746), Sheet 5 of 7, Graphite Core, End of Life, Normal Mode Operation

NSS MALFUNCTION MODE, SINGLE TURBOPUMP OPERATION, GRAPHITE CORE													NSS MALFUNCTION MODE, SINGLE TURBOPUMP OPERATION, COMPOSITE CORE												
EVENTS	STEADY STATE PERFORMANCE START OF LIFE SINGLE TURBOPUMP OPERATION (80% THRUST)			STEADY STATE PERFORMANCE END OF LIFE SINGLE TURBOPUMP OPERATION (80% THRUST)			THROTTLED PERFORMANCE START OF LIFE SINGLE TURBOPUMP OPERATION (65% POWER)			THROTTLED PERFORMANCE END OF LIFE SINGLE TURBOPUMP OPERATION (65% POWER)			EVENTS	STEADY STATE PERFORMANCE START OF LIFE SINGLE TURBOPUMP OPERATION (80% THRUST)			STEADY STATE PERFORMANCE END OF LIFE SINGLE TURBOPUMP OPERATION (80% THRUST)			THROTTLED PERFORMANCE START OF LIFE SINGLE TURBOPUMP OPERATION (65% POWER)			THROTTLED PERFORMANCE END OF LIFE SINGLE TURBOPUMP OPERATION (65% POWER)		
	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R		W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R
1** PUMP OUTLET(EACH)	73.1 ± 1.5	1295 ± 29.4	60 ± 1.6	73.1 ± 1.5	1276 ± 29.9	60 ± 1.6	59.3	959	55	59.3	942	54		73.1 ± 0.94	1310 ± 31.9	60 ± 1.6	73.1 ± 1.3	1292 ± 32.5	60 ± 1.6	59.3	969	55	59.3	953	54
2 SSCA INLET	8.1 ± 2.1	1278 ± 28.9	60 ± 1.6	12.1 ± 2.6	1260 ± 29.4	60 ± 1.6	9.8	948	55	14.0	931	54		7.5 ± 1.7	1293 ± 31.4	60 ± 1.6	11.1 ± 2.3	1276 ± 32.0	60 ± 1.6	9.2	958	55	13.0	943	54
3 SSA INLET PLENUM	8.1 ± 2.1	1150 ± 25.7	81 ± 3.7	12.1 ± 2.6	1167 ± 31.0	72 ± 3.0	9.8	883	67	13.9	904	65		7.5 ± 1.7	1160 ± 28.1	74 ± 3.7	11.1 ± 2.3	1174 ± 27.9	72 ± 3.1	9.2	885	67	12.9	903	65
4 SSA FEED INLET LINE AT P/V DOME	8.1 ± 2.1	1151 ± 25.7	61 ± 1.6	12.1 ± 2.6	1170 ± 31.0	61 ± 1.6	9.8	884	55	14.0	908	55		7.5 ± 1.7	1162 ± 28.1	61 ± 1.6	11.1 ± 2.3	1176 ± 27.9	61 ± 1.6	9.2	887	55	13.0	906	55
5* SSA BYPASS LINE AT P/V DOME	2.5 ± 0.16	1107 ± 21.4	61 ± 1.6	2.4 ± 0.16	1104 ± 21.9	61 ± 1.5	2.2	818	55	2.1	816	55		2.5 ± 0.16	1122 ± 24.9	62 ± 1.5	2.4 ± 0.16	1118 ± 24.7	61 ± 1.6	2.2	827	55	2.1	825	55
6 SSA OUTLET AFTER MIXING	10.6 ± 2.1	1103 ± 21.5	544 ± 54.3	14.5 ± 2.6	1099 ± 21.9	436 ± 41.3	12.0	814	475	16.1	810	383		10.0 ± 1.8	1118 ± 24.8	537 ± 55.9	13.6 ± 2.3	1114 ± 24.7	436 ± 43.3	11.5	823	471	15.1	820	384
7* REFLECTOR INLET PLENUM	62.4 ± 2.3	1144 ± 22.2	205 ± 11.3	58.6 ± 2.6	1137 ± 22.6	213 ± 12.9	47.3	847	215	43.3	841	227		63.0 ± 2.1	1158 ± 25.1	205 ± 10.8	59.5 ± 2.4	1151 ± 25.3	211 ± 12.1	47.9	856	213	44.3	850	224
8 REFLECTOR OUTLET	57.0 ± 2.0	1103 ± 21.6	289 ± 22.3	53.4 ± 2.3	1099 ± 22.0	302 ± 25.0	43.1	814	311	39.4	810	332		57.5 ± 1.8	1118 ± 24.8	281 ± 16.1	54.3 ± 2.1	1114 ± 24.9	291 ± 18.1	43.6	823	301	40.3	820	317
9 REFLECTOR PRESSURE VESSEL ANNULUS OUTLET	5.4 ± 0.39	1103 ± 21.5	269 ± 23.9	5.2 ± 0.39	1099 ± 21.9	280 ± 26.7	4.2	814	284	3.9	810	302		5.5 ± 0.38	1118 ± 24.8	257 ± 15.6	5.2 ± 0.39	1114 ± 24.7	266 ± 17.7	4.3	823	270	4.0	820	285
10 PERIPHERAL SHIELD INLET PLENUM	73.1 ± 1.5	1103 ± 21.5	322 ± 21.6	71.3 ± 1.3	1099 ± 21.9	326 ± 22.0	59.3	814	341	59.3	810	344		73.1 ± 1.5	1118 ± 24.8	312 ± 17.5	73.1 ± 1.3	1114 ± 24.7	315 ± 18.2	59.3	823	330	59.3	820	332
11 PERIPHERAL SHIELD OUTLET	53.1 ± 1.8	1096 ± 21.2	324 ± 21.9	53.1 ± 1.8	1092 ± 21.8	328 ± 22.3	42.9	807	343	42.9	803	345		53.1 ± 1.8	1111 ± 24.8	313 ± 17.5	53.1 ± 1.8	1107 ± 24.7	317 ± 18.2	43.0	816	332	43.0	813	334
12 PERIPHERAL SHIELD P/V ANNULUS OUTLET	20.0 ± 1.4	1096 ± 21.2	327 ± 21.9	20.0 ± 1.4	1092 ± 21.8	330 ± 22.3	16.4	807	345	16.4	803	348		20.0 ± 1.4	1111 ± 24.8	315 ± 17.6	20.0 ± 1.4	1107 ± 24.7	318 ± 18.4	16.4	816	334	16.4	813	336
13* NSS EXIT TO TURBINE	73.1 ± 1.5	1096 ± 21.2	325 ± 21.9	73.1 ± 1.5	1092 ± 21.8	328 ± 22.3	59.3	807	344	59.3	803	346		73.1 ± 1.5	1111 ± 24.8	314 ± 17.5	73.1 ± 1.3	1107 ± 24.7	317 ± 18.3	59.3	816	332	59.3	813	334
14* NSS EXIT FROM TURBINE	22.9 ± 1.3	546 ± 9.9	308 ± 20.7	22.9 ± 1.3	546 ± 10.1	308 ± 21.0	59.2	451	328	59.2	452	331		22.9 ± 1.3	543 ± 9.2	294 ± 16.7	22.9 ± 1.3	544 ± 9.4	297 ± 17.5	59.2	449	317	59.2	449	319
15 CENTRAL SHIELD INLET PLENUM	22.9 ± 1.3	522 ± 8.9	305 ± 20.6	22.9 ± 1.3	522 ± 9.1	305 ± 20.9	59.2	431	328	59.2	431	331		22.9 ± 1.3	520 ± 8.5	294 ± 16.7	22.9 ± 1.3	520 ± 8.6	297 ± 17.4	59.2	429	317	59.2	429	319
16 SUPPORT PLATE INLET PLENUM	72.9 ± 1.3	515 ± 8.8	308 ± 20.4	72.9 ± 1.3	513 ± 9.0	311 ± 20.7	59.2	423	332	59.2	423	334		72.9 ± 1.3	511 ± 8.5	297 ± 16.5	72.9 ± 1.3	511 ± 8.5	300 ± 17.3	59.2	421	320	59.2	421	322
17 CORE INLET PLENUM	72.9 ± 1.3	503 ± 8.2	313 ± 20.1	72.9 ± 1.3	503 ± 8.3	315 ± 20.3	59.2	414	336	59.2	414	337		72.9 ± 1.3	502 ± 8.0	301 ± 16.4	72.9 ± 1.3	502 ± 8.0	303 ± 17.0	59.2	413	323	59.2	413	324
18 CORE CENTRAL REGION FUEL CHANNEL OUTLET	29.7 —	360 —	4309 —	29.7 —	360 —	4326 —	24.1	293	4318	24.1	293	4337		29.7 ± 0.59	360 ± 5.0	4303 ± 98.8	29.7 —	360 —	4320 —	24.2	298	4312	24.1	293	4330
19 CORE MID REGION FUEL CHANNEL OUTLET	33.4 —	360 —	4307 —	33.5 —	360 —	4301 —	27.1	293	4312	27.2	293	4303		33.4 ± 0.72	360 ± 5.0	4300 ± 83.4	33.4 —	360 —	4301 —	27.1	293	4315	27.1	293	4298
20 CORE PERIPHERAL REGION FUEL CHANNEL OUTLET	8.2 —	360 —	4244 —	8.2 —	360 —	4208 —	6.7	293	4173	6.7	293	4149		8.2 ± 0.20	360 ± 5.0	4277 ± 16.2	8.3 —	360 —	4219 —	6.7	293	4187	6.7	293	4200
21 FILLER STRIP CHANNEL OUTLET	1.1 —	360 —	1367 —	1.1 —	360 —	1364 —	0.9	293	4123	0.9	293	1426		1.1 ± 0.15	360 ± 5.0	1384 ± 22.2	1.1 —	360 —	1376 —	0.9	293	1437	0.9	293	1439
22 LATERAL SUPPORT CHANNEL OUTLET	0.5 —	360 —	1407 —	0.5 —	360 —	1405 —	0.4	293	1402	0.4	293	1408		0.5 ± 0.067	360 ± 5.0	1410 ± 23.2	0.5 —	360 —	1403 —	0.4	293	1405	0.4	293	1408
23* CORE OUTLET CHAMBER	72.9 ± 1.3	360 ± 5.0	4250 ± 40.0	72.9 ± 1.3	360 ± 5.0	4250 ± 40.0	59.2	293	4250	59.2	293	4250		72.9 ± 1.3	360 ± 5.0	4250 ± 40.0	72.9 ± 1.3	360 ± 5.0	4250 ± 40.0	59.2	293	4250	59.2	293	4250
REACTOR TOTAL THERMAL POWER, MW	1206			1206			978			978				1206			1206			978			978		
CONTROL DRUMS POSITION, DEGREES	55.2			55.2			57.2			57.2				46.1			46.1			46.1			46.1		
FEEDBACK REACTIVITY, \$	0.76			0.75			0.75			0.76				1.10			1.09			1.10			1.09		
REACTIVITY LOSS, \$	0.00			1.00			0.00			1.00				0.00			1.00			0.00			1.00		
CALCULATION RUN REFERENCE	156 10-2-70			156 10-2-70			156 10-2-70			156 10-2-70				101 10-6-70			101 10-6-70			101 10-6-70			101 10-6-70		

NOTE: * NSS AND ENGINE INTERFACE STATE POINT. ** ENGINE DATA INCLUDED FOR REFERENCE ONLY.

*** ONE SIDED UNCERTAINTY LIMIT FOR 99% PROPORTION WITH 95% CONFIDENCE BASED ON 30 RANDOM SAMPLE CASES ARE GIVEN. NOTE EITHER THE UPPER (+) OR THE LOWER (-) UNCERTAINTY APPLIES; BOTH UNCERTAINTIES DO NOT APPLY SIMULTANEOUSLY. (THESE) UNCERTAINTIES REPRESENT THE ESTIMATED VARIATIONS AFTER THE COMPLETION OF THE ENGINE QUALIFICATION PROGRAM.

Figure 2-1F. Thermal and Fluid Environment Drawing (939J746), Sheet 6 of 7, Composite and Graphite Cores, Single TPA Operation, Malfunction Mode

EVENTS	NSS GROWTH MODE PERFORMANCE CHAMBER TEMP = 4500°R, COMPOSITE CORE						NSS GROWTH MODE PERFORMANCE CHAMBER TEMP = 4500°R, GRAPHITE CORE						
	STEADY STATE GROWTH MODE PERFORMANCE START OF LIFE			STEADY STATE GROWTH MODE PERFORMANCE END OF LIFE			STEADY STATE GROWTH MODE PERFORMANCE START OF LIFE			STEADY STATE GROWTH MODE PERFORMANCE END OF LIFE			
	LOCATION DESCRIPTION	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R	W-LBS/SEC	P-PSIA	T-°R
1**	PUMP OUTLET (EACH)	44.2	1342	58	44.2	1319	57	44.2	1333	58	44.2	1307	57
2	SSCA INLET	77	1337	58	11.8	1313	57	18.3	1327	58	12.9	1301	57
3	SSA INLET PLENUM	77	1111	72	11.7	1131	70	8.3	1107	73	12.8	1137	70
4	SSA AFFED INLET LINE AT P/V DOME	77	1113	60	11.8	1134	59	8.3	1109	59	12.9	1140	59
5*	SSA BYPASS LINE AT P/V DOME	32	1064	60	3.0	1061	60	3.2	1055	60	3.0	1052	59
6	SSA OUTLET AFTER MIXING	10.9	1059	567	14.8	1055	457	11.4	1050	576	15.9	1046	464
7*	REFLECTOR INLET PLENUM	77.5	1120	204	73.6	1118	210	76.9	1112	205	72.5	1104	212
8	REFLECTOR OUTLET	70.8	1059	281	67.2	1055	290	70.3	1050	289	66.2	1046	300
9	REFLECTOR PRESSURE VESSEL ANNULUS OUTLET	6.7	1059	260	6.4	1055	268	6.6	1050	272	6.3	1046	282
10	PERIPHERAL SHIELD INLET PLENUM	88.3	1059	312	88.4	1055	315	88.3	1050	323	88.4	1046	327
11	PERIPHERAL SHIELD OUTLET	64.3	1048	314	64.3	1045	317	64.3	1039	325	64.3	1035	329
12	PERIPHERAL SHIELD P/V ANNULUS OUTLET	24.0	1048	316	24.0	1045	319	24	1039	327	24.1	1035	332
13*	NSS EXIT TO TURBINE	88.3	1048	314	88.4	1045	317	88.3	1039	325	88.4	1035	330
14*	NSS EXIT FROM TURBINE	88.4	671	295	88.4	672	298	88.3	674	306	88.4	675	310
15	CENTRAL SHIELD INLET PLENUM	88.4	643	295	88.4	643	298	88.3	645	306	88.4	646	310
16	SUPPORT PLATE INLET PLENUM	88.4	632	298	88.4	633	301	88.3	634	309	88.4	634	314
17	CORE INLET PLENUM	88.4	621	303	88.4	621	305	88.3	622	315	88.4	623	318
18	CORE CENTRAL REGION FUEL CHANNEL OUTLET	36.0	450	4563	35.9	450	4583	35.9	450	4568	35.9	450	4588
19	CORE MID REGION FUEL CHANNEL OUTLET	40.0	450	4560	40.5	450	4533	40.5	450	4555	40.5	450	4548
20	CORE PERIPHERAL REGION FUEL CHANNEL OUTLET	10.0	450	4521	10.0	450	4521	9.9	450	4511	9.9	450	4482
21	FILLER STRIP CHANNEL OUTLET	1.4	450	1404	1.4	450	1406	1.4	450	1384	1.4	450	1385
22	LATERAL SUPPORT CHANNEL OUTLET	0.6	450	1513	0.6	450	1517	0.6	450	1509	0.6	450	1511
23*	CORE OUTLET CHAMBER	88.4	450	4500	88.4	450	4500	88.3	450	4500	88.4	450	4500
	REACTOR TOTAL THERMAL POWER, MW	1576			1576			1576			1576		
	CONTROL DRUMS POSITION, DEGREES	55.6			55.6			66.8			66.8		
	FEEDBACK REACTIVITY, \$	0.83			0.83			0.48			0.48		
	REACTIVITY LOSS, \$	0.00			1.00			0.00			1.00		
	CALCULATION RUN REFERENCE	80 10/10/70			80 10/10/70			500 10/14/70			500 10/14/70		

NOTE:
 ** ENGINE DATA INCLUDED FOR REFERENCE ONLY
 * NSS AND ENGINE INTERFACE STATE POINT

Figure 2-1G. Thermal and Fluid Environment Drawing (939J746), Sheet 7 of 7,
 Composite and Graphite Cores, Chamber Temperature = 4500°R, Growth Mode Operation

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Figure 2-2. Flow Chart for Nuclear, Thermal and Structural Analyses

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Figure 2-3. Flow Chart for Thermal Analyses Model Development

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Figure 2-4. Flow Chart for NSS Level Thermal Analyses

613419-21B

Figure 2-5. Flow Chart for Component Level Thermal Analyses

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~~RESTRICTED DATA~~

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Figure 2-7. TNT-II Hydraulic Model

Thermal Conductivity - $\frac{\text{Btu}}{\text{in-sec-}^{\circ}\text{R}}$

Figure 2-8. Equivalent Thermal Conductivity for the Cluster Hardware Pyrosleeve

Figure 2-9. Equivalent Specific Heat for the Cluster Hardware Pyrosleeve

RESTORED DATA
 Thermal Conductivity - $\frac{\text{Btu}}{\text{in-sec-}^{\circ}\text{R}}$

Figure 2-10. Equivalent Thermal Conductivity for Cluster Hardware Support Stem

Figure 2-11. Equivalent Specific Heat for Cluster Hardware Support Stem

Figure 2-12. Equivalent Thermal Conductivity for Core Periphery Insulation

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Figure 2-13. Equivalent Specific Heat for Core Periphery Insulation

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Figure 2-14. NERVA Engine Operational Phases

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Figure 2-15. "Reference Profiles" for Startup and Shutdown

Figure 2-16. Composite Core SSCV Demand Profile for Startup and Shutdown

Figure 2-17. Composite Core SSCV Loss Coefficient vs % Travel

Figure 2-18. Graphite Core SSCV Demand Profile for Startup and Shutdown

Figure 2-19. Graphite Core SSCV Loss Coefficient vs % Travel

Figure 2-20. Typical Cycles of Normal Mode Operations

STARTUP TO RATED CONDITIONS
FUEL EXIT AND CORE TEMPERATURES

SHUTDOWN--FUEL EXIT AND
CORE STATION TEMPERATURES

STARTUP TO RATED CONDITIONS
PLENUM PRESSURES

SHUTDOWN--PLENUM PRESSURES

Figure 2-21. Comparison of NRX-A6 Reactor Test and TNT Predicted Temperatures and Pressures for Typical Startup and Shutdown

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Figure 2-22 . Cumulative Distribution Function for the Transformation of Random Numbers to Random Multiplication Factors

LOCATIONS OF RMF	INDEX NUMBERS ASSIGNED TO TNT-II AND RATS PARAMETER RANDOMLY VARIED	COMMENTS
1 . 144		RMF Not Used
145 . 260	1 . 116	RMF Used to Prepare TNT-II Input for Calculation No. 1
261 . 344	117 . 200	RMF Not Required
345 . 744	201 . 600	RMF Used to Prepare RATS input For Calculation No. 1
745 . 860	1 . 116	RMF Used to Prepare TNT-II Input for Calculation No. 2
861 . 944	117 . 200	RMF Not Required
945 . 1344	201 . 600	RMF Used to Prepare RATS Input for Calculation No. 2
. . .	. . .	
17545 . 17660	. . 116	RMF Used to Prepare TNT-II Input for Calculation No. 30
17661 . 17744	117 . 200	RMF Not Required
17745 . 18144	201 . 600	RMF Used to Prepare RATS Input for Calculation No. 30

*Structural Design Code R-1, RATS

Figure 2-23. Assignment of Random Multiplication Factors to TNT-II and RATS Parameters for 30 Calculations

Figure 2-24. NSS Reactivity Insertion Capability with Composite Core

CHAMBER 1 FUEL-CENT 2 MID 3 PERIPHERAL 4 FILLER STRIPS 5 LATERAL SUPPORT 6

Figure 2-25. Composite Core Start of Life Startup Chamber and Individual Chamber
Inlet Temperatures

CHAMBER 1 REFLECTOR 2 SUPPORT SYSTEM FEED 3 SUPPORT SYSTEM BYPASS 4

Figure 2-26. Composite Core Start of Life Startup Flow Rates

TOTAL THERMAL 1 FISSION 2 DECAY 3

Figure 2-27. Composite Core Start of Life Startup Power

PUMP 1 REFLECTOR INLET 2 REFLECTOR OUTLET 3 PERIPHERAL DOME 4

Figure 2-28. Composite Core Start of Life Startup Plenum Pressures (A)

CENTRAL DOME 1 SUP PLATE UNLET 2 CORE INLET 3 CHAMBER 4

Figure 2-29. Composite Core Start of Life Startup Plenum Pressures (B)

PUMP 1 REFLECTOR INLET 2 REFLECTOR OUTLET 3 PERIPHERAL DOME 4

Figure 2-30. Composite Core Start of Life Startup Plenum Temperatures (A)

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CENTRAL DOME 1 SUP PLATE INLET 2 CORE INLET 3

Figure 2-31. Composite Core Start of Life Startup Plenum Temperatures (B)

79 10/3/70

REACTOR PD 1 REFLECTOR PD 2 CORE PD 3

Figure 2-32. Composite Core Start of Life Startup Pressure Drops

79 10/3/70

MAXIMUM 1 AVERAGE 2 MINIMUM 3

Figure 2-33. Composite Core Start of Life Startup Cluster Hardware Support Stem Temperature

79 10/3/70

MAXIMUM 1 AVERAGE 2 MINIMUM 3

Figure 2-34. Composite Core Start of Life Startup Cluster Hardware Liner Tube Temperature

TURN AROUND-CENTRAL 1 MID 2 PERIPHERY 3 EXIT-CENTRAL 4 MID 5 PERIPHERY 6

Figure 2-35. Composite Core Start of Life Startup Cluster Hardware Support Stem Fluid Temperatures

CONTROL DRUM POSITION 1

79 10/3/70

Figure 2-36. Composite Core Start of Life Startup Control Drum Position

Figure 2-37. Composite Core Start of Life Startup Reactivity

Figure 2-38. Composite Core Start of Life Startup Core Radial Power Distribution
Perturbation Fractions

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STA2.89-1 STA14.44-3 STA26-5 STA37.55-7 STA49.11-9

Figure 2-39. Composite Core Start of Life Startup Temp. Difference (Central Fuel - Peripheral Fuel)

STA2.09-1 STA14.44-3 STA26-5 STA37.55-7 STA49.11-9

Figure 2-40. Composite Core Start of Life Startup Core Central Region Temp. Diff.
(Fuel-Unfuel)

STA2.09-1 STA14.44-3 STA26-5 STA37.55-7 STA49.11-9

Figure 2-41. Composite Core Start of Life Startup Core Mid-Region Temp. Diff. (Fuel-Unfuel)

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STA2.89-1 STA14.44-3 STA26-5 STA37.55-7 STA49.11-9

Figure 2-42. Composite Core Start of Life Startup Core Peripheral Region Temp. Diff.
(Fuel-Unfuel)

STA2.89-1 STA14.44-3 STA26-5 STA37.55-7 STA49.11-9

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Figure 2-43. Composite Core Start of Life Startup Temp. Diff. (Peripheral Fuel - Filler Strip)

CHAMBER 1 FUEL-CENT 2 MID 3 PERIPHERAL 4 FILLER STRIPS 5 LATERAL SUPPORT 6

Figure 2-44. Composite Core, Start of Life, Shutdown - Chamber and Individual Chamber Inlet Temperatures

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CHAMBER 1 REFLECTOR 2 SUPPORT SYSTEM FEED 3 SUPPORT SYSTEM BYPASS 4

Figure 2-45. Composite Core Start of Life Shutdown Flow Rates

596 10/9/70

TOTAL THERMAL 1 FISSION 2 DECAY 3

Figure 2-46. Composite Core, Start of Life, Shutdown Power

PUMP 1 REFLECTOR INLET 2 REFLECTOR OUTLET 3 PERIPHERAL DOME 4

Figure 2-47. Composite Core Start of Life Shutdown Plenum Pressures (A)

CENTRAL DOME 1 SUP PLATE UNLET 2 CORE INLET 3 CHAMBER 4

Figure 2-48. Composite Core Start of Life Shutdown Plenum Pressures (B)

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PUMP 1 REFLECTOR INLET 2 REFLECTOR OUTLET 3 PERIPHERAL DOME 4

Figure 2-49. Composite Core Start of Life Shutdown Plenum Temperatures (A)

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CENTRAL DOME 1 SUP PLATE INLET 2 CORE INLET 3

Figure 2-50. Composite Core Start of Life Shutdown Plenum Temperatures (B)

Figure 2-51. Composite Core Start of Life Shutdown Pressure Drops

MAXIMUM 1 AVERAGE 2 MINIMUM 3

Figure 2-52. Composite Core Start of Life Shutdown Cluster Hardware Support Stem Temperature

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MAXIMUM 1 AVERAGE 2 MINIMUM 3

Figure 2-53. Composite Core Start of Life Shutdown Cluster Hardware Liner Tube Temperature

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TURN AROUND-CENTRAL 1 MID 2 PERIPHERY 3 EXIT-CENTRAL 4 MID 5 PERIPHERY 6

Figure 2-54. Composite Core Start of Life Shutdown Cluster Hardware Support Stem Fluid Temperatures

CONTROL DRUM POSITION 1

Figure 2-55. Composite Core Start of Life Shutdown Control Drum Position

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FEEDBACK 1 IMPRESSED 2 EXCESS 3

Figure 2-56. Composite Core Start of Life Shutdown Reactivity

CENTRAL REGION 1 MID REGION 2 PERIPHERAL REGION 3

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Figure 2-57. Composite Core Start of Life Shutdown Core Radial Power Distribution Perturbation Fractions

STA2.89-1 STA14.44-3 STA26-5 STA37.55-7 STA49.11-9

Figure 2-58. Composite Core Start of Life Shutdown Temp. Difference (Central Fuel - Peripheral Fuel)

STA2.89-1 STA14.44-3 STA26-5 STA37.55-7 STA49.11-9

Figure 2-59. Composite Core Start of Life Shutdown Core Central Region Temp. Diff.
(Fuel - Unfuel)

STA2.89-1 STA14.44-3 STA26-5 STA37.55-7 STA49.11-9

Figure 2-60. Composite Core Start of Life Shutdown Core Mid-Region Temp. Diff. (Fuel - Unfuel)

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STA2.89-1 STA14.44-3 STA26-5 STA37.55-7 STA49.11-9

Figure 2-61. Composite Core Start of Life Shutdown Core Peripheral Region Temp. Diff. (Fuel - Unfuel)

STA2.89-1 STA14.44-3 STA26-5 STA37.55-7 STA49.11-9

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Figure 2-62. Composite Core Start of Life Shutdown Temp. Diff. (Peripheral Fuel - Filler Strip)

Figure 2-63. Composite Core End of Life Start Up Chamber and Individual Chamber Inlet Temperatures

Figure 2-64. Composite Core End of Life Start Up Flow Rates

Figure 2-65. Composite Core End of Life Start Up Power

Figure 2-66. Composite Core End of Life Start Up Plenum Pressures (A)

Figure 2-67. Composite Core End of Life Start Up Plenum Pressures (B)

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PUMP 1 REFLECTOR INLET 2 REFLECTOR OUTLET 3 PERIPHERAL DOME 4

Figure 2-68. Composite Core End of Life Start Up Plenum Temperatures (A)

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CENTRAL DOME 1 SUP PLATE INLET 2 CORE INLET 3

Figure 2-69. Composite Core End of Life Start Up Plenum Temperatures (B)

Figure 2-70. Composite Core End of Life Start Up Pressure Drops

Figure 2-71. Composite Core End of Life Start Up Cluster Hardware Support Stem Temperature

Figure 2-72. Composite Core End of Life Startup Cluster Hardware
Liner Tube Temperature

Figure 2-73. Composite Core End of Life Startup Cluster Hardware
Support Stem Fluid Temperatures

CONTROL DRUM POSITION 1

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Figure 2-74. Composite Core End of Life Startup Control Drum Position

Figure 2-75. Composite Core End of Life Startup Reactivity

Figure 2-76. Composite Core End of Life Startup Core Radial Power Distribution Perturbation Fractions

CHAMBER 1 FUEL-CENT 2 MID 3 PERIPHERAL 4 FILLER STRIPS 5 LATERAL SUPPORT 6

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10/13/70

Figure 2-77. Composite Core End of Life Shutdown Chamber and Individual Chamber Inlet Temperatures

Figure 2-78. Composite Core End of Life Shutdown Flow Rates

Figure 2-79. Composite Core End of Life Shutdown Power

Figure 2-80. Composite Core End of Life Shutdown Plenum Pressures (A)

CENTRAL DOME 1 SUP PLATE UNLET 2 CORE INLET 3 CHAMBER 4

Figure 2-81. Composite Core End of Life Shutdown Plenum Pressures (B)

PUMP 1 REFLECTOR INLET 2 REFLECTOR OUTLET 3 PERIPHERAL DOME 4

Figure 2-82. Composite Core End of Life Shutdown Plenum Temperatures (A)

CENTRAL DOME 1 SUP PLATE INLET 2 CORE INLET 3

Figure 2-83. Composite Core End of Life Shutdown Plenum Temperatures (B)

Figure 2-84. Composite Core End of Life Shutdown Pressure Drops

Figure 2-85. Composite Core End of Life Shutdown Cluster Hardware Support Stem Temperature

Figure 2-86. Composite Core End of Life Shutdown Cluster Hardware
Liner Tube Temperature

Figure 2-87. Composite Core End of Life Shutdown Cluster Hardware Support Stem Fluid Temperatures

Figure 2-88. Composite Core End of Life Shutdown Control Drum Position

Figure 2-89. Composite Core End of Life Shutdown Reactivity

Figure 2-90. Composite Core End of Life Shutdown Core Radial Power Distribution Perturbation Fractions

Figure 2-91. NSS Reactivity Insertion Capability with Graphite Core

CHAMBER 1 FUEL-CENT 2 MID 3 PERIPHERAL 4 FILLER STRIPS 5 LATERAL SUPPORT 6

Figure 2-92. Graphite Core Start of Life Start Up Chamber and Individual Chamber Inlet Temperatures

REFERENCE		PREPARED BY	APPROVED BY	ASTRONUCLEAR
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CHAMBER 1 REFLECTOR 2 SUPPORT SYSTEM FEED 3 SUPPORT SYSTEM BYPASS 4

Figure 2-93. Graphite Core Start of Life Startup Flow Rates

Figure 2-94. Graphite Core Start of Life Start Up Power

Figure 2-95. Graphite Core Start of Life-Start Up Plenum Pressures (A)

Figure 2-96. Graphite Core Start of Life Start Up Plenum Pressures (B)

Figure 2-97. Graphite Core Start of Life Start Up Plenum Temperatures (A)

CENTRAL DOME 1 SUP PLATE INLET 2 CORE INLET 3

Figure 2-98. Graphite Core Start of Life Start Up Plenum Temperatures (B)

Figure 2-99. Graphite Core Start of Life Start Up Pressure Drops

Figure 2-100. Graphite Core Start of Life Start Up Cluster Hardware Support Stem Temperature

Figure 2-101. Graphite Core Start of Life Start Up Cluster Hardware
Liner Tube Temperature

TURN AROUND-CENTRAL 1 MID 2 PERIPHERY 3 EXIT-CENTRAL 4 MID 5 PERIPHERY 6

Figure 2-102. Graphite Core Start of Life Start Up Cluster Hardware Support Stem Fluid Temperatures

CONTROL DRUM POSITION 1

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Figure 2-103. Graphite Core Start of Life Start Up Control Drum Position

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FEEDBACK 1 IMPRESSED 2 EXCESS 3

Figure 2-104. Graphite Core Start of Life Start Up Reactivity

Figure 2-105. Graphite Core Start of Life Start Up Core Radial Power Distribution Perturbation Fractions

CHAMBER 1 FUEL-CENT 2 MID 3 PERIPHERAL 4 FILLER STRIPS 5 LATERAL SUPPORT 6

Figure 2-106. Graphite Core Start of Life Shutdown Chamber and Individual Chamber Inlet Temperatures

CHAMBER 1 REFLECTOR 2 SUPPORT SYSTEM FEED 3 SUPPORT SYSTEM BYPASS 4

Figure 2-107. Graphite Core Start of Life Shutdown Flow Rates

Figure 2-108. Graphite Core Start of Life Shutdown Power

Figure 2-109. Graphite Core Start of Life Shutdown Plenum Pressures (A)

Figure 2-110. Graphite Core Start of Life Shutdown Plenum Pressures (B)

Figure 2-111 Graphite Core Start of Life Shutdown Plenum Temperatures (A)

Figure 2-112. Graphite Core Start of Life Shutdown Plenum Temperatures (B)

Figure 2-113. Graphite Core Start of Life Shutdown Pressure Drops

Figure 2-114. Graphite Core Start of Life Shutdown Cluster Hardware Support Stem Temperature

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Figure 2-115. Graphite Core Start of Life Shutdown Cluster Hardware
Liner Tube Temperature

TURN AROUND-CENTRAL 1 MID 2 PERIPHERY 3 EXIT-CENTRAL 4 MID 5 PERIPHERY 6

Figure 2-116, Graphite Core Start of Life Shutdown Cluster Hardware Support Stem Fluid Temperatures

CONTROL DRUM POSITION 1

Figure 2-117. Graphite Core Start of Life Shutdown Control Drum Position

Figure 2-118. Graphite Core Start of Life Shutdown Reactivity

Figure 2-119. Graphite Core Start of Life Shutdown Core Radial Power Distribution Perturbation Fractions

Figure 2-120. Graphite Core, End of Life, Startup Chamber and Individual Chamber Inlet Temperatures

CHAMBER 1 REFLECTOR 2 SUPPORT SYSTEM FEED 3 SUPPORT SYSTEM BYPASS 4

Figure 2-121. Graphite Core, End of Life, Startup Flow Rates

Figure 2-122. Graphite Core, End of Life, Startup Power

Figure 2-123. Graphite Core, End of Life, Startup Plenum Pressures (A)

CENTRAL DOME 1 SUP PLATE UNLET 2 CORE INLET 3 CHAMBER 4

Figure 2-124. Graphite Core, End of Life, Startup Plenum Pressures (B)

PUMP 1 REFLECTOR INLET 2 REFLECTOR OUTLET 3 PERIPHERAL DOME 4

Figure 2-125. Graphite Core, End of Life, Startup Plenum Temperatures (A)

CENTRAL DOME 1 SUP PLATE INLET 2 CORE INLET 3

Figure 2-126. Graphite Core, End of Life, Startup Plenum Temperatures (B)

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REACTOR PD 1 REFLECTOR PD 2 CORE PD 3

Figure 2-127. Graphite Core, End of Life, Startup Pressure Drops

Figure 2-128. Graphite Core, End of Life, Startup Cluster Hardware Support Stem Temperature

MAXIMUM 1 AVERAGE 2 MINIMUM 3

Figure 2-129. Graphite Core, End of Life, Startup Cluster Hardware
Liner Tube Temperature

TURN AROUND-CENTRAL 1 MID 2 PERIPHERY 3 EXIT-CENTRAL 4 MID 5 PERIPHERY 6

Figure 2-130. Graphite Core, End of Life, Startup Cluster Hardware Support Stem Fluid Temperatures

CONTROL DRUM POSITION 1

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Figure 2-131. Graphite Core, End of Life, Startup Control Drum Position

FEEDBACK 1 IMPRESSED 2 EXCESS 3

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Figure 2-132. Graphite Core, End of Life, Startup Reactivity

CENTRAL REGION 1 MID REGION 2 PERIPHERAL REGION 3

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Figure 2-133. Graphite Core, End of Life, Startup Core Radial Power Distribution Perturbation Fractions

Figure 2-134. Graphite Core End of Life Shutdown Chamber and Individual Chamber Inlet Temperatures

Figure 2-135. Graphite Core End of Life Shutdown Flow Rates

Figure 2-136. Graphite Core End of Life Shutdown Power

PUMP 1 REFLECTOR INLET 2 REFLECTOR OUTLET 3 PERIPHERAL DOME 4

Figure 2-137. Graphite Core End of Life Shutdown Plenum Pressures (A)

Figure 2-138. Graphite Core End of Life Shutdown Plenum Pressures (B)

Figure 2-139. Graphite Core End of Life Shutdown Plenum Temperatures (A)

Figure 2-140. Graphite Core End of Life Shutdown Plenum Temperatures (B)

Figure 2-141. Graphite Core End of Life Shutdown Pressure Drops

Figure 2-142, Graphite Core End of Life Shutdown Cluster Hardware Support Stem Temperature

MAXIMUM 1 AVERAGE 2 MINIMUM 3

Figure 2-143. Graphite Core End of Life Shutdown Cluster Hardware
Liner Tube Temperature

Figure 2-144. Graphite Core End of Life Shutdown Cluster Hardware Support Stem Fluid Temperatures

CONTROL DRUM POSITION 1

Figure 2-145. Graphite Core End of Life Shutdown Control Drum Position

Figure 2-146. Graphite Core End of Life Shutdown Reactivity

CENTRAL REGION 1 MID REGION 2 PERIPHERAL REGION 3

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Figure 2-147. Graphite Core End of Life Shutdown Core Radial Power Distribution Perturbation Fractions

3.0 FUEL ELEMENTS

3.1 INTRODUCTION

The Fuel Element design has not been selected, therefore, information will be presented in S-054, TS 772 - Fuel Element Trade Study, R-1 Selection.

4.0 CLUSTER HARDWARE

4.1 INTRODUCTION

The Cluster Hardware design has not been selected, therefore, information will be presented in S-054, TS 774 - NERVA Cluster and Hot End Hardware, R-1 Selection.

5.0 CORE PERIPHERY

5.1 INTRODUCTION

The Core Periphery design has not been selected, therefore, information will be presented in S-054, TS 778 - Core Periphery Trade Study for R-1 Selection.

6.0 SUPPORT PLATE AND PLENA

6.1 INTRODUCTION

This Chapter describes the thermal and fluid flow analyses performed on the Support Plate and Plena (SPP). The functional requirements of the Support Plate are to provide support for the core, distribute and collect stem and bypass flow, and provide a mechanism for separating the turbine inlet from the turbine outlet flow within the NSS. Additionally, the SPP must carry the structural loads imposed upon it by the Internal Shield.

The SPP is part of the Contract End Item described as the NERVA Nuclear Subsystem and is listed as an Engineering Critical Component EC-677561 in CEI Specification CP-677555A. This EC specification establishes the thermal hydraulic design requirements for the support plate and plena system components.

6.1.1 Description of Support Plate and Plena

The following general design features are given in EC-677561:

"3.3.1. General Design Features

- a. A core support plate with three integral plena (an SSCA bypass flow plenum, a support stem inlet flow plenum and a plenum which combines the bypass flow with the support stem effluent).
- b. A piping arrangement which distributes the SSCA outlet flow to the support plate.
- c. Flow separation baffles and associated hardware which separate the flow to the turbine from the turbine exit flow.
- d. A diffuser or baffle and associated hardware which distributes turbine exit flow to the central shield."

Supplemental descriptive information follows:

6.1.1.1 Support Plate and Plena and Plenum Closure Ring

The Core Support Plate and Plena consists of a six inch thick aluminum plate, with a diameter of 44.5 inches, internally machined to form three separate plena. The plena consist of cylindrical cells on three axial levels within the plate, at each support stem location, interconnected by radial holes.

The periphery of the forward plenum is sealed by a plenum closure ring. This ring also distributes flow to the forward plenum for each of the core support stems. The peripheral area of the central plenum is penetrated by the radial holes which interconnect the cells at the second level of the plate. The aft plenum is sealed at the periphery by the interface with the forward extension ring of the reflector.

From a flow standpoint, the support plate structure comprises a network of radial flow channels at three different axial stations, with a fourth flow network passing axially through the plate, as shown on Figure 6-1. The forward radial flow channel is the feed plenum; the middle radial flow channel is the mixing plenum; and the aft radial flow channel is the bypass plenum. The feed plenum flow originates from the inlet piping discharge at the plate O. D. This plenum distributes the fluid to all the support stem inlets. The bypass plenum flow originates at the plate O. D. and this plenum distributes the flow to each stem location, where the flow passes to the mixing plenum. The mixing plenum collects the bypass flows and support stem exit flows and discharges them at the plate O. D. into the reflector exit plenum. Propellant flow to the core is accommodated by axial flow holes through the support plate. This flow enters at the forward face and discharges into the core inlet plenum.

The support plate transmits the core load to the reflector barrel and thence into the engine load path.

6.1.1.2 Support Plate Plenum, Feed and Bypass System

a. Inlet Torus

The SSCA feed flow enters the pressure vessel closure through a single pipe with a flexible joint and enters the inlet torus. The flow is channeled from the torus to thirty sections of inlet tubing distributed around the torus.

b. Inlet Tubing

The inlet tubing directs the support stem inlet flow through the internal shield, into the plenum closure ring and subsequently through the feed plenum.

c. Bypass Torus

The bypass flow enters the pressure vessel closure through a single pipe with a flexible joint and enters the bypass torus. This torus directs the flow to six sections of bypass tubing uniformly spaced around the circumference.

d. Bypass Tubing

The bypass tubing directs the flow through the internal shield through the plenum closure ring and subsequently into the aft or bypass plenum.

6.1.1.3 Piping Cylinder

The piping cylinder is an aluminum structure which keeps the flow to the turbine inlet separated from the turbine discharge flow. It serves an additional function of carrying the axial load imposed by the internal shield and transmits this load to the support plate.

6.1.1.4 Central Dome

The central dome is an aluminum structure which separates the turbine inlet from the turbine discharge flow and mates with the forward flange of the piping cylinder. The dome has a penetration and accommodates an interface seal through which the turbine discharge flow re-enters the NSS.

a. Flow Diffuser

The flow diffuser is a radial diffuser mounted to the central dome in the vicinity of its penetration and serves to direct the flow uniformly into the forward portion of the central shield.

6.2 SUMMARY OF RESULTS AND CONCLUSIONS

Thermal analyses have been performed for the Support Plate and Plena (SPP) with a graphite core for Reference Design Drawing No. 940J449. The analyses are applicable to the thermal and hydraulic performance requirements defined in the Specification ECC-677561. The results of these analyses provided steady state and transient environments for structural analyses of the support plate and plena components.

The analyses were performed using a three-dimensional finite element TAP-A model. Boundary conditions for these analyses were obtained from the TNT-II studies reported in Chapter 2. The NSS with graphite core was selected for detailed analysis because it represents a more severe thermal environment in the support plate component material than the composite core. A summary tabulation of these analyses is contained on Table 6-2.

The effect of unmixed fluids discharging from the support stems upon the support plate temperatures have been evaluated and determined to be acceptable. The results of these studies indicate that, even with the assumption of severely unmixed gases, support plate material temperatures are below the 800°R material temperature limit. However, the study identified aspects of the design effected by mixing, and modifications were made to make the support plate even less susceptible to an unmixed fluid environment. Furthermore, the mixing study confirmed the applicability of the analytical procedures used to calculate the three-dimensional temperature distributions in the support plate structure.

The minimum feed plena flow occurs at rated SOL conditions, resulting in a maximum material temperature of 507°R . Simultaneously, the temperature difference between the feed and bypass regions (which relate to deflection) is 60°R . At EOL rated conditions, the maximum material temperature is 437°R , but the temperature difference between feed and bypass plena regions increases to 73°R , because of increased feed plenum flow.

During throttled operation, material temperatures in the support plate are lower than at rated operation. However, the temperature difference between the feed and bypass regions (related to deflection) achieves its maximum value of 84°R at throttled EOL operation.

The feed, bypass and mixing plena fluid temperatures vary with support plate radius. The feed flow and bypass flow temperature increases of 48°R and 120°R , respectively, between the plate OD and the central stem region occur at rated SOL conditions. The corresponding mixing plenum fluid temperature decrease from centerline to plate OD is 17°R . At EOL rated conditions, the feed and bypass flow temperature rises are 30°R and 120°R , respectively, with a mixing plenum decrease of 7°R . The feed plena temperature variation will be considered in defining the support stem orificing.

The pressure losses in the radial flow passages within the support plate vary from 1.0 psi to 2.0 psi for rated conditions. The axial pressure drop across the SPP was 11 psi for rated conditions.

Sensitivity analyses were performed to evaluate the effect of variations in thermal conductivity, film coefficient, feed and bypass flows. The results indicated minimal effect on support plate temperature due to variations in these parameters.

An uncertainty analysis of key support plate thermal parameters was performed, based on the Monte Carlo studies reported in Chapter 2. The nominal and one-sided uncertainty limits for 99% proportion with 95% confidence are reported for material temperatures, temperature differences and pressure drops.

An evaluation was made of the effect of growth mode operation on support plate performance. The maximum material temperature increases by 23°R and the temperature difference between feed and bypass regions increases by 8°R , relative to the normal mode.

An evaluation was made of fluid heat pickup in the support plate feed flow systems. The fluid temperature rise in the uninsulated feed flow system varies from 37°R at rated SOL to 26°R at throttled EOL. This temperature rise is undesirable because it reduces flow controlled reactivity adjustment capability. Since insulation will mitigate this heat pickup, a thermal impedance equivalent to a five mil stagnant gap around the piping is recommended to decrease the fluid temperature increase by a factor of seven in the inlet

tubes and by a factor of three in the inlet torus.

Startup and shutdown calculations were obtained from TNT-II analyses to evaluate the support plate performance during these transients. The conditions during startup were judged to be no more severe than during steady state. During shutdown, the maximum temperature differences between feed and bypass regions occur at the throttled hold condition previously discussed.

In conclusion, a Step 4 detailed analyses has been performed for the Support Plate and Plena. The analysis was performed on a three-dimensional transient basis with variable material properties. These studies produced temperature levels and temperature gradients for the various components of the support plate assembly. In addition, an uncertainty analysis was performed employing the Monte Carlo techniques described in Chapter 2. The Monte Carlo techniques resulted in prediction of uncertainties for temperature level, temperature gradients, and pressure drops. The resulting temperature levels, temperature gradient and their corresponding uncertainties indicate that this ECC meets the thermal/hydraulic requirements for operation as specified in EC-677561.

6.3 APPLICABLE REQUIREMENTS AND COMPATIBILITY OF THERMAL PERFORMANCE WITH THE NSS SPECIFICATION

The requirements and design conditions stated in this section are specified in EC-677561, Section 3, issued on November 30, 1970.

The following requirements are applicable:

"3.1.1.1.1 Operational Modes

The SPP shall support and/or accommodate all operational modes and their respective operational requirements as defined in 3.1.1.1.1 (Operational Modes) and specified in 3.1.1.1.5 (Operational Requirements) of CP-677555 with no degradation of performance below that specified herein."

The analyses presented in this Chapter support and/or accommodate all normal operational modes and operational requirements of CP-677555A. The single TPA component malfunction mode and the emergency modes were judged less severe than the normal mode. The analysis performed on the Support Plate and Plena resulted in no degradation of performance.

"3.1.1.1.3 Operational Requirements

The SPP shall provide structural support and flow distribution for NSS components in accordance with the following specific requirements for each operating mode.

3.1.1.1.3.1 Normal Mode

The primary performance characteristics of the SPP supporting the requirements of 3.1.1.1.5.1 (Normal Mode) of CP-677555 are as follows:

3.1.1.1.3.1.2 Fluid Distribution and Collection

The SPP shall distribute the regulated flow from the Structural Support Coolant Assembly (SSCA) to the

cluster hardware support stems. The SPP shall also collect the effluent from the support stems, mix it with the SSCA bypass flow and duct the mixture to the reflector outlet plenum. The performance requirements related to this function are as follows:

3.1.1.1.3.1.2.1 Flow Impedance

The static pressure loss from the inlet of the SPP piping to the inlet of the cluster hardware support stems shall not exceed (tbd) psi with a total support stem flow of (tbd) lb/sec at a temperature of (tbd)[°]R and a pressure of (tbd) psia at the SPP inlet (The SPP interface with the pressure vessel and closure). In addition, the difference in static pressure at the inlet of any two support stems shall not exceed (tbd) psi."

During EOL throttled steady state operation, the static pressure loss from the inlet of the SPP piping to the inlet of the cluster hardware support stem is 8 psi.

"3.1.1.1.3.1.2.2 Temperature Variations

The SPP shall distribute the flow to the support stems such that with the engine at rated conditions and the total support stem flow at (tbd) lb/sec, the azimuthal and radial temperature variations at the support stem inlets shall not exceed (tbd)[°]R."

The SPP satisfies the requirement to distribute the flow to the support stems such that, with the engine at rated conditions and the support stem flow greater than or equal to 7.8 lb/sec, the combined azimuthal and radial temperature variations at the support stem inlet is not expected to exceed 48[°]R.

"3.1.1.1.3.1.3 Flow Separation

The SPP shall separate the NSS flow (the combined reflector, SSCA, and SSCA bypass flows) as it passes through the peripheral shield and is ducted to the turbine inlet line, from the flow returning from the turbine as it passes through the central shield,

the support plate and to the core inlet. The SPP shall include baffling to evenly distribute the turbine exit flow to the central shield inlet to limit the azimuthal and radial temperature variations at the central shield inlet to (tbd) °R. The loss in static pressure associated with this baffling shall not exceed (tbd) psi at rated conditions."

For all NSS rated conditions, the combined azimuthal and radial temperature variations attributable to the SPP baffling do not exceed 1°R. The corresponding static pressure loss associated with this baffling does not exceed 30 psi.

"3.1.1.1.3.1.4 Support Plate Axial Flow Characteristics

The SPP shall provide axial flow passage through the core support plate to uniformly distribute the flow from the central shield outlet plenum to the core inlet plenum. The performance requirements are as follows:

3.1.1.1.3.1.4.1 Support Plate Flow Impedance

The static pressure loss from the inlet to the support plate to the core inlet plenum shall not exceed tbd psi with the support plate inlet pressure at tbd psia and the inlet temperature at tbd °R and the flow at tbd lb/sec."

At rated performance, the calculated static pressure loss from the inlet to the support plate to the core inlet is 11 psi.

"3.1.1.1.3.1.4.2 Axial Flow Temperature Variations

The azimuthal and radial temperature variations shall not exceed tbd °R at the support plate exit (core inlet plenum) under all NSS rated temperature operations."

For all NSS rated temperature operations, the combined azimuthal and radial temperature variations attributable to the support plate do not exceed 5°R.

"3.1.1.1.3.1.5 Thermal-Hydraulic Characteristics

The SPP shall accommodate the requirements of 3.1.1.1.5.1.2 (Startup Operations), 3.1.1.1.5.1.3 (Steady State Operations), 3.1.1.1.5.1.4 (Shutdown Operations), and 3.1.1.1.5.1.5 (Cooldown Operations) of CP-677555A. The steady state and throttle hold thermal-hydraulic characteristics of the SPP pertinent to Normal Mode shall be in accordance with Tables 1 through 4."

Table 6-1 summarizes the Induced Thermal Environment of the SPP for Normal Mode Operation for the graphite core design.

"3.1.1.1.3.2.1 Single Turbopump Operation Mode

The SPP shall meet the requirements of 3.1.1.1.5.2.1 (Single Turbopump Operation Mode) of CP-677555. In supporting Single Turbopump Operation Mode, the performance requirements of the SPP are within the range of performance characteristics specified in 3.1.1.1.3.1 (Normal Mode) except that the steady state and throttle hold thermal-hydraulic characteristics shall be in accordance with the values of Tables 5 through 8.

The flow characteristics referred to above are presented on Table 6-1. These data indicate that the range of flow parameters during Single Turbopump Operation are within the performance requirements of the Normal Mode of Operation.

"3.3.1.9 Growth Characteristics

The SPP shall satisfy the requirements of 3.3.1.17 (Growth Characteristics) of CP-677555A. The steady state thermal-hydraulic characteristics ($T_c = 4500^\circ\text{R}$) shall be in accordance with Tables 14 and 15."

The growth mode characteristics were evaluated and are presented in Section 6.5.2.1.

6.4 METHOD OF ANALYSIS (DESIGN PRACTICES)

This section presents the design practices used to obtain the support plate and plena thermal and fluid environment. The analytical procedures and the analytical models used to implement the design practices are described. In addition, a discussion of the maturity of the input data and the validity of the analysis are given. The detail analysis is within the framework of the overall computational network discussed in Chapter 2.4.1, and is designated a Step 4 calculation.

6.4.1 Analytical Procedures

In this subsection, the analytical procedures selected for the evaluation of the thermal-hydraulic model are presented. The justification for using the procedure, the assumptions used in the analysis, and computer codes selected to evaluate the analytical model are discussed. The analytical procedures are consistent with the overall thermal design procedures presented in Section 2.4.1.2.

A study was performed to evaluate temperature stratification in the support plate mixing plenum and local hot spots in the support plate due to the impingements of jets of support stem effluent against the aluminum walls of the annular mixing cells. This study indicated that the support plate design was not sensitive to any possible stratification or local jet impingement effects and confirmed the applicability of the analytical procedures used to calculate the three-dimensional temperature distributions in the support plate structure.

A three-dimensional finite element model, using the TAP-A computer code, was used to calculate the thermal-hydraulic performance of the support plate during steady state and transient operation. Refer to section 2.4.1.2 for a description of the TAP-A computer code. The TAP-A model provides a good representation of the complex, three-dimensional geometry of this ECC as reported in the E-105 Data Item. Since the radiation environment of the support plate is more severe when the NSS employs a graphite core than a composite core, the analysis of the support plate was performed using heating rate data and a thermal-hydraulic environment corresponding to a graphite core. Fluid boundary conditions for this TAP-A model were obtained from Chapter 2 of this Data Item.

The analytical procedures used can be justified on the basis of the complexity of the SPP, in particular, the three plena mixing design and the variability in boundary conditions. The indicated depth of analysis is necessary to provide sufficiently detailed steady state and transient temperature distributions of the SPP components for the computation of the structural reliability.

Temperatures in the piping, piping cylinder, and central dome were calculated based on one-dimensional analysis at the points of interest. Pressure drops in the feed piping were calculated using isothermal, incompressible fluid properties.

The following is a summary of the major assumptions related to the SPP analytical model:

1. All flow channels were assumed to contain completely mixed flow. Mixing studies reported in Section 6.5.2.1 confirm the applicability of this assumption in the mixing plenum.
2. Heat transfer coefficients were calculated from the modified Petukhov correlation.
3. The thermal contact impedance between the support plate and the reflector forward extension ring was assumed to be negligible at the bolted joint.
4. The support plate OD surface was considered an adiabatic surface.
5. The feed and bypass piping were assumed to be insulated for support plate calculations.
6. The flow distribution in the support plate feed plenum was determined by assuming the flow in each individual support stem to be proportional to the corresponding unfueled element radial power factor.
7. The bypass flow distribution was considered the same as the feed flow distribution.
8. Nominal dimensions are used for all parts and coolant channels.
9. Heat removal or input at the pressure vessel OD by radiation to the space environment during powered operation was neglected.

6.4.2 Analytical Models

This subsection describes the analytical models which were used to calculate temperatures and pressures throughout the support plate and plena components. The component Step 4 thermal-hydraulic models of these components were prepared from WANL Drawing No. 940J449.

6.4.2.1 Support Plate TAP-A Model

The support plate thermal model consists of a representative section, 1.7278 inches wide, extending center line to the periphery of support plate, as shown on Figure 6-1. The remainder of the plate is assumed to have the same average radial temperature profiles. In this model, all radial locations have 10 axial layers which correspond to the 10 axial layers used for structural analyses. Figure 6-2 shows the node division lines from both the top view and the side view. The external surfaces of this model in the circumferential and radial direction are assumed to be adiabatic. The forward and aft surfaces are coupled by convection to the fluids present in the support plate inlet plenum and in the core inlet plenum. The peripheral aft face of the plate is coupled by conduction to the aluminum structure of the reflector.

The internal nodes are coupled by convection to the feed plena, mixing plena, bypass plena, and the axial-flow channels. Figure 6-3 shows the surface node locations. The surfaces represent all fluid interfaces to the support plate aluminum structure in the short radial holes, in the annuli around each stem holder, and in the axial flow holes.

To obtain the proper fluid boundary conditions for the internal surfaces of the support plate plena, several iterations were performed between the TAP-A calculations and the specified boundary temperatures. The surface flux output from a TAP-A calculation are summed and the fluid temperature rises within the support plate are calculated for the feed, mixing, and bypass plena. The new fluid conditions are then applied to another TAP-A calculation and the process is repeated until a converged solution is obtained.

6.4.2.2 Model for Calculating Radial Pressure Distributions

The radial pressure distributions in the support plate were calculated by analyzing the pressure losses in each radial flow path. A schematic diagram of the flow network is shown in Figure 6-4. The support plate was considered to have eleven radial regions. The feed and bypass flow rates were adjusted according to the radial power factor to provide approximately uniform SSA outlet temperatures. Each radial region contains the appropriate number of support stem sinks, each having a feed, bypass and mixing plenum as shown in Figure 6-4.

The pressure drops in the support plate radial flow channels were calculated using the equation for an isothermal, incompressible fluid:

$$\Delta P = \frac{(C_L + f L/D)}{2 g A^2} V W^2 = R V W^2 \quad (1)$$

where	ΔP	=	pressure drop (psi)
	C_L	=	local loss coefficient
	f	=	friction factor
	L	=	flow passage length (in.)
	D	=	hydraulic diameter (in.)
	g	=	gravitational constant (386.4 in/sec ²)
	A	=	flow area (in. ²)
	V	=	specific volume (in ³ /lb)
	W	=	flow rate (lb/sec)
	R	=	the total impedance coefficient (sec ² /in ⁵)

The values of the loss coefficients are given in Section 6.4.2.7.

6.4.2.3 Model for Calculating Piping Conditions

The schematic of the feed piping is shown in Figure 6-5. The local pressure losses were calculated for each section of the piping according to equation (1) and were summed to obtain the total pressure loss. The pressure drops were itemized for three separate sections. The circled numbers on the feed piping schematic show the end points of each section. The loss coefficients used in the pressure drop analysis are presented in Section 6.4.2.7.

Temperatures in the feed piping were calculated at four different locations. These four locations are shown on Figure 6-5 by the circled letters A, B, C, and D.

A is the torus at the feed pipe closest to the torus inlet.

B is the torus at the feed pipe farthest from the torus inlet.

C is the feed pipe outside the peripheral shield.

D is the feed pipe within the peripheral shield.

The temperatures in the bypass piping were calculated at the corresponding four points in the bypass piping system.

6.4.2.4 Model for Mixing Study

The drawing of the mixing plenum at a support stem, the region considered in the mixing analyses, is presented in Figure 6-6. This figure shows the chamber where the stem discharge and bypass flows mix. This combined flow discharges into the portion of the support plate mixing plenum, which is an annulus about the stem holder, where it is channeled into the three 0.562" channels of the mixing plenum.

6.4.2.5 Compatibility of Analytical Model with the Design

The support plate TAP-A model explicitly represents the actual component, as evidenced by a comparison of the support plate analytical model configuration shown on Figure 6-1 with the actual component shown on Drawing 939J440. Axial and radial heat transfer by conduction and convection, spacial variation of internal heat generation, temperature effect on material thermal conductivity are all accounted for under steady state and transient conditions.

6.4.2.6 Boundary Conditions

It is necessary to specify boundary conditions applicable to the conduction calculations. These boundary conditions include heat transfer coefficients, fluid bulk temperatures, plenum temperatures and pressures. The steady state boundary conditions applicable to the SPP are shown in Table 6-1 for the graphite core. Similar information for the composite core is available in the NSS thermal and fluid environmental tables in Figure 2-1B and 2-1C. Heat transfer coefficients are calculated from these environmental steady state data or the applicable TNT-II transient startup and shutdown results, and the geometrical configuration. The heat transfer coefficients are obtained from the simplified Petukhov correlation in Reference 1.

$$Nu = C (Re)^{0.8} (Pr)^{0.4} \left(\frac{T_b}{T_w} \right)^P \quad (2)$$

where

Nu = Nusselt modulus , Evaluated at Bulk Fluid Conditions

Re = Reynolds Number , Evaluated at Bulk Fluid Conditions

Pr = Prandtl modulus , Evaluated at Bulk Fluid Conditions

T_b = Fluid bulk temperature

T_w = Wall temperature

C = Constant which is determined as a function of X/D

P = Constant which is determined as a function of X/D

X = Length from channel entrance

D = Channel hydraulic diameter

The values of C and P in the radial channels were taken for an X/D ratio of 0.5. This value was used because the plate radial flow channels are a series of short channels which compose the radial flow paths. For the axial flow channels, an X/D ratio of 6 was used to determine C and P. The following values of C and P were used:

C = 0.025

P = 0.13 for the radial flow channels

P = 0.15 for the axial flow channels

The McCarthy-Wolf turbulent heat transfer correlation was used to determine the film coefficients at the feed and bypass piping ID surfaces and at the OD surfaces within the peripheral shield. This equation is the same as equation (2) with C = 0.025 and P = 0.55. (Refer to Section 2.4.3.5 for further discussion of this correlation.).

The film coefficient at the OD of the feed and bypass piping in the dome region was taken from Page 490, Figure 17-6 of Reference 2.

6.4.2.7 Pressure Drop Relationships

The pressure drops in the feed piping and support plate radial flow passages were calculated based on information in Reference 3. The general form of the equation for calculating pressure drops is equation (1) of Section 6.4.2.2.

$$\Delta P = \frac{(C_L + fL/D)}{2gA^2} V_W^2 = R V_W^2$$

Refer to Section 6.4.2.2 for definition of variables.

The values of the loss coefficients are discussed below.

a. Support Plate Feed, Mixing and Bypass Plena

Conservative loss coefficients (those which give pressure drops on the high side) were used for the calculation of the radial flow channel pressure drops. Figure 6-7 presents a schematic of the radial flow channel about a typical support stem. The flow locations of interest are labeled 1, 2, 3 and 4. The table below presents the typical values of loss coefficients, C_L , and impedance coefficients, R , for each typical location in the radial flow path. This table also shows that 90% of the radial pressure drop is a result of losses at the inlets to and the exits from the annular plena.

<u>Flow Passage</u>	<u>Location</u>	<u>C_L</u>	<u>$R(\text{sec}^2/\text{in}^5)$</u>	<u>% of total ΔP</u>
Plenum supply channel	1	0.04	0.001	1%
Plenum supply channel outlet	2	1.8	0.061	70%
Annular plenum	3	0.4	0.005	9%
Plenum supply channel inlet	4	0.5	0.017	20%

Refer to equation (1), Section 6.4.2.2 for definition of C_L and R . The frictional loss term in the pressure drop calculation is included in the C_L values given.

Figure 6-4 is a schematic of the feed mixing and bypass flow passages. This figure shows that as the fluid in the feed and bypass plenums flows from the plate OD, fluid is bled from these plenums at each stem. The rate of bleed flow into each stem was assumed to be directly proportional to the core unfueled power factor at each stem radius. This flow distribution provides approximately uniform mixed plenum temperatures. The mixing plenum carries the stem discharge and the bypass flow back to the plate OD.

b. Feed Piping

The loss coefficients were obtained from Reference 3. The feed piping pressure losses were divided into three sections: (1) the screen at the pressure vessel penetration; (2) the torus and torus inlet pipe; and (3) the inlet tubes. Table 6-3 lists all the loss coefficients and corresponding impedance coefficients which determine the losses in each section. The frictional loss terms are presented in terms of the head loss, which equals fL/D .

6.4.3 Maturity of Input Data

This subsection describes the major input data required for the analytical model and the maturity of these data.

6.4.3.1 Reference Profiles

The startup and shutdown boundary condition data used to perform the SPP analysis were obtained from the "Reference NSS Profiles" discussed in Section 2.4.3.1. These Profiles reflect the extreme rate of chamber temperature change of $+175^{\circ}\text{R}/\text{sec}$ during the thrust buildup phase of startup and $-175^{\circ}\text{R}/\text{sec}$ during temperature retreat phase of shutdown.

6.4.3.2 Materials Properties Input

The support plate is made from aluminum 6061T61. The material properties were taken from the Thermal Design material properties library which is described as material number 74 in Reference 4. Irradiated data was unavailable for this material; however, data on aluminum 6061T61 showed no significant change on thermal conductivity due to irradiation; therefore, the unirradiated aluminum 6061T61 thermal conductivity was used for both the SOL and EOL conditions. The 800°R support plate material temperature limit was obtained from Reference 5.

The piping is made from aluminum 6061T6. The material properties are obtained from material number 51 of the Thermal Design material properties library as described in Reference 4.

The fluid properties were obtained from the WANL library of parahydrogen properties. Section 2.4.3.2 describes more fully the use of the parahydrogen properties.

6.4.3.3 Heating Rates

The heating rates used in these analyses were obtained from Reference 6. The average support plate heating rate is $.243 \text{ BTU/sec/in}^3$. The radial power factors vary from 1.58 for the column of nodes near the centerline to 0.525 for the column of nodes at the OD. The axial power factor varies from a value of 1.67 for the thermal model axial layer number 1 to a value of 0.562 for axial layer 10. These heating rates agree within 3% of the values presented in Reference 7.

6.4.4 Validity of Analysis

In this subsection, applicable test data used to substantiate the method of analysis are presented. The uncertainty analysis is presented for each design parameter relevant to the Support Plate and Plena.

6.4.4.1 Applicable Test Results

a. Reactor Tests

The analysis techniques and procedures described in Section 6.4.1 were applied to the aluminum support plate during the NRX Technology program. Although the NRX geometry was a different design concept than those discussed herein for R-1, the same engineering analysis approach was used on both. Boundary conditions from TNT were applied to detailed components analysis. The NRX A-6 Test Report (Reference 8) shows the results of such analyses compared with test data.

6.4.4.2 Uncertainty Analysis

The uncertainties of important thermal parameters of the SPP components (such as uncertainty of material temperatures, temperature differences, and pressure differentials, etc.) were obtained from the TNT-II Monte Carlo uncertainty analyses reported in Section 2.4.4.2.

The uncertainties are one sided limits obtained from 30 analysis cases, plus the nominal case for a 99% proportion with 95% confidence, based on 30 degrees of freedom as discussed in Section 2.4.4.2. The TNT-II NSS model calculates material temperatures and fluid conditions. Selected uncertainties for input parameters were varied by Monte Carlo to obtain the mean values, standard deviations, and 99%/95% confidence tolerance limits for the calculated output parameters.

The composite core NSS model was the basis of the Monte Carlo analyses; however, the results are applicable to the graphite core. The percentage uncertainty (99%/95% confidence) shown in Tables 6-4 and 6-5 were applied to the nominal parameters calculated in the detailed Step 4 analysis. These results are those reported as uncertainties.

The tables in this report which present nominal calculated conditions, also list the 99%/95% uncertainty values. This 99%/95% uncertainty range is 3.06 times the standard deviation value of the Monte Carlo for 30 degrees of freedom and are considered one sided limits (i. e., 99% proportion is below the upper tolerance limit or 99% proportion is above the lower tolerance limit at 95% confidence; the limits are not applied simultaneously).

6.5 RESULTS, ANALYSES, AND INTERPRETATION

This section presents the results of detailed Step 4 analyses to determine the support plate and plena system Thermal and Fluid Flow performance at "worst case" operating conditions. Included are: (1) a general discussion of the thermal analyses and their significance to other Data Items, and (2) a presentation of a study of fluid mixing internal to the support plate. Results of this mixing study confirmed the applicability of the methods of calculating three-dimensional temperature distributions reported.

The thermal analysis of the support plate and plena provides three-dimensional temperature distributions in the component, which are input to stress and deflections analyses as reported in the S-036 Data Item (Reference 9). Axial pressure drop loading and internal temperature distributions are two key thermal parameter inputs to structural analyses.

6.5.1 Composite Core

The heating rates and the thermal environment of the support plate is more severe when the NSS has a graphite core rather than a composite core; therefore, the analysis of the support plate was performed using heating rate data and a thermal hydraulic environment corresponding to an NSS with the graphite core. In addition to the higher heating rates, other factors which result in the more severe graphite core designs are listed below.

1. The composite core feed flow is less than the graphite core feed flow at the comparable operating steady state conditions; thus, the material temperature difference between feed plena and bypass plenum regions (which relate to deflection) are somewhat less for the composite core than for the graphite core design.

2. The support stem fluid discharge temperatures are similar for the composite and the graphite core; however, when combining the higher stem flows at essentially the same exit effluent temperature with essentially the same bypass, the mixed mean bulk temperature and heat transfer coefficient in the mixing plenum is higher for the graphite core. This trend results in slightly higher channel wall temperatures. For the above reasons, the graphite core support plate was analyzed as the worst case.

6.5.2 Graphite Core

The following sections present the results of thermal and fluid flow analyses made on the Support Plate and Plena system, comprising the support plate, its associated piping for feed and bypass fluids, the piping cylinder separating the peripheral shield flow from the central shield flow, and the central dome components. Fluid mixing internal to the support plate is also discussed. One sided 99%/95% tolerance limits on the key thermal and fluid flow parameters are given in summary form with the nominal values.

6.5.2.1 Steady State Performance

a. Fluid Mixing Internal to the Support Plate

The effect of unmixed fluids discharging from the stem upon the support plate temperatures have been evaluated and determined to be acceptable. However, the mixing

study, Reference 10, identified the aspects of the support plate design that were effected by mixing, and the design was modified to make the support plate less susceptible to an unmixed fluid environment from the stems. The modifications included the support stem holder being changed so that the bypass and stem discharge gases are mixed within the holder before being discharged into the support plate mixing plenum. The schematic of this stem holder design is given on Figure 6-6, which corresponds to WANL Drawing No. 939J738. This design avoids the fluid stratification problem by mixing the constituent gases prior to entry into the mixing plenum.

To further assure the support plate adequacy, the mixing study results discussed herein are for a condition of severely unmixed stem effluent, which is judged to be an improbable operating environment in the mixing plenum, and the mixing analysis was performed using the conservative assumption that the mixing plenum gases are unmixed. The results of this analysis, presented below, show that even with unmixed gases, the wall temperatures do not exceed the maximum temperature limitations.

The complete analysis, presented in Reference 10, was performed for the minimum stem flow SOL condition, with a stem discharge temperature of 1033°R . (Refer to Section 6.4.2.4 for the description of the mixing plenum model which was analyzed.). The bypass flow and the support stem discharge flow exit into an annular region about the stem holder. The flow then passes into three 0.562" diameter flow channels.

One case analyzed in Reference 10 was the condition of incomplete mixing prior to the fluid entry into the three 0.562" channels. In this case, the forward most channel was assumed to carry 1033°R gas. The aft channel carried only the gas from the bypass plenum, and the mid channel carried the remaining mixture of support stem discharge and bypass gas. At this unrealistically severe condition, the maximum wall temperature was calculated to be 491°R . To allow for possible film coefficient errors, the heat transfer coefficient value was doubled and this produced a wall temperature of 607°R , which is below the 800°R material temperature limit.

The second mixing effect analyzed was hot jet impingement upon the support plate wall. This impingement of 1033°R stem discharge gas on the aluminum structure produces a maximum calculated wall temperature of 628°R. A variation of this condition was analyzed to account for deviations from the nominal. The thermal conductivity of the support plate was reduced by 20% (10% is the 1 σ value), the axial flow channel film coefficient was reduced by 20% and the jet impingement film coefficient was doubled. The local wall temperature then was calculated to be 770°R, below the 800°R maximum allowable temperature.

These cases of extreme unmixed gases in the mixing plenum do not cause the plate temperature to exceed the upper limit. With the current design of the stem holder, the possibility of grossly unmixed gas in the support plate as discussed above is very unlikely. It is concluded that in the present design of the support plate with the internal mixing of the stem discharge and bypass fluid within the stem holder, the support plate is not susceptible to the unmixed condition. In an "improbable case" situation, the temperature of the support plate is still satisfactory.

b. Support Plate and Plena Thermal and Fluid Flow Analysis

1. Rated Performance, Start of Life (SOL), Normal Mode Operation

This operating condition has the lowest nominal feed flow rate which results in the highest support plate temperatures. Figure 6-8 shows the radial temperature profile at rated performance SOL for each of the 10 axial layers (See Figure 6-2). Throughout the center portion of the plate, the axial flow passages account for the majority of the heat transferred, the plate average temperatures are similar to the axial flow temperatures. Near the OD, the void fraction of axial coolant channels decreases so that the plate material temperatures approach the fluid temperatures in the adjacent radial channels of the plate; thus, in the outer radial region the axial temperature differences are larger than in the central region. The material temperatures are highest in the mixing plenum region near the OD, because at that location the mixing plenum wall temperatures are near the fluid temperatures in the mixing plena. The nominal maximum material temperature is 507°R, well below the maximum allowable temperature of 800°R.

Feed flow is lowest at SOL; therefore, temperature differences between the feed and bypass region are minimal. As shown in Table 6-6, the feed region nominal material temperature is 289°R , the mixing region nominal material temperature is 387°R , and the bypass region nominal temperature is 349°R . Since this condition represents the minimum nominal temperature difference between feed and bypass regional material temperatures, the support plate thermal induced deflection would be expected to be least at the SOL operating condition.

Each average temperature in Table 6-6 is an average of a portion of the 10 axial nodes used in the TAP-A model. Figure 6-2 shows the location of each of the 10 axial nodes. The following list shows which layers were averaged to obtain the summary averages.

Feed plenum = Layers 10, 9, 8, and half of 7

Mixing plenum = Layers 6, 5, half of 7, and half of 4

Bypass plenum = Layers 3, 2, 1, and half of 4

The table shows the maximum and minimum nominal material temperatures, and the volume weighted average nominal temperature for the feed plenum region, mixing plenum region, and the bypass plenum region for each condition analyzed. The maximum and minimum nominal temperatures shown are local nodal conditions in the plate.

The feed, bypass, and mixing plenum fluid temperatures vary with the radius. Figure 6-9 shows these fluid temperatures as a function of radial location. The fluid temperature rises shown are a result of the heat transferred from the aluminum structure. The temperatures given for the feed fluid represent the fluid temperature at the inlet to the stem holder and do not include the heat pick up of the gas passing through the stem holder entering the stem. The indicated feed fluid temperature rise is 48°R between the OD and the central stem. This temperature rise is approximately 10° higher, for a feed flow at the lower specification extreme value of 5.8 lb/sec. This feed flow radial temperature distribution will factor into the support stem orificing as detailed design progresses. Figure 6-9 also presents a bypass flow temperature rise of about 120°R from the plate inlet to the central stem region to the OD region. The mixing plenum nominal temperature is about 557°R at the centerline and about 540°R at the OD.

2. Support Plate at Rated Performance, End of Life, (EOL), Normal Mode

This condition has a higher feed flow than the SOL condition; consequently, the support plate temperatures are lower than they are at SOL. Detailed radial temperature profiles at EOL for each of the 10 axial layers are presented in Figure 6-10. The general temperature distributions are similar to those at SOL. The maximum nominal material temperature is 440°R at EOL.

The summary temperatures, presented in Table 6-6, indicate that the average nominal material temperatures are 269°R in the feed plenum region, 360°R in the mixing plenum region, and 342°R in the bypass plenum region. Since this ΔT between the feed and bypass is higher than the SOL value, the thermal induced deflection is expected to be greater at EOL than at SOL.

The feed, mixing, and bypass fluid temperature within the plate are shown on Figure 6-11 for the EOL condition. These temperatures were calculated in the same manner as those for Figure 6-9, as described in Section 6.5.2.1.b.1. The total nominal fluid temperature rise radially in the feed channel is 30°R from the plate OD to the central stem.

The corresponding bypass flow temperature rise was 120°R , and the mixing plenum temperatures varied radially only 7°R .

3. Support Plate at Throttle Hold Performance, Start of Life (SOL), Normal Mode

The throttle hold thermal environment has lower bypass flows and higher feed flows than the rated performance cases. The resulting temperature differences are higher than the corresponding SOL rated performance values. Figure 6-12 shows the radial temperature distribution in the support plate for each of the 10 calculated axial stations. These temperature distributions are similar to the EOL temperatures except the SOL throttled temperatures are 10°R to 25°R higher.

Figure 6-13 shows the temperature distributions of the feed, mixing, and bypass fluids in the plate for throttled SOL. The feed flow temperature increases by 30°R between the point it enters the plate and the point it reaches the central stem holder. The bypass fluid temperature increases 140°R . The mixing plenum fluid temperature varies radially by only 2°R .

4. Support Plate at Throttle Hold Performance, End of Life (EOL), Normal Mode

This condition is of interest because the support plate is the coldest and the temperature differences between the feed region and bypass region material temperature is the highest. Figure 6-14 presents the detailed radial temperature distributions in the support plate for each of the 10 calculational axial layers. The average nominal material temperatures presented in Table 6-6 are 262°R in the feed regions, 349°R in the mixing region, and 346°R in the bypass region. The maximum nominal temperature is 390°R while the minimum nominal temperature is 129°R .

Figure 6-15 shows the throttled EOL fluid temperature distributions in the feed, mixing, and bypass channels. The feed fluid temperature rises about 20°R as it flows from the plate OD to the central stem holder. The bypass fluid temperature rises 140°R . The fluid temperature in the mixing plenum remains about constant with respect to radial location.

5. Support Plate Pressure Distributions

The pressure losses in the radial flow passages within the support plate are relatively small. Figure 6-16 shows the pressure drops in the feed and mixing plenums as a function of radius for the nominal rated performance SOL condition. The temperature of the fluid for

the pressure loss calculations were taken from the radial fluid temperature profiles of Figure 6-9 . The feed pressure loss from the OD to the central stem is 0.95 psi. The mixing plenum pressure loss is 1.2 psi from the central region to the plate OD.

The pressure losses in the feed and mixing plenums as a function of radius are presented in Figure 6-17 for the nominal EOL rated performance condition. The fluid radial distribution shown in Figure 6-11 was used to obtain the fluid conditions. At EOL, the maximum radial nominal pressure drop in the feed plenum is 2.05 psi. The maximum radial pressure loss in the mixing plenum is nominally 1.83 psi.

6. Influence of Specification Extreme on Support Plate Performance

Sensitivity analyses were performed at the Throttled End of Life (EOL) operating condition where the greatest temperature difference between the feed region and bypass region material temperatures were observed. The effect of the variances in thermal conductivity values, in film coefficient values, and in feed and bypass flows were evaluated.

The support plate temperatures were calculated with the thermal conductivity value raised by the one sigma value. This produced a maximum material temperature variation of 4.5°R from the nominal value. The maximum variation from the nominal condition in the average temperature of any of the three axial regions was only 1.1°R , which occurred in the bypass plenum. The conclusion is that thermal conductivity uncertainties have minimal effect on the support plate performance.

The effect of a 25% increase in the radial channel film coefficient values was evaluated. This condition caused the heat pickup in the feed channel to increase by 8.5%. The relative temperature difference between the feed and bypass plenum regions, however, changed insignificantly.

The most significant variation analyzed was a variation in feed and bypass flow rates. The flow uncertainties were based on the Monte Carlo analyses reported in Section 2.4.2. The Monte Carlo results showed that at a 95% confidence, there is a 99% proportion where the stem flow will not differ from the nominal flow by more than 2 lb/sec at the EOL Throttle operation. The bypass flow uncertainty was 0.1 lb/sec. The support plate, therefore,

was analyzed at a feed flow of 17.2 lb/sec (2 lb/sec higher than the nominal flow) and a bypass flow of 2.1 lb/sec (0.1 lb/sec lower than the nominal flow). The detail radial temperature profiles for this condition are presented in Figure 6-18 . The summary temperature table, Table 6-6 , shows the average temperatures to be 254°R in the feed plenum region, 335°R in the mixing plenum region, and 342°R in the bypass plenum region. This ΔT between the feed and bypass region is only 4°R greater than nominal ΔT .

In addition, the Monte Carlo results from the TNT-II analysis were applied on a percentage basis to determine the 99/95% one sided tolerance limits on key support plate parameters as shown in Summary Table 6-2 . The upper and lower tolerance limits are shown with the nominal key parameter values resulting from the Step 4 detailed analyses.

7. Support Plate at Rated Performance, Growth Mode

A comparison was made between the conditions of the growth mode of operation and the conditions of the normal mode rated operation. During the growth mode operation, the feed flow is slightly larger than the feed flow at the comparable normal mode operation. The stem discharge temperatures are approximately the same for the two modes of operation. The bypass flows do not change significantly between the two modes of operation. (Refer to Section 2.5.2 for more information on the growth mode operating conditions).

At the SOL condition, the stem flow is 6.4% higher for the growth mode than for normal mode analysis. This flow change would tend to increase the ΔT between the feed and bypass regions. Based on the sensitivity of temperature to stem flow, the increase in temperature differences is small.

At the EOL condition, the feed flow is 8.4% higher in growth mode operation than in normal mode operation. This increased feed flow results in an increase in the ΔT between the feed and bypass regions. At EOL, TNT-II calculated this ΔT to be 8°R greater in growth mode operation than in normal mode operation. A corresponding increase of 23°R occurs in the material maximum temperature. These increases would have minor effect on the support plate thermal performance.

c. Support Plate Feed and Bypass Flow Supply System

The feed and bypass piping system comprise the inlet torus and bypass torus and the tubing lines from the torus to the support plate plena as shown on WANL Drawing 939J725.

1. Feed Flow Supply System

The feed fluid flows from the dome, through the inlet torus, and through the inlet tubing to the support plate feed plenum. The feedline pressure drops, together with the impedance coefficients are given in Table 6-7. This table lists the pressure drops and impedance coefficients for the screen, torus, and inlet tubes. The pressure drops are calculated for the normal mode operation at rated performance SOL, EOL, and throttle hold EOL. The maximum nominal feedline pressure drop, 5.2psi, occurs at throttled EOL. The plot of feedline pressure drop as a function of stem flow is presented in Figure 6-19.

The material temperatures of the Feed Flow supply system are presented in Table 6-8. The nominal temperatures range between 155°R and 285°R at rated SOL conditions, and range between 119°R and 302°R at the throttled EOL condition.

Fluid heat pickup in the feed flow supply system is important because this heat pickup influences the support stem and support plate performance. In the region of the feed torus, the heat transfer varies with azimuthal distance from the entrance to the torus because flow is distributed to each of the 30 feed pipes as the fluid passes through the torus. At SOL, the fluid temperature rise in the feed torus, as presented in Table 6-9, is 0.6°R at the inlet tube nearest the torus inlet and 15°R at the inlet tube farthest from the torus inlet. These two torus locations are respectively the locations of minimum and maximum fluid nominal temperature rise in the torus. Refer to Figure 6-5 for the schematic of the inlet piping.

The inlet tubes originate at the torus, pass through the peripheral shield exit plenum, pass through the peripheral shield, and terminate at the support plate OD. Within the peripheral shield, a 5 mil radial gap was assumed to exist between each feed pipe OD and the peripheral shield. The gas velocity in this gap was assumed to be the same as the gas velocity through the holes in the peripheral shield. The fluid temperature rise in the inlet tubing shown in Table 6-9 is nominally 22°R at SOL and 18°R at EOL.

The fluid temperature rise in the uninsulated inlet torus and in the inlet tubes has undesirable effects. The heat pickup in the torus causes non-uniform feed fluid temperatures in the plate, resulting in azimuthal pressure and temperature variations in the plate feed

plenum. These variations will affect the orificing of the stems. Heat pickup in the inlet piping, which raises the support stem inlet temperatures, causes a decrease in the stem inlet fluid density thus affecting the reactivity control available by stem flow control.

WANL Drawing No. 939J725 has uninsulated inlet torus and inlet tubing. Insulating the feed flow supply system tubing will improve support stem performance. The effect of adding the thermal impedance of a 5 mil stagnant hydrogen gap to the piping OD was investigated. This insulation decreases the fluid temperature rise in the inlet tubes by a factor of 7 and decreases the maximum fluid temperature rise in the torus by a factor of 3. Thus during the post PDR design period, it is recommended that investigations of insulating the post PDR design period, it is recommended that investigations of insulating the feed flow supply system be made to reduce the heat pickup in this section. The support plate detailed calculations were based on the assumption that the feed system could be insulated effectively.

2. Bypass Flow Supply System

The bypass flow supply system carries hydrogen flow from the dome penetration to the support plate bypass plenum. The temperatures and heat fluxes are calculated in the same manner as those for the feed flow system. Table 6-8 shows the material temperatures in this flow system. The nominal temperatures vary between 125°R and 308°R . The fluid temperature rises in the bypass torus and tubing are shown in Table 6-9. The maximum nominal fluid temperature rises occur at throttled EOL. At this condition, the fluid temperature rise in the bypass tubes is 19°R . In the bypass torus, the temperature rise is 3°R to the first bypass tube entrance and 11°R to the last bypass tube entrance. It is recommended that the bypass system also be insulated to reduce the variations of bypass fluid conditions in the support plate. Insulated bypass piping was assumed for the support plate analyses.

3. Influence of Specification Extreme on Feed and Bypass Flow Systems

The 99/95% upper and lower tolerance limit on key parameters are shown with the nominal values in the Summary Table 6-2. The tolerance limits were derived from the TNT-II Monte Carlo runs.

4. Growth Mode Operation

The thermal and fluid flow environment of the feed and bypass flow systems under the growth mode operation is very similar to that under the equivalent rated performance or throttle hold conditions. Thus no major thermal difference during growth mode operation is anticipated.

d. Piping Cylinder Conditions

The temperatures in the piping cylinder and the baffle which separates the peripheral shield flow from the central shield flow, were calculated at the normal mode rated performance SOL conditions and at the single turbopump SOL conditions. These Temperatures are represented in Figure 6-20 as a function of axial station. WANL Drawing No. 939J725 shows the cylinder.

The piping cylinder is cooled by the central shield flow on the ID and by the peripheral shield flow on the OD. At the aft end of the baffle, the adjacent central shield flow is small; therefore, all the cooling at this point is assumed to be from the peripheral shield flow. The temperatures, presented in Figure 6-20, were calculated at the normal SOL and single TPA, SOL conditions. The single TPA condition is of interest because the maximum radial ΔP occurs at this steady state operating condition. Temperatures at any other condition can be obtained from the temperatures presented since the material temperatures will vary according to fluid temperature variation. The cylinder OD temperature remains within 2°R of the peripheral shield fluid temperature. The forward ID temperature of the cylinder is about 2°R higher than the central shield fluid temperature. The aft ID temperature of the cylinder is about 19°R higher than the OD at rated power conditions. This radial ΔT vary proportionally to any other reactor power level. Summary Table 6-2 tabulates the nominal values of the key thermal parameters with the 99/95% one sided upper and lower tolerance limit derived from the TNT-II material results. All operating temperatures are well within any materials limit.

e. Central Dome Conditions

The central dome is the baffle which separates the peripheral shield exit flow from the central shield inlet flow. The average temperatures in this plate are about midway

between the fluid temperatures of the NSS exit to the turbine and NSS inlet from the turbine. The internal heating in the central dome causes negligible temperature gradients in this component. Summary Table 6-2 shows the nominal temperature of the central dome with the 99/95% tolerance limit. All temperatures are well within the material capability.

6.5.2.2 Transient Performance

The TNT-II support plate calculations provide temperature trends which can be used to predict support plate performance variations during startup and shutdown. As reported in Section 2.4, TNT-II represents the support plate with a three node model. The support plate temperature levels calculated by TNT-II are not expected to coincide exactly with those obtained from the TAP-A model temperatures, but the TNT-II calculated temperature trends are in agreement. The TNT-II support plate temperatures calculated during the normal mode startup and shutdown were used to provide design insight of the plate performance under transient conditions.

a. Start of Life and End of Life Startup Performance

The startup support plate temperatures calculated by TNT-II are presented in Figure 6-21 for SOL and Figure 6-22 for EOL. These figures show that the temperature differences between the feed and bypass plenum regions are not significantly greater at any point in the startup than they are at steady state operation. The detailed Step 4 calculations of support plate temperatures during the startup were not performed, since the conditions during startup are judged to not be significantly more severe than the steady state conditions.

b. Start of Life and End of Life Shutdown Performance

Figures 6-23 and 6-24 show the temperatures in the support plate during SOL and EOL shutdowns as calculated by TNT-II. These figures show that the maximum temperature difference between the feed and bypass regions occur at the 65% throttle hold condition. The detailed temperatures in the support plate at the throttle hold condition were calculated and are presented in Section 6.5.2.1.

6.5.2.3 Single TPA Operation

The thermal performance of the support plate is a function of the flow rates and temperatures of the fluids flowing through the plate. Since the fluid conditions for the single

TPA (80% thrust) operation are within the range of conditions between the rated performance and the throttle hold steady state operation (See the Induced Thermal Environment Table 6-1.), the detailed Step 4 calculations of support plate performance if done at single TPA conditions would show temperature distributions and temperature differences within the range calculated for the normal steady state operating mode.

6.5.2.4 Space Soak Effects

Summary Table 6-2 shows the temperature ranges expected in the support plate and plena components during space soak prior to operation. These data are a summary of that presented in Data Item S-001 (Reference 11).

6.5.2.5 Probability of Failure Analysis

At PDR technical justification is required to demonstrate that the Support Plate and Plena design concepts have a reasonable chance of achieving the NPRD requirements. The procedure is presented in Reference 12 and involves making analytical estimates of component reliability at the mode of failure level during the pre-PDR period.

The approach followed to insure that all support plate components have a high inherent reliability was to first make a thorough and unbiased listing of all the credible ways a support plate component can fail to perform. Subsequently, design changes were made to eliminate as many failure points as possible. Finally, the probability of occurrence of each remaining failure is assessed. This final calculation is presented in this subsection for failure modes directly involving thermal design aspects.

The general procedure consists of obtaining the reliability value from two overlapping normal distributions, e.g., operating temperature vs constraint. Usually the population standard deviation of the two normal distributions are not known and the reliability value is computed from the sample standard deviation (S) and the sample size (n) from each of these distributions.

The procedure as described in SNSO-C-1 is as follows:

Given: $\bar{X}_L, S_L, n$, (Operating temperature see Table 6-10)

$\bar{X}_S, S_S, n$, (Limiting temperature see Table 6-10)

Calculate: $X_{R'} = \frac{\bar{X}_S - \bar{X}_L}{\sqrt{S_S^2 + S_L^2}}$ and, $n' = \frac{(S_S^2 + S_L^2)^2}{S_S^4 / n_2 + S_L^4 / n_1}$

Obtain the population reliability (R) at 90% confidence level from curves relating sample reliability to population reliability, Reference 13.

Table 6-10 lists the modes and the mechanism of failure for support plate components which are relevant to the Thermal Design. The probability of failure (F) is $(1 - R)$ and is given in the last column of Table 6-10. The values $\ll 10^{-11}$ and $\ll 10^{-19}$ indicate the occurrence of these failure modes are highly incredible.

6.6 REFERENCES

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TABLE 6-1
INDUCED THERMAL ENVIRONMENT OF SUPPORT PLATE AND PLENA (GRAPHITE CORE)

<u>Description</u>	<u>Flow (lb/sec)</u>	<u>Pressure (Psia)</u>	<u>Temperature (°R)</u>
<u>Steady State Performance at Rated Conditions - Start of Life (SOL)</u>			
Support Plate Inlet Plenum (Main Flow)	91.2 ± 1.4	631 ± 9.4	286 ± 18.3
Core Inlet Plenum	91.2 ± 1.4	620 ± 8.6	292 ± 18.1
Structural Support Feed Line at P/V Dome	7.8 ± 2.0	1117 ± 40.7	59.7 ± 1.5
Structural Support Bypass Line at P/V Dome	3.2 ± 0.21	1070 ± 21.1	60.1 ± 1.5
Support Stem Outlet (Average)	7.8 ± 2.0	1067 ± 30.1	799 ± 1.35
Support Plate Mixing Chamber Exit	11.0 ± 2.0	1065 ± 21.1	558 ± 61.4
NSS Exit to Turbine	91.2 ± 1.4	1054 ± 20.8	303 ± 19.5
NSS Inlet from Turbine	91.2 ± 1.4	671 ± 10.6	283 ± 18.6
<u>Steady State Performance at Rated Conditions - End of Life (EOL)</u>			
Support Plate Inlet Plenum (Main Flow)	91.2 ± 1.4	632 ± 9.7	290 ± 18.6
Core Inlet Plenum	91.2 ± 1.4	620 ± 8.8	294 ± 18.6
Structural Support Feed Line at P/V Dome	11.9 ± 2.4	1137 ± 41.6	59.1 ± 1.5
Structural Support Bypass Line at P/V Dome	3.1 ± 0.21	1067 ± 21.1	59.7 ± 1.5
Support Stem Outlet (Average)	11.9 ± 2.4	1063 ± 29.5	553 ± 84.5
Support Plate Mixing Chamber Exit	15.0 ± 2.4	1061 ± 21.0	445 ± 46.8
NSS Exit to Turbine	91.2 ± 1.4	1051 ± 20.6	306 ± 19.7
NSS Inlet from Turbine	91.2 ± 1.4	672 ± 10.8	287 ± 18.8
<u>Steady State Performance at 65% Throttle Hold - Start of Life (SOL)</u>			
Support Plate Inlet Plenum (Main Flow)	59.2 ± 1.3	423 ± 8.9	333 ± 24.3
Core Inlet Plenum	59.2 ± 1.3	414 ± 8.3	336 ± 24.6
Structural Support Feed Line at P/V Dome	10.9 ± 2.1	738 ± 36.0	51.9 ± 1.5
Structural Support Bypass Line at P/V Dome	2.4 ± 0.15	650 ± 15.7	52.6 ± 1.4
Support Stem Outlet (Average)	10.9 ± 2.1	648 ± 3.2	528 ± 36.0
Support Plate Mixing Chamber Exit	13.3 ± 2.0	644 ± 15.4	440 ± 43.3
NSS Exit to Turbine	59.2 ± 1.3	640 ± 14.9	342 ± 25.3
NSS Inlet from Turbine	59.2 ± 1.3	452 ± 10.0	329 ± 25.5
<u>Steady State Performance at 65% Throttle Hold - End of Life (EOL)</u>			
Support Plate Inlet Plenum (Main Flow)	59.2 ± 1.3	423 ± 8.8	334 ± 20.0
Core Inlet Plenum	59.2 ± 1.3	414 ± 8.3	337 ± 20.0
Structural Support Feed Line at P/V Dome	15.2 ± 2.0	768 ± 36.0	51.2 ± 1.6
Structural Support Bypass Line at P/V Dome	2.2 ± 0.14	649 ± 15.3	52.2 ± 1.5
Support Stem Outlet (Average)	15.2 ± 2.0	647 ± 15.3	400 ± 44.0
Support Plate Mixing Chamber Exit	17.4 ± 2.0	642 ± 15.3	360 ± 39.7
NSS Exit to Turbine	59.2 ± 1.3	634 ± 15.0	344 ± 21.0
NSS Inlet from Turbine	59.2 ± 1.3	452 ± 9.5	331 ± 19.6

TABLE 6-1 (CONT'D)

Description	Flow (lb/sec)	Pressure (Psia)	Temperature (°R)
<u>Steady State Performance at 80% Thrust - Single TPA Malfunction - Start of Life (SOL)</u>			
Support Plate Inlet Plenum (Main Flow)	72.9 + 1.3	513 + 8.8	308 + 20.4
Core Inlet Plenum	72.9 + 1.3	503 + 8.2	313 + 20.1
Structural Support Feed Line at P/V Dome	8.1 + 2.1	1151 + 25.7	61.1 + 1.6
Structural Support Bypass Line at P/V Dome	2.5 + 0.16	1107 + 21.4	61.4 + 1.6
Support Stem Outlet (Average)	8.1 + 2.1	1106 + 19.5	724 + 10.4
Support Plate Mixing Chamber Exit	10.6 + 2.1	1103 + 21.3	544 + 54.3
NSS Exit to Turbine	73.1 + 1.3	1096 + 21.9	325 + 21.9
NSS Inlet from Turbine	72.9 + 1.3	546 + 9.9	305 + 20.7
<u>Steady State Performance at 80% Thrust - Single TPA Malfunction - End of Life (EOL)</u>			
Support Plate Inlet Plenum (Main Flow)	72.9 + 1.3	513 + 9.0	311 + 20.7
Core Inlet Plenum	72.9 + 1.3	503 + 8.3	315 + 20.3
Structural Support Feed Line at P/V Dome	12.1 + 2.6	1170 + 31.0	60.7 + 1.6
Structural Support Bypass Line at P/V Dome	2.4 + 0.16	1104 + 21.9	61.2 + 1.5
Support Stem Outlet (Average)	12.1 + 2.6	1101 + 68.7	515 + 21.7
Support Plate Mixing Chamber Exit	14.5 + 2.6	1099 + 21.9	436 + 41.3
NSS Exit to Turbine	73.1 + 1.3	1092 + 21.8	328 + 22.3
NSS Inlet from Turbine	72.9 + 1.3	546 + 10.1	308 + 21.0
<u>Steady State Performance at 65% Throttle Hold - Single TPA Malfunction - Start of Life (SOL)</u>			
Support Plate Inlet Plenum (Main Flow)	59.2	423	332
Core Inlet Plenum	59.2	414	336
Structural Support Feed Line at P/V Dome	9.8	884	54.9
Structural Support Bypass Line at P/V Dome	2.2	818	55.3
Support Stem Outlet (Average)	9.8	816	581
Support Plate Mixing Chamber Exit	12.0	814	475
NSS Exit to Turbine	59.3	807	344
NSS Inlet from Turbine	59.2	451	328
<u>Steady State Performance at 65% Throttle Hold - Single TPA Malfunction - End of Life (EOL)</u>			
Support Plate Inlet Plenum (Main Flow)	59.2	423	334
Core Inlet Plenum	59.2	414	337
Structural Support Feed Line at P/V Dome	14.0	908	54.5
Structural Support Bypass Line at P/V Dome	2.1	816	55.1
Support Stem Outlet (Average)	14.0	813	430
Support Plate Mixing Chamber Exit	16.1	810	383
NSS Exit to Turbine	59.3	803	346
NSS Inlet from Turbine	59.2	452	331

TABLE 6-2. SUMMARY OF SUPPORT PLATE AND PLENA COMPONENT MATERIAL TEMPERATURES AND OTHER KEY PERFORMANCE PARAMETERS (GRAPHITE CORE)

COMPONENT	LOCATION	PARAMETER	NORMAL MODE OPERATION						COOLDOWN OPERATION RANGE	SPACE SOAK RANGE	
			RATED PERFORMANCE 99/95 TOLERANCE LIMIT			THROTTLE HOLD 99/95 TOLERANCE LIMIT				Solar Flux of 300 Btu/HR/Ft ²	Solar Flux of 3000 Btu/HR/Ft ²
			NOMINAL	UPPER	LOWER	NOMINAL	UPPER	LOWER		(1)	(2)
Support Plate	Structure	SOL T max (°R)	507	558	456	432	470	394	(250-530°R) (1) 800°R (2)	350-550	550-900
		T min (°R)	180	158	202	151	131	171			
		T avg (°R)	342	373	311	337	367	307			
		T _{bypass} -T _{feed} (°R)	60	78	42	72	90	54			
		EOL T max (°R)	437	475	399	390	421	359			
		T min (°R)	149	169	129	129	117	141			
		T avg (°R)	324	354	294	319	343	295			
		T _{bypass} -T _{feed} (°R)	73	91	55	84	105	63			
	Feed Plenum Radial Flow Channel	Radial Fluid Temperature Rise at SOL (°R)	48	58	38	30	36	24			
		Radial Fluid Temperature Rise at EOL (°R)	30	36	24	20	24	16			
		Radial ΔP at EOL (Psi)	2	2.4	1.6						
	Bypass Plenum Radial Flow Channel	Radial Fluid Temperature Rise at SOL (°R)	120	150	90	137	171	103			
		Radial Fluid Temperature Rise at EOL (°R)	118	148	88	139	173	105			
	Mixing Plenum Radial Flow Channel	Radial Fluid Temperature Rise at SOL (°R)	-18	-22	-14	-6	-7	-5			
		Radial Fluid Temperature Rise at EOL (°R)	-7	-8	-6	-1	-1.2	-0.8			
		Radial ΔP at EOL (psi)	1.8	2.2	1.4						
	Axial Flow Channel	Fluid ΔT at EOL	3	3.5	2.5	-1.5	-2	-1			
		Fluid ΔP at EOL	11	13	9	3	7	9			

TABLE 6-2 (CONT'D) SUMMARY OF SUPPORT PLATE AND PLENA COMPONENT MATERIAL TEMPERATURES AND OTHER KEY PERFORMANCE PARAMETERS (GRAPHITE CORE) (CONT'D)

COMPONENT	LOCATION	PARAMETER	NORMAL MODE OPERATION						COOLDOWN OPERATION RANGE	SPACE SOAK RANGE	
			RATED PERFORMANCE 99/95 TOLERANCE LIMIT			THROTTLE HOLD 99/95 TOLERANCE LIMIT				Solar Flux ⁽³⁾ of 300 Btu/HR/Ft ²	Solar Flux ⁽⁴⁾ of 3000 Btu/HR/Ft ²
			NOMINAL	UPPER	LOWER	NOMINAL	UPPER	LOWER			
Feed Flow Supply System	————	SOL T max (°R)	285	301	269				(200-550°R) (1) 800°R (2)	350-550	550-900
		T min (°R)	155	175	135						
		EOL T max (°R)	282	298	266	302	323	281			
		T min (°R)	138	156	120	119	133	105			
		SOL Maximum Fluid Temperature Rise (°R)	37	42	30						
		EOL Maximum Fluid Temperature Rise (°R)	27	33	21	26	31	21			
		ΔP at EOL	3.2	4.2	2.2	5.2	6.8	3.6			
Bypass Flow Supply System	————	SOL T max (°R)	274	290	258				(275-600°R) (1) 800°R (2)	350-550	550-900
		T min (°R)	125	140	110						
		EOL T max (°R)	278	294	262	308	330	284			
		T min (°R)	128	143	113	131	147	115			
		SOL-Maximum Fluid Temperature Rise (°R)	24	29	19						
		EOL-Maximum Fluid Temperature Rise (°R)	24	29	19	30	36	24			
Piping Cylinder	————	Max. SOL Temperature	325	342	308	338	359	317	(275-600°R) (1) 800°R (2)	350-550	550-900
		Min. SOL Temperature	285	300	270	305	325	385			
Central Dome	————	Max. SOL Temperature	298	314	282	340	361	319	(275-600°R) (1) 800°R (2)	350-550	550-900
		Min. SOL Temperature	288	304	272	335	356	314			

(1) This is the temperature range within 3.65 hours after a ten minute burn and throttle hold, as reported in WANL-TME 2678 "Systems Analysis Summary Report, Nuclear Subsystem", Section 5.2.6.3

(3) This is the minimum flux shown in WANL-TME-2678 "Systems Analysis Summary Report, Nuclear Subsystem" Section 5.2.6.3. Solar Flux in earth orbit is 444 Btu/Hr/Ft² as reported in WANL-TIME-2678

(2) This is the maximum allowable temperature between cooling pulses.

(4) This is the extreme solar flux, in the vicinity of mercury as reported in WANL-TME-2678.

TABLE 6-3 LOSS COEFFICIENTS IN THE FEED PIPING

$$R = K/2gA^2$$

$$\Delta P = R V W^2$$

V = Specific Volume (in³/lb)

W = Flow Rate (lb/sec)

g = 386.4 in/sec²

	K	R (sec ² /in ⁵)
Region 1-2 Pipe I.D. = 2.62 Conical Screen No. 20 Mesh (46% Void)	.5	2.01 X 10 ⁻⁵
Region 2-3 Pipe I.D. = 2.62 55° Curve (4.3 ⁹ Radius) "T" at Manifold Torus Manifold Due to Curve and Length Manifold due to Parts Total	.143 .250 .016 .004 .413	.578 X 10 ⁻⁵ 1.010 X 10 ⁻⁵ .065 X 10 ⁻⁵ .017 X 10 ⁻⁵ 1.670 X 10 ⁻⁵
Region 3-4 30 Pipes I.D. = 0.80" Entrance Entrance Curvature 25" Length 45° Miter Bend 2-11° Miter Bends Discharge Total	.178 .232 .778 .24 .18 1.0 2.608	.125 X 10 ⁻⁵ .163 X 10 ⁻⁵ .546 X 10 ⁻⁵ .170 X 10 ⁻⁵ .126 X 10 ⁻⁵ .702 X 10 ⁻⁵ 1.832 X 10 ⁻⁵

TABLE 6-4 SUMMARY OF UNCERTAINTY TOLERANCES FOR KEY SUPPORT PLATE AND PLENA PARAMETERS (COMPOSITE CORE)*

COMPONENT	LOCATION	PARAMETER	NORMAL MODE OPERATION					
			RATED PERFORMANCE, SOL 99/95 TOLERANCE LIMIT			THROTTLE HOLD, EOL 99/95 TOLERANCE LIMIT		
			NOMINAL	TOLERANCE	TOL. %	NOMINAL	TOLERANCE	TOL. %
Plenum Temperatures	Peripheral Shield Exit Plenum	$T_{Avg.} (^{\circ}R)$	292	15.6	5.3	330	20.8	6.3
	Central Shield Inlet Plenum	$T_{Avg.} (^{\circ}R)$	273	15.0	5.5	317	19.8	6.2
Support Plate	Feed Plenum Region Material	$T_{Avg. Feed} (^{\circ}R)$	289	14.9	5.2	292	21.5	7.4
	Mixing Plenum Region Material	$T_{Avg. Mix} (^{\circ}R)$	437	40.7	9.3	363	29.0	8.0
	Bypass Plenum Region Material	$T_{Avg. Bypass} (^{\circ}R)$	353	27.6	7.8	374	25.9	6.9
	Feed, Bypass Regions	$T_{Avg. Bypass} - T_{Avg. Feed}$	64	19.2	30.	82	21	25.6
Flowrates		Feed Flow - (lb/sec)	7.1	1.8	25.4	14.1	2	14.2

*Data Obtained from TNT-II Monte Carlo Analysis
160, 10/14/70

TABLE 6-5 SUMMARY OF UNCERTAINTY TOLERANCES FOR KEY SUPPORT PLATE & PLENA PARAMETERS (GRAPHITE CORE)*

COMPONENT	LOCATION	PARAMETER	NORMAL MODE OPERATION					
			RATED PERFORMANCE, EOL 99/95 TOLERANCE LIMIT			THROTTLE HOLD, SOL 99/95 TOLERANCE LIMIT		
			NOMINAL	TOLERANCE	TOL. %	NOMINAL	TOLERANCE	TOL. %
Support Plate	Feed Plenum Region Material	$T_{Avg. Feed} (^{\circ}R)$	280	25.3	9.0	295	30.3	10.3
	Mixing Plenum Regional Material	$T_{Avg. Mix} (^{\circ}R)$	408	36.8	9.0	418	36.3	8.7
	Bypass Plenum Regional Material	$T_{Avg. Bypass} (^{\circ}R)$	351	31.5	9.0	367	31.8	8.7
	Feed, Bypass Regions	$T_{Avg. Bypass} - T_{Avg. Feed}$	69	17	24.6	72	18.4	25.6
*Data Obtained From RAM Monte Carlo Analysis, Data End Item Report S-001								

TABLE 6-6. SUMMARY OF SUPPORT PLATE STRUCTURE NOMINAL TEMPERATURES

	Average Material Temperature in Each Support Plate Region - °R					
Reactor Condition	Feed Plenum	Mixing Plenum	Bypass Plenum	$T_{\text{Bypass}} - T_{\text{Feed}}$	Maximum Mtl. Temperature - °R	Minimum Mtl. Temperature - °R
SOL	289 ± 24	387 ± 39	349 ± 31	60 ± 18	507 ± 51	180 ± 22
EOL	269 ± 25	360 ± 32	342 ± 31	73 ± 18	437 ± 38	149 ± 20
Throttle SOL	281 ± 29	376 ± 33	353 ± 31	72 ± 18	432 ± 38	151 ± 20
Throttle EOL	262 ± 19	349 ± 29	346 ± 23	84 ± 21	390 ± 31	129 ± 17
Maximum Flow Throttle EOL	254	335	342	88	388	121

TABLE 6-7. FEEDLINE PRESSURE LOSSES

$$\Delta P = RW^2V \text{ where } W = \text{Flow Rate (lb/sec)}$$

$$V = \text{Specific Volume (in}^3/\text{lb)}$$

$$R = \text{Impedance Coefficient (sec}^2/\text{in}^5)$$

Region	R	ΔP - PSI		
		Rated Performance Start of Life W = 7.8 lb/sec V = 415 in ³ /lb (60° R at 1125 psia)	Rated Performance End of Life W = 11.9 lb/sec V = 415 in ³ /lb (60° R at 1125 psia)	Throttle Hold End of Life W = 15.2 lb/sec V = 408 (52° R at 750° R)
1-2	2.01×10^{-5}	.5	1.2	1.9
2-3	1.668×10^{-5}	.4	1.0	1.6
3-4	1.832×10^{-5}	.5	1.1	1.7
1-4	5.510×10^{-5}	1.4 ± 0.4	3.2 ± 1.0	5.2 ± 1.6

TABLE 6-8 MATERIAL TEMPERATURES IN THE FEED AND BYPASS FLOW SUPPLY SYSTEM IN NORMAL MODE STEADY STATE OPERATION

	Feed Inlet Torus Temperature - °R				Bypass Torus Temperature - °R				Feed Inlet Tubing Temperature - °R				Bypass Tubing Temperature - °R			
	At Entrance		At Final Exit		At Entrance		At Final Exit		In Dome Plenum		In Peripheral Shield		In Dome Plenum		In Peripheral Shield	
	ID	OD	ID	OD	ID	OD	ID	OD	ID	OD	ID	OD	ID	OD	ID	OD
SOL	187 ± 25	199 ± 25	280 ± 30	282 ± 30	176 ± 24	189 ± 24	227 ± 21	235 ± 21	155 ± 20	164 ± 20	267 ± 16	285 ± 16	125 ± 15	135 ± 15	245 ± 16	274 ± 16
EOL	168 ± 22	182 ± 22	274 ± 30	278 ± 30	176 ± 24	189 ± 24	229 ± 21	237 ± 21	138 ± 18	147 ± 18	257 ± 16	282 ± 16	128 ± 15	138 ± 15	248 ± 16	278 ± 16
EOL (Throttled)	151 ± 20	165 ± 20	290 ± 32	296 ± 32	195 ± 26	207 ± 26	255 ± 25	262 ± 25	119 ± 14	128 ± 14	271 ± 21	302 ± 21	131 ± 16	140 ± 16	282 ± 22	308 ± 22

TABLE 6-9 FLUID TEMPERATURE RISE IN FEED AND BYPASS FLOW SUPPLY SYSTEM

		REACTOR CONDITION		
		Rated Performance SOL	EOL	Throttle Hold SOL
Fluid Temperature Rise In Inlet Torus - °R	At Inlet Tube Nearest the Torus Inlet	0.6 ± 0.1	0.4 ± 0.1	0.3 ± 0.1
	At Inlet Tube Furthest From the Torus Inlet	15 ± 3	9 ± 2	9 ± 2
Fluid Temperature Rise in Inlet Tubing	- °R	22 ± 4	18 ± 4	17 ± 3
Fluid Temperature Rise In Bypass Torus - °R	At Bypass Tube Nearest the Torus Inlet	2 ± 0.4	2 ± 0.4	3 ± 0.6
	At Bypass Tube Furthest From the Torus Inlet	9 ± 2	9 ± 2	11 ± 2
Fluid Temperature Rise in Bypass Tubing	- °R	15 ± 3	15 ± 3	19 ± 4

TABLE 6-10 FAILURE MECHANISM PROBABILITY OF OCCURRENCE

Made Ident. No.	Modes and Mechanisms of Failure	Mission Phase	Environmental Factors
-----------------	---------------------------------	---------------	-----------------------

"Stress"	"Strength"	Design Analysis (Calculated or Estimated Failure Probability or Evaluation Comments)
Mean, $\bar{X}_L$; Variance, S_L^2 ; n or Stress Comment	Mean, $\bar{X}_S$; Variance, S_S^2 ; n or Strength Comment	

Part O Ring It. No. 3			
3	Does not contain turbine inlet/turbine discharge fluid (seal leakage)		Temperature Pressure
Part Support Plate It. No. 1			
3	Melts Locally	Temperature at center portion separating the support stem feed plenum and mixing plenum is excessive	Steady State Operations Temperature
Part Segment, Baffle It. No. 9			
27	Melts	B. Temperature at inside radius is excessive	Steady State Operations Temperature
Part Plenum Closure Ring It. No. 8			
23	Melts	B. Temperature at outermost surface (O.D.) is excessive	Steady State Operations Temperature
Part Instrumentation Ring It. No. 10			
29	Melts	B. Temperature at outermost surface (O.D.) is excessive	Steady State Operation Temperature

Revision 0			
2.1×10^{-5} lb/sec	$S_L = 2.0 \times 10^{-5}$	0.01 lb/sec	$F < 1 \times 10^{-19}$
Dwg. No. 940J449			
370°R	$S_L = 112$	1150°R	$S_S = 25$ $F < 1 \times 10^{-11}$
Dwg. No. 940J410			
350°R	$S_L = 35°R$	1150°R*	$S_S = 25$ $F < 1 \times 10^{-19}$
Dwg. No. 940J410			
250°R	$S_L = 50°R$	1150°R	$S_S = 25$ $F < 1 \times 10^{-19}$
Dwg. No. 940J449			
250°R	$S_L = 50°R$	1150°R	$S_S = 25$ $F < 1 \times 10^{-19}$

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Figure 6-1. Support Plate Schematic

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Figure 6-2. Internal Nodal Diagram for Support Plate TAP-A Model

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The drawing shows a complex roof truss system. The top chord (ridge) consists of several curved members, each labeled with a number. The bottom chord (eave) also consists of curved members. Vertical posts support the truss at various points. Dashed lines represent hidden members. The overall shape is a long, narrow truss with a series of peaks and valleys.

6-53

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Figure 6-4. Schematic Diagram of Support Plate Flow Network

Note: Circled numbers refer to the points at which the ΔP 's were tabulated.

Circled letters refer to the points where the material temperatures were calculated.

Figure 6-5. Schematic of the Feed Flow Supply System

Figure 6-6. Schematic of Mixing Plenum

Figure 6-7. Sketch of Support Plate Flow Passages

639 10/19/70
741 10/20/70

A	Axial Station 1	D	Axial Station 4	G	Axial Station 7
B	Axial Station 2	E	Axial Station 5	H	Axial Station 8
C	Axial Station 3	F	Axial Station 6	I	Axial Station 9
				J	Axial Station 10

(See Figure 6-2 for location of axial stations.)

Figure 6-8. Graphite Core, Rated Performance, Start of Life, Normal Mode, Support Plate Temperature Distributions

Figure 6-9. Graphite Core, Rated Performance, Start of Life, Normal Mode, Support Plate Fluid Temperatures

639 10/19/70
741 10/19/70

A	Axial Station 1	D	Axial Station 4	G	Axial Station 7
B	Axial Station 2	E	Axial Station 5	H	Axial Station 8
C	Axial Station 3	F	Axial Station 6	I	Axial Station 9
				J	Axial Station 10

(See Figure 6-2 for location of axial stations.)

Figure 6-10. Graphite Core, Rated Performance, End of Life, Normal Mode, Support Plate Temperature Distributions

- A Bypass Temperatures
- B Mixing Plenum Temperatures
- C Feed Temperatures

Figure 6-11. Graphite Core, Rated Performance End of Life, Normal Mode, Support Plate Fluid Temperatures

Figure 6-12. Graphite Core, Throttle Hold Performance, Start of Life, Normal Mode Support Plate Temperature Distributions

- A Bypass Temperatures
B Mixing Plenum Temperatures
C Feed Temperatures

131 10/23/70
852 10/23/70

Figure 6-13. Graphite Core, Throttle Hold Performance, Start of Life, Normal Mode, Support Plate Fluid Temperatures

A Axial Station 1	D Axial Station 4	G Axial Station 7
B Axial Station 2	E Axial Station 5	H Axial Station 8
C Axial Station 3	F Axial Station 6	I Axial Station 9
		J Axial Station 10

(See Figure 6-2 for location of axial stations.)

Figure 6-14. Graphite Core, Throttle Hold Performance, End of Life, Normal Mode, Support Plate Temperature Distributions

639 10/19/70
741 10/19/70

- A Bypass Temperatures
- B Mixing Plenum Temperatures
- C Feed Temperatures

Figure 6-15. Graphite Core, Throttle Hold Performance, End of Life, Support Plate Fluid Temperatures

Figure 6-16. Graphite Core, Rated Performance, Start of Life, Normal Mode, Pressure Losses in Support Plate Feed and Mixing Plena

Figure 6-17. Graphite Core, Rated Performance, End of Life, Normal Mode, Pressure Losses in Support Plate Feed and Mixing Plena

(See Figure 6-2 for location of axial stations.)

Figure 6-18. Graphite Core, Throttle Hold Performance, End of Life, Normal Mode, 99/95 Tolerance Stem Flow Extreme, Support Plate Temperature Distributions

Figure 6-19. Pressure Drop in Feed Flow Supply System

MS932-1

Figure 6-20. Graphite Core, Steady State Performance, Start of Life, Normal Mode, and Single Turbopump Operation - Temperatures in the Piping Cylinder

FEED 1 MIXING 2 BYPASS 3

082 10/10/70

Figure 6-21. Graphite Core Start of Life Start Up Support Plate Layers Average Temperatures

144 10/7/70

Figure 6-22. Graphite Core End of Life Start Up Support Plate Layers Average Temperatures

039 9/30/70

Figure 6-23. Graphite Core Start of Life Shutdown Support Plate Layers Average Temperatures

FEED 1 MIXING 2 BYPASS 3

542 10/9/70

Figure 6-24. Graphite Core End of Life Shutdown Support Plate Layers Average Temperatures

7.0 INTERNAL SHIELD

7.1 INTRODUCTION

This Chapter describes the thermal and fluid flow analyses performed on the Internal Shield. The Internal Shield is required to attenuate radiation to specified levels to protect engine components and to provide flow passages for reactor propellant.

The Internal Shield is part of the contract end item described as the NERVA Nuclear Subsystem (NSS) and is listed as an Engineering Critical Component EC-677562 in CEI Specification No. CP-677555A. This specification establishes the thermal and hydraulic design requirements for the Internal Shield critical component.

7.1.1 Description of Internal Shield

The following general design features are given in EC-677562:

"3.3.1. General Design Features

The Internal Shield consists of a lead and boron carbide-aluminum-titanium hydride (BATH) central shield located forward of the core extending in radius to the outer radius of the core, and a peripheral shield located above the reflector extending from the inner radius of the reflector to the inner radius of the pressure vessel."

Supplemental descriptive information follows:

7.1.1.1 Supporting Structure

The central shield is supported by an 0.805 inch thick aluminum plate located at the aft end of the BATH material. The plate is attached at its outer periphery to a radial flange on the piping cylinder (see Chapter 6 Support Plate and Plena for description).

The shield load is transmitted from the shield support plate to the piping cylinder plenum closure ring and thence into the reactor core load path.

The peripheral shield is supported by the forward radial flange of the piping cylinder.

7.1.1.2 Central Shield

a. BATH Module

The central shield is made up of hexagonal BATH modules. The array of these modules extends radially to the support plate and plena piping cylinder. BATH is an extruded material consisting of a boron carbide, aluminum and titanium hydride mixture. The across flats dimension of the module is 1.997 inches and the length is 11.1 inches. In the peripheral region of the central shield, irregular modules required to form the circumference are fabricated from the regular hexagonal modules. Coolant channels are provided by grooving three faces of each module and by drilling six axial holes through the module. Assembly of the modules to form the central shield by locating grooved faces against ungrooved faces effectively provides flow channels on all faces. The coolant void fraction is 8.7%.

Modules are arranged in arrays of seven, wherein the central module is located by a stud through the cover plate, lead cluster, BATH module and into the support plate. The six surrounding modules are pinned to the support plate. Close tolerances on hexagonal envelope, pin, and pin hole locations minimize gaps between adjacent modules.

b. Lead Cluster

The lead cluster covers the forward end of a seven module BATH array and extends radially to the support plate and plena piping cylinder. The lead cluster, 1.3 inches thick, is retained by a stud which passes through the cover plate, lead cluster, central BATH module of the array and into the support plate. Flow channels in the lead align with those in the BATH modules.

7.1.1.3 Peripheral Shield

a. BATH Peripheral Module

The peripheral shield BATH modules are rectangular shapes (sections of rings) which are located in the region between the support plate and plena piping cylinder and the pressure vessel. Four circumferential rows of modules make up the peripheral shield. Each module is grooved on either two or three faces, depending upon its location in the shield. The modules of the peripheral shield are also provided with internal axial coolant channels. Assembly of the modules is such that coolant channels are provided at all module faces. Specially shaped modules surround the propellant flow and bypass feed pipes. The coolant void fraction is 3.7%.

b. Lead Peripheral Sector

The peripheral shield lead sectors are located between the support plate and plena piping cylinder and the pressure vessel. Eighteen lead sectors, 1.3 inches thick, cover the forward end of the BATH modules circumferentially between the control drum drive shaft penetrations and radially from the feed and bypass pipes to the support ring. Lead filler blocks cover the outer row of BATH modules between the feed and bypass pipes and piping cylinder.

7.2 SUMMARY OF RESULTS AND CONCLUSIONS

Thermal analyses have been performed for the Internal Shield Assembly shown on Drawing 939J741 in a NSS with a graphite core. The analyses are applicable to the thermal and hydraulic performance requirements in the Critical Component Specification EC-677562. The analyses were performed using a finite element TAP-A computer model of the primary shielding materials and conventional hand calculations on some of the shield supporting structure. Boundary conditions for these analyses were obtained from the TNT-II studies reported in Chapter 2 of this Data Item.

In conclusion, a Step 4 detailed analyses has been performed for the Internal Shield. The analysis was performed on a three-dimensional transient basis with variable material properties for the normal mode of operation. This operation produced temperature levels and temperature gradients for the various components of the shield. In addition, an uncertainty analysis was performed employing the Monte Carlo techniques described in Chapter 2. The Monte Carlo techniques resulted in prediction of uncertainties for temperature level, temperature gradients, and pressure drops. The resulting temperature levels, temperature gradient and their corresponding uncertainties indicate that the amount of coolant channel configurations enables the shield to meet the thermal/hydraulic requirements for operation as specified in EC-677562. The internal shield will perform satisfactorily for the normal mode of operation.

The following is a summary of the analysis results reported in this chapter:

a. Rated Performance, SOL

1) The maximum temperature levels occur at the aft end of the internal shield. These temperatures are 410°R for the central BATH shield and 446°R for the peripheral BATH shield.

2) The temperature difference ($\Delta T_{\text{AVG-MIN}}$) is 36°R for the central shield and 67°R for the peripheral shield. This is a result of the lower void fraction in the peripheral shield.

3) Both the peripheral shield lead sector and central shield lead cluster exhibit low $\Delta T_{AVG-MIN}$, $4^{\circ}R$ and $2^{\circ}R$, respectively and maximum temperatures ($293^{\circ}R$ and $305^{\circ}R$) that are very close to the bulk fluid temperatures.

4) The uncertainties shown in Table 7-6 are calculated from the TNT-II Monte Carlo analysis.

b. Throttled SOL

The highest temperature levels occur during the throttle hold at 65% power level. This is due to the reduced coolant flow and increased bulk temperatures (as compared to rated performance) that occur. As shown on Table 7-6, the maximum material temperatures increase by $9^{\circ}R$ in the BATH material and by $35^{\circ}R$ in the lead material in going from rated to throttled operation.

c. Transient SOL

The largest temperature differences ($\Delta T_{AVG-MIN}$) occur during the normal startup. In all cases, the temperature gradient is reduced at the design rated condition. A typical example of this is found in the BATH peripheral shield in which the maximum $\Delta T_{AVG-MIN} = 120^{\circ}R$ during startup reduces to $65^{\circ}R$ during steady state performance. These values for each component are given in Section 7.5.2.1.

During the shutdown mode, all conditions, i.e., temperature gradients and temperature levels are less severe than any other operating mode.

7.3 APPLICABLE REQUIREMENTS AND COMPATIBILITY OF THERMAL PERFORMANCE WITH THE NSS SPECIFICATION

The requirements and design conditions stated in this section are specified in EC-677562, Section 3.0 issued on November 30, 1970. The following requirements are applicable:

"3.1.1.1.1 Operational Modes

The Internal Shield shall support and/or accommodate all operational modes and their respective operational requirements as defined in 3.1.1.1.1 (Operational Modes) and specified in 3.1.1.1.5 (Operational Requirements) of CP-677555 with no degradation of performance below that specified herein."

The analysis presented in this chapter support and/or accommodate all operational requirements and results in no degradation of performance below that specified in CP-677555A.

The operational modes which presented the most severe thermal cases were evaluated.

"3.1.1.1.3.1 Normal Mode

The primary performance characteristics of the Internal Shield supporting the requirements of 3.1.1.1.5.1 (Normal Mode) of CP-677555 are as follows.

3.1.1.1.3.1.2 Flow Characteristics

The Internal Shield shall provide axial flow passage. The maximum allowable radial and azimuthal temperature variation at the central shield inlet shall be as specified in 3.1.1.1.3.1.3 (Flow Separation) of EC-677561. The Internal Shield shall accommodate the requirements of 3.1.1.1.5.1.2 (Startup Operations), 3.1.1.1.5.1.3 (Steady State Operations), 3.1.1.1.5.1.4 Shutdown Operations), and 3.1.1.1.5.1.5 (Cooldown Operations) of CP-677555. The steady state and throttle hold thermal-hydraulic characteristics of the Internal Shield pertinent to the Normal Mode shall be in accordance with Tables 1 through 4."

Flow channels have been arranged so that adequate cooling is provided, pressure drops are within system limits, and the undesirable effect of radiation streaming are minimized. The flow characteristics were evaluated and are presented in the Induced Thermal Environment Table in Section 7.5 of this Chapter. For all NSS rated conditions, the combined azimuthal and radial temperature variations attributable to the shield do not exceed 2°R .

The Internal Shield accommodates the thrust buildup, the throttle mode and the temperature retreat specified in the requirements of CP-677555A. Tables 2-1B through 2-1E of the Thermal and Fluid Environment in Chapter 2 summarize the calculated environment during ramp up, throttle mode and temperature retreat for both the graphite and composite core.

"3.1.1.1.3.2.1 Single Turbopump Operation Mode

The Internal Shield shall meet the requirements of 3.1.1.1.5.2.1 (Single Turbopump Operation Mode) of CP-677555. In supporting Single Turbopump Operation Mode, the performance requirements of the Internal Shield are within the range of performance characteristics specified in 3.1.1.1.3.1 (Normal Mode) except that the steady state and throttle hold thermal-hydraulic characteristics shall be in accordance with the values of Tables 5 through 8."

The flow characteristics as specified were evaluated and are presented on Table 7-1 of the Induced Thermal Environment given in Section 7.5 of this Chapter.

"3.3.1.7 Growth Characteristics

The Internal Shield shall satisfy the requirements of 3.3.1.17 (Growth Characteristics) of CP-677555. The steady state thermal hydraulic characteristics ($T_c = 4500^{\circ}\text{R}$) shall be in accordance with Tables 15 and 16. "

The growth mode characteristics were evaluated and presented in Section 7.5.2.1.

7.4 METHOD OF ANALYSIS (DESIGN PRACTICES)

This section presents the design practices used by Thermal Design to obtain the thermal and fluid environment within the Internal Shield. The analytical procedures and the analytical models used to implement the design practices are described. In addition, a discussion of the maturity of the input data and the validity of the analysis are given. The detail analysis is within the framework of the overall computational network discussed in Section 2.4.1, and is designated a Step 4 calculation.

7.4.1 Analytical Procedures

In this subsection the analytical procedures selected for the evaluation of the thermal-hydraulic model are presented. The justification for using the procedure, the assumptions used in the analysis, and the computer codes selected to evaluate the analytical model are discussed. The analytical procedures are consistent with the overall thermal design procedures presented in Section 2.4.1.2.

For the Internal Shield BATH module and lead cluster components, a three-dimensional finite element computer code was used to predict the thermal-hydraulic performance characteristics of the shield modules during steady state and transient operation. The TAP-A computer code was used for this purpose since it has the capability to couple conduction heat transfer with convective heat transfer boundary conditions in a transient thermal environment. Temperature distributions in other shield components were calculated from one dimensional heat transfer equations, when judged applicable. The analyses were performed with a thermal environment corresponding to a graphite core at SOL operation. The radiation environment of the Internal Shield is more severe when the NSS employs a graphite core as compared to the radiation environment of a composite core; therefore, the analysis of the Internal Shield was performed using heating rate data and a thermal-hydraulic environment corresponding to a graphite core.

The SOL analysis was also considered applicable to EOL operation. Preliminary analysis of the shield indicated that slightly higher bulk fluid temperatures occurred during the EOL operation; but these would not have any significant effect upon the cooling requirement of the shield. Furthermore, the thermal properties of the materials used in the components of the shield, i.e., BATH, lead, and aluminum, are not significantly affected by nuclear radiation. (Ref. 1 and 11). On these bases, the SOL analysis was considered valid for the EOL operation.

7.4.2 Analytical Models

This subsection describes the analytical models used to calculate temperatures and pressures throughout the peripheral and central shield components. The component Step 4 thermal-hydraulic models of the shield were prepared for WANL Drawing No. 940J440 and are applicable to the current design as defined by WANL Drawing 939J741.

7.4.2.1 Description and Derivation of Analytical Model

The analytical models used in the component analysis of the central and peripheral shields include:

1. The central shield analytical model represents the typical module assembly shown on Figure 7-1A and includes the BATH and the lead cluster corresponding to the BATH cross-section. The detailed two-dimensional finite element nodal pattern used in the TAP-A model is shown on Figure 7-1. This same pattern applies to each of the 4 axial layers of the module assembly shown on Figure 7-1A.

To construct the node pattern of Figure 7-1, an electronic digitizer was used to establish the geometrical coordinates of the node boundary. The digitizer data were input to

the W-MESHER code which generates the two-dimensional node geometrical description data required for input to the TAP-A conduction code. Additional work to complete the calculational model included the geometrical coupling of the nodes in the axial direction to provide a three-dimensional model, specification of heat generation rates and material properties, and specification of convective boundary conditions. This general analytical procedure is discussed in the design practice logic in Section 2.4.1.2.

2. The peripheral shield analytical model represents the typical module assembly shown on Figure 7-2A and includes the BATH and the lead cluster corresponding to the BATH cross-section. The detailed two dimensional finite element nodal pattern used in the TAP-A model is shown. This same pattern applies to each of the four axial layers of the module assembly shown on Figure 7-2A. The peripheral shield model represents the module located between radii of 20.505 inches and 22.23 inches. This region has the highest heating rates and the least accessible coolant holes.

The peripheral shield thermal models were prepared in the same manner as those of the central shield.

3. Temperature distributions were calculated in the 0.805 inch thick aluminum supporting plate at the aft end of the shield. By considering the plate to be a heat generating solid with equilaterally spaced coolant holes, the calculation was repeated with different heating rates to represent the variation of heating with radius and thus provide a radial temperature profile in the supporting plate. Figure 7-3 shows the coolant hole geometry used in conjunction with the following equations to calculate the support plate temperature distributions:

$$T_{MIN} = T_{BULK} + \frac{[Q (.9094 R_o)^2 - R_i]^2}{2 R_i h}$$

$$T_{AVH} = T_{MIN} + \frac{Q (.9094 R_o)^2}{4 K} \left\{ \frac{1}{2} \left[\left(\frac{R_i}{.9094 R_o} \right)^2 - 3 \right] - \ln \frac{\left(\frac{R_i}{.9094 R_o} \right)^2}{1 - \left(\frac{R_i}{.9094 R_o} \right)^2} \right\}$$

$$T_{MAX} = T_{MIN} + \frac{Q R_o^2}{K} \left\{ .07463 + \frac{1}{4} \left[1.6541 \ln \left(\frac{R_o}{R_i} \right) - 1 + \left(\frac{R_i}{R_o} \right)^2 \right] \right\}$$

Q	=	INTERNAL HEAT GENERATION RATE
h	=	FILM COEFFICIENT
K	=	THERMAL CONDUCTIVITY
T _{MIN}	=	WALL TEMPERATURE
T _{AVG}	=	AVERAGE MATERIAL TEMPERATURE
T _{MAX}	=	MAXIMUM MATERIAL TEMPERATURE
T _{BULK}	=	BULK FLUID TEMPERATURE

7.4.2.2 Compatibility of Analytical Model with the Design

The shield TAP-A model explicitly represents the actual component, as evidenced by a comparison of the shield analytical model configuration shown on Figure 7-1A with the actual component shown on Drawing 940J741. Axial and radial heat transfer by conduction and convection, spacial variation of internal heat generation, temperature effect on material thermal conductivity are all accounted for under steady state and transient conditions.

Calculations of temperature distribution in the shield supporting plate were made by considering the plate as a heat generating solid with equilateral coolant holes. This is an adequate representation of the actual component which is illustrated on Dwg 940J741. because of the two dimensional nature of the plate. Furthermore, the coolant hole pattern shown on Dwg 940J741 closely resembles an equilateral triangle.

The values for the rated performance phase of operation are specified and these are adjusted for the power profile during startup, throttle hold, or shutdown in accordance with the results of TNT-II calculations. Figure 2-94 shows a typical fraction of rated power vs time for a startup which is used to define the power boundary conditions of the shield analysis.

7.4.3 Maturity of Input Data

This subsection describes the major input data and the maturity of these data required in addition to the analytical model to perform the thermal-hydraulic performance calculations.

7.4.3.1 Reference Profiles

The startup and shutdown profile boundary condition data used to obtain the shield components analysis results were obtained from the NSS calculations discussed in Section 2.4.3.1. These Profiles reflect the extreme rate of chamber temperature change of $+175^{\circ}\text{R/sec.}$ during the thrust buildup phase of startup and $-175^{\circ}\text{R/sec.}$ during the temperature retreat phase of shutdown.

7.4.3.2 Material Properties

The maturity of property data for the shield materials and the manner in which the thermal properties vary are briefly discussed in Section 2.4.3.2. Table 7-2 lists the materials used in the major components and reference the Specification identifying the material. The thermal properties of shield materials, i.e., BATH, and aluminum, are not significantly effected by nuclear irradiation, as reported in References 1 and 11. Consequently, the unirradiated properties were used in the analysis of this ECC. The thermal properties used are reported in the E-105 Data Item, Reference 2.

7.4.2.3 Boundary Conditions

Boundary conditions applicable to the heat conduction calculations are specified.

These boundary conditions include heat transfer coefficients and fluid bulk temperatures. The steady state boundary conditions applicable to the shield are shown in Table 7-1 for the graphite core. Similar information for the composite core is available in the NSS thermal and fluid environmental tables in Figure 2-1B and 2-1C. Heat transfer coefficients are calculated from these environmental steady state data or the applicable TNT-II transient startup and shutdown results and the geometrical configuration. The heat transfer coefficient is obtained from the simplified Petukhov correlation.

$$N_u = C (Re)^{0.8} (Pr)^{0.4} \left(\frac{T_b}{T_w} \right)^P$$

This correlation was previously discussed in Chapter 6 of this Data Item. The fluid boundary conditions were calculated by TNT-II for the inlet plena of the peripheral and central shield. The values for steady state normal mode operation are given in Table 7-1; for startup and shutdown operation, the boundary conditions are shown on Figures 2-98 and 2-112 for the central shield and on Figures 2-97 and 2-111 for the peripheral shield.

The external boundary of the shield BATH module is considered an adiabatic surface. This assumption is justified since only negligible axial leakage flow will occur in the gaps between the modules. This leakage flow will be minimized by the "cap" on the BATH modules created by the larger lead clusters in the central shield and the lead sectors in the peripheral shield. This assumption of an adiabatic external surface as a module boundary condition results in "worst case" temperature distribution analysis, since any external surface heat removal by leakage will reduce the temperature variations across the module cross-section.

Additional input to the thermal calculational model includes the specification of internal heat generation rates for the shield materials for each phase of operation.

7.4.3.3 Hydrogen Properties

Para hydrogen properties (Reference 3) were used in calculating boundary conditions as input to the analysis.

7.4.3.4 Heating Rates

The heating rates and their distributions for the shield with the graphite core components were obtained from the results of preliminary analysis performed by nuclear design and reported in Reference 4.

A comparison of these data with subsequent results reported in the S-100 Data Item was made in Reference 10. This comparison indicated the following conclusions:

(1) The maximum heating rates in the internal shield are 4% lower than those reported in Reference 4. This effect will reduce the temperature levels in the shield.

(2) The total heat deposition in the shield is 15% higher than the amount used in the present calculation. This will result in a slightly higher fluid bulk temperature ($<1^{\circ}\text{R}$). This will not have a significant effect upon the results and conclusions of this report.

7.4.4 Validity of Analysis

In this subsection applicable test data used to substantiate the method of analysis are presented. The uncertainty analysis is presented for each design parameter relevant to the Internal Shield.

7.4.4.1 Applicable Test Results

a. Reactor Tests

The analysis techniques and procedures used in the thermal and hydraulic analyses of this ECC have, in the past, been applied to an aluminum shield model of the NRX Technology program. The NRX/EST Test Report (Reference 5) shows the results of such

analyses compared with measured test data. The post-test calculated temperatures at different full-power hold points agree with measured material temperatures within a maximum temperature difference of 8°R at the nozzle end of the shield and 19° at the dome end of the shield. This agreement is within the 2σ variation of 23°R for the thermocouple.

b. Component Tests

(1) In addition to reactor testing, the analytical procedures and modeling have been applied to component test evaluation. One such test applicable to the shield component was the Thermal Shock Test of the shield BATH material. The T-119 Data Item for this test is reported in Reference 6. In this test, a hexagonal piece of BATH material initially at ambient temperature, was thermally shocked by flowing 1.1 lb/sec. of 140°R helium through an internal coolant hole.

The T-119 Data Item for this test reports that a thermal shock of 27°R/sec. was sustained at the external surface of the test section. Thermal shock induced strains were recorded, converted to stresses, and compared to calculated stresses obtained from the FEATS computer code. The thermal model and analytical results input to the FEATS code are shown in Reference 6, Section 5.1.1. The post-test thermal analysis using a finite element, 134 node model with the TRACK computer code, provided temperature distributions throughout the test specimens, the coolant channel flow, the channel pressure distribution, the heat flux from the surface nodes, and the total power transferred to the fluid as a function of time. Comparison of the measured and calculated temperatures from this analysis performed to verify the measured surface temperatures, resulted in the conclusion that the best behaved temperature sensor was 3.5 inches from the specimen inlet. In this case, there was good agreement (within approximately 10°) between calculated and measured transient surface temperatures. The transient temperature distributions within the specimen stresses were calculated and shown to be in fair agreement with the test results. There was no observable damage to the BATH shield module.

(2) The Shield Element Corrosion Development Test was performed to determine the resistance of BATH shield material to hydriding, dehydriding, nitriding, and contact corrosion with structural material when exposed to flowing hydrogen or nitrogen at 600 psia and 900°R for two hours. Test results reported in the T-119 Data Item of Reference 7 for this test indicated no corrosion or decomposition of the specimens or holders. There was no significant change in hydrogen or nitrogen content after two hours exposure at the above conditions.

7.4.4.2 Uncertainty Analysis

The uncertainties of important thermal parameters of the shield components (such as material temperatures, temperature difference, and pressure differentials) were obtained from the results of the TNT-II Monte Carlo analyses reported in Section 2.4.4.2. All uncertainties are one sided limits obtained from 30 analysis cases, plus the nominal case for a 99% proportion with 95% confidence (99/95), based on 30 degrees of freedom as discussed in Section 2.4.4.2. For a one-sided limit, either 99% of the parameter values are above the lower tolerance limit at 95% confidence or 99% of the parameter values will be below the upper tolerance limit at 95% confidence. The plus and minus uncertainty values do not apply simultaneously. The TNT-II NSS model calculates material temperatures and fluid conditions. Selected uncertainties for input parameters were varied by Monte Carlo to obtain the mean values, standard deviations, and 99/95 confidence tolerance limits for the calculated output parameters. The composite core NSS model was the basis of the Monte Carlo analyses; however, the results are applicable to the graphite core. The percentage uncertainty (99%/95% confidence) were applied to the nominal parameters calculated in the detailed Step 4 analysis. Table 7-3 tabulates the nominal values of the selected Monte Carlo parameters and the 99/95 uncertainty values of these parameters. These results are also discussed in Section 7.5.2.1.c. This 99/95 uncertainty is 3.06 times the one standard deviation value for the Monte Carlo sample size of 30.

7.5 RESULTS, ANALYSIS, AND INTERPRETATION

This section presents the results of analysis on the graphite core to determine the thermal and fluid environment of the central and peripheral shields at steady state and transient conditions. Selection of the operating modes for detailed step 4 analysis was made by comparison of the composite core and the graphite core TNT-II results at steady state rated condition (SOL) normal mode operation. The parameters considered in this selection include the axial pressure drop, material temperature and material temperature differences.

7.5.1 Composite Core

On the basis of the key performance parameters shown in Table 7-4, it is concluded that the shield with the graphite core represents a more severe condition than with the composite core. With the graphite core, material temperatures are 12-14°R higher, due to higher coolant temperatures and material temperature differentials are 1-2°R, due to the higher internal heat generation.

7.5.2 Graphite Core

Detailed step 4 thermal and fluid analyses were performed for the shield with a graphite core, during normal mode steady state rated performance operation, 65% throttle hold operation, normal mode startup, and shutdown.

7.5.2.1 Steady State

The thermal and fluid environmental table on the shield is given in Table 7-1 for the graphite core. These data, taken from the NSS environmental tables, Figure 2-1, are the steady state boundary conditions applicable to the results shown in subsequent paragraphs.

a. Start of Life - Rated Performance

The following shield components were evaluated at the SOL rated performance operation:

- (1) The peripheral shield BATH module, at the inner diameter of the peripheral shield in the region of highest internal heat generation and least accessible coolant holes.
- (2) The peripheral shield lead sector, at the inner diameter of the peripheral shield in the region of highest internal heat generation and least accessible coolant holes.
- (3) The central shield BATH module, on the reactor centerline in the region of highest internal heat generation.
- (4) The central shield lead cluster, on the reactor centerline in the region of highest internal heat generation.
- (5) The central shield aft end supporting plate.

1. Peripheral Shield and Peripheral Shield Pressure Vessel Annulus Flow Distribution

As shown in Table 7-1, the total flow of 91.2 lb/sec in the peripheral shield is divided such that 27% (or 24.8 lb/sec.) flows through the peripheral shield - pressure vessel annulus and 73% (or 66.5 lb/sec.) through the peripheral shield modules, drum drive ports, and other shield penetration areas. Preliminary scoping analyses reported in Reference 8 show that the peripheral shield modules could be adequately cooled, and the pressure vessel was expected to be more than adequately cooled. The axial pressure drop across the peripheral shield was set at 10 psia nominal at rated conditions.

2. Peripheral Shield BATH Module Thermal Analysis

The temperature distribution in the BATH peripheral shield module at rated conditions are shown on Figure 7-4. The maximum temperature at the aft end of the peripheral shield

is 446°R . The minimum temperature at this axial location was 305°R . The average temperature of the module is 372°R .

Figure 7-5 shows the axial temperature distribution in the peripheral BATH shield module as a function of distance from the aft face region. The aft region average temperature of 372°R decreases to 306°R in the forward region.

On the basis of these Step 4 detailed component analysis results, the peripheral shield BATH module is adequately cooled under rated performance conditions.

3. Peripheral Shield Lead Sector

The temperatures in the lead sector of the peripheral shield located forward of the BATH material are reported in Table 7-5. The node numbers given in the table correspond to those shown on the model in Figure 7-2. The maximum temperature of the lead is 310°R ; the minimum temperature is 300°R . The steady state temperature variation across the lead sector is low (10°R) because of the relatively low internal heat generation in the lead at the forward end of the shield and the good thermal conductivity of the lead.

On the basis of these Step 4 detailed component analysis results, the peripheral shield lead cluster is adequately cooled when operating at steady state rated conditions.

4. Central Shield BATH Module

The temperature distribution in the aft region of the central shield BATH module are shown on Figure 7-6. The

maximum BATH temperature is 410°R , and the maximum temperature difference ($T_{\text{AVG}} - T_{\text{MIN}}$) across the module is 53°R . Figure 7-7 shows the axial temperature distribution in the BATH module. The 393°R average temperature at the aft region of the module decreases to 295°R in the forward region where the BATH module interfaces with the lead cluster.

On the basis of these Step 4 detailed component analysis results, the BATH central shield module is adequately cooled under rated performance conditions.

5. Central Shield Lead Cluster

The temperature distribution in the central shield lead cluster is shown on Figure 7-8. The maximum temperature shown on the isothermal plot is 293°R , the minimum temperature is 290°R , with the average temperature being 292°R . As indicated on Figure 7-8, the temperature variations across the lead are small (less than 4°R) since the heating rate at this location, forward of the BATH shield, is low. Analysis indicates that the lead sector temperatures in the outer diameter regions of the central lead shield will closely approach bulk fluid temperature.

On the basis of these Step 4 detailed component analysis results, the central shield lead cluster is adequately cooled under rated performance conditions.

6. Central Shield Aft Supporting Plate

The radial temperature distribution in the aft supporting plate of the central shield is shown in Figure 7-9. This figure shows the maximum, average, and minimum temperatures calculated vs radial location. The radial temperature varies from 400°R at the core centerline to approximately the bulk temperature of 283°R at the outside diameter region of the plate. These temperatures are well within the allowable temperature of the plate material. On the basis of these Step 4 detailed component analysis results, the central shield supporting plate is adequately cooled under rated operating conditions.

b. Throttle Hold SOL/EOL

The thermal and fluid environment of the peripheral and central shield at the throttled hold (65% reactor power and flow) is shown in Table 7-1. Comparing this environment with the rated performance conditions shows the fluid temperatures increased 40°R at the peripheral shield inlet and 46°R at the central shield inlet. The net effect of this change in environment on peripheral component temperatures is shown in the shutdown Figures 7-18 through 7-25 by comparing temperatures at 600 seconds (rated conditions) and 643 sec. (throttle hold conditions at 65% power). At 643 sec., the maximum temperatures in the peripheral shield range from 448°R in the BATH module aft end to 345°R in the lead sector at the forward end. This is an increase in material temperatures varying from 2°R at the aft end to 35°R at the forward end of the peripheral module, relative to the 600 sec. conditions. Similar data for the central shield is shown on Figures 7-22 to 7-25. At 643 sec., the maximum temperatures range from 419°R at the aft face of the BATH module to 333°R in

the lead cluster at the forward end of the shield. This is an increase in material temperature of up to about 40°R, relative to the 600 sec. condition. This increase is about the same as the increase in hydrogen coolant temperature environment.

On the basis of these Step 4 detailed component analysis results, the complete shield assembly (BATH and lead, in both center and periphery) is adequately cooled during the throttled hold operation. This operating condition results in the highest steady state temperature levels in this ECC.

The shield material temperature differences at the throttle hold condition are less severe than rated performance because of the reduced internal heat condition.

c. Influence of Spec. Extreme on Operating Conditions

Table 7-6 summarizes the nominal maximum, minimum, and average temperatures, temperature differentials, and other key performance parameters of the shield components during steady state operation, rated conditions, and throttle hold conditions. The nominal values are shown with their 99% proportion at 95% confidence, one sided specification extreme tolerance limit. The tolerance limit was derived by use of the % tolerance limit with the nominal value for the graphite core discussed in Section 7.4.4.2.

In addition to the steady state operational values, the data summarized on Table 7-6 included the range of temperature which the component will experience during space soak prior to pre-start operations and during the cooldown operation subsequent to shutdown operations, normal mode. These temperatures were reported in Reference 9 and do not include tolerance limits.

On the basis of the nominal temperatures summarized on Table 7-6 and the associated tolerance limits, all shield components are adequately cooled under steady state conditions and the allowable temperature of the material is not exceeded even when the upper tolerance limit is applied to the nominal operating condition. During cooldown operation, the analyses show the allowable temperature limits are not violated.

d. Central and Peripheral Shield Growth Mode Operation (SOL)

The purpose of this section is to consider the effect of growth mode operation.

Growth mode operation is defined as operation at a chamber pressure of 450 psia and a chamber temperature of 4500°R, for a minimum of 120 minutes accumulated in multiple cycles, up to 12, of varying duration up to 60 minutes.

A comparison of the thermal environments of the growth mode and design rated condition for the central and peripheral shield is presented in Table 7-7. The following observations may be made from the data in the table:

1. The coolant flow rates are essentially the same for both cases.
2. The pressure drop across the central and peripheral shields is the same for both cases.
3. While the coolant temperature levels are higher (23°R) for the growth mode, the rise in coolant temperature is practically the same for both modes of operation.

Because the coolant flow rates and pressure drops are essentially the same for both modes of operation, it may be concluded that the shield material temperatures will increase by an amount proportional to the coolant temperature. This will not have any significant effect upon the shield operation because temperature levels are still well below the materials temperature capability. In conclusion, the growth mode of operation will not have any significant effect upon the shield thermal performance.

7.5.2.2 Transient Performance

This section contains a discussion of the central shield operating characteristics for the SOL startup and shutdown modes of operation for the graphite core. Included in the discussion are the temperature levels and temperature differences for BATH and lead materials. Figures 7-10 through 7-24 show various material temperatures versus time for the internal shield modules during the startup and shutdown operations. The time scales as shown are the same as shown in the discussion of "Reference Profiles" in Chapter 2.

a. Peripheral Shield BATH Module Startup (SOL)

This section contains the discussion of the performance characteristics of the BATH peripheral shield during the normal startup. The reference startup profile encompasses the following phase of operation:

1. Temperature Conditioning	0-25 seconds
2. Bootstrap	25-32 seconds
3. Thrust Buildup	32-53 seconds
4. Initiate Full Power Run	53 seconds

Included in the discussion are effects of temperature level and temperature differences that occur during the startup phase.

Figures 7-10 through 7-12 are plots of material temperature versus time for the BATH peripheral shield. A maximum $\Delta T_{\text{AVG-MIN}}$ of 120°R occurs in the module during startup. This temperature difference which is the largest ΔT for the normal mode, then decreases to 65°R during the steady state operation at design rated conditions. The maximum temperature decreases from the 530°R initial condition to a value of 455°R during steady state operations. The maximum steady state temperature and temperature difference occurs at the aft end of the peripheral shield where the highest heating rate exists. The analysis for normal startup indicates the peripheral BATH module satisfies the startup requirements specified in EC-677562.

b. Lead Peripheral Shield, Startup, SOL

The performance characteristics of the lead peripheral shield are illustrated in Figure 7-13, which is a plot of material temperature versus time. The maximum temperature difference, $\Delta T_{\text{AVG-MIN}}$, that occurs during the startup is 110°R . This difference which is the largest ΔT for the normal mode, decreases to 4°R at steady state operation (See Table 7-6.). The analysis for normal startup indicates the lead module satisfies the startup requirements specified in EC-677562.

c. BATH Central Shield, Startup, SOL

This section contains the discussion of the performance characteristics of the BATH Central Shield during the normal startup. Included in the discussion are effects of temperature level and temperature gradients that occur during this operating phase.

Figures 7-14 through 7-16, plots of material temperature versus time, show the BATH temperature difference, $\Delta T_{\text{AVG-MIN}}$ that occurs during the startup is 45°R at the aft end. This difference which is the largest ΔT for the normal mode, decreases to a steady state value of 36°R (See Table 7-6.). During the startup, the maximum material temperature, which occurs at the aft end of the BATH module, decreases from an initial value of 530°R to the steady state value of 410°R . The central shield thermal analysis for the normal startup indicates the central shield design will meet the startup requirements specified in EC-677562.

d. Central Shield Lead Cluster Startup, SOL

The thermal characteristics of the central shield lead cluster for the SOL, startup, are illustrated in Figure 7-17. The maximum temperature is seen to vary from the initial temperature of 530°R to 293°R at the design rated condition. The maximum temperature gradient, $\Delta T_{\text{AVG-MIN}}$ that occurs during startup is 45°R . This difference, which is the largest ΔT for the normal mode, decreases to 2°R at steady state operation for design rated performance conditions (See Table 7-6.). In conclusion, the central shield lead cluster analysis indicates the central shield will meet the startup requirements specified in EC-677562.

e. Peripheral Shield, BATH Module Normal Shutdown, SOL

The thermal characteristics of the peripheral shield, BATH module for normal shutdown, SOL, graphite core are illustrated in Figures 7-18 through 7-20, which are plots of temperature versus time. These figures reflect the following shutdown operation:

1. Throttling from 600 to 603.15 seconds
2. Throttle hold of 40 seconds from 603.15 to 643.15 seconds
3. Temperature retreat from 643.15 to 657 seconds

A further description of the shutdown operation is found in Chapter 2.

The temperature histories shown in Figure 7-18 illustrate the rise in maximum material temperature from 446°R to 448°R during the 40 second throttle hold. The temperature

retreat which begins at 643.15 seconds shows the subsequent decrease in material temperature with time. The maximum temperature difference ($\Delta T_{\text{AVG-MIN}}$) is less than startup values as can be seen comparing Figures 7-10 and 7-18. Thus thermally the startup is a "worst" condition for ΔT 's. This is also true of all other shield components. In conclusion, the analysis indicates the peripheral shield, BATH module satisfies the shutdown requirements specified in EC-677562.

f. Lead Peripheral Shield Normal Shutdown, SOL, Graphite Core

The thermal characteristics of the Lead Peripheral Sector for normal shutdown, SOL, graphite core are illustrated in Figure 7-21, which is a plot of material temperature versus time. This figure reflects the effects of the shutdown phase of operation. Examination of Figure 7-21 and Table 7-6 indicates that the maximum material temperature rises from the steady state values of 310°R to 345°R during the 40 second throttle hold. The temperature retreat which begins at 643.15 seconds shows the subsequent decrease in material temperature with time. In conclusion, the analysis indicates the lead sector satisfies the shutdown requirements specified in EC-677562.

g. Central Shield BATH Cluster, Normal Shutdown, SOL, Graphite Core

The thermal characteristics of the Central Shield BATH Cluster for normal shutdown, SOL, graphite core are illustrated in Figures 7-22 through 7-24. Examination of Figure 7-22 and Table 7-6 indicates that the maximum material temperature rise from the steady state value of 410°R to 419°R occurs during the 40 second throttle hold. The temperature retreat which begins at 643.15 seconds shows the subsequent decrease in material temperature with time. In conclusion, the analysis indicates the central shield BATH cluster satisfies the shutdown requirements specified in EC-677562.

h. Central Shield Lead Cluster, Normal Shutdown, SOL, Graphite Core

The thermal characteristics of the central shield lead cluster for normal shutdown, SOL, graphite core, are illustrated in Figure 7-25. Examination of Figure 7-25 and Table 7-6 indicates that the maximum material temperature rises from the steady state value of

293°R to 329°R during the 40 second throttle hold. In conclusion, the analysis indicates the central shield lead cluster satisfies the shutdown requirements specified in EC-677562.

7.5.2.3 Space Soak Effect

The temperature ranges expected to be encountered during the space soak period prior to having any internal heat generation are shown on Table 7-6. This data was also reported in Data Item S-001 (Reference 9).

7.5.2.4 Probability of Failure Analysis

At PDR technical justification is required to demonstrate that the shield design concepts have a reasonable chance of achieving the NPRD requirements. The procedure is presented in Reference 12 and involves making analytical estimates of component reliability at the mode of failure level during the pre-PDR period.

The approach followed to insure that all shield components have a high inherent reliability was to first make a thorough and unbiased listing of all the credible ways a shield component can fail to perform. Subsequently, design changes were made to eliminate as many failure points as possible. Finally, the probability of occurrence of each remaining failure is assessed. This final calculation is presented in this subsection for failure modes directly involving thermal design aspects.

The general procedure consists of obtaining the reliability value from two overlapping normal distributions, e.g., operating temperature vs constraint. Usually the population standard deviation of the two normal distributions are not known and the reliability value is computed from the sample standard deviation (S) and the sample size (n) from each of these distributions.

The procedure as described in SNSO-C-1 is as follows:

Given: $\bar{X}_L, S_L, n$, (Operating temperature see Table 7-8)
 $\bar{X}_S, S_S, n$, (Limiting temperature see Table 7-8)

Calculate: $X_{R'} = \frac{\bar{X}_S - \bar{X}_L}{\sqrt{S_S^2 + S_L^2}}$ and, $n' = \frac{(S_S^2 + S_L^2)^2}{S_S^4/n_2 + S_L^4/n_1}$

Obtain the population reliability (R) at 90% confidence level from curves relating sample reliability to population reliability, Reference 13.

Table 7-8 lists the modes and the mechanism of failure for shield components which are relevant to the Thermal Design. The probability of failure (F) is $(1 - R)$ and is given in the last column of Table 7-8. The values $\ll 1 \times 10^{-19}$ indicates the occurrence of these failure modes are highly incredible.

7.6 REFERENCES

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TABLE 7-1

INDUCED THERMAL ENVIRONMENT OF INTERNAL SHIELD (GRAPHITE CORE)

<u>Description</u>	<u>Flow-Lb/Sec</u>	<u>Pressure-Psia</u>	<u>Temp-Deg R</u>
<u>Steady State Performance at Rated Conditions-Start of Life (SOL)</u>			
Peripheral Shield Inlet	66.5 + 2.0	1065 + 21.2	300 + 19.4
Peripheral Shield Exit	66.5 + 2.0	1054 + 20.8	302 + 19.5
Peripheral Shield - Pressure Vessel Annulus Inlet	24.8 + 1.7	1065 + 21.2	300 + 19.4
Peripheral Shield - Pressure Vessel Annulus Outlet	24.8 + 1.7	1054 + 20.8	304 + 19.5
Central Shield Inlet	91.2 + 1.4	642 + 9.5	283 + 18.4
Central Shield Outlet	91.2 + 1.4	631 + 9.4	287 + 18.3
<u>Steady State Performance at Rated Conditions-End of Life (EOL)</u>			
Peripheral Shield Inlet	66.5 + 2.0	1061 + 21.0	303 + 19.6
Peripheral Shield Exit	66.5 + 2.0	1051 + 20.6	305 + 19.7
Peripheral Shield - Pressure Vessel Annulus Inlet	24.8 + 1.0	1061 + 21.0	303 + 19.6
Peripheral Shield - Pressure Vessel Annulus Outlet	24.8 + 1.7	1051 + 20.6	307 + 19.7
Central Shield Inlet	91.2 + 1.4	643 + 9.5	287 + 18.7
Central Shield Outlet	91.2 + 1.4	632 + 9.7	290 + 18.6
<u>Steady State Performance at 65% Throttle Hold-Start of Life (SOL)</u>			
Peripheral Shield Inlet	42.8 + 1.5	644 + 15.4	340 + 25.0
Peripheral Shield Exit	42.8 + 1.5	636 + 14.9	342 + 25.4
Peripheral Shield - Pressure Vessel Annulus Inlet	16.4 + 1.2	644 + 15.4	340 + 25.0
Peripheral Shield - Pressure Vessel Annulus Outlet	16.4 + 1.2	636 + 14.9	345 + 25.2
Central Shield Inlet	59.2 + 1.3	431 + 9.0	329 + 25.5
Central Shield Outlet	59.2 + 1.3	423 + 8.9	333 + 24.3
<u>Steady State Performance at 65% Throttle Hold-End of Life (EOL)</u>			
Peripheral Shield Inlet	42.8 + 1.5	642 + 15.3	341 + 20.9
Peripheral Shield Exit	42.8 + 1.5	634 + 15.0	343 + 20.9
Peripheral Shield - Pressure Vessel Annulus Inlet	16.4 + 1.1	642 + 15.3	341 + 20.9
Peripheral Shield - Pressure Vessel Annulus Outlet	16.4 + 1.1	634 + 15.0	345 + 21.0
Central Shield Inlet	59.2 + 1.3	431 + 8.8	331 + 20.1
Central Shield Outlet	59.2 + 1.3	423 + 8.8	334 + 20.6

TABLE 7-1 (CONT'D)

<u>Description</u>	<u>Flow (Lb/Sec)</u>	<u>Pressure-Psia</u>	<u>Temp-Deg R</u>
<u>Steady State Performance at 80% Thrust-Single TPA Malfunction-Start of Life (SOL)</u>			
Peripheral Shield Inlet	53.1 + 1.8	1103 + 21.3	322 + 21.6
Peripheral Shield Exit	53.1 + 1.8	1096 + 21.2	324 + 21.9
Peripheral Shield - Pressure Vessel Annulus Inlet	20.0 + 1.4	1103 + 21.3	322 + 21.6
Peripheral Shield - Pressure Vessel Annulus Outlet	20.0 + 1.4	1096 + 21.2	327 + 21.9
Central Shield Inlet	72.9 + 1.3	522 + 8.9	305 + 20.6
Central Shield Outlet	72.9 + 1.3	513 + 8.8	308 + 20.4
<u>Steady State Performance at 80% Thrust-Single TPA Malfunction-End of Life (EOL)</u>			
Peripheral Shield Inlet	53.1 + 1.8	1099 + 21.9	326 + 22.0
Peripheral Shield Exit	53.1 + 1.8	1092 + 21.8	328 + 22.3
Peripheral Shield - Pressure Vessel Annulus Inlet	20.0 + 1.4	1099 + 21.9	326 + 22.0
Peripheral Shield - Pressure Vessel Annulus Outlet	20.0 + 1.4	1092 + 21.8	330 + 22.3
Central Shield Inlet	72.9 + 1.3	522 + 9.1	308 + 20.9
Central Shield Outlet	72.9 + 1.3	513 + 9.0	311 + 20.7
<u>Steady State Performance at 65% Throttle Hold-Single TPA Malfunction-Start of Life (SOL)</u>			
Peripheral Shield Inlet	52.9	814	341
Peripheral Shield Exit	42.9	807	343
Peripheral Shield - Pressure Vessel Annulus Inlet	16.4	814	341
Peripheral Shield - Pressure Vessel Annulus Outlet	16.4	807	345
Central Shield Inlet	59.2	431	328
Central Shield Outlet	59.2	423	332
<u>Steady State Performance at 65% Throttle Hold-Single TPA Malfunction-End of Life (EOL)</u>			
Peripheral Shield Inlet	52.9	810	344
Peripheral Shield Exit	42.4	803	345
Peripheral Shield - Pressure Vessel Annulus Inlet	16.4	810	344
Peripheral Shield - Pressure Vessel Annulus Outlet	16.4	803	348
Central Shield Inlet	59.2	431	331
Central Shield Outlet	59.2	423	334

TABLE 7-2. MATERIALS USED IN INTERNAL SHIELD ANALYSIS

<u>COMPONENT</u>	<u>MATERIAL</u>	<u>SPECIFICATION IDENTIFICATION</u>	<u>MATERIAL LIBRARY NO. *</u>
Shield Module	BATH	PDS-30259	10
Lead Sector Lead Cluster	Lead	DRM 51297	69
Supporting Plate	AL 6061	QQ-A-250/11-T651	51

* Material Library Designations Used in Analytical Model, See Section 2.4.3.2.

TABLE 7-3

SUMMARY OF UNCERTAINTY TOLERANCES FOR KEY SHIELD ASSEMBLY PARAMETERS (COMPOSITE CORE)*

COMPONENT	LOCATION	PARAMETER	NORMAL MODE OPERATION					
			RATED PERFORMANCE, SOL 99/95 TOLERANCE LIMIT			THROTTLE HOLD, EOL 99/95 TOLERANCE LIMIT		
			NOMINAL	TOLERANCE	TOL. %	NOMINAL	TOLERANCE	TOL. %
Peripheral Shield Bath Cluster	Aft End	T avg (°R) T min (°R) (T avg - T min) (°R)	309 296 13	16.4 15.7 4.1	5.3 5.2 32.6	343 335 8	21.3 20.9 2.6	6.2 6.2 32.5
Peripheral Shield Lead Sector	Forward End	T avg (°R) T min (°R) (T avg - T min) (°R)	296 292 4	15.4 15.5 1.3	5.2 5.3 33.1	334 331 3	20.6 20.7 0.9	6.2 6.3 33.6
Peripheral Shield Axial Pressure Drop		ΔP - Psi	10	1.4	13.5	8	1.2	14.1
Peripheral Shield Fluid Temperature Rise		ΔT - °R	2	0.4	22.8	2	0.5	21.9
Central Shield Bath Cluster	Aft End	T avg (°R) T min (°R) (T avg - T min) (°R)	292 284 8	16.8 16.1 2.7	5.8 5.7 33.6	334 328 5	20.9 20.6 1.7	6.3 6.3 33.7
Central Shield Lead Cluster	Forward End	T avg (°R) T min (°R) (T avg - T min) (°R)	275 273 2	16.1 14.9 0.6	5.4 5.5 27.9	321 319 2	19.2 19.3 0.6	6.0 6.0 27.6
Central Shield Axial Pressure Drop		ΔP - Psi	10	1.2	11.3	8	0.9	11.7
Central Shield Fluid Temperature Rise		ΔT - °R	3	0.8	29.4	3	1.1	36.2
Central Shield Aluminum Support Plate	Aft End	T avg (°R) T min (°R) (T avg - T min) (°R)	291 284 7	16.5 16.0 3.1	5.7 5.6 42.2	333 329 4	20.9 20.7 1.9	6.3 6.3 42.4

* Data Obtained from TNT-II Monte Carlo Analysis

Computer Run No.'s

058 - 11/13/70

507 - 11/18/70

206 - 11/23/70

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TABLE 7-4
COMPARISON OF KEY PERFORMANCE PARAMETERS OF THE SHIELD COMPONENTS
FOR THE COMPOSITE AND GRAPHITE CORES (TNT-II RESULTS)

<u>Component</u>	<u>Location</u>	<u>Parameter</u>	SOL VALUE	
			<u>Composite Core</u>	<u>Graphite Core</u>
Peripheral Shield	Aft End	Avg. Mtl. Temp. ($\bar{T}$) °R	309	323
Peripheral Shield	Aft End	($\bar{T} - T_w$) °R	13	15
Peripheral Shield	N/A	Axial Pressure Drop (psid)	10	11
Central Shield	Forward End	Avg. Mtl. Temp. ($\bar{T}$) °R	292	304
Central Shield	Forward End	($\bar{T} - T_w$) °R	8	9
Central Shield	N/A	Axial Pressure Drop (psid)	10	11
Supporting Plate Central Shield	Forward End	Avg. Mtl. Temp. °R ($\bar{T} - T_w$) °R	291 7	303 8

TABLE 7-5. PERIPHERAL SHIELD LEAD SECTOR TEMPERATURE - RATED
PERFORMANCE, START OF LIFE, GRAPHITE CORE

<u>Node</u>	<u>Temperature - °R</u>
19	306
38	305
41	304
48	308
62	310
63	308
88	300
91	308
96	305
116	306
166	306
168	305

All Temperatures Refer to the Above Node Numbers.

TABLE 7-6 SUMMARY OF SHIELD COMPONENT MATERIAL TEMPERATURES AND OTHER KEY PERFORMANCE PARAMETERS (GRAPHITE CORE)

COMPONENT	LOCATION	PARAMETER	NORMAL MODE OPERATION						COOLING RANGE °R	SPACE SOAK RANGE	
			RATED PERFORMANCE 99/95 TOLERANCE LIMIT			THROTTLE HOLD 99/95 TOLERANCE LIMIT				Solar Flux (3) of 300 Btu Hr/Ft ²	Solar Flux (4) of 3000 Btu Hr/Ft ²
			NOMINAL	UPPER	LOWER	NOMINAL	UPPER	LOWER			
Peripheral Shield BATH Cluster	Aft End	T max (°R)	446	470	422	448	476	420	(300 - 600) (1) with 800 max (2)	350 - 550	550 - ≈ 900
		T avg (°R)	372	392	352	398	423	363			
		T min (°R)	305	321	289	345	366	324			
		(T avg - T min) (°R)	67	89	46	53	70	36			
Peripheral Shield Lead Sector	Forward End	T max (°R)	310	326	294	345	366	324	(300 - 600) (1) with 800 max (2)	350 - 550	550 - ≈ 900
		T avg (°R)	304	320	288	343	364	322			
		T min (°R)	300	315	285	340	361	319			
		(T avg - T min) (°R)	4	5.3	207	3	4	2			
Peripheral Shield		Axial Pressure difference ΔP (psid)	11	12.5	8.5	8	9.2	6.8			
Peripheral Shield		Fluid Temperature Rise (°R)	2	2.5	1.5	2	2.5	1.5			
Central Shield BATH Cluster	Aft End	T max (°R)	410	434	386	419	445	393	(280 - 600) (1) with 800 max (2)	350 - 550	550 - ≈ 900
		T avg (°R)	393	416	370	408	434	382			
		T min (°R)	357	377	337	383	417	359			
		(T avg - T min) (°R)	36	48	24	25	33	17			
Central Shield Lead Cluster	Forward End	T max (°R)	293	308	278	329	353	313	(280 - 600) (1) with 800 max (2)	350 - 550	550 - ≈ 900
		T avg (°R)	292	297	277	332	352	312			
		T min (°R)	290	295	275	330	350	310			
		(T avg - T min) (°R)	2	2.6	1.4	2	2.5	1.5			

TABLE 7-6 (CONT'D) SUMMARY OF SHIELD COMPONENT MATERIAL TEMPERATURES AND OTHER KEY PERFORMANCE PARAMETERS (GRAPHITE CORE)

COMPONENT	LOCATION	PARAMETER	NORMAL MODE OPERATION						COOLDOWN OPERATION RANGE °R	SPACE SOAK RANGE	
			RATED PERFORMANCE 99.95 TOLERANCE LIMIT			THROTTLE HOLD 99.95 TOLERANCE LIMIT				Solar Flux ⁽³⁾ of 300 Btu Hr/Ft ²	Solar Flux ⁽⁴⁾ of 3000 Btu Hr/Ft ²
			NOMINAL	UPPER	LOWER	NOMINAL	UPPER	LOWER			
Aft Central Shield Support Plate	Aft Face	T max (°R)	400	423	377				(280 - 600) ⁽¹⁾ with 800 max ⁽²⁾	350 - 550	550 - ~900
		T avg (°R)	385	408	362						
		T min (°R)	360	380	340						
		T avg - T min (°R)	15	21	9						
Central Shield		Axial Pressure Difference, (psid)	11	12.1	8.9	8	8.9	7.1	(280 - 600) ⁽¹⁾		
Central Shield		Fluid Temperature Rise	4	5.2	2.8	3	4.1	1.9	800 ⁽²⁾		
<p>1. This is the temperature range within 3.65 hours after a ten minute burn and throttle hold, as reported in WANL-TME-2678, "Systems Analysis Summary Report, Nuclear Subsystem," Section 5.2.6.3.</p> <p>2. This is the maximum allowable temperature between cooling pulses.</p> <p>3. This is the minimum flux shown in WANL-TME-2678, "Systems Analysis Summary Report, Nuclear Subsystem," Section 5.2.6.3. Solar flux in earth orbit is 444 BTU/HR-FT² as reported in WANL-TME-2678.</p> <p>4. This is the extreme solar flux, in the vicinity of Mercury, as reported in WANL-TME-2678.</p>											

TABLE 7-7
COMPARISON OF GROWTH MODE WITH DESIGN RATED CONDITIONS, GRAPHITE
CORE (SOL)

	<u>Flow Rate</u> <u>Lbs/sec</u>	<u>Pressure (Psi)</u>		<u>Temperature - °R</u>	
		<u>Inlet</u>	<u>Outlet</u>	<u>Inlet</u>	<u>Outlet</u>
Central Shield:					
$T_c = 4500^\circ\text{R}$	88.3	645	634	306	309
Design Rated	91.2	642	631	283	287
Peripheral Shield:					
$T_c = 4500^\circ\text{R}$	88.3	1050	1039	323	325
Design Rated	91.2	1065	1054	300	302

TABLE 7-8. FAILURE MECHANISM PROBABILITY OF OCCURRENCE

Part Cluster, Regular, It. No. 16

Mode* Ident. No.	Modes and Mechanisms of Failure		Mission Phase	Environmental Factors
16	B. Lead Melts	B. Radiation Attenuation is Reduced	Steady State	Temperature

Dwg. No. 940J440Revision 0

"Stress"***		"Strength"***		: Design Analysis (Calculated or Estimated Failure Probability or Evaluation Comments)
Mean, $\bar{X}_L$; Variance, S_L^2 ; n or Stress Comment		Mean, $\bar{X}_S$; Variance, S_S^2 ; n or Strength Comment		
333°R : :	$S_L = 6.53^\circ R$: n = 30	1081°R : :	$S_S = 0$	
				$F \ll 1.0 \times 10^{-19}$ (90% Confidence Level)

Part Cluster, Irregular, It. No. 17

Mode* Ident. No.	Modes and Mechanisms of Failure		Mission Phase	Environmental Factors
17	B. Lead Melts	B. Radiation Attenuation is Reduced	Steady State	Temperature

Dwg. No. 940J440Revision 0

"Stress"		"Strength"		Design Analysis (Calculated or Estimated Failure Probability or Evaluation Comments)
Mean, $\bar{X}_L$; Variance, S_L^2 ; n or Stress Comment		Mean, $\bar{X}_S$; Variance, S_S^2 ; n or Strength Comment		
345°R	$S_L = 6.85^\circ R$ n = 30	1081°R	$S_S = 0$	$F \ll 1.0 \times 10^{-19}$ (90% Confidence Level)

* Refer to Data Item R-202, "Reliability Allocations, Assessments and Analysis Report, NSS."

** For thermal failure mode evaluation "Stress" is considered. The calculated mean temperature and its tolerance distribution are listed.

*** For thermal failure mode evaluation "Strength" is considered limiting temperature. The limiting temperature and its tolerance distribution are listed.

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Figure 7-1. Detail Nodal Pattern Used for Calculations of Central Shield Module

TAPA-A NODAL MODEL

A12419-528

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Figure 7-1A. Nodal Pattern Used for Calculation of Central Shield Module

Figure 7-2. Detail Nodal Pattern Used for Calculations of Peripheral Shield Module

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Figure 7-2A. Nodal Pattern Used for Calculation of Peripheral Shield Module

Figure 7-3. Aft Aluminum Supporting Structure Plate Configuration for Closed Form Heat Transfer Solution

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Figure 7-4. Graphite Core, Rated Performance, Start of Life, BATH Peripheral Shield, Material Temperature, Aft End

111 10/27/70

MS932-1

Figure 7-5. Graphite Core, Rated Performance, Start of Life, Peripheral BATH Shield Axial Temperature Variation

Figure 7-6. Graphite Core, Rated Performance, Start of Life, BATH Central Shield,
Material Temperature Aft End

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Figure 7-7. Graphite Core, Rated Performance, Start of Life, Central BATH Shield Axial Temperature Distribution

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Figure 7-8. Graphite Core, Rated Performance, Start of Life (SOL), Lead Central Shield, Material Temperature

690 10/26/70

Figure 7-9. Graphite Core, Rated Performance, Start-of-Life (SOL)
Radial Temperature Distribution Aft Central Shield Plate

W5892-1

Figure 7-10. Graphite Core, Normal Startup, Start of Life (SOL) BATH Peripheral Shield Material Temperature, Aft End

Figure 7-11. Graphite Core, Normal Startup, Start of Life (SOL) BATH Peripheral Shield
Material Temperature, Midplane

Figure 7-12. Graphite Core, Normal Startup, Start of Life (SOL) BATH Peripheral Shield
Material Temperature, Forward End

Figure 7-13. Graphite Core, Normal Startup, Start of Life (SOL) Lead Peripheral Shield Material Temperature

Figure 7-14. Graphite Core, Normal Startup, Start of Life (SOL) BATH Central Shield Temperature
Aft End

Figure 7-15. Graphite Core, Normal Startup, Start of Life (SOL) BATH Central Shield Temperature Midplane

Figure 7-16. Graphite Core, Normal Startup, Start of Life (SOL) BATH Central Shield Material Temperature, Forward End

Figure 7-17. Graphite Core, Normal Startup, Start of Life (SOL) Lead Central Shield Material Temperature

Figure 7-18. Graphite Core, Normal Shutdown, Start of Life (SOL) BATH Peripheral Shield
Material Temperature, Aft End

Figure 7-19. Graphite Core, Normal Shutdown, Start of Life (SOL) BATH Peripheral Shield, Material BATH Temperature, Midplane

MS832-1

Figure 7-20. Graphite Core, Normal Shutdown, Start of Life (SOL) BATH Peripheral Shield Material Temperature, Forward End

Figure 7-21. Graphite Core, Normal Shutdown, Start of Life (SOL) Lead Peripheral Shield Material Temperature

Figure 7-22. Graphite Core, Normal Shutdown, Start of Life (SOL) BATH Central Shield, Material Temperature, Aft End

Figure 7-23. Graphite Core, Normal Shutdown, Start of Life (SOL) BATH Central Shield, Material Temperature, Midplane

Figure 7-24. Graphite Core, Normal Shutdown, Start of Life (SOL) BATH Central Shield, Material Temperature, Forward End

Figure 7-25. Graphite Core, Normal Shutdown, Start of Life, (SOL) Lead Central Shield Material Temperature

8.0 REFLECTOR ASSEMBLY

8.1 INTRODUCTION

This Chapter describes the thermal and fluid flow analysis performed on the Reflector Assembly (RA). The primary function of the RA is to provide a means of controlling the reactivity of the nuclear reactor. The RA must also be structurally adequate to transmit loads imposed upon it by the other components within the pressure vessel as well as the fluid pressure differentials to which it is exposed.

The Reflector Assembly is part of the contract end item described as the NERVA Nuclear Subsystem (NSS) and is listed as an Engineering Critical Component EC-677559 in CEI Specification No. CP-677555A. This ECC specification establishes the thermal and hydraulic design requirements for the RA critical component.

8.1.1 Description of Aluminum Structure Reflector

The following general design features are given in EC-677559:

"3.3.1. General Design Features

The Reflector Assembly consists of a hollow right circular cylinder which encompasses the core from its forward to aft surface. The basic load-bearing member is an aluminum support structure to which are attached beryllium segments required to fulfill the primary function of neutron reflection. The reactivity control function is satisfied by 18 control drums which are mounted within the reflector and rotate on bearings mounted on each end of the reflector. Rotation of the drums changes the position of the control plates to vary the reactivity."

Supplemental descriptive information follows:

8.1.1.1 Structure

The primary support structure is the aluminum structural cylinder which is utilized

to transmit the NSS axial and radial loads to the interfacing nozzle flange and ultimately to the aft pressure vessel flange. Additionally, the structure must withstand the radial fluid pressure drop and support the reflector beryllium segments and control drums.

8.1.1.2 Forward Extension Ring and Aft Support Ring

The forward extension ring is an extension of the aluminum structural cylinder which mates with the core support plate at its forward surface. The radial flange of the ring supports the axial and radial load developed by the 18 control drums. The outer most axial cylindrical portion of the forward support ring serves the function of a coolant flow restrictor for the pressure vessel coolant flow passage. The aft support ring located at the aft end of the aluminum structure positions the aft end of the control drums and the baffle can.

8.1.1.3 Standoff, Pad, and Clamp Ring

A set of 18 standoffs are located at the aft end of the reflector assembly to provide an axial loading capability to force the aluminum structure - nozzle interface together. The load is transmitted from the standoffs into the pads which are bolted to the pressure vessel interior. The standoffs are adjusted for proper preload after installation of the nozzle at final assembly. A redundant feature to assure closure of the aluminum structure-nozzle interface is provided by the clamp ring. The forward lip of the nozzle is clamped to the aft end of the aluminum structure by the clamp ring and its bolts.

8.1.1.4 Locating Cylinder

The locating cylinder is sandwiched between the pads (previous paragraph) and the forward face of the aft pressure vessel flange. The forward rim of the cylinder mates with a circumferential groove near the outer diameter of the clamp ring. The cylinder centers the NSS within the pressure vessel prior to insertion of the nozzle and supports the NSS during assembly.

8.1.1.5 Reflector Segments

Beryllium segments, required to provide the necessary nuclear characteristics for neutron reflection, are attached to the aluminum structure. Small segments of beryllium are utilized and are attached by the lateral support spring capsules; hence the beryllium

is not used as a part of the structural support system of the reflector assembly. The beryllium segments consist of inner and outer segments which interface approximately at the control drum centerline. Division into inner and outer segments is required to facilitate operation within acceptable limits established by thermal - structural considerations.

8.1.1.6 Control Drums

Eighteen control drums are located within the beryllium portion of the reflector assembly. They are supported by bearings located in the forward extension ring and aft support rings. The cylindrical beryllium drums have copper boron composite control vanes mounted within a recess at the outer diameter of the beryllium. The control drum is encased within a thin wall aluminum structure which is welded to aluminum bearing shafts located at each end of the control drum. Axial holes through the beryllium cylinder and a channel around the control vane provide for removal of heat from the control drum assembly. Thermal Insulation between the beryllium cylinder and the control vane coolant annulus is provided by a 0.100 inch grafoil insert held in place by an aluminum retainer plate.

8.1.1.7 Reflector Baffle Can and Control Drum Bore Liner

The diameter of the reflector is essentially defined by the outer surface of the beryllium segments mounted upon the aluminum structural cylinder. The complete reflector is surrounded by a thin aluminum cylinder which provides a circumferential barrier between the pressure vessel and the reflector assembly to eliminate radial flow of the fluid. Tubular control drum bore liners are located between the forward and aft bearing support rings to line the control drum cavities and separate the drums from the beryllium segments. This directs the coolant flow through drums and segments to provide more efficient utilization of the coolant fluid.

8.1.1.8 Seal Segments and Insulation Segment*

8.1.1.9 Lateral Support Spring, Plunger, Capsule Assembly*

*The Lateral Support System is the subject of a Trade Study and is discussed in S-054 TS 782, Lateral Support.

8.2 SUMMARY OF RESULTS AND CONCLUSIONS

Thermal analyses have been performed for the Reflector Assembly (RA) components shown in WANL Dwg. No. 939J733 and related to the thermal and fluid flow performance requirements defined in the RA Specification EC-677559. Tables 8-1 and 8-2 show the induced thermal environment for the RA when used with a graphite core and a composite core respectively. These environment tables were taken from the TNT-II NSS analysis reported in Chapter 2 of this Data Item.

Tables 8-3 and 8-4 summarize key performance parameters from four "worst cases." The method of selecting these "worst cases" is presented in Section 8.5 and the cases are: (1) Graphite Core, Rated Performance, End of Life, Normal Mode; (2) Graphite Core, Throttle Hold Performance, End of Life, Normal Mode; (3) Graphite Core, Startup, End of Life, Normal Mode; and (4) Composite Core, Steady State Performance, Start of Life, Single Turbopump Operation.

8.2.1 Graphite Core

Table 8-3 contains the summary information for the three "worst cases" resulting when the RA is used with a graphite core.

Rated Performance, End of Life, Normal Mode

Operation at this condition results in the highest heat addition to the reflector coolant, (21.46 MW). Combining this fact with the reduced thermal conductivity of beryllium after irradiation results in the largest temperature gradients in the beryllium segments and control drums that will be experienced at steady state conditions. The inner segments are seen to have an average to minimum temperature difference of $31 \pm 10^{\circ}\text{R}$ and a maximum to average temperature difference of $65 \pm 20^{\circ}\text{R}$ at midplane. The tolerance limits given in the table are for a 99% proportion at a confidence level of 95% and were obtained by applying the results presented in Section 8.4.4.2 to the nominal results presented in Section 8.5. The corresponding temperature differences in the outer segments are $15 \pm 5^{\circ}\text{R}$ and $12 \pm 4^{\circ}\text{R}$ respectively. The control drum cylinders are seen to have an average to minimum temperature difference of $43 \pm 15^{\circ}\text{R}$ and a maximum to average temperature

difference of $37 \pm 13^{\circ}\text{R}$. These temperature differences are important to establishing the thermal stresses and evaluating the structural adequacy of the beryllium pieces, and to determining the thermal bowing of the control drums.

The maximum temperatures shown for the reflector baffle can, control drum cans, control drum bore liners, control vanes, and various other parts are all less than earth ambient temperature and are also less than the corresponding values at other operating conditions. The radial pressure difference across the reflector structure, is 670 ± 19 psi. This operating condition does not result in the maximum value of reflector radial Δp .

Throttle Hold Performance, End of Life, Normal Mode

Operation at this condition results in the largest power to flow ratio of any steady state operating mode for the RA. This gives rise to values of material temperatures that exceed those for other steady state operating conditions. The maximum temperature in the aluminum structure is $493 \pm 30^{\circ}\text{R}$ and occurs near midplane, and the maximum temperature in the control vanes is $495 \pm 36^{\circ}\text{R}$. Maximum temperatures in the other reflector parts are well below these values. The heat addition to the coolant passing through the RA has a nominal value of 14.25 MW at this operating condition. Temperature differences in the RA parts are less severe at this condition than they are at other steady state operating conditions.

Startup, End of Life, Normal Mode

Operation at this condition results in the maximum thermal gradients in the reflector components. Table 8-3 summarizes the temperatures and temperature differences in the beryllium segments and control drum cylinders at three axial positions. The values shown apply at the time when the maximum value of average to minimum temperature difference occurs or at 42 seconds if this maximum has not occurred before. The maximum ΔT is seen to propagate from the aft end to the forward end of the RA as the startup progresses.

For the inner segments, the average to minimum temperature difference is about twice as large as it is in the "worst" steady state condition and the maximum to average temperature difference is approximately equal to its "worst" steady state value. For the outer segments, both of these temperature differences are considerably in excess of the "worst" steady state values. The control drums also experience their greatest temperature

differences during startup. These temperature differences are important to establishing the thermal stresses in the beryllium parts and the thermal bow of the control drums.

8.2.2 Composite Core

Table 8-4 contains the summary information for the one "worst case" resulting when the RA is used with a composite core.

Steady State Performance, Start of Life, Single Turbopump Operation

Operation at this condition results in the maximum radial pressure difference across the reflector structure. This pressure difference is shown to be 798 ± 21 psi and occurs at the aft end of the structure. The maximum temperatures in the structure at this condition are $446 \pm 30^{\circ}\text{R}$ near midplane and 390°R at the aft end flange design. Tolerance limits of the same quality available for other parameters do not exist for the temperatures in the aft end flange region at this time, but a conservatively high estimate of 590°R (99/95% upper tolerance) was used in the probability of failure analysis reported in Section 8.5.6. The maximum temperature in the forward extension ring is $394 \pm 33^{\circ}\text{R}$ at this condition and occurs at the forward extension ring-core support plate interface.

An analysis of the RA aft end support configuration was made for this operating mode and included a simulation of the aft end seal row. The skirts of the outer seal segments extend below the exit end of the fuel elements and are, therefore, exposed to convective heat transfer from the hot chamber gas. With hot side gas conditions obtained from ANSC, the maximum calculated surface temperature is 2610°R . The ANSC boundary conditions are based on NRX-A3 to A5 braze patch data and do not take into account the differences in configuration and bypass flow which exist between those designs and the NERVA design. It is judged that the actual skirt temperatures will be substantially lower than those reported here.

Temperatures and temperature differences in other RA parts are less severe at this condition than at other steady state operating conditions. The heat addition to the coolant flow through the RA has a nominal value of 15.81 MW.

8.2.3 Conclusions

Step 4 detailed analyses have been performed on the Reflector Assembly components. These analyses were accomplished using models and procedures that are more refined than those used in the analysis of any reflector system in the NRX series of reactors. The analysis included the identification of "worst cases" from TNT analysis of all operating modes, the calculation of thermal conditions at the "worst case" conditions using detailed TRACK-II and TAP-A models, the assessment of uncertainty tolerances using the Monte Carlo technique, the identification of failure modes for RA components, and the calculation of the probability of occurrence of each of these modes. The results of these analyses indicate that all of the RA components analyzed will meet the thermal-hydraulic requirements specified in EC-677559. The performance of the lateral support parts in the RA have not been included in this Data Item. This portion of the RA is the subject of Trade Study No. 782.

The results of the thermal analyses described in this chapter are input to Structural Design for use in detailed structural analyses reported in the S-036 Data Item.

It is felt that the following items are required during the detailed component design phase to continue to upgrade confidence in the reliability of the Reflector Assembly components:

1. Continuous Thermal Design input to define the design details for the detailed design release.
2. Verification of the flow and thermal characteristics of the control drum through component testing (Refer to Sections 8.4.4.1 and 8.5.6.).
3. Verification of the RA flow impedances through component testing (Refer to Section 8.4.4.1.).
4. Improved understanding of the hot side boundary conditions at the RA nozzle interface and design effort to reduce the sensitivity of the RA - nozzle interface configuration to hot side boundary conditions (Refer to Section 8.5.3.).

8.3 APPLICABLE REQUIREMENTS AND COMPATIBILITY OF THERMAL PERFORMANCE WITH THE NSS SPECIFICATION

The requirements and design conditions stated in this Section are specified in EC-677559, Section 3.0, issued on November 30, 1970. The following specifications are applicable:

"3.1.1.1.1 Operational Modes

The RA shall support and/or accommodate all operational modes and their respective operational requirements as defined in 3.1.1.1.1 (Operational Modes) and specified in 3.1.1.1.5 (Operational Requirements) of CP-677555 with no degradation of performance below that specified herein."

In this Chapter, only the Normal Mode and Malfunction Mode, Single Turbopump Operation will be evaluated. The analysis of the Reflector Assembly showed no degradation of performance below that specified in CP-677555A.

"3.1.1.1.3.1.2.3. Core Bundling Function

To satisfy the lateral support function,* the RA shall include the means to provide a radially inward pneumatic load on the core during all operating conditions. The pneumatic bundling force shall be equivalent to an average pressure of (tbd) psi. In addition, at assembly the RA shall provide a mechanical bundling force at the Core Periphery surface. This force shall be equivalent to an average pressure of 10 psi over the forward one-seventh of the core and (tbd) psi over the aft six-sevenths of the core."

*The Lateral Support System is the subject of a Trade Study and is discussed in S-054, Trade Study 782 Lateral Support.

"3.1.1.1.3.1.3. Thermal-Hydraulic Performance

The RA shall channel the flow from the nozzle tube outlet to a plenum at the forward end of the reflector in accordance with the following requirements.

3.1.1.1.3.1.3.1 Flow Impedance

With the nozzle tube exit flow of (tbd) lb/sec, at (tbd)[°]R and (tbd) psia, the pressure drop from the reflector inlet plenum to the reflector outlet plenum shall not exceed (tbd) psi. "

During rated steady state operation, the pressure drop from the reflector inlet plenum to the reflector outlet plenum was calculated to be 52 ± 3.9 psi, for a nozzle tube exit flow of 76.2 lb/sec at 198[°]R and 1120 psia at EOL.

"3.1.1.1.3.1.3.2 Heat Addition

When the NSS is operating at Rated Performance, the heat addition to the propellant as it passes from the inlet plenum to the exit plenum shall be (tbd) $\pm$ (tbd) Btu/sec. "

During rated steady state operation the heat addition to the propellant as it passes from the inlet plenum to the exit plenum was calculated to be $20,345 \pm 2,294$ Btu/sec.

"3.1.1.1.3.1.3.3 Pressure Vessel Cooling

The RA shall provide the means to meter the propellant flow between the reflector and the pressure vessel to (tbd) $\pm$ (tbd) lb/sec while operating at rated performance."

During rated steady state operation the RA satisfies the requirement of metering the propellant flow between the reflector and pressure vessel. The calculated flow between the reflector and pressure vessel was 7.2 ± 0.48 lb/sec at EOL.

3.1.1.1.3.1.3.4 Lateral Support Seal Flow

The RA shall be designed to limit the axial coolant flow bypassing the core to (tbd) $\pm$ (tbd) lb/sec while operated at Rated Performance.

3.1.1.1.3.1.3.5 Inlet Plenum Temperature Variation

The RA shall accommodate an azimuthal temperature variation of (tbd) °R at the reflector inlet/nozzle tube outlet interface.

3.1.1.1.3.1.3.6 Thermal - Hydraulic Characteristics

The RA shall accommodate the requirements of 3.1.1.1.5.1.1 (Prestart Operations), 3.1.1.1.5.1.2 (Startup Operations), 3.1.1.1.5.1.3 (Steady State Operations), 3.1.1.1.5.1.4 (Shutdown Operations), and 3.1.1.1.5.1.5 (Cooldown Operations) of CP-677555. The steady state and throttle hold thermal-hydraulic characteristics of the RA pertinent to the Normal Mode shall be in accordance within the range of performance characteristics specified in 3.1.1.1.3.1 (Normal Mode) except that the steady state and throttle hold thermal-hydraulic characteristics shall be in accordance with the values of Tables 5 through 8."

Table 8-1 in Section 8.2 presents the Induced Thermal Environment of the RA for the normal mode operation. The values presented on this Table are in accordance with Tables 5 through 8 in the specification.

"3.1.1.1.3.2.1 Single Turbopump Operation Mode

The RA shall meet the requirement of 3.1.1.1.5.2.1 (Single Turbopump Operation Mode) of CP-677555. In supporting the Single Turbopump Operation Mode, the performance requirements are within the range of performance characteristics specified in 3.1.1.1.3.1 (Normal Mode) except that the steady state and throttle hold thermal-hydraulic characteristics shall be in accordance with the values of Tables 5 through 8. "

The flow characteristics as specified were evaluated and are presented on Table 8-1 and 8-2 of the Induced Thermal Environment given in Section 8.2 of this Chapter.

8.4 METHOD OF ANALYSIS (DESIGN PRACTICES)

This section presents the design practices used by Thermal Design to obtain the thermal and fluid environment within the Reflector Assembly. The analytical procedures and the analytical models used to implement the design practices are described. In addition, a discussion of the maturity of the input data and the validity of the analysis are given including the method for obtaining uncertainties. The component level analysis is within the framework of the overall computational network discussed in Chapter 2, Section 2.4.1, and is designated as a Step 4 calculation.

8.4.1 Analytical Procedures

In this subsection, the analytical procedures selected for the evaluation of the thermal-hydraulic model are described. The assumptions used in the analysis and the computer codes selected to evaluate the analytical model are summarized and the justification for using the procedure is discussed. The analytical procedures are consistent with the overall thermal design procedures presented in Section 2.4.1.2.

Evaluation of the thermal-fluid environment of the Reflector Assembly begins with an assembly level thermal-fluid flow computation. The assembly model includes the pressure vessel in addition to the major RA components with the exception of the lateral support seals and the end support components (e.g., the forward extension, aft support ring, locating cylinder, standoffs, clamp ring, etc.). The lateral support seal system is analyzed in conjunction with the core periphery analysis because of the parallel flow overlap between these regions and the absence of an insulating interface. The assembly level analysis is executed on the TRACK-II computer code which couples the fluid flow and thermodynamic calculations with finite element conduction solutions for a symmetric section of the assembly repeated at a number of axial locations. This analysis provides the fluid environment within the reflector assembly and detailed material temperature distributions in most RA components suitable for use in structural evaluation of the component. The output is made available to Structural Analysis on computer tape for direct input to compatible structural models. For traceability, the

computer run sequence numbers and output tape designations are listed in the applicable subsection of the presentation of results. (Refer to Section 8.5.).

TAP-A, finite element conduction analyses are performed for components which are not included in the reflector assembly model or which require additional definition. Fluid boundary conditions for these analyses are obtained from the assembly computations. This category includes the end support configurations and the beryllium reflector segments which exhibit an axial geometry irregularity which cannot be adequately simulated with the assembly model. The TAP-A results are also reserved on computer tape for direct input to structural calculations.

The following is a summary of the major assumptions related to the Reflector Assembly analytical model:

1. Nominal dimensions are used for all parts and coolant channels except for the operating clearances between the reflector segments and bore liners and the pressure vessel annulus size during operation. These exceptions are discussed in Section 8.4.2.1.

2. Axial conduction is neglected in the reflector assembly model - this is justified on the basis of the small "in plane" impedances inherent in the design and by the smooth axial temperature variations (conduction into the cross-section from one direction tends to nullify the effect of conduction out the other direction).

3. Transverse flow in annular cooling passages is neglected. These channels are arbitrarily subdivided into individual channels with no intermediate flow linkage between the inlet and outlet plena. This limitation in the analytical technique is not judged to be significant because of the relative uniformity of coolant condition in the affected channels. Temperature variations are greater in the control vane annuli than in any of the other affected channels. Some flow redistribution is expected in these channels. However, the condition as analyzed with the present technique is judged to result in more severe thermal gradients in the vane material and is, therefore, conservative relative to determining the acceptability of the design.

4. Intermediate flow mixing in the plena formed by the segment interfacing is assumed to be negligible. This assumption is similar to Item 3 above and the same discussion applies.

5. Convective heat transfer at the end faces is not included in the Reflector Assembly level analysis, either at the forward and aft end of the reflector or at the beryllium segment interfaces.

6. Intimate contact is assumed at all component interfaces except those designated as flow channels in Figure 8-2 . Thermal resistance at the component interfaces is judged to have an insignificant effect on the material temperature distributions at steady state operation because of the temperature uniformity designed into the Reflector Assembly. It is considered that the most important interface condition is the structural cylinder-inner segment interface during startup. The thermal resistance at this interface is expected to be small, because the segments are spring loaded against the structure. Furthermore, intimate contact at this location tends to chill the segment ID more rapidly relative to the segment average material resulting in more severe thermal gradients in this component.

7. The heat influx from the LSS seal system is distributed uniformly in the axial direction and nonuniformly in the circumferential direction. The nonuniformity around the cylinder ID is controlled by establishing a uniform temperature at the middle of the 0.030 inch grafoil insulating segment. This results in a redistribution of this heat flow away from the lateral support plunger region which is the maximum temperature region in the structure. This representation is considered to be adequate.

8. Heat removal or input at the pressure vessel OD by radiation to the space environment is of very small relative magnitude during powered operation and has, therefore, been ignored in the analytical model.

Three categories of computer codes are used in the thermal-hydraulic analysis of the Reflector Assembly at the ECC level: (1) A coupled fluid flow-heat conduction code (TRACK II), (2) a finite element conduction code (TAP-A), and (3) codes which aid in preparing conduction model input. The computer codes used are itemized below.

1. TRACK II* (Fluid flow-heat conduction)
2. TAP-A* (Heat conduction)
3. W-MESHER* (Model preparation)
4. MLEVEL (Model preparation)

* A brief description of these codes is given in Section 2.4.1.

The MLEVEL code can be used to modify an existing TAP-A conduction model. The code can arbitrarily renumber the internal and surface elements, make duplicate layers of specified depth and make the appropriate connections between layers. Each layer is numbered with the base layer numbering plus a specified adder. This program was used to generate three-dimensional TAP-A conduction models of the beryllium reflector segments from the two-dimensional models used in the TRACK II reflector assembly model.

The analytical procedures described above are required on the basis of the complexity of the Reflector Assembly and the variability in boundary conditions, material properties and correlations of physical phenomenon. The indicated depth of analysis is required to provide sufficiently detailed steady state and transient temperature distributions of reflector components for the computation of their structural adequacy. The design goals of minimum weight and maximum reliability in a system as complex as the Reflector Assembly cannot be achieved with a simplified approach. For example, the structural cylinder is designed to meet SNPO-C1 requirements with a minimum thickness and, therefore, the temperature distributions and pressure loads for this component must be well defined. The beryllium components require sophisticated analysis procedures because of the degradation of the physical properties exhibited by beryllium in a neutron irradiation field and because of the incompatibility between steady state and transient design approaches. This latter effect has been partially overcome by subdividing the beryllium reflector into multiple segments with separate inner and outer regions. Post test analysis of the NRX-A6 reflector assembly showed that meticulous thermal and structural design procedures are warranted.

8.4.2 Analytical Model

The component level thermal-hydraulic models of the Reflector Assembly components were prepared for reflector study layout, WANL-Dwg.-940J418 and are consistent with the current design as defined by WANL-Dwg.-939J733 except for the details of the aft end support region. Although the aft end redesign invalidated the detailed model of the aft end support configuration, the effect on the overall reflector system analyses are considered to be negligible.

8.4.2.1 Description of the Analytical Models

a. Reflector Assembly Model

Thermal-hydraulic analyses of the assembled reflector components between core stations 0 and 52 inches were performed with the TRACK model shown in Figure 8 - 1 (WANL-Dwg.-940J434). One control drum assembly and a 10 degree, symmetric section of the reflector are represented by the finite element, two dimensional conduction model. The model includes the following components: structure, beryllium segments, drum cylinder, drum can, control vane, drum cylinder insulator, insulation retainer, drum bore liner, reflector baffle can and pressure vessel. The lateral support seals and spring capsule assemblies are not included in this model.

The fluid flow model consists of two groups of parallel coolant channels totaling 100 channels as shown in Figure 8-2. Each coolant hole is individually represented by a coolant channel in the model. Annular flow passages are arbitrarily subdivided into a number of separate channels with transverse mixing between these channels assumed to be negligible. The coolant channel input data is summarized in Table 8- 5. The flow paths around the LSS spring capsules and through the drum bore liner-beryllium segment gaps are of particular interest. Figure 8-3 shows the estimated flow rate in coolant channels which intersect the LSS spring capsules relative to the flow rate in a straight

through channel. Because this model of the Reflector Assembly does not explicitly include the spring capsules, these channels are treated as straight through channels and the additional flow impedance is simulated with a friction factor multiplier.

A significant portion of the reflector flow passes through the annular clearances at the segment external boundaries, particularly through the beryllium segment-bore liner gaps. Calculation of the flow rate through these gaps is complicated by the required assembly tolerances and by relative motions between the bore liners and the beryllium segments. Figure 8-4 shows the estimated circumferential variation of gap size for assembly and steady state operation at rated conditions. This estimate is based on the analytical results from a previous reflector trade study (Trade Study 763, WANL-TME-2673). The nominal average assembly gap is 0.020 inches with a tolerance of ± 0.010 inches. At assembly the bore liner is located eccentric in the reflector drum bore such that the nominal gap is 0.030 inches at the I.D. and 0.010 inches at the O.D. The reflector analytical model assumed that full length "plugs" would be provided to restrict axial flow at the beryllium segment web regions. The reference reflector layout (WANL-Dwg.-939J733) includes a segment filler to close off the flow path at the reflector O.D. web, but does not provide a flow impedance device at the I.D. web. On the basis of comparison of results for concepts 1 and 2 in Reflector Trade Study No. 763, it is judged that restriction of this flow channel is a significant factor in reducing the thermal gradients in the beryllium segments.

Two separate finite element conduction models are used to represent the Reflector Assembly. The first model represents the structure, beryllium segments, reflector baffle can and pressure vessel. The second model represents the control drum assembly and drum bore liner. The beryllium component sub-models (inner and outer segments and drum cylinder) were prepared by the W-MESHER computer program using a typical node size of 0.166 inches square. The remaining components were modeled manually. Each of the two models contains approximately 600 internal elements and 300 surface elements. Conduction calculations are performed at seven axial locations in the following order: core stations 52, 42, 32, 26, 20, 10 and

0 inches. Since the LSS spring assemblies are not included, the heating rates in the beryllium segment nodes in the capsule region are modified to simulate the total heat input to the fluid from the beryllium and the spring assemblies. This modification is discussed in Section 8.4.2.3.

- b. Lateral Support Seal Models
(To be included in Trade Study No. 782 Lateral Support Concepts)
- c. Lateral Support Spring Assembly Model
(To be included in Trade Study No. 782 Lateral Support Concepts)
- d. Aft End Support Model

A two dimensional TAP-A conduction model of the aft end of the reflector structure including the LSS seal segments and insulation segments was prepared for the design given in WANL-Dwg. 939J733. The coolant channel arrangement for the aft end seal row is not defined on the reference drawing, but it is proposed to divert a portion of the lateral support seal flow through the outer seal segments to provide positive cooling of these segments which are exposed to hot gas on their inner surfaces. Figure 8-5 shows the design configuration and the thermal model used to represent this region. The expected relative radial and axial motion between the core and the reflector structural cylinder are indicated on the figure. The rated operating position is used for the thermal model. At this condition, the reflector structural cylinder extends 0.700 inches below the end of the filler strips.

- e. Forward Extension Ring Model

The temperature distribution in the forward extension ring was calculated with the TAP-A, finite element conduction model shown in Figure 8-6. This is a two dimensional, R-Z model representing a typical slice of the forward extension ring taken between control drums. Coolant boundary conditions are obtained from the TRACK reflector assembly model.

f. Beryllium Segment Models

Temperature distributions in the beryllium segments are computed with the three dimensional, TAP-A conduction models shown in Figures 8-7 and 8-8 . The use of three dimensional models to represent the beryllium segments is an extension of analysis beyond the two dimensional models used for previous NRX and R-1 reflector analyses. This extension of the analytical technique was considered necessary because of the large size and anticipated thermal effect of the LSS spring bores. Each of the models is a symmetric segment (one quarter) and contains five axial layers of nodes. Each layer is identical with the TRACK reflector assembly segment models except where material is removed at the spring bores. The model was prepared with identical layers of the specified depth by the computer code M LEVEL. The alterations of the model to conform with the axial geometry variations were made manually. Coolant boundary conditions were supplied for each coolant channel from the reflector TRACK analyses via punched card output. Coolant temperatures and average convective heat transfer coefficients around the spring bore surfaces were hand calculated from the TRACK reflector output. In contrast to the TRACK reflector model, the heating distribution in the beryllium segment models was obtained directly from Radiation and Shielding data.

8.4.2.2 Compatability of Analytical Model with Design

The analytical models discussed in the preceeding paragraph are compatible with the Reflector Assembly design defined by WANL DWG 939J733 with two exceptions as previously noted:

1. The aft end support configuration was originally modeled from reflector study layout, WANL DWG 940J418. The improvement in the aft end design affects the temperature distributions in the aft end of the reflector structure and in the aft end support components. It also results in minor perturbations in the inlet impedance to the reflector coolant channels. Only the pressure vessel annulus impedance is judged to be significantly affected. The orificing of this channel in the analytical model was set to provide the required flow rate (per agreement with ANSC) with equal pressure drops across the inlet and outlet metering devices but the inlet metering device has been eliminated by the aft end redesign. To accommodate this change without perturbing the reflector flow distribution, the outlet metering device for the pressure vessel annulus was sized to match the pressure drop in this channel to the reflector pressure drop. The pressure plots in the presentation of results are consistent with the reference design configuration.
2. The analytical model of the reflector assembly assumes a full length "plug" for the triangular flow gap at the inner segment web region even though no flow impedance device is presently included at this location in the reference reflector layout. On the basis of design experience gained from previous reflector analyses, the plugging of this flow gap is judged to be essential to the attainment of acceptable temperature distributions in the inner beryllium segments.

8.4.2.3 Boundary Conditions

The boundary conditions required for the Reflector Assembly component level analyses are (1) inlet fluid conditions, (2) power level, (3) heating rates, (4) heat flux at the lateral support reflector interface and (5) neutron fluence distribution.

The inlet fluid conditions (pressure, temperature and flow rate) and the NSS power level are obtained from the Thermal and Fluid Environment Tables presented in Chapter 2.

Preliminary R-1 radiation heating rates from Reference 1 were used in the Reflector Assembly analyses. The pertinent radial and axial distributions are shown on Figure 8-9. The heating rates in the LSS spring capsule regions of the beryllium segments were modified in the reflector assembly TRACK model (8.4.2.1) to produce the equivalent total heating of the beryllium and spring assemblies. For this calculation, it was assumed that the rate of heat removal from the spring capsules to the reflector coolant was uniform over the length of the capsules. Although heat is conducted nonuniformly into the capsules from the lateral support rings and plungers, it is expected that the distribution of heat being convected to the coolant will be smoothed by conduction in the capsule walls. This assumption has subsequently been confirmed by thermal analyses of the spring capsule assemblies. These results, which are reported in the Trade Study No. 782, Lateral Support Concepts, show a variation of ± 15 percent in heat removal along the capsule axis. Figure 8-10 shows how the radial heating profiles for beryllium and for the spring capsule assemblies were combined to obtain the equivalent radial heating distribution used in the TRACK reflector model for the capsule region.

The heat influx to the reflector structure from the lateral support seals was obtained from core periphery - lateral support analyses performed for the reference core periphery design (Concept 1) and reported in Reference 2. Axial heat flux distributions are available for both rated and throttle hold performance for graphite core, normal mode

operation. For steady state performance, composite core, single turbopump operation (80 percent thrust), the rated performance axial profile was used with a total heat flow normalizing factor calculated as a linear function of NSS power level between the rated and throttle hold performance values. During transient operation, the temperature of the outer seal segments is applied at the inner surface of the insulation segments instead of the heat flux. The seal temperatures are obtained from the TNT analyses of the Nuclear Subsystem and are adequate for this calculation because the transient response of the reflector structure is relatively insensitive to this boundary temperature.

The fast neutron flux field ($E > 1$ Mev) was obtained from preliminary Radiation and Shielding calculations for a previous R-1 Reference Design, (WANL DWG 939J685E) as reported in Reference 3. The neutron flux at the ID of the reflector structure, midplane was reported as 9.6×10^{14} n/cm² sec for a power level of 1575 MW. This was reduced to 9.2×10^{14} to account for the reduction in NSS power to 1510 MW. The fluence distribution used in the reflector analyses for EOL conditions was taken as the neutron flux field multiplied by 3600 seconds. The resultant maximum EOL neutron fluence in the reflector (structure ID, midplane) is 3.31×10^{18} n/cm². The radial and axial distributions are shown in Figure 8-11.

The hot side gas conditions applied to the inner surfaces of the aft end outer seal segments were obtained from ANSC (Reference 4) and are based on NRX-A5 braze patch data. The chamber gas recovery temperature and convective heat transfer coefficient are given in Figure 8-12 as a function of the distance from the end of the filler strips.

8.4.3 Maturity of Input Data

This subsection describes the major input and the maturity of these data required in addition to the analytical model to perform the RA thermal-hydraulic performance calculations.

8.4.3.1 Reference Profiles

The startup and shutdown profile boundary condition data used to obtain the reflector components analysis results were those resulting from the NSS calculations using the "Reference Profiles" discussed in Section 2.4.3.1. These profiles reflect the extreme rate of chamber temperature increase and decrease of $+175^{\circ}/\text{sec}$ during the thrust buildup phase of startup and $-175^{\circ}/\text{sec}$ during the temperature retreat phase of shutdown, respectively.

8.4.3.2 Material Properties

The maturity of properties for the RA and the manner in which the thermal properties are used in the analysis are briefly discussed in Section 2.4.3.2. Table 8-6 lists the materials used in the detail analysis for the major RA components, excluding the LSS, and the specification identification of the materials. The thermal properties used are reported in the E-105 Data Item, Reference 5.

8.4.3.3 Hydrogen Properties

The hydrogen fluid properties used for the RA thermal analysis are those for 100 percent para hydrogen as obtained from the National Bureau of Standards para hydrogen property subroutines (Refer to Section 2.4.3.3). On the basis of previous reflector analyses, the conversion of para to ortho hydrogen has been shown to have an adverse effect on the thermal gradients in the beryllium reflector segments. This effect is due to a reduction of the convective heat transfer coefficients with increasing proportion of ortho hydrogen. A comparison between para and equilibrium hydrogen was made for rated performance at the

EOL with the normal operating mode using NBS equilibrium hydrogen property subroutines (Reference 6). The percentage change in temperature variations in the beryllium segments is summarized in Table 8-7. The Reflector Assembly fluid boundary conditions (inlet temperature and pressure, flow rate) were the same for both calculations as obtained from NSS thermal analyses with para hydrogen fluid properties. The use of equilibrium hydrogen properties instead of para hydrogen properties results in increased average to minimum temperature differences of about 15 percent and 25 percent in the inner and outer reflector segments. Further experimental work in this area is required to define the rates of conversion from para to ortho as a function of the neutron flux. Additional development effort would then be required to modify the existing thermal analysis computer programs to permit a variation of fluid properties as a function of the neutron flux field.

8.4.3.4 Heating Rates and Fast Neutron Fluence

The preliminary R-1 radiation heating rates and fast neutron flux field used for the thermal analyses of the Reflector Assembly components are presented in Section 8.4.2.3. These heating rates were obtained for a previous conceptual version of the R-1 NSS design per WANL-Dwg. 940J385. Similarly, the fast neutron fluence data used in the thermal analysis are based on a previous NSS design. A comparison of these data with that reported in the S-100 Data Item (Reference 7) is made in Table 8-8. There is excellent agreement in heating rates for all components except the control vane which decreased from 4.4 to 3.5 MW total heating with the graphite core (-22 percent change). The fluences are in good agreement except that the attenuation in the aluminum structural cylinder is less than assumed resulting in an increased fluence at the beryllium I. D. of about 23 percent.

8.4.3.5 Heat Transfer Coefficients and Friction Factor Correlations

A low temperature, heat transfer correlation developed by Los Alamos Scientific

Laboratory (LASL) is used in the reflector thermal analyses. This correlation is considered to be superior to those discussed in Section 2.4.3.5 for the reflector temperature range.

Los Alamos Scientific Laboratory Correlation (Reference 8)

$$h = 0.023 \left(\frac{k_b}{D} \right) (Re_b)^{0.8} (Pr_b)^{0.4} C_1 \left(\frac{T_w}{T_b} \right)^{-C_2}$$

The constants C_1 and C_2 are defined as follows:

For $T_w/T_b < 1.8$

$$C_1 = 1.0$$

$$C_2 = 0.765$$

For $T_w/T_b \geq 1.8$

$$C_1 = 0.7$$

$$C_2 = 0.20$$

where,

D = Hydraulic diameter of flow channel, in.

h = Local heat transfer film coefficient, Btu/sec-in.²-°R

k = Thermal conductivity, Btu/sec-in.°R

Pr = Prandtl number

Re = Reynolds number

T = Fluid bulk or material temperature, °R

and subscripts b and w indicate fluid bulk and wall conditions, respectively.

The Taylor smooth tube, turbulent friction factor correlation discussed in Section 2.4.2.3 is used in the reflector analyses (Reference 9).

8.4.3.6 Reflector Flow Impedances

The Reflector Assembly is a complex flow network with combined entrance and exit pressure losses for multiple parallel channels and with flow communication between many channels at repeating intervals along the channel length. An example of combined entrance losses is exhibited by the control drum end configuration. The total control drum assembly flow enters through the aft bearing support in series with the aft drum shaft and then distributes between the various drum channels. This entrance involves contractions, expansions, and turning losses in the fluid streams. The entrance and exit loss coefficients used in the analytical model and given in Table 8-5 are set for the individual channels such that the inlet pressure loss to each channel is the sum of the common entrance pressure drop plus a local channel entrance loss plus one velocity head to represent the momentum change between the channel and the plenum. The coefficients are adjusted to the rated performance operating conditions and are good approximations at other operating conditions.

Coolant flowing through the reflector channels which intersect the LSS spring capsules is diverted around the spring capsules in an 0.060 inch annular clearance. This gap was sized to minimize expansion and contraction losses. However, the turning losses are very substantial resulting in up to 60 percent flow reduction in the affected channels.

The calculation of static pressure losses due to stream contractions, expansions, turns, and mixing are made with standard hydraulic resistance correlations. Reference 10 was used extensively for this purpose. Due to the complexity of the reflector geometry, it is judged to be necessary to verify the calculated Reflector Assembly flow distribution with appropriate reflector and control drum flow tests.

8.4.4 Validity of Analysis

In this subsection, applicable test data used to substantiate the method of analysis are presented. The uncertainty analysis is presented for each design parameter relevant to the RA.

8.4.4.1 Applicable Test Results

The method of constructing detailed thermal analysis models and the use of these models with the TRACK-II computer code have been investigated in extensive post test analyses of the NRX-A6 test and in analysis of the Beryllium Reflector Transient Response Test. References 11, 12, and 13 present comparisons of calculated and measured data from these tests and the conclusions are summarized here.

1. The maximum observed deviations between measured and post test calculated temperatures in the NRX-A6 beryllium rings were 34°R at SOL and 58°R at EOL. These deviations include both the calculation uncertainty and the measurement uncertainty due to thermocouple installation.
2. The maximum observed deviations between measured and post test calculated temperatures in NRX-A6 control drums were 22°R at SOL and 14°R at EOL including thermocouple installation uncertainty.
3. Using a finer and more uniform nodal model (676 nodes versus 295 nodes) to analyze the Beryllium Reflector Transient Response Test resulted in reducing the maximum observed deviations between measured and calculated temperatures by a factor of two (20°R with 295 nodes to 11°R with 676 nodes).
4. Using the finer model to analyze the NRX-A6 steady state and transient temperature distributions resulted in essentially the same comparison of measured to calculated temperatures that was found with the original coarser model.

Thermal design and analysis of the NERVA reflector assembly have been guided by these findings. The following guidelines were established to decrease local thermal gradients, channel to channel variations, and uncertainties.

1. Minimize local temperature difference by minimizing coolant hole size and spacing.

2. Minimize overall temperature difference ($T_{\text{average}} - T_{\text{minimum}}$) by designing for uniformity of coolant condition. The minimum temperatures in beryllium reflector components occur at coolant channel walls and, therefore, it is essential that the channel to channel wall temperature variations be minimized. This can be achieved by using coolant holes with uniform hydraulic diameter and flow impedance spaced in such a way that the heat input to each channel is the same.

3. Minimize uncertainties by designing for coolant channel uniformity. Variations in coolant channel diameters, flow impedance, and surface heat flux should be minimized so that uncertainties in correlation of heat transfer coefficient, para-ortho concentration, friction factor, and loss coefficient will affect each channel to the same extent, causing a shift in the temperature level without changing the channel to channel temperature variations. The application of these three guidelines will decrease the uncertainty in the key thermal performance parameters relative to those for NRX reactors.

Other factors which enhance the validity of the NERVA reflector assembly thermal analysis are:

1. Improved material property data, including radiation effects.

2. Conduction heat transfer analysis programs capable of using thermal conductivity as a function of temperature and neutron fluence distribution.

3. The use of three dimensional models of the beryllium segments to more correctly represent the existence of relatively large lateral support capsules in the beryllium segments.

4. The use of finer nodal patterns in the models to better represent the material surrounding the increased number of cooling channels in the design.

5. The use of a greatly increased number of independent parallel flow channels in the model to represent the individual cooling channels in the design. Models of NRX designs lumped groups of neighboring cooling channels into single model channels.

Two other factors that have a strong influence on the validity of the thermal analysis are the radiation heating rate distribution and the flow impedances of the numerous cooling channels in the reflector assembly. Experimental verification of these factors will enhance the validity of the thermal analysis results. Two key component tests are planned to provide verification of the flow impedances prior to R-1 testing. These tests are the Control Drum Flow and Bow Test and the Flow Characteristics at Reflector Block Interfaces Test. The purpose of the control drum test is to verify the predicted flow through and around the control drum and to provide assurance that the control drum cylinder will not contact the reflector during the startup transient. The purpose of the block interface test is to experimentally determine the flow impedances and leakage characteristics of a typical section of the reflector assembly.

8.4.4.2 Uncertainty Analysis

The method of determining the uncertainties of the Reflector Assembly components parameters was to relate the Monte Carlo uncertainty analysis of the NSS to the detailed reflector nominal calculations. It is assumed that the variability of RA component parameters as defined by detailed fluid flow-heat conduction analyses is proportional to the variability of associated thermal parameters in the simplified TNT-II simulation of the Reflector Assembly. The percent variation of important reflector parameters was extracted from the results of the TNT-II Monte Carlo uncertainty analysis and applied directly to the nominal calculated values of equivalent or closely related parameters in the detailed analytical models. The Monte Carlo analysis of the NSS is reported in Section 2.4.4.2. Table 8-9 lists the parameters selected from the TNT-II reflector model, denotes the associated parameter in the component level model and gives the percent variability for 99%/95% confidence tolerance limits. The resultant uncertainty in selected parameters is included in the summaries of key Reflector Assembly parameters, Tables 8-3 and 8-4. The percent uncertainties given in Table 8-9 can be used to find the uncertainty of any of the nominal values included in the presentation of results, Section 8.5.

8.5 RESULTS, ANALYSIS, AND INTERPRETATION

Selection of operating modes requiring detailed Reflector Assembly computations was made by analyzing the TNT-II results for the NSS assembly level performance studies. A comparison of operating modes for several critical reflector parameters is given in Table 8-10. The critical parameters and their significance are as follows:

Radial pressure drop - Primary load on the reflector structure

Structure maximum temperature - Temperature limit

Beryllium segments ($\bar{T} - T_{WALL}$) - Thermal stress

Control drum ($\bar{T} - T_{WALL}$) - Thermal stress and drum bowing

Considering the trends evidenced by the TNT-II results, three steady state and one transient operating modes were judged to be "worst cases" requiring component level analyses. These cases are circled on Table 8-10.

Graphite Core, Rated Performance, End of Life, Normal Mode

This operating mode was selected because it results in the largest steady state thermal gradients in the beryllium segments and control drums. This is attributed to the high heat generation rates with the graphite core at rated performance and to the reduction in beryllium thermal conductivity at EOL.

Graphite Core, Throttle Hold Performance, End of Life, Normal Mode

This operating mode was selected because it results in the highest temperature level in reflector components. This is due to the high power to flow ratio and to the heat conducted into the structure from the lateral support system which is relatively higher than the internal heat generation as compared to the rated power condition.

Composite Core, Steady State Performance, Start of Life, Single Turbopump Operation

This operating mode was selected because it results in the maximum fluid pressure drop across the reflector structure.

Graphite Core, Startup, End of Life, Normal Mode

This operating mode was selected because it results in the largest thermal gradients in the reflector components, particularly the beryllium segments and control drum cylinders.

The thermal results for the selected operating conditions are discussed in the following subsections. Key thermal performance parameters for the Reflector Assembly have been summarized in Tables 8-3 and 8-4 and discussed previously in Section 8.2. The operating ranges shown for these parameters were calculated from the 99/95% tolerance limits obtained from the TNT-II Monte Carlo analysis of the NSS and applied to RA component level results as discussed in Section 8.4.4.2.

An analysis for failure modes related to thermal design aspects of the Reflector Assembly follows the presentation of results for the conditions analyzed.

8.5.1 Graphite Core, Rated Performance, End of Life, Normal Mode

The nominal calculated results for this operating condition are presented in Table 8-11 and Figures 8-13 through 8-23. The Reflector Assembly power and flow balance is summarized in the table. The heat pickup in the reflector coolant is 21.5 MW including 2.72 MW conducted from the lateral support seals and 1.0 MW generated in the pressure vessel side. The coolant mixed mean temperature rise is 70°R (198 in, 268 out). The flow distribution to the major RA components is 29 percent through the structural cylinder, 25 percent through the beryllium reflector, 37 percent through the control drum assembly and 9 percent through the pressure vessel annulus. The reflector axial pressure drop at this operating condition is 52 psi. This pressure drop is set by the desired flow rates and coolant channel hydraulic impedance of the structural cylinder and the reflector segments. More than adequate pressure head is available to provide the desired flow rate through the control drum assembly and pressure vessel annulus. Figure 8-13 shows the axial pressure distribution in the reflector and lateral support seal system. The aft end radial pressure drop across the structural cylinder is 670 psi.

As discussed in the introduction to this subsection (8.5), this operating condition is expected to result in the most severe steady state thermal gradients in the reflector components. The axial temperature variation in the structural cylinder is shown in Figure 8-14. The peak temperature occurs at mid plane where the axial and radial average is 350°R with a corresponding maximum of 485°R on the ID at the location of the LSS seal plunger penetrations and a minimum of 270°R near the OD at the drum centerline. Axial temperature profiles and midplane isotherms are shown for the inner and outer beryllium segments

in Figures 8-15 through 8-18. The midplane average to minimum temperature differences are 31°R and 15°R for the inner and outer segments respectively. This compares with calculated steady state temperature differences of 40°R and 50°R for the beryllium segments reported for the aluminum structure concept in the Reflector Trade Study (Reference 14). Post test calculations indicate that the NRX-A6 beryllium rings experienced a steady state average to minimum temperature difference of about 140°R and a measured maximum to minimum temperature difference of 266°R .

The control drum cylinder axial temperature profile and midplane isotherms are shown in Figures 8-19 and 8-20. The average to minimum temperature difference is 43°R with the maximum occurring at the side nearest the core and the temperature falls off on a traverse radially outward from the core centerline. The control vane temperature distribution is shown in Figure 8-21. The maximum temperature is 475°R at core station 23 inches on the edge of the vane nearest the core. The corresponding average and minimum temperatures are 360°R and 285°R . As noted in Section 8.4.3 (Maturity of Input Data), the heating rates reported for the control vane in the S-100 Data Item are 20 percent lower than the preliminary values used in the thermal analysis. This reduction in radiation heating rates would tend to reduce the temperature variation in the control vanes.

The axial temperature distributions in the reflector baffle can and control drum bore liner are shown in Figures 8-22 and 8-23. There is negligible radial and circumferential temperature variation in the baffle can. The maximum to minimum circumferential temperature difference in the drum bore liner is about 40°R with the minimum occurring on the surface

adjacent to the control vane cooling annulus. Detailed finite element models were not constructed for the aft end support ring or for the control drum end hardware such as bearings, bearing housings, and end shafts. The heating rates in these regions are relatively low and the components are abundantly cooled by the fluid entering and exiting the Reflector Assembly so that they operate near the gas temperature. For the rated performance operating condition, the estimated operating temperature range for the aft end miscellaneous hardware is 210–220°R. The forward end control drum hardware is estimated to operate in the temperature range, 260–300°R.

8.5.2 Graphite Core, Throttle Hold Performance, EOL, Normal Mode

The thermal analysis results for throttle hold performance at end of life with the graphite core and normal mode of operation are presented in Table 8-11, Part B and Figures 8-24 through 8-28. This operating condition results in the highest steady state temperature levels in the Reflector Assembly even though material temperature gradients are less than at rated performance. This is due to the combination of reduced power level (65 percent), but increased power to flow ratio (1.18 relative to rated performance at EOL). The power and flow balance are given in Part B of Table 8-11. The pressure distribution is shown in Figure 8-24. The reflector axial pressure drop is 31 psi and the maximum radial pressure drop across the structural cylinder is 385 psi.

The nominal maximum temperature in the structural cylinder is 493°R at core station 25 inches. The upper tolerance limit for this temperature based on the TNT-II Monte Carlo analysis is 523°R. Axial temperature profiles for the reflector baffle can and drum bore liner are included on Figures 8-22 and 8-23.

Temperature distributions in the control drum cylinders and control vanes are shown in Figures 8-26 to 8-28. The nominal maximum temperature for the control vane is 495°R with an upper limit of 531°R.

8.5.3 Composite Core, Steady State Performance, SOL, Single Turbopump Operation

This malfunction mode of operation was selected for analysis because it results in the maximum radial pressure drop across the aluminum structural cylinder. This pressure drop

is nominally 798 psi as illustrated on the reflector-lateral support pressure plot, Figure 8-29. The tolerance on this value is 21 psi and the resultant upper limit is 819 psi.

The power and flow balance for this operating condition is given in Table 8-11, Part C. The power level relative to rated performance is 80 percent. The heat conducted from the LSS seals at this condition was estimated to be 2.52 MW based on linear interpolation between the rated and throttle hold values as a function of NSS power level. The total reflector coolant heat pickup is 15.81 MW with a flow rate of 63 lbs/sec, exit gas temperature of 266°R and an axial pressure drop of 35 psi.

Temperature distributions are shown in Figures 8-30 through 8-32 for the structural cylinder, control drum cylinders, and control vanes. The temperature levels are below those for the throttle hold performance (Section 8.5.2) and the temperature differences are less than those for rated performance (Section 8.5.1).

The forward end extension ring and structural cylinder aft end support configuration were analyzed for this operating mode because of their direct implication on the structural analysis of the aluminum cylinder at the maximum pressure load condition. Isotherms in a typical slice of the forward extension ring taken between control drums is shown in Figure 8-33. The temperature in the plate region located above the beryllium segments ranges from 270°R to 280°R, about 10–20°R above the gas temperature. The ring portion ranges in temperature from 290°R at the interface with the aluminum structure to 400°R at the interface with the core support plate. The average temperature of the forward extension ring at this operating condition is 310°R.

Isotherms are shown in Figure 8-34 for the structural cylinder aft end support configuration. Represented in the model are the aft end of the structural cylinder, the aft row of inner and outer seal segments, the 0.080 inch grafoil insulating segments and the nozzle-structure clamp ring. The hot side gas temperatures and heat transfer coefficients used in the calculation of temperatures in the aft end region are those received from ANSC (Refer to Section 8.4.2.3.) and are based on NRX-A3 through NRX-A5 braze patch data. Since

these engine configurations differ considerably from NERVA with respect to the separation of the Reflector Assembly ID from the fuel exhaust and to the quantity of core bypass flow, WANL has indicated reservation with regard to the utilization and validity of these boundary conditions. WANL believes these boundary conditions are very conservative and that the actual temperatures will be lower than those shown. While additional investigation is required in this area, the present calculations are based on the extracted data. The average temperature of the aft end of the structural cylinder is 280°R with a maximum at the ID of 390°R and a minimum at the OD of 219°R . The average temperature of the outer seal segment is 1210°R , but the temperature level and thermal gradients appear to be excessive in the extended skirt which protects the aluminum cylinder from the hot chamber gases. The maximum temperature is 2610°R at the lower inside surface of the skirt. The temperature falls off rapidly to about 1800°R at the interface with the insulating segment.

8.5.4 Graphite Core, Startup, End of Life, Normal Mode

This operating mode was selected for analysis because it represents the most severe thermal gradients in the beryllium components of the Reflector Assembly. Of particular interest are the thermal stresses in the beryllium segments and control drum cylinder and thermal bowing of the control drums. The data for this operating condition is presented in Figures 8-35 through 8-45. Temperatures and temperature differences are shown as a function of time during the startup for RA components at three axial locations, aft end, midplane, and forward end. The time scale begins at the initiation of temperature conditioning (0-25 seconds), followed by bootstrap (25-32 seconds), and thrust buildup. The component level analysis of the startup was terminated when the point of maximum temperature variations in the RA components had been reached. The calculations were performed with material thermal properties corresponding to one hour operation at rated performance preceeding the startup.

The transient average temperature profiles for the structural cylinder are shown in Figure 8-35. The temperature differences (maximum to average and average to minimum) are shown in Figure 8-36. The average to minimum ΔT peaks at 110°R in the cylinder.

The inner beryllium average temperature and temperature difference profiles are presented in Figures 8-37 and 8-38. The outer beryllium segment profiles are shown in Figure 8-39 and 8-40. The peak average to minimum temperature differences in the inner segments are 66, 36, and 66°R for the aft end, midplane and forward end. The corresponding peak values in the outer segments are 105, 65 and approximately 90°R. The forward end peak temperature difference in the outer segment is an extrapolated value since the peak had not occurred at the termination of the problem (42 seconds). This compares with average to minimum temperature differences in the NRX-A6 in the order of 250-300°R based on measured minimum temperature at the OD web and post test calculated average temperature. Predicted values of startup ΔT for NRX beryllium reflectors have generally been in the 250-300°R range. The reduction in this ΔT for the R-1 design is due to dividing the beryllium into inner and outer segments so that the inherent incompatibility between steady state and transient operation of this component has been alleviated.

The control drum average temperature and temperature difference transient profiles are shown in Figures 8-41 and 8-42. The peak average to minimum temperature difference in the drum cylinder is 80°R at midplane. The control drum was redesigned for the R-1 relative to the NRX-A5 and A6. The coolant slot opposite the control vane was eliminated. The function of this slot was to match the cooling characteristics of the vane cooling annulus during startup to minimize thermal bowing of the drum. That purpose was accomplished, but an excessive amount of reflector coolant was used and the resultant thermal gradients were undesirable. The present design incorporates an 0.100 inch grafoil insulating segment to thermally isolate the beryllium control drum cylinder from the control vane coolant. With this design approach, it is considered that acceptable thermal stresses and drum bow can be achieved while attaining efficient coolant usage throughout the Reflector Assembly.

Control vane temperature profiles are shown in Figures 8-43 and 8-44. The peak average to minimum ΔT in the vanes is 60°R at midplane at 44 seconds after initiation of temperature conditioning. The steady state ΔT at rated performance is 76°R.

Average temperature profiles during the startup are shown in Figure 8-45 for the reflector baffle can.

8.5.5 Space Soak Effects

Summary Table 8-3 shows the temperature ranges expected for the reflector assembly components during space soak prior to operation. These data are a summary of that presented in Data Item S-001 (Reference 15).

8.5.6 Probability of Failure Analysis

Technical justification is required at PDR to demonstrate that the Reflector Assembly components have a reasonable chance of achieving the NPRD requirements. The procedure is presented in Reference 16 and involves making analytical estimates of component reliability at the mode of failure level during the pre-PDR period.

The approach followed to insure that all support plate components have a high inherent reliability was to first make a thorough and unbiased listing of all the credible ways a Reflector Assembly component can fail to perform. Subsequently, design changes were made to eliminate as many failure points as possible. Finally, the probability of occurrence of each remaining failure is assessed. This final calculation is presented in this subsection for failure modes directly involving thermal design aspects. The general procedure consists of obtaining the reliability value from two overlapping normal distributions, e.g., operating temperature vs constraint. Usually the population standard deviation of the two normal distributions are not known and the reliability value is computed from the sample standard deviation (S) and the sample size (n) from each of these distributions.

The procedure as described in SNPO-C-1 is as follows:

Given: $\bar{X}_L, S_L, n$, (Operating temperature - Refer to Table 8-12)

$\bar{X}_S, S_S, n$, (Limiting temperatures - Refer to Table 8-12)

Calculate: $X_{R1} = \frac{\bar{X}_S - \bar{X}_L}{S_S^2 + S_L^2}$ and, $n' = \frac{(S_S^2 + S_L^2)^2}{S_S^4 / n_2 + S_L^4 / n_1}$

Obtain the population reliability (R) at 90% confidence level from curves relating sample reliability to population reliability, Reference 17.

Table 8-12 lists the modes and mechanisms of failure for the reflector assembly components that are directly related to thermal design aspects. Failure modes for the lateral support components are not included here because they are addressed in Trade Study 782, Data Item S-054. The probability of failure (F) is equal to $(1-R)$ and is given in the last column of Table 8-12. The probability of failure values of $<10^{-19}$ indicate the occurrence of the material melting modes are highly incredible.

The probability of losing material from the drum cylinder insulator (mode no.78) cannot be quantitatively identified at this time. As indicated on Table 8-12, both reactor and laboratory tests have shown that corrosion and erosion are negligible for the hydrogen flow environment that this part will experience. However, some surface blistering was observed in laboratory tests when grafoil samples were depressurized at a rate of approximately 17 psi/sec while depressurization at a rate of 4 psi/sec did not result in blistering (Reference 18). Because the anticipated depressurization rates in NERVA are in excess of 17 psi/sec, the occurrence of this blistering phenomena and the effect it has on the thermal impedance of grafoil requires further investigation. However, the sample which blistered displayed a negligible weight loss after 25 pressurization - depressurization cycles. Since the blistering did not result in a loss of material, it may have little effect on thermal conductivity, especially when the grafoil is sandwiched between two other materials. For this reason, it is judged that this failure mode is incredible. The planned control drum development testing will give data relative to the occurrence of blistering and its effect on material loss and thermal impedance.

8.6 REFERENCES

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TABLE 8-1;
INDUCED THERMAL ENVIRONMENT OF REFLECTOR ASSEMBLY (GRAPHITE CORE)

<u>Description</u>	<u>Flow-Lb/Sec</u>	<u>Pressure-Psia</u>	<u>Temp-Deg R</u>
<u>Steady State Performance at Rated Conditions-Start of Life (SOL)</u>			
Reflector Inlet Plenum	80.3 + 2.3	1127 + 23.0	192 + 11.0
Pressure Vessel Annulus Inlet	6.9 ± 0.46	1127 ± 23.0	192 ± 11.0
Reflector Outlet (Excluding PV Annulus)	73.4 ± 2.0	1065 ± 21.0	269 ± 19.6
Pressure Vessel Annulus Outlet	6.9 ± 0.46	1065 ± 21.2	254 ± 22.9
Core Inlet Plenum	91.2 ± 1.4	620 ± 8.6	292 ± 18.1
Lateral Support Outlet	0.6	450	1406
<u>Steady State Performance at Rated Conditions-End of Life (EOL)</u>			
Reflector Inlet Plenum	76.2 + 2.5	1120 + 22.7	198 + 12.1
Pressure Vessel Annulus Inlet	6.6 ± 0.45	1120 ± 22.7	198 ± 12.1
Reflector Outlet (Excluding PV Annulus)	69.7 ± 2.2	1061 ± 20.8	278 ± 20.8
Pressure Vessel Annulus Outlet	6.6 ± 0.45	1061 ± 21.0	262 ± 24.8
Core Inlet Plenum	91.2 ± 1.4	620 ± 8.8	294 ± 18.3
Lateral Support Outlet	0.6	450	1400
<u>Steady State Performance at 65% Throttle Hold-Start of Life (SOL)</u>			
Reflector Inlet Plenum	45.9 + 2.2	684 + 16.9	215 + 13.0
Pressure Vessel Annulus Inlet	4.1 ± 0.33	684 ± 16.9	215 ± 13.0
Reflector Outlet (Excluding PV Annulus)	41.8 ± 1.9	644 ± 15.7	314 ± 24.9
Pressure Vessel Annulus Outlet	4.1 ± 0.33	644 ± 15.4	287 ± 24.9
Core Inlet Plenum	59.2 ± 1.3	414 ± 8.3	336 ± 24.6
Lateral Support Outlet	0.4	293	1400
<u>Steady State Performance at 65% Throttle Hold-End of Life (EOL)</u>			
Reflector Inlet Plenum	41.8	678	229
Pressure Vessel Annulus Inlet	3.8	678	229
Reflector Outlet (Excluding PV Annulus)	38.1	642	336
Pressure Vessel Annulus Outlet	3.8	642	305
Core Inlet Plenum	59.2	414	338
Lateral Support Outlet	0.4	293	1407

TABLE 8-1 (CONT'D)

<u>Description</u>	<u>Flow-Lb/Sec</u>	<u>Pressure-Psia</u>	<u>Temp-Deg R</u>
<u>Steady State Performance at 80% Thrust-Single TPA Malfunction-Start of Life (SOL)</u>			
Reflector Inlet Plenum	62.4 + 2.3	1143 + 22.2	205 + 11.3
Pressure Vessel Annulus Inlet	5.4 + 0.39	1143 + 22.2	205 + 11.3
Reflector Outlet (Excluding PV Annulus)	57.0 + 2.0	1103 + 21.6	289 + 22.3
Pressure Vessel Annulus Outlet	5.4 + 0.39	1103 + 21.3	269 + 23.9
Core Inlet Plenum	72.9 + 1.3	503 + 8.2	313 + 20.1
Lateral Support Outlet	0.5	360	1407
<u>Steady State Performance at 80% Thrust-Single TPA Malfunction-End of Life (EOL)</u>			
Reflector Inlet Plenum	58.6 + 2.6	1137 + 22.6	213 + 12.9
Pressure Vessel Annulus Inlet	5.1 + 0.39	1137 + 22.6	213 + 12.9
Reflector Outlet (Excluding PV Annulus)	53.5 + 2.3	1099 + 22.0	302 + 25.0
Pressure Vessel Annulus Outlet	5.1 + 0.39	1099 + 21.9	280 + 26.7
Core Inlet Plenum	72.9 + 1.3	503 + 8.3	315 + 20.3
Lateral Support Outlet	0.5	360	1405
<u>Steady State Performance at 65% Throttle Hold-Single TPA Malfunction-Start of Life (SOL)</u>			
Reflector Inlet Plenum	47.3	848	215
Pressure Vessel Annulus Inlet	4.2	848	215
Reflector Outlet (Excluding PV Annulus)	43.1	814	311
Pressure Vessel Annulus Outlet	4.2	814	284
Core Inlet Plenum	59.2	414	336
Lateral Support Outlet	0.4	293	1402
<u>Steady State at 65% Throttle Hold-Single TPA Malfunction-End of Life (EOL)</u>			
Reflector Inlet Plenum	43.3	841	227
Pressure Vessel Annulus Inlet	3.9	841	227
Reflector Outlet (Excluding PV Annulus)	39.4	810	332
Pressure Vessel Annulus Outlet	3.9	810	302
Core Inlet Plenum	59.2	414	337
Lateral Support Outlet	0.4	293	1408

TABLE 8-2
INDUCED THERMAL ENVIRONMENT OF REFLECTOR ASSEMBLY (COMPOSITE CORE)

<u>Description</u>	<u>Flow-Lb/Sec</u>	<u>Pressure-Psia</u>	<u>Temp-Deg R</u>
<u>Steady State Performance at 80% Thrust-Single TPA Malfunction-Start of Life (SOL)</u>			
Reflector Inlet Plenum	63.0 + 2.1	1158 + 25.1	205 + 10.8
Pressure Vessel Annulus Inlet	5.5 + 0.38	1158 + 25.1	205 + 10.8
Reflector Outlet (Excluding PV Annulus)	57.5 + 1.8	1118 + 24.8	281 + 16.1
Pressure Vessel Annulus Outlet	5.5 + 0.38	1118 + 24.8	257 + 15.6
Core Inlet Plenum	72.9 + 1.3	502 + 8.0	301 + 16.4
Lateral Support Outlet	0.5 + 0.067	360 + 5.0	1410 + 232
<u>Steady State Performance at 80% Thrust-Single TPA Malfunction-End of Life (EOL)</u>			
Reflector Inlet Plenum	59.5 + 2.4	1151 + 25.3	211 + 12.1
Pressure Vessel Annulus Inlet	5.2 + 0.39	1151 + 25.3	211 + 12.1
Reflector Outlet (Excluding PV Annulus)	54.3 + 2.1	1114 + 24.9	291 + 18.1
Pressure Vessel Annulus Outlet	5.2 + 0.39	1114 + 24.7	266 + 17.7
Core Inlet Plenum	72.9 + 1.3	502 + 8.0	303 + 17.0
Lateral Support Outlet	0.5	360	1403

TABLE 8 - SUMMARY OF REFLECTOR ASSEMBLY COMPONENT MATERIAL TEMPERATURES AND OTHER KEY PERFORMANCE PARAMETERS (GRAPHITE CORE)

COMPONENT	LOCATION	PARAMETER	NORMAL MODE OPERATION						COOLDOWN OPERATION RANGE	SPACE SOAK RANGE	
			RATED PERFORMANCE, EOL 99/95 TOLERANCE LIMIT			THROTTLED HOLD, EOL 99/95 TOLERANCE LIMIT				Solar Flux ⁽³⁾ of 302 Btu/Hr/Ft ²	Solar Flux ⁽⁴⁾ of 3000 Btu/Hr/Ft ²
			NOMINAL	UPPER	LOWER	NOMINAL	UPPER	LOWER			
Reflector Assembly	C.S. 0 to 52	Heat Addition to Coolant - MW	21.46	23.88	19.04	14.25	15.77	12.73			
	C.S. 0 to 52	Axial Δp - psi	52.0	55.9	48.1	31.0	34.0	28.0			
	Reflector Exit (including Pressure Vessel Annulus)	Mixed Mean Coolant Temp. deg R	268.	283.	253.	312.	332.5	291.5			
Structure	C.S. 52	Radial Δp - psi	670	689.	651.	386.	398.	374.	(360-710) ⁽¹⁾ 800 ⁽²⁾	350-550	550-900
	C.S. 25	$\bar{T}$ - deg. R	350.	389.	311.	380.	423.	337.			
	C.S. 25	T_{max} - deg. R	485.	519.	451.	493.	523.	463.			
Inner Segments	C.S. 26	$\bar{T}$ - deg. R	276.	292.	260.	—	—	—	(290-760) ⁽¹⁾ 800 max ⁽²⁾ with	350-550	550-900
	C.S. 26	$T - T_{min}$ deg. R	31.	41.	21.	—	—	—			
	C.S. 26	$T_{max} - \bar{T}$	65.	85.	45.	—	—	—			
Outer Segments	C.S. 26	$\bar{T}$	255.	270.	240.	—	—	—	(290-760) ⁽¹⁾ 800 max ⁽²⁾ with	350-550	550-900
	C.S. 26	$T - T_{min}$	15.	20.	10.	—	—	—			
	C.S. 26	$T_{max} - \bar{T}$	12.	16.	8.	—	—	—			
Reflector Baffle Can	C.S. 0	T_{max}	269.	284.	254.	295.	313.	277.	(290-760) ⁽¹⁾ 800 max ⁽²⁾ with	350-550	550-900
	Control Drum Cylinders	$\bar{T}$	309.	332.	286.	335.	359.	311.			
Drum Cans	C.S. 26	$T - T_{min}$	43.	58.	28.	32.	43.	21.	(290-760) ⁽¹⁾ 800 max ⁽²⁾ with	350-550	550-900
	C.S. 26	$T_{max} - \bar{T}$	37.	50.	24.	30.	41.	19.			
	C.S. 26	T_{max}	300.	322.	278.	334.	358.	310.			
Control Vanes	C.S. 26	T_{max}	470.	504.	436.	495.	531.	459.	(290-760) ⁽¹⁾ 800 max ⁽²⁾ with	350-550	550-900
	Control Drum Bare Liners	T_{max}	291.	311.	271.	311.	334.	288.			
Aft End Hardware	C.S. 52	T Coolant	198.	210.	186.	229.	240.	218.	(290-760) ⁽¹⁾ 800 max ⁽²⁾ with	350-550	550-900
Forward Control Drum Hardware	C.S. 0	T Coolant	272.	290.	254.	315.	339.	291.			

(1) This is the temperature range within 3.65 hours after a ten minute burn and throttle hold, as reported in WANL-TME-2678, "Systems Analysis Summary Report, Nuclear Subsystem," Section 5.2.6.3

(2) This is the maximum allowable temperature between cooling pulses.

(3) This is the minimum flux shown in WANL-TME-2678, "Systems Analysis Summary Report, Nuclear Subsystem," Section 5.2.6.3 Solar flux in earth orbit is 444 Btu/Hr·ft² as reported in WANL-TME-2678.

(4) This is the extreme solar flux, in the vicinity of Mercury, as reported in WANL-TME-2678.

TABLE 8-3 (CONT'D)

GRAPHITE CORE, STARTUP, END OF LIFE, NORMAL MODE

COMPONENT	LOCATION	PARAMETER	TIME* (sec.)	T or ΔT °R
Inner Segments	C.S. 52	$\bar{T}$	32	321.4
		$\bar{T} - T_{min}$	↓	66.7
		$T_{max} - \bar{T}$	↓	69.3
	C.S. 26	$\bar{T}$	40	346.2
		$\bar{T} - T_{min}$	↓	35.9
		$T_{max} - \bar{T}$	↓	66.3
	C.S. 0	$\bar{T}$	42	417.1
		$\bar{T} - T_{min}$	↓	65.6
		$T_{max} - \bar{T}$	↓	60.0
Outer Segments	C.S. 52	$\bar{T}$	32	292.5
		$\bar{T} - T_{min}$	↓	104.1
		$T_{max} - \bar{T}$	↓	110.6
	C.S. 26	$\bar{T}$	42	354.5
		$\bar{T} - T_{min}$	↓	64.2
		$T_{max} - \bar{T}$	↓	37.1
	C.S. 0	$\bar{T}$	42	463.7
		$\bar{T} - T_{min}$	↓	82.2
		$T_{max} - \bar{T}$	↓	60.6
Control Drum Cylinders	C.S. 52	$\bar{T}$	36	376.4
		$\bar{T} - T_{min}$	↓	68.4
		$T_{max} - \bar{T}$	↓	31.0
	C.S. 26	$\bar{T}$	38	416.8
		$\bar{T} - T_{min}$	↓	79.0
		$T_{max} - \bar{T}$	↓	33.2
	C.S. 0	$\bar{T}$	38	471.1
		$\bar{T} - T_{min}$	↓	75.5
		$T_{max} - \bar{T}$	↓	29.7

* Time selected corresponds to occurrence of maximum $\bar{T} - T_{min}$, within first 42 seconds.

TABLE 8 - 4
SUMMARY OF REFLECTOR ASSEMBLY COMPONENT MATERIAL TEMPERATURES
AND OTHER KEY PERFORMANCE PARAMETERS (COMPOSITE CORE)

COMPONENT	LOCATION	PARAMETER	SINGLE TPA MALFUNCTION 80% THRUST, SOL 99/95 TOLERANCE LIMIT		
			NOMINAL	UPPER	LOWER
Reflector Assembly	C.S. 0 to 52	Heat Addition to Coolant - MW	15.81	17.56	14.06
	C.S. 0 to 52	Axial ΔP - psia	35.0	37.8	32.2
	Reflector Exit (including Pressure Vessel Annulus)	Mixed Mean Coolant Temperature - $^{\circ}R$	266.	281.	251.
Structure	C.S. 52	Radial ΔP - psia	798.	819.	777.
	C.S. 25	$\bar{T} - ^{\circ}R$	325.	360.	290.
	C.S. 25	$T_{max} - ^{\circ}R$	446.	476.	416.
	Aft Flange Region	$\bar{T} - ^{\circ}R$	280.	—	—
	Aft Flange Region	$T_{max} - ^{\circ}R$	390.	—	—
Forward Extension Ring	Forward of C.S. 0	$\bar{T} \quad ^{\circ}R$	310.	336.	284.
	Forward of C.S. 0	$T_{max} \quad \downarrow$	394.	427.	361.
	Forward of C.S. 0	T_{min}	272.	287.	257.
Control Drum Cylinder	C.S. 26	$\bar{T}$	293.	313.	273.
	C.S. 26	$\bar{T} - T_{min} \quad \downarrow$	30.	40.5	19.5
	C.S. 26	$T_{max} - \bar{T}$	22.	29.7	14.3
Control Vane	C.S. 26	$T_{max} \quad \downarrow$	460.	492.	428.

TABLE 8-5
REFLECTOR ASSEMBLY COOLANT CHANNEL INPUT DATA

Channel ⁽¹⁾	Hydraulic Diameter, D _h (in) ⁽²⁾	No. of Equivalent ⁽³⁾ Holes, N	Loss Coefficients, CL ⁽⁴⁾		Friction ⁽⁵⁾ Multiplier
			Inlet	Outlet	
Group 1					
1	0.2500	36.00	4.0	3.0	1.15
2	0.2500	36.00	4.0	3.0	1.15
3	0.2000	18.00	4.0	3.0	1.15
4	0.2000	36.00	4.0	3.0	1.12
5	0.2000	36.00	4.0	3.0	1.15
6	0.2000	36.00	4.0	3.0	1.15
7	0.2000	36.00	4.0	3.0	1.15
8	0.2000	36.00	4.0	3.0	1.15
9	0.2000	18.00	4.0	3.0	1.15
10	0.2000	36.00	3.0	3.0	1.12
11	0.2000	36.00	3.0	3.0	1.12
12	0.2000	36.00	3.0	3.0	1.12
13	0.2000	36.00	3.0	3.0	1.12
14	0.2000	36.00	3.0	3.0	1.12
15	0.1875	18.00	9.5	12.0	1.00
16	0.1875	18.00	9.5	12.0	1.00
17	0.1875	18.00	9.5	12.0	1.00
18	0.1875	18.00	9.5	12.0	1.00
19	0.1875	18.00	9.5	12.0	1.00
20	0.1875	18.00	9.5	12.0	1.00
21	0.1875	18.00	9.5	12.0	1.00
22	0.1875	18.00	9.5	12.0	1.00
23	0.1875	18.00	9.5	12.0	1.00
24	0.1875	18.00	9.5	12.0	1.00
25	0.1875	18.00	9.5	12.0	1.00
26	0.1875	18.00	9.5	12.0	1.00
27	0.1600	52.60	5.5	4.0	1.00
28	0.1600	49.10	5.5	4.0	1.00
29	0.1600	92.40	5.5	4.0	1.00
30	0.1600	92.00	5.5	4.0	1.00

TABLE 8-5 (CONT'D)
REFLECTOR ASSEMBLY COOLANT CHANNEL INPUT DATA

Channel ⁽¹⁾	Hydraulic Diameter, D_h (in) ⁽²⁾	No. of Equivalent ⁽³⁾ Holes, N	Loss Coefficients, CL ⁽⁴⁾		Friction ⁽⁵⁾ Multiplier
			Inlet	Outlet	
31	0.1600	73.30	5.5	4.0	1.00
32	0.1600	53.70	5.5	4.0	1.00
33	0.1600	101.20	5.5	4.0	1.00
34	0.1600	117.30	5.5	4.0	1.00
35	0.1500	120.00	20.0	70.0	1.00
36	0.1500	109.00	20.0	70.0	1.00
37	0.1500	165.00	20.0	70.0	1.00
38	0.1500	117.00	20.0	70.0	1.00
39	0.1500	121.00	20.0	70.0	1.00
40	0.1500	141.00	20.0	70.0	1.00
41	0.1500	109.00	20.0	70.0	1.00
42	0.1500	157.00	20.0	70.0	1.00
43	0.4800	52.00	370.0	435.0	1.00
44	0.4800	45.50	370.0	435.0	1.00
45	0.4800	31.50	370.0	435.0	1.00
46	0.4800	48.50	370.0	435.0	1.00
47	0.4800	47.50	370.0	435.0	1.00
<u>Group 2</u>					
1	0.1250	36.00	3.0	2.0	1.15
2	0.1250	36.00	3.0	2.0	1.15
3	0.1250	36.00	3.0	2.0	1.15
4	0.1250	36.00	3.0	2.0	1.15
5	0.1250	36.00	3.0	2.0	1.15
6	0.1250	36.00	3.0	2.0	1.15
7	0.1250	18.00	3.0	2.0	1.15
8	0.1250	36.00	3.0	2.0	1.15
9	0.1250	36.00	3.0	2.0	1.15
10	0.1250	36.00	3.0	2.0	1.15
11	0.1250	36.00	3.0	2.0	1.15

TABLE 8-5 (CONT'D)

REFLECTOR ASSEMBLY COOLANT CHANNEL INPUT DATA

Channel ⁽¹⁾	Hydraulic Diameter, D_h (in) ⁽²⁾	No. of Equivalent Holes, N ⁽³⁾	Loss Coefficients, CL ⁽⁴⁾		Friction ⁽⁵⁾ Multiplier
			Inlet	Outlet	
12	0.1250	36.00	3.0	2.0	4.90
13	0.1250	36.00	3.0	2.0	4.90
14	0.1250	36.00	3.0	2.0	4.90
15	0.1250	36.00	3.0	2.0	4.90
16	0.1250	36.00	3.0	2.0	4.90
17	0.1250	36.00	3.0	2.0	4.90
18	0.1250	36.00	3.0	2.0	4.90
19	0.1250	36.00	3.0	2.0	4.90
20	0.1250	36.00	3.0	2.0	7.50
21	0.1250	36.00	3.0	2.0	7.50
22	0.1250	36.00	3.0	2.0	7.50
23	0.1250	36.00	3.0	2.0	7.50
24	0.1250	36.00	3.0	2.0	7.50
25	0.1250	36.00	3.0	2.0	7.50
26	0.1250	36.00	3.0	2.0	7.50
27	0.1250	36.00	3.0	2.0	7.50
28	0.1250	36.00	3.0	2.0	10.50
29	0.1250	36.00	3.0	2.0	10.50
30	0.1250	36.00	3.0	2.0	10.50
31	0.1250	36.00	3.0	2.0	10.50
32	0.1250	36.00	3.0	2.0	10.50
33	0.1250	36.00	3.0	2.0	10.50
34	0.1250	36.00	3.0	2.0	10.50
35	0.1250	36.00	3.0	2.0	6.10
36	0.1250	36.00	3.0	2.0	6.10
37	0.1250	36.00	3.0	2.0	6.10
38	0.1250	36.00	3.0	2.0	6.10
39	0.1250	36.00	3.0	2.0	6.10
40	0.1250	36.00	3.0	2.0	6.10
41	0.1250	36.00	3.0	2.0	6.10
42	0.1250	36.00	3.0	2.0	6.10
43	0.0600	763.00	3.0	2.0	15.00
44	0.0440	463.00	3.0	2.0	1.10
45	0.0320	147.00	3.0	2.0	1.10
46	0.0380	515.00	3.0	2.0	1.10
47	0.0350	568.00	3.0	2.0	1.10
48	0.0320	576.00	3.0	2.0	1.10

TABLE 8-5 (CONT'D)
REFLECTOR ASSEMBLY COOLANT CHANNEL INPUT DATA

<u>Channel⁽¹⁾</u>	<u>Hydraulic⁽²⁾ Diameter, D_h (in)</u>	<u>No. of Equivalent⁽³⁾ Holes, N</u>	<u>Loss Coefficients, CL⁽⁴⁾</u>		<u>Friction⁽⁵⁾ Multiplier</u>
			<u>Inlet</u>	<u>Outlet</u>	
<u>Group 1</u>					
49	0.0320	684.00	3.0	2.0	1.10
50	0.0330	536.00	3.0	2.0	1.10
51	0.0340	652.00	3.0	2.0	1.10
52	0.0350	302.00	3.0	2.0	1.10
53	0.0370	431.00	3.0	2.0	1.10

- Channel locations are shown on Figure 8-2 . All channels are 52 inches long.
- Coolant channels are represented as equivalent circular tubes. $D_h = \frac{4A}{P}$ where A = total flow area, P = wetted perimeter
- $N = A / \left(\frac{\pi}{4} D_h^2 \right)$
- Total pressure loss coefficients (negative indicates pressure regain) $\Delta P = CL \frac{G^2 v}{2g}$ where ΔP = pressure drop, G = mass flow rate per unit area (based on channel area), v =specific volume, g = gravitational constant
- Friction multiplier modifies smooth tube friction factor to simulate channel roughness or local channel impedances such as flow interruption at LSS spring capsule locations. Also used to simulate additional length of the structural cylinder channels.

TABLE 8-6 . MATERIALS USED IN REFLECTOR ASSEMBLY ANALYSIS

<u>Component</u>	<u>Material</u>	<u>Specification Identification</u>	<u>Material* Library No.</u>
Structural Cylinder	Aluminum	PDS30258-1(6061-T61)	74
Forward Extension Ring	Aluminim	PDS30258-1(6061-T61)	74
Aft Support Ring	Aluminum	QQ-A-250/11-T6(6061)	3
Inner Reflector Segment	Beryllium	PDS30018-1	4
Outer Reflector Segment	Beryllium	PDS30018-1	4
Reflector Baffle Can	Aluminum	QQ-A-250/11-T6(6061)	3
Drum Bore Liner	Aluminum	WW-T-700/6-T6(6061)	3
Drum Cylinder	Beryllium	PDS30018-1	4
Drum Can	Aluminum	WW-T-700/6-T6(6061)	3
Control Vane	Cu B ¹⁰	PDS30127-1	90

*Material Library designation used in analytical model (Refer to Section 2.4.3.2.).

TABLE 8-7
EFFECT OF EQUILIBRIUM HYDROGEN PROPERTIES ON REFLECTOR ASSEMBLY
TEMPERATURE VARIATIONS

Component	Location	Φ^1 , Percent Change		
		Average Temperature $\bar{T}$	$(T_{\max} - \bar{T})$	$(\bar{T} - T_{\min})$
Structural Cylinder:	Midplane	+3.5%	+3.6%	+5.7%
	Forward End	+4.0%	+4.2%	+7.6%
Inner Beryllium Segments:	Midplane	+3.2%	+8.2%	+15.4%
	Forward End	+4.1%	+8.8%	+21.3%
Outer Beryllium Segments:	Midplane	+1.5%	+15.8%	+24.3%
	Forward End	+2.8%	+42%	+63%
Control Drum Cylinder:	Midplane	+3.8%	+6.4%	+12.7%
	Forward End	+4.2%	+14.3%	+14.1%
Control Vane:	Midplane	+7.7%	+23.6%	+22.8%
	Forward End	+5.8%	+17.6%	+19%

Mixed mean coolant temperature rise changed +11%, ΔP Changed +17%

1. $\Phi = \left(\frac{B-A}{A} \right) \times 100$ where A = para hydrogen value and
B = equilibrium hydrogen value
2. Comparison is made for rated performance at EOL, normal mode of operation with a graphite core.
3. National Bureau of Standards (NBS) equilibrium hydrogen property routines are substituted for NBS para hydrogen routines in the TRACK-II computer code to obtain the comparison.
4. Computer run sequences: 352, 10/27/70 and 607, 11/16/70.

TABLE 8-8

COMPARISON OF RADIATION HEATING RATES AND FAST NEUTRON FLUENCE - REFERENCE
VS PRELIMINARY DATA USED IN THERMAL ANALYSES1. Radiation Heating Rate Comparison

Component	Percent Change, Φ^*	
	Graphite Core	Composite Core
Structural Cylinder	-6.8%	-3.1%
Aluminum in Reflector Region	-2.3%	+3.4%
Beryllium Segments	-5.8%	0.0%
Control Vane	-21.6% (4.44 to 3.48 MW Total)	-23.4%

2. Fast Neutron Fluence Comparison ($E > 1.0$ MeV)

Radius	Percent Change, Φ^*	
	(Graphite Core at Midplane, C. S. 26)	
Structural Cylinder I.D., 21.115 Inches	+2%	
Beryllium Segment I.D., 22.115 Inches	+27%	$(5.4 \times 10^{14} \text{ to } 7 \times 10^{14} \text{ n/cm}^2 - \text{sec})$
Control Drum Centerline, 24.5 Inches	+33%	
Reflector Assembly O.D., 27 Inches	+84%	$(0.48 \times 10^{14} \text{ to } 0.92 \times 10^{14} \text{ n/cm}^2 - \text{sec})$

$$*\Phi = \frac{(A - B)}{B} \times 100$$

where A = S-100 Data Item values (Reference 7).
B = Preliminary R-1 values used in thermal analysis (Reference 3).

TABLE 8-9

SUMMARY OF UNCERTAINTY TOLERANCES FOR KEY REFLECTOR ASSEMBLY PERFORMANCE PARAMETERS (COMPOSITE CORE)

COMPONENT	LOCATION	PARAMETER	NORMAL MODE OPERATION						SINGLE TPA MALFUNCTION		
			RATED PERFORMANCE, SOL 99/95 TOLERANCE LIMIT			THROTTLE HOLD, EOL 99/95 TOLERANCE LIMIT			80% THRUST, SOL 99/95 TOLERANCE LIMIT		
			NOMINAL	TOLERANCE	TOLERANCE %	NOMINAL	TOLERANCE	TOLERANCE %	NOMINAL	TOLERANCE	TOLERANCE %
Reflector Assembly	Inlet Plenum	Coolant Flow - lb/sec	80.96	2.20	2.70	42.73	2.13	4.99	63.04	2.06	3.26
	Inlet Plenum	Coolant Temp - deg R	191.4	10.3	5.38	225.5	14.4	6.37	204.6	10.8	5.28
	Inlet Plenum	Coolant Pressure - Psia	1135.	23.1	2.04	681.	16.2	2.38	1157.	25.1	2.17
	Outlet Plenum Mixed	Coolant Temp - deg R	260.1	14.6	5.60	319.0	21.0	6.57	279.2	15.7	5.65
	Outlet Plenum Mixed	Coolant Pressure - Psia	1074.	21.4	1.99	644.9	15.1	2.35	1117.5	24.8	2.22
	Reflector Inlet to Outlet	Heat Addition - MW	22.79	2.575	11.30	16.85	1.80	10.70	19.63	2.18	11.10
	Reflector Inlet to Outlet	Axial Δp - psi	61.0	4.54	7.44	35.8	3.5	9.83	39.8	3.2	8.03
Structure	Reflector Inlet to Chamber	Radial Δp - psi	685.1	19.6	2.86	388.4	11.9	3.08	797.9	21.0	2.63
	CS 2.88	Heat Flux at ID - Btu/sec-in ²	0.248	0.051	20.50	0.209	0.041	19.87	0.235	0.048	20.20
	CS 26.0	Heat Flux at ID - Btu/sec-in ²	0.716	0.108	15.10	0.663	0.091	13.71	0.698	0.101	14.44
	CS 49.12	Heat Flux at ID - Btu/sec-in ²	0.775	0.109	14.0	0.758	0.097	12.85	0.775	0.105	13.49
	Cooling Channel Exit	Coolant Flow - lb/sec	21.54	1.05	4.86	11.44	0.78	6.85	16.78	0.88	5.27
	Cooling Channel Exit	Coolant Temp - deg R	280.3	22.7	8.11	356.6	35.0	9.82	305.8	25.5	8.33
	CS 2.88	$\bar{T}$ - deg R	299.3	24.7	8.26	376.6	35.8	9.5	325.0	27.2	8.36
	CS 26.0	$\bar{T}$ - deg R	302.9	33.3	11.0	375.7	42.9	11.4	327.0	35.4	10.8
	CS 49.12	$\bar{T}$ - deg R	247.7	26.7	10.76	304.5	35.4	11.6	267.7	28.7	10.7
	CS 2.88	$\bar{T} - T_{wall}$ - deg R	1.20	0.31	26.16	0.98	0.25	25.5	0.73	0.184	25.4
	CS 26.0	$\bar{T} - T_{wall}$ - deg R	3.09	0.83	26.88	2.17	0.59	27.2	2.66	0.71	26.9
	CS 49.12	$\bar{T} - T_{wall}$ - deg R	2.57	0.77	30.07	2.06	0.60	29.2	2.35	0.69	29.4
	CS 2.88	T_{max} - deg R	366.	23.6	6.44	423.	27.6	6.52	385	23.9	6.21
	CS 26.0	T_{max} - deg R	505.	35.1	6.95	542.	33.1	6.10	517.	34.2	6.63
	CS 49.12	T_{max} - deg R	491.	43.4	8.84	519.	41.6	8.02	502.	43.4	8.64

TABLE 8-99 (CONT'D)

COMPONENT	LOCATION	PARAMETER	NORMAL MODE OPERATION						SINGLE TPA MALFUNCTION		
			ACCRATED PERFORMANCE, SOL 99/95 TOLERANCE LIMIT			THROTTLE HOLD, EOL 99/95 TOLERANCE LIMIT			80% THRUST, SOL 99/95 TOLERANCE LIMIT		
			NOMINAL	TOLERANCE	TOLERANCE %	NOMINAL	TOLERANCE	TOLERANCE %	NOMINAL	TOLERANCE	TOLERANCE %
Inner Reflector Seg- ments	Cooling Channel Exit	Coolant Flow - lb/sec	15.51	0.69	4.46	7.94	0.47	5.97	11.95	0.56	4.67
	Cooling Channel Exit	Coolant Temp - deg R	226.1	12.5	5.53	281.7	17.1	6.08	245.1	13.4	5.47
	CS 2.88	$\bar{T}$ - deg R	235.3	13.0	5.53	293.3	18.0	6.15	254.7	13.9	5.47
	CS 26.0	$\bar{T}$ - deg R	220.4	12.5	5.68	270.2	17.7	6.54	237.2	13.5	5.68
	CS 49.12	$\bar{T}$ - deg R	196.7	10.8	5.51	234.5	15.5	6.61	210.9	11.5	5.47
	CS 2.88	$\bar{T} - T_{wall}$ - deg R	0.65	0.22	33.25	0.53	0.167	31.1	0.57	0.19	32.3
	CS 26.0	$\bar{T} - T_{wall}$ - deg R	0.84	0.26	30.85	0.69	0.20	28.9	0.74	0.22	30.0
	CS 49.12	$\bar{T} - T_{wall}$ - deg R	0.28	0.08	29.48	0.26	0.08	30.9	0.25	0.076	30.0
Outer Reflector Seg- ments	Cooling Channel Exit	Coolant Flow - lb/sec	4.98	0.24	4.85	2.58	0.16	6.17	3.85	0.19	4.97
	Cooling Channel Exit	Coolant Temp - deg R	268.4	15.3	5.70	322.2	20.5	6.36	284.8	16.1	5.67
	CS 2.88	$\bar{T}$ - deg R	274.6	15.6	5.70	326.1	20.3	6.22	289.9	16.3	5.60
	CS 26.0	$\bar{T}$ - deg R	262.5	15.5	5.89	304.6	18.4	6.04	274.9	15.5	5.60
	CS 49.12	$\bar{T}$ - deg R	204.6	9.94	4.86	238.6	14.4	6.04	216.9	10.7	4.92
	CS 2.88	$\bar{T} - T_{wall}$ - deg R	4.52	2.16	47.8	2.60	1.34	51.5	3.52	1.72	49.1
	CS 26.0	$\bar{T} - T_{wall}$ - deg R	16.98	5.65	33.3	11.53	3.89	33.8	13.96	4.70	33.7
	CS 49.12	$\bar{T} - T_{wall}$ - deg R	6.07	1.90	31.3	4.17	1.26	30.2	4.95	1.52	30.7
Reflector Segments	CS 2.88	$\bar{T}_{outer} - T_{inner}$ - deg R	39.3	9.8	25.0	32.8	10.6	32.5	35.2	9.66	27.4
	CS 26.0	$\bar{T}_{outer} - T_{inner}$ - deg R	42.1	10.8	25.7	34.4	10.9	31.6	37.7	10.3	27.3
	CS 49.12	$\bar{T}_{outer} - T_{inner}$ - deg R	7.86	2.69	34.2	4.15	2.97	71.7	6.03	2.55	42.3
Control Drum	Cooling Channel Exit	Coolant Flow - lb/sec	26.0	1.46	5.62	13.67	1.0	7.28	20.26	1.23	6.07
	Cooling Channel Exit	Coolant Temp - deg R	266.4	17.9	6.73	320.2	24.4	7.60	283.1	19.1	6.73
	Drum Annulus Exit	Coolant Flow - lb/sec	5.94	0.29	4.85	3.25	0.20	6.17	4.68	0.23	4.86
	Drum Annulus Exit	Coolant Temp - deg R	256.9	14.5	5.65	310.3	18.8	6.07	273.6	15.2	5.54

TABLE 8-9 (CONT'D)

COMPONENT	LOCATION	PARAMETER	NORMAL MODE OPERATION						SINGLE TPA MALFUNCTION		
			RATED PERFORMANCE, SOL 99/95 TOLERANCE LIMIT			THROTTLE HOLD, EOL 99/95 TOLERANCE LIMIT			80% THRUST, SOL 99/95 TOLERANCE LIMIT		
			NOMINAL	TOLERANCE	TOLERANCE %	NOMINAL	TOLERANCE	TOLERANCE %	NOMINAL	TOLERANCE	TOLERANCE %
Control Drum	CS 2.88	$\bar{T}$ - deg R	276.3	18.7	6.78	330.3	24.7	7.49	292.5	19.7	6.74
	CS 26.0	$\bar{T}$ - deg R	258.3	18.9	7.30	303.4	22.1	7.31	272.2	19.0	6.99
	CS 49.12	$\bar{T}$ - deg R	202.8	11.3	5.58	237.6	15.5	6.52	215.6	11.8	5.50
	CS 2.88	$\bar{T} - T_{wall}$ - deg R	2.72	0.93	34.2	1.89	0.63	33.1	2.26	0.77	34.0
	CS 26.0	$\bar{T} - T_{wall}$ - deg R	6.34	2.21	34.9	4.42	1.55	35.0	5.28	1.85	35.0
	CS 49.12	$\bar{T} - T_{wall}$ - deg R	2.02	0.71	35.4	1.30	0.45	34.9	1.60	0.56	34.9
Pressure Vessel Annulus	Cooling Channel Exit	Coolant Flow - lb/sec	6.97	0.46	6.62	3.85	0.31	8.00	5.5	0.38	6.94
	Cooling Channel Exit	Coolant Temp. - deg R	242.2	15.7	6.50	288.3	19.7	6.84	257.6	15.6	6.07
Reflector Baffle Can	CS 2.88	$\bar{T}$ - deg R	269.7	15.2	5.63	322.1	19.9	6.18	285.6	15.9	5.56
	CS 26.0	$\bar{T}$ - deg R	256.1	14.4	5.61	300.0	17.7	5.91	269.5	14.7	5.45
	CS 49.12	$\bar{T}$ - deg R	202.9	9.9	4.88	237.6	14.3	6.03	215.6	10.6	4.91

NOTE: Data obtained from TNT Monte Carlo analysis. Tolerance limits, on percentage basis, can be applied to nominal results from detailed component analyses.

502 11/11/70
 504 11/11/70
 506 11/11/70
 642 11/17/70
 685 11/18/70
 267 11/19/70
 754 11/19/70
 538 11/20/70

TABLE 8-10 EFFECT OF OPERATING CONDITIONS ON REFLECTOR PERFORMANCE

REFLECTOR PARAMETERS⁽¹⁾

Operating Condition	Radial ΔP (Reflector Inlet-Chamber) Psi		Structure Maximum Temperature deg R		Beryllium Segment (T̄ - T _{wall}) _{max} deg R				Drum Cylinder (T̄ - T _{wall}) _{max} deg R	
	Graphite Core	Composite Core	Graphite Core	Composite Core	Inner Segment		Outer Segment		Graphite Core	Composite Core
					Graphite Core	Composite Core	Graphite Core	Composite Core		
<u>Normal Mode</u>										
Rated, SOL	676.7	685.4	328.9	315.0	1.0	0.9	19.5	17.0	6.8	6.4
Rated, EOL ⁽²⁾	670.1	678.9	338.4	323.3	1.0 ⁽²⁾	0.8	19.3 ⁽²⁾	16.9	6.8 ⁽²⁾	5.9
Throttle Hold, SOL	391.7	394.9	390.7	373.5	0.7	0.7	13.1	11.5	4.7	4.4
Throttle Hold, EOL ⁽²⁾	385.5	388.9	415.6	394.0	0.7	0.7	13.1	11.5	4.7	4.4
Startup, SOL	----	----	----	----	1.4	1.4	33.8	32.8	4.0	4.0
Startup, EOL ⁽²⁾	----	----	----	----	1.4	1.4	33.7 ⁽²⁾	32.7	4.0	4.0
Shutdown, SOL	----	----	----	----	0.9	0.9	11.1	10.7	1.5	1.6
Shutdown, EOL ⁽²⁾	----	----	----	----	0.9	0.8	11.6	11.2	1.6	1.5
<u>Single TPA Malfunction</u>										
80 % Thrust, SOL	783.8	797.8	354.9	340.6	0.8	0.8	15.9	13.8	5.6	5.2
80 % Thrust, EOL ⁽²⁾	776.5	790.8	368.7	351.8	0.8	0.7	15.8	13.9	5.6	5.0
Throttle Hold, SOL	555.2	563.7	386.3	369.9	0.8	0.7	13.2	11.5	4.7	4.4
Throttle Hold, EOL ⁽²⁾	548.8	447.9	409.3	388.5	0.7	0.7	13.1	11.5	4.7	4.4

(1) Table based on TNT data discussed in Chapter 2. Temperature and ΔT to be used only for comparing effect of operating conditions.

(2) TNT results for EOL conditions do not include effect of radiation on material thermal conductivity. Temperature differences shown above would increase at EOL conditions if radiation effects were included.

NOTE: Circled values indicate "worst cases" selected for component level analysis (Refer to Section 8.5.).

Table 8-11 . Reflector Assembly Power and Flow Balance

A. Graphite Core, Rated Performance, EOL, Normal Mode³

$T_{IN} = 198^{\circ}R$, $P_{IN} = 1120$ psia, $\Delta P = 52.0$ psi

Coolant Channels			Flow Rate (lbs/sec)	Power ² (MW)	T _{OUT} (°R)
Identification ¹	Description	Principal Components			
Group 1					
1-14	Structure Holes	Structure and LSS Conduction (2.72 MW)	21.9	6.24	266
15-26	Drum Cylinder Holes	Drum Cylinder	5.1	1.72	286
27-34	Control Vane Annuli	Control Vane (4.4 MW)	14.9	4.71	275
35-42	Control Drum Annulus	Drum Cylinder, Can, Vane and Bore Liner	8.2	1.97	258
43-47	Pressure Vessel Annulus	Pressure Vessel (1.0 MW) Baffle Can and Outer Segments	7.2	1.22	240
Group 2					
1-6 } 12-31 }	Inner Segment Holes	Inner Segment	9.1	2.89	267
7-11 } 32-43 }	Outer Segment Holes	Outer Segment	6.3	1.63	261
44-53	Segment-Bore Liner Clearances	Inner and Outer Segments, Bore Liner	3.5	1.08	274
TOTAL			76.2	21.46	268

¹ Coolant channels are identified on Figure 8-2 .

² This power represents the heat added to these coolant channels.

³ Computer run sequence 515, 11/18/70.

Table 8-11 . Reflector Assembly Power and Flow Balance (Continued)

B. Graphite Core, Throttle Hold Performance, EOL, Normal Mode³

$$T_{IN} = 232^{\circ}\text{R}, P_{IN} = 678 \text{ psia}, \Delta P = 31 \text{ psi}$$

Coolant Channels			Flow Rate (lbs/sec)	Power ² (MW)	T _{OUT} (°R)
Identification ¹	Description	Principal Components			
Group 1					
1-14	Structure Holes	Structure and LSS Conduction (2.27 MW)	11.9	4.74	325
15-26	Drum Cylinder Holes	Drum Cylinder	2.9	1.13	325
27-34	Control Vane Annuli	Control Vane (2.86 MW)	8.2	3.23	325
35-42	Control Drum Annulus	Drum Cylinder, Can, Vane and Bore Liner	4.7	1.13	290
43-47	Pressure Vessel Annulus	Pressure Vessel (1.65 MW) Baffle Can and Outer Segments	4.0	0.81	280
Group 2					
1-6 } 12-31 }	Inner Segment Holes	Inner Segment	4.8	1.80	320
7-11 } 32-43 }	Outer Segment Holes	Outer Segment	3.4	0.90	295
44-53	Segment-Bore Liner Clearances	Inner and Outer Segments, Bore Liner	1.9	0.50	295
TOTAL			41.8	14.25	312

¹ Coolant channels are identified on Figure 8-2 .² This power represents the heat added to these coolant channels.³ Computer sequence 093, 11/20/70.

Table 8-11. Reflector Assembly Power and Flow Balance (Continued)

C. Composite Core, Steady State Performance, SOL, Single Turbopump³

$T_{IN} = 205^{\circ}R$, $P_{IN} = 1158$ psia, $\Delta P = 35$ psi.

Coolant Channels			Flow Rate ¹ (lbs/sec)	Power ² (MW)	$T_{OUT} (^{\circ}R)$
Identification ¹	Description	Principal Components			
<u>Group 1</u>					
1-14	Structure Holes	Structure and LSS Conduction (2.52 MW)	18.2	4.61	267
15-26	Drum Cylinder Holes	Drum Cylinder	4.2	1.27	278
27-34	Control Vane Annuli	Control Vane (3.7 MW)	12.3	3.74	284
35-42	Control Drum Annulus	Drum Cylinder, Can, Vane and Bore Liner	6.8	1.45	258
43-47	Pressure Vessel Annulus	Pressure Vessel (.64 MW) Baffle Can and Outer Segments	6.0	0.84	240
<u>Group 2</u>					
1-6 } 12-31 }	Inner Segment Holes	Inner Segment	7.5	1.99	270
7-11 } 32-43 }	Outer Segment Holes	Outer Segment	5.2	1.11	258
44-53	Segment-Bore Liner Clearances	Inner and Outer Segments, Bore Liner	2.8	0.80	273
TOTAL			63.0	15.81	266

¹ Coolant channels are identified on Figure 8-2 .

² This power represents the heat added to these coolant channels.

³ Computer run sequence 631, 11/17/70.

TABLE 8-12 FAILURE MECHANISM PROBABILITY OF OCCURRENCE

Mode Ident. No.	Modes and Mechanisms of Failure		Mission Phase	Environmental Factors
3	Structure Melts	Part <u>Structure</u> Item No. 1		
		E. Aft end overheats	Steady State	Temperature
34	Vane Melts	F. Ledge overheats	Steady State	Mechanical Load Temperature
		Part <u>Vane, Control</u> Item No. 16		
78	Material is lost	A. Overheating of the control vane	Steady State	Temperature Hydrogen Flow Radiation
		Part <u>Insulator, Drum Cylinder</u> Item No. 42		
79	Retainer Melts	A. Corrosion/Erosion at any point	Steady State	Pressure Temp. Hydrogen Gas Flow Rates
		Part <u>Retainer, Insulation</u> Item No. 43		
		A. Overheating of the part	Steady State	Temperature

"Stress"		"Strength"		Design Analysis (Calculated or Estimated Failure Probability or Evaluation Comments)
Mean, $\bar{X}_L$, Variance, S_L ; n	or Stress Comment	Mean, $\bar{X}_S$, Variance, S_S ; n	or Strength Comment	
Dwg No. 939J733			Revision 0	
431 ^u R	$S_L = 87^{\circ}\text{R}$	1610 ^o R	$S_S = 25^{\circ}\text{R}$	$F < 1. \times 10^{-19}$
493 ^o R	$S_L = 13^{\circ}\text{R}$	1610 ^o R	$S_S = 25^{\circ}\text{R}$	$F < 1. \times 10^{-19}$
Dwg No. 939J733			Revision 0	
495 ^o R	$S_L = 15.5^{\circ}\text{R}$	2360 ^o R	$S_S = 25^{\circ}\text{R}$	$F < 1. \times 10^{-19}$
Dwg No. 939J733			Revision 0	
This part operates at temperatures less than 540 ^o R and hydrogen flow velocities less than 100 ft/sec even if large flow gaps exist in the insulator. Previous reactor experience and results reported in WANL-TME-1192, "Erosion of Grafoil Insert Development Test Report" indicate negligible corrosion/erosion at these conditions. WANL-TME-1992 also indicates that surface blistering occurs at a depressurization rate of 17 psi/sec. Control drum development testing will be used for further investigation of this phenomena, but present judgement is that this failure mode is incredible.				$F < 1. \times 10^{-19}$
Dwg No. 939J733			Revision 0	
310 ^o R	$S_L = 10^{\circ}\text{R}$	1610 ^o R	$S_S = 25^{\circ}\text{R}$	$F < 1. \times 10^{-19}$

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Figure 8-1. Reflector Node Diagram

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NOTE: GROUP ONE CHANNELS ARE UNDERLINED.

Figure 8-2 . Reflector Assembly TRACK Model--Coolant Channel Identification

Figure 8-3. Estimated Flow in Channels which Intersect the LSS Spring Capsules

Figure 8-4 . Drum Bore Liner - Reflector Segment Gaps as Function of Position and Operating Condition

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 Atomic Energy Act of 1954

Figure 8-5 . Reflector Assembly Aft End Nodal Model

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 Atomic Energy Act of 1954

Figure 8-6 . Forward Extension Ring Model

SURFACE NOTATION

Hole	Node to Node
1	3001 3002
2	3003 3006
3	3007 3008
4	3009 3010
5	3011 3012
6	3013 3016
7	3017 3020
8	3021 3024
9	3025 3026
10	3027 3028
11	3029 3030
12	3031 3034
13	3035 3038
14	3039 3042
15	3043 3044
16	3045 3046
17	3047 3049
18	3050 3053
19	3054 3057
20	3058 3061
21	3026 3026
22	3064 3065
23	3066 3069
24	3070 3073
25	3074 3075
26	3076 3077

Figure 8-7 . Analytical Inner Beryllium Segment Model

Figure 8-8 . Analytical Outer Beryllium Segment Model

Figure 8-9 . Heating Rates Used in Reflector Assembly Thermal Analysis

1. Beryllium radial heating factor ($Q'_{avg} = 1015 \text{ Btu/hr in}^3$)
2. LSS capsule, spring, and plunger radial heating factor ($Q'_{avg} = 490 \text{ Btu/hr in}^3$ based on spring bore volume)
3. Combined capsule region radial heating factor ($Q'_{avg} = 765 \text{ Btu/hr in}^3$)

Beryllium volume is 52.4 percent of region volume.

Heating distribution from DRM 52841.

Figure 8-10. Equivalent Radial Heating Distribution for LSS Capsule Region Used in TRACK Reflector Model

Peak Flux at 1510 MW Reactor Power with Graphite Core =
 $9.2 \times 10^{14} \text{ N/CM}^2 - \text{SEC} (E > 1 \text{ Mev})$

Local Neutron Flux = Axial Factor X Radial Factor X Peak Flux ($\text{N/CM}^2 - \text{SEC}$)

Local Fluence = Local Flux X Time (N/CM^2)

Peak Fluence at 60 Minutes Full Power = $3.31 \times 10^{18} \text{ N/CM}^2$

Figure 8-11 . Neutron Flux Field Used in the Reflector Assembly Thermal Analysis

Figure 8-12 . Chamber Fluid Boundary Conditions Affecting the Reflector Assembly Aft End Support

Figure 8-13. Graphite Core, Rated Performance, End of Life, Normal Mode - Reflector and Lateral Support Axial Pressure Profiles

Figure 8-14. Graphite Core, Rated Performance, End of Life, Normal Mode - Reflector Structure Axial Temperature Profile

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Figure 8-15 . Graphite Core, Rated Performance, End of Life Normal Mode - Inner Beryllium Segment Axial Temperature Profile

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Figure 8-16. Graphite Core, Rated Performance, End of Life, Normal Mode--Inner Beryllium Segment, Mid Plane Isotherms

Figure 8-17. Graphite Core Rated Performance, End of Life, Normal Mode - Outer Beryllium Segment Axial Temperature Profile

NOTE: TEMPERATURES ARE IN DEGREES RANKINE.

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Figure 8-18 . Graphite Core, Rated Performance, End of Life, Normal Mode--Outer Beryllium Segment, Midplane Isotherms

Figure 8-19. Graphite Core, Rated Performance, End of Life, Normal Mode - Control Drum Axial Temperature Profile

Figure 8-20 . Graphite Core, Rated Performance, End of Life, Normal Mode, -
Control Drum Mid Plane Isotherms

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Figure 8-21 . Graphite Core, Rated Performance, End of Life, Normal Mode - Control
 Drum Vane (CuB^{10} 18 v/o) Axial Temperature Profile

Figure 8-22 . Reflector Baffle Can Axial Temperature Profile for Various Steady State Operating Modes

Figure 8-23 . Drum Bore Liner Axial Temperature Profiles for Various Steady State Operating Modes

Figure 8-24. Graphite Core, Throttle Hold Performance, End of Life, Normal Mode - Reflector and Lateral Support Axial Pressure Profiles

Figure 8-25 . Graphite Core, Throttle Hold Performance, End of Life, Normal Mode - Reflector Structure Axial Temperature Profile

Figure 8-26 . Graphite Core, Throttle Hold Performance, End of Life, Normal Mode - Control Drum Axial Temperature Profile

Figure 8-27. Graphite Core, Throttle Hold Performance, End of Life, Normal Mode - Control Drum Midplane Isotherms

Figure 8-28. Graphite Core, Throttle Hold Performance, End of Life, Normal Mode - Control Drum Vane (CuB^{10}_{18} v/o) Axial Temperature Profile

Figure 8-29. Composite Core, Steady State Performance, Start of Life, Single Turbopump Operation - Reflector and Lateral Support Axial Pressure Profiles

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Figure 8-30 . Composite Core, Steady State Performance, Start of Life, Single Turbopump Operation - Reflector Structure Axial Temperature Profiles

Figure 8-31 . Composite Core, Steady State Performance, Start of Life Single Turbopump Operation - Control Drum Axial Temperature Profile

Figure 8-32. Composite Core, Steady State Performance, Start of Life, Single Turbopump Operation - Control Vane (CuB^{10} 18 v/o) Axial Temperature Profile

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Figure 8-33 . Composite Core, Steady State Performance, Start of Life, Single Turbopump Operation—Forward Extension Ring Isotherms

Figure 8-34 . Composite Core, Steady State Performance, Start of Life, Single Turbopump Operation - Reflector Aft End Support Isotherms

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Figure 8-35 . Graphite Core, Startup, End of Life, Normal Mode - Structural Cylinder
Average Temperatures

figure 8-36 . Graphite Core, Startup, End of Life, Normal Mode - Structural Cylinder Temperature Differences

Figure 8-37 . Graphite Core, Startup, End of Life, Normal Mode - Inner Beryllium Segment
Average Temperature

Figure 8-38 . Graphite Core, Startup, End of Life, Normal Mode - Inner Beryllium Segment Temperature Differences

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Figure 8-39. Graphite Core, Startup, End of Life, Normal Mode - Outer Beryllium Segment Average Temperature

Figure 8-40. Graphite Core, Startup, End of Life, Normal Mode - Outer Beryllium Segment Temperature Differences

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Figure 8-41. Graphite Core, Startup, End of Life, Normal Mode - Control Drum Average Temperatures

Figure 8-42. Graphite Core, Startup, End of Life, Normal Mode - Control Drum Temperature Differences

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Figure 8-43 . Graphite Core, Startup, End of Life, Normal Mode - Control Vane Average Temperatures

Figure 8-44 . Graphite Core, Startup, End of Life, Normal Mode - Control Vane Temperature Difference:

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Figure 8-45 . Graphite Core, Startup, End of Life, Normal Mode - Reflector Baffle Can Average Temperatur

9.0 CONTROL DRUM DRIVE ASSEMBLY

9.1 INTRODUCTION

This Chapter describes the thermal and fluid flow analysis performed on the Control Drum Drive Assembly (CDDA). The primary function of the CDDA is to supply torque to the control drums imparting rotation to the response to signals from the actuator controller.

The CDDA is part of the contract end item described as the NERVA Nuclear Subsystem (NSS) and is listed as an Engineering Critical Component EC-677585 in CEI Specification No. CP-677555A. This ECC Specification establishes the thermal and hydraulic design requirements for the Control Drum Drive Assembly critical components.

9.1.1 Description of Control Drum Drive Assembly

The following general design features are given in EC-677585:

"3.3.1. General Design Features. - The CDDA consists of eighteen (18) individual subassemblies, each consisting of an electrical stepper motor actuator mechanism, a controller, and an actuator malfunction override device. "

Supplemental descriptive information follows:

a. Actuator Housing

The housing serves as both the frame of the actuator, mounting all of the component subassemblies, and as a pressure vessel, capable of containing the coolant pressure.

b. Motor

The motor is of the type generally referred to as a "stepper" since its rotor motion is usually incremental, responding to discrete pulse excitation of the stator, and would only be continuous when slewing at synchronous speed. The rotor has twelve radially

salient poles of permanent magnet material, alternately polarized.

The motor stator has 24 poles, which establish a step angle of 15° , with a two phase power winding. Auxiliary coils wound on the stator act in conjunction with the rotor permanent magnets to supply step response feedback signals.

c. Transmission

A two stage epicyclic transmission (EPIC) carries motor torque to the actuator output shaft and, with a ratio of 150/1, reduces the incremental motion of the drum to one tenth degree. This transmission is comprised of two internal ring gears and a duplex pinion. The pinion gears are carried by two bearings on an eccentric extension of the motor shaft.

d. Potentiometer

Although the stepper motor and transmission which comprise the drive elements of the actuator have the capability and are intended to accurately position the drum under conditions of widely varying load and environmental conditions without dependence on closed loop position feedback, the system is nevertheless augmented by diagnostic position instrumentation. This is provided by two potentiometers monitoring the output shaft. They are electrically independent by virtue of having separate power supplies. Used in conjunction with a count of the stepper motor pulse feedback, there is thus provided triple redundancy of position information for use in diagnosing and correcting malfunctions.

e. Actuator Malfunction Override Device (AMOD) Trigger

Adjacent to the potentiometer and at the aft end of the actuator there is a trigger mechanism used to activate the actuator malfunction override device.

f. AMOD

The AMOD mechanism utilizes components of the drive shaft to effect economies in system weight and complexity. A helical compression spring, which supplies the AMOD drive energy, is housed inside the drive shaft tube.

g. CDA Controller

The actuator controller utilizes digital techniques to interpret binary coded control signals transmitted from the EPIC for motor stator phase control. The mode of control is primarily open loop in nature, although step detection techniques are utilized to signal completion of a rotor incremental step to the EPIC.

9.2 SUMMARY OF RESULTS AND CONCLUSIONS

Thermal analyses have been performed for the Control Drum Drive Actuator (CDDA) shown on Drawing 939J990. The thermal environment used for the analysis corresponds to a graphite core, SOL Normal Mode of operation. The analyses are applicable to the thermal/hydraulic performance requirement specified in EC-677585. The TAP-B computer code was used to solve a finite element model of the CDDA.

Results of the analyses, which are summarized in Table 9-1, indicate that the actuator can be adequately cooled. During the design rated performance mode, the CDDA operates at $\sim 310^{\circ}\text{R}$ and the control drum drive shaft that extends to the reflector operates at a range of $503\text{--}596^{\circ}\text{R}$. These temperatures are achieved with a coolant flowrate of 0.0975 lb/sec per actuator and a 10 psi pressure differential across the actuator.

During throttled operation, the coolant temperature increases by 20°R and the actuator temperature increases by 24°R . The analysis reports the actuator characteristics for startup and shutdown. A discussion of these trends is contained in Section 9.5.

In conclusion, a Step 4 detailed analysis has been performed for the CDDA. The analysis was performed using a three-dimensional transient computer model for the SOL normal mode of operation. Results of these analysis indicate that this ECC meets the thermal/hydraulic requirements for operation as specified in EC-677585.

9.3 APPLICABLE REQUIREMENTS AND COMPATIBILITY OF THERMAL PERFORMANCE WITH THE NSS SPECIFICATION

The requirements and design conditions stated in this Section are specified in EC-677585, Section 3.0, issued on November 30, 1970.

The following Specifications are applicable:

"3.1.1.1.1 Operational Modes

The CDDA shall support and/or accommodate all operational modes and their respective operational requirements as defined in 3.1.1.1.1 (Operational Modes) and specified in 3.1.1.1.5 (Operational Requirements) of CP-677555 with no degradation of performance below that specified herein."

Detailed analyses were performed for the normal mode of operation. However, based on the adequate thermal performance shown for this mode, it is expected that the CDDA will operate satisfactorily for the malfunction mode. The analysis performed on the Control Drum Drive Assembly indicated no degradation of performance below that specified in CP-677555A.

"3.1.1.1.3.2.1 Single Turbopump Operation Mode

The CDDA shall meet the requirements of 3.1.1.1.5.2.1 (Single Turbopump Operation Mode) of CP-677555. In supporting Single Turbopump Operation Mode, the performance requirements of the CDDA are within the range of performance characteristics specified in 3.1.1.1.3.1 (Normal Mode)."

The Single Turbopump Operation satisfies the performance requirements specified in EC-677585 and are presented in Table 9-1, Induced Thermal Environment, in Section 9.2 of this Chapter.

"3.1.2.4.2.3 Thermal Environment

The CDDA shall be designed to withstand the thermal environment which is attendant to the thermal-hydraulic data specified in Table 4 (tbd)."

The Thermal Environment was evaluated and presented in Table 9-1, Induced Thermal Environment, in Section 9.2 of this Chapter.

"3.3.1.11 Growth Characteristics

The CDDA shall satisfy the requirements of 3.3.1.17 (Growth Characteristics) of CP-677555."

The growth characteristics were evaluated and are presented in Section 9.5.2.1.d.

9.4 METHOD OF ANALYSIS (DESIGN PRACTICES)

This Section presents the design practices used by Thermal Design to obtain the thermal and fluid environment within the CDDA. The analytical procedures and the analytical models used to implement the design practices are described. In addition, a discussion of the maturity of the input data and the validity of the analysis are given. The detail analysis is within the framework of the overall computational network discussed in Chapter 2.4.1, and is designated a Step 4 calculation.

9.4.1 Analytical Procedures

In this subsection, the analytical procedures selected for the evaluation of the thermal-hydraulic model are presented. The justification for using the procedure, the assumptions used in the analysis, and the computer codes selected to evaluate the analytical model are discussed. The analytical procedures are consistent with the overall thermal design procedures presented in Section 2.4.1.2.

A finite element computer model was used to predict the thermal-hydraulic performance of the CDDA during the various modes of operation described in Section 9.5 of this Chapter. The analysis is performed with a thermal environment corresponding to a graphite core SOL operation. The radiation environment of the CDDA is more severe when the NSS employs a graphite core than a composite core, therefore, the analysis of the CDDA was performed using heating rate data and a thermal-hydraulic environment corresponding to a NSS with a graphite core.

A preliminary analysis of the CDDA revealed that bulk temperatures are $\sim 14^{\circ}\text{R}$ higher during the EOL operation relative to SOL, but this would not have any noticeable effects upon the cooling requirements of the CDDA. Furthermore, the thermal properties of the materials used in the components of the CDDA, i.e., copper, stainless steel, and aluminum were not significantly effected by nuclear radiation (Reference 1, 2). Therefore, the SOL operation was considered valid for the EOL operation, thus eliminating the need for an EOL calculation.

The necessary requirements for deriving a model representing the Control Drum Drive Actuator are the ability of coupling conduction heat transfer with convective heat transfer and the ability of performing hydraulic calculations of flow rate and pressure drop on a three dimensional basis. The TNT-II code was used to perform these analyses.

9.4.2 Analytical Models

This subsection describes the analytical models which were used to calculate temperatures and pressures throughout the CDDA. The component level 4 thermal-hydraulic models of the shield were prepared for WANL Drawing No. 939J990 and are applicable to the current design as defined by WANL Drawing 939J441.

9.4.2.1 Description and Derivation of Analytical Model

The analytical model required a selection of subcomponents of the actuator that could be represented by a finite element nodal system and a selection of fluid flow channels that adequately represent the actual flow in the physical model. With these requirements, the model, illustrated in Figure 9-1 was chosen to represent the CDDA.

Figure 9-1 illustrates the following nodal groupings of subcomponents:

<u>NODE</u>	<u>SUBCOMPONENT</u>
1	D. C. stepping motor field coil
14	D. C. stepping motor shaft
11	Epicyclic transmission
10	Pots and main bearings
12	Connectors
3-9,15	Actuator housing
16	AMOD

Figures 9-2 and 9-2A are flow schematics of the CDDA. The loss coefficients associated with each channel are also shown in Figure 9-2. It is assumed that the loss coefficients remain constant throughout the modes of operation of the actuator. This is not entirely true because the degree of turbulence varies with flow rate through the various channels. Therefore, the loss coefficients shown in Figure 9-2 were chosen to be most representative of all modes of operation. △

9.4.2.2 Compatibility of Analytical Model with the Design

By comparing the analytical model configuration with the shield module as shown in Drawing 939J441, it is observed that a good representation of the actuator mechanism resulted. The thermal and fluid boundary conditions that the CDDA would be exposed to during reactor operation were input to the analysis.

9.4.2.3 Boundary Conditions

Since the CDDA is represented with a heat conduction nodal model and hydraulic model, it is necessary to specify the proper thermal and fluid boundary conditions to the model. These boundary conditions include such parameters as heat transfer coefficients, fluid pressures, flow rates, and fluid bulk temperatures at the external and internal boundaries.

In the CDDA many of the subcomponents are represented by solid finite nodes as described in Section 9.4.2.1. However, many internal nodes adjacent to boundaries, for example, nodes 10 and 11 in Figure 9-1 have surface areas which are different from the solid finite nodes. When this is the case, the physically correct surface area is used in the analytical model. In this manner, the correct heat transfer to each subcomponent was achieved. ✓

The flow schematic, Figure 9-2, illustrates that the flow through the actuator begins at plenum 1, flows through the various subcomponents of the actuator and exhausts into plenum 4. In Fig. 9-2 the control drum inlet plenum is designated plenum 1 and the ---

peripheral shield exit plenum is designated plenum 4. From the TNT-II results given in Chapter 2 the boundary conditions were obtained to calculate the flow rate through the actuator for startup, steady state and shutdown. The appropriate flow rates for each of the CDDA internal channels were calculated by specifying the loss coefficients and hydraulic diameters for the flow channels (channels 1, 2, 3, and 4 in Figure 9-2) and specifying the TAP-B control drum inlet plenum pressures and peripheral shield exit plenum pressures as a function of time for all modes of operation. The heat transfer by convection to the fluid is achieved by specifying the appropriate film coefficient on the surface nodes in the fluid channels.

Additional input to the model includes the specification of internal heat generation rate for the CDDA materials for each phase of operation. The procedure for specifying the internal heat generation consists of:

1. Specifying the nominal value of rated performance phase of operation
2. From TNT-II calculations performed for the startup, throttle hold, and shutdown phases of operation, the fraction of rated power as a function of time or of percent power is used as input conditions.

9.4.3 Maturity of Input Data

This subsection describes the major input data and the maturity of these data required in addition to the analytical model to perform the CDDA thermal-hydraulic performance calculations.

9.4.3.1 Reference Profiles

The startup and shutdown profile boundary condition data used to obtain the CDDA components analysis results were those resulting from the NSS calculations using the "Reference Profiles" discussed in Section 2.4.3.1. These profiles reflect the extreme rate of chamber temperature rate of change of $175^{\circ}\text{R}/\text{sec}$ during the thrust buildup phase of startup and $-175^{\circ}\text{R}/\text{sec}$ during the temperature retreat phase of shutdown.

9.4.3.2 Material Properties

The maturity of properties data for the CDDA and the manner in which the thermal properties are used in the analysis are briefly discussed in Section 2.4.3.2. Table 9-2 lists the materials used in the detail analysis for the major components and the specification identification of the materials. The thermal properties used are reported in the E-105 Data Item.

9.4.3.3 Hydrogen Properties

Para hydrogen properties, (Reference 3) were used to calculate boundary conditions as input to the analysis.

9.4.3.4 Heat Transfer Relationships

The heat transfer relation employed in this analysis is the simplified Petukhov relation described in Chapter 2 of this Data Item.

9.4.3.5 Heating Rates

The heating rates and their distributions for the CDDA with the graphite core components were obtained from the results of preliminary analysis performed by nuclear design and reported in Reference 4.

9.4.4 Validity of Analysis

The general methods and techniques used in the analysis of the CDDA have been used for all the thermal analyses of the components reported in this Data Item. The adequacy of these methods has been demonstrated in their application to the NRX Technology program and to numerous component test analyses. In the NRX-A6 reactor test, a side-by-side actuator test was performed to obtain data on the effects of a radiation environment on the component and its operation. Although the CDDA design differs from that used in the NRX-A6 side-by-side test, the analysis techniques applicable to that reactor test are used in this Data Item.

9.5 RESULTS, ANALYSIS, AND INTERPRETATION

This section presents the results of the analysis performed on the graphite core to determine the thermal and fluid environment of the CDDA at various steady state and transient conditions.

9.5.1 Composite Core

The radiation environment of the CDDA is more severe when the NSS employs a graphite core than a composite core; therefore, the analysis of the CDDA was performed using heating rate data and a thermal-hydraulic environment corresponding to a NSS with a graphite core.

9.5.2 Graphite Core

The CDDA detailed level 4 thermal and fluid analysis was performed with the graphite core during normal mode operation including SOL rated performance, SOL normal startup, SOL normal shutdown, and 65% power throttled condition.

9.5.2.1 Steady State Performance

a. Steady State Rated Performance at SOL

The subcomponent operating temperatures for this condition are summarized in Table 9-3 and Figure 9-1A. It is shown that the component temperatures, excluding the actuator shaft, have approximately the same value. The low magnitude of the temperatures ($\sim 310^{\circ}\text{R}$) indicates that the coolant supplied to the actuator is adequate.

The actuator shaft temperatures are higher than the remaining subcomponent temperatures. The primary reason for the higher shaft temperatures is that the heat generation rates present in the shaft are higher than those present in the actuator device. The shaft extends from the reflector exit plenum, peripheral shield, peripheral shield exit plenum, and then to the actuator. All of these regions are subject to heating rates of a

substantially higher order of magnitude than the actuator housing. The calculated shaft temperature nearest the actuator (503°R) is considered to be higher than the temperature that the shaft would probably achieve under operating conditions. This is due to the conservative nature of contact resistance which is used to represent the heat transfer area between the AMOD and actuator shaft and the transmission output shaft. However, since the calculated shaft temperature is within reasonable limits, it is believed that the change in contact resistance is not warranted at this time.

The steady state rated performance conditions of the coolant flow are presented in Figures 9-3 to 9-5.

Figure 9-3 is a plot of coolant temperature rise vs time. The graph indicates a temperature rise of 16°R for steady state operation. This overall temperature rise, together with the low actuator housing temperature (316°R , Table 9-3) indicates that the amount of coolant is more than adequate for steady state operation at rated power. However, before any conclusions are made increasing the amount of coolant flow, it is necessary to consider the transient cases. These cases will be discussed in Section 9.5.2.2.

Figures 9-4 and 9-7 illustrate the pressure drop across the actuator as a function of time. The pressure drop at rated power is seen to be 10 psi. It should be noted from the analysis in Section 9.4.2 that these plots represent input data. This pressure drop, which represents the difference in pressure levels between the reflector exit plenum and peripheral shield exit plenum, is the driving pressure head for the actuator flow. These pressures are tabulated in the NSS data in Chapter 2. Using these pressure differences and the internal loss coefficients as input data, the TAP-B is used to calculate the coolant flow rate within the actuator.

Figures 9-3 and 9-6 are plots of coolant flow rate per actuator vs time. The rated power coolant flow rate is .0975 lbs/sec. per actuator. This amount of coolant flow will insure proper level of component operating temperatures during rated performance operation.

b. Steady State Rated Performance, EOL

A steady state analysis at rated performance at the EOL was not performed on the CDDA because it was observed that the small differences in the inlet condition to the CDDA for the SOL and EOL would not have an effect upon the steady state rated performance. In addition, it was observed that there was no significant effect during steady state performance of the nuclear radiation upon the thermal properties of the materials used in the CDDA. For these reasons, it was concluded that the thermal-hydraulic calculations performed for the SOL were valid for the EOL.

c. Throttled SOL

This section contains a discussion of the thermal-hydraulic characteristics of the Control Drum Drive Actuator during operation at 65% power, throttled condition. The NSS calculations (See Chapter 2) give information for a 65% power throttle hold for 40 seconds. Using the pressures and temperatures from these data, a similar calculation was performed with the analytical model of the CDDA. The results are shown in Figure 9-6 , through Figure 9-9. It is pertinent to first consider the input information, the pressure drop across the actuator, which is found in Figure 9-7. This is a plot of pressure drop across the actuator vs time for a throttle hold and normal shutdown. The pressure drop for the 65% power throttle hold, 9 psi, is shown from time 603 seconds to 643 seconds. These data are procured from the NSS calculation of Chapter 2.

Figure 9-6 , is a plot of flow rate vs time and shows that the mass flow rate decreases slightly during the throttle hold. This may be explained with the use of Figure 9-9 which is a plot of housing temperature vs time and Figure 9-7 which is a plot of coolant temperature rise vs time. In Figure 9-9 the housing temperature, which is typical of all other actuator subcomponents, indicates a 24°R temperature rise in temperature. This rise in material temperature is reflected in a rise in coolant temperature to 20°R , as seen in Figure 9-7 . The rise in coolant temperature results in a decrease in coolant density, which for a given pressure drop results in a decrease in mass flow rate.

In summarizing the actuator performance during a throttle hold at 65% power level, it may be said that the calculations indicate that the actuator operates at satisfactory temperature levels and coolant flow rates. The present design presents no thermal-hydraulic difficulties for this mode of operation.

d. Growth Mode Operation

The growth mode operation defines reactor operation with a chamber temperature of 4500°R as compared with chamber temperature of 4250°R which occurs during a rated performance, steady state mode of operation. The thermal environment table (See 9-1) indicates a slight decrease in coolant flow coupled with a 20°R increase in coolant inlet temperature. This slight variation in inlet conditions will not perturb the control drum drive actuator operation.

9.5.2.2 Transient

a. Normal Startup, SOL

The normal startup consists of a $175^{\circ}\text{R}/\text{sec}$ chamber temperature ramp until a chamber temperature of 4250°R is achieved. The input for this mode of operation is illustrated in Figure 9-4 which is a plot of pressure drop across the actuator vs time. The pressure drop which represents the difference in pressure levels between the inlet (reflector exit) and exit (peripheral shield exit) plenums, is the driving force for the coolant flow.

The increase in pressure drop across the actuator is reflected in the increase in coolant flow rate. This may be seen in Figure 9-3 which is a plot of flow rate vs time for the normal startup mode. Of interest is the rise in temperature of the coolant flow which is illustrated in Figure 9-5. This figure indicates a rapid rise in coolant flow temperature followed by a decrease in temperature rise to the steady state condition. This may be explained with the use of Figure 9-3 which is a plot of a flow rate vs time and Figure 9-10 which is a plot of actuator housing temperature vs time. Examination of these plots for the time interval of 30 - 40 seconds shows the following trends:

(1) Figure 9-3 the coolant flow rate is rapidly increasing but is at most 45% of the steady state flow rate.

(2) Figure 9-10 actuator housing temperature, which is typical of all components in the actuator is still within 10° of the initial temperature.

Because of these two conditions, the net effect is the high (58 - 65°R) rise in coolant temperature as shown in Figure 9-5 .

In summary, the results for the calculations during the normal startup indicate that the CDDA can perform satisfactorily from a thermal standpoint.

b. Normal Shutdown, SOL

The purpose of this section is to describe the thermal-hydraulic characteristics of the CDDA during the normal shutdown.

The input for this mode of operation is illustrated in Figure 9-7 , which is a plot of pressure drop across the actuator vs time. This pressure drop, which represents the difference in pressure levels between the inlet (reflector exit) and exit (peripheral shield exit) plenums, is the driving force for the coolant flow. The shutdown mode corresponds from the time of 643 to 670 seconds and beyond.

The decrease in pressure drop is reflected by the decrease in coolant flow rate, which is plotted vs time on Figure 9-6 . The effects of this decrease in coolant flow rate can be seen in Figures 9-8 and 9-9 .

Figure 9-8, which is a plot of coolant temperature rise vs time, indicates a rise in coolant temperature for the normal shutdown. This rise in coolant temperature should reflect a rise in material temperature. Figure 9-9 illustrates this is the case. The actuator housing temperature variation is typical of all the subcomponents of the actuator. The material temperatures will ultimately reach the ambient temperature.

In conclusion, this section has described thermal-hydraulic characteristics of the CDDA during a normal shutdown mode. It is concluded that the component operates satisfactorily under this mode of operation.

9.6 REFERENCES

1. R. Shollenberger, "Copper 99.99% Pure. DRM 51213 dated March 12, 1969.
2. R. Shollenberger, "Estimated Properties of Type 304 Stainless Steel Plate, Sheet, and Tube Annealed" DRM 51234 dated March 7, 1969.
3. B. L. Pierce, "NBS Para Hydrogen Codes, Para Hydrogen Properties Subroutines," NSS and FA:022, dated October 1969, also DRM 51479, Revision A, dated March 2, 1970.
4. D. J. Hill and A. H. Fero, "Preliminary Radiation Heating Rates in the R-1 Conceptual Design at Steady State Conditions," DRM 52841, dated July 29, 1970.

TABLE 9-1
INDUCED THERMAL ENVIRONMENT OF CONTROL DRUM DRIVE ACTUATOR (GRAPHITE CORE)

<u>Description</u>	<u>Flow -Lb/Sec*</u>	<u>Pressure - Psi</u>	<u>Temperature °R</u>
<u>Steady State Performance at Rated Conditions-Start of Life (SOL)</u>			
Actuator Drive Shaft Inlet (Control Drum Exit)	9.66×10^{-2}	1067	292
Actuator Exit (Peripheral Shield Exit Plenum)	9.66×10^{-2}	1057	308
<u>Steady State Performance at Rated Conditions, End of Life (EOL)</u>			
Actuator Drive Shaft Inlet (Control Drum Exit)	9.80×10^{-2}	1061	278
Actuator Exit (Peripheral Shield Exit Plenum)	9.80×10^{-2}	1050	307
<u>Steady State Performance at Single TPA-Start of Life (SOL) 80% Thrust</u>			
Actuator Drive Shaft Inlet (Control Drum Exit)	6.51×10^{-2}	1103	289
Actuator Exit (Peripheral Shield Exit Plenum)	6.51×10^{-2}	1096	304
<u>Steady State Performance at Single TPA, End of Life (EOL) 80% Thrust</u>			
Actuator Drive Shaft Inlet (Control Drum Exit)	6.51×10^{-2}	1098	301
Actuator Exit (Peripheral Shield Exit Plenum)	6.51×10^{-2}	1091	316
<u>Steady State Performance at 65% Throttle Hold-Start of Life (SOL)</u>			
Actuator Drive Shaft Inlet (Control Drum Exit)	6.49×10^{-2}	643	334
Actuator Exit (Peripheral Shield Exit Plenum)	6.49×10^{-2}	635	349
<u>Steady State Performance, 65% Throttle Hold End of Life (EOL)</u>			
Actuator Drive Shaft Inlet (Central Drum Exit)	6.49×10^{-2}	642	343
Actuator Exit (Peripheral Shield Exit Plenum)	6.49×10^{-2}	633	358
<u>Steady State Performance at Single TPA-65% Throttle Hold Start of Life (SOL)</u>			
Actuator Drive Shaft Inlet (Control Drum Exit)	7.0×10^{-2}	814	283
Actuator Exit (Peripheral Shield Exit Plenum)	7.0×10^{-2}	808	298

* Flow Rate Per Drum

TABLE 9-1 (CONT'D)

<u>Description</u>	<u>Flow-Lb/Sec*</u>	<u>Pressure-Psi</u>	<u>Temperature °R</u>
<u>Steady State Performance at Single TPA 65% Throttle Hold End of Life (EOL)</u>			
Actuator Drive Shaft Inlet (Control Drum Exit)	7.0×10^{-2}	810	331
Actuator Exit (Peripheral Shield Exit Plenum)	7.0×10^{-2}	803	346
<u>Steady State Performance at $T_c = 4500^\circ\text{R}$, Start of Life (SOL)</u>			
Actuator Drive Shaft Inlet (Control Drum Exit)	9.60×10^{-2}	1050	289
Actuator Exit (Peripheral Shield Exit Plenum)	9.60×10^{-2}	1039	305
<u>Steady State Performance at $T_c = 4500^\circ\text{R}$, End of Life (EOL)</u>			
Actuator Drive Shaft Inlet (Control Drum Exit)	9.70×10^{-2}	1046	300
Actuator Exit (Peripheral Shield Exit Plenum)	9.70×10^{-2}	1035	316

*Flow Rate Per Drum

TABLE 9- 2 . MATERIALS USED IN CDDA ANALYSIS

<u>COMPONENT</u>	<u>MATERIAL</u>	<u>SPECIFICATION IDENTIFICATION</u>	<u>MATERIAL LIBRARY NO. *</u>
Field Coil	Copper	QQ-C-502	6
Motor Shaft	Stainless Steel	QQ-5-763CL304	47
Transmission	Stainless Steel		47
Pots	Plastic		-
Housing	Stainless Steel	QQ-S-763CL304	47
Shaft	Stainless Steel	AMS 5734	47

* Material Library Designation Used in Analytical Model See Section 2.4.3.2

TABLE 9-3

COMPONENT TEMPERATURES, GRAPHITE CORE, RATED PERFORMANCE, NORMAL MODE

<u>Component</u>	<u>Temperature - °R</u>
Motor shaft	310
Field coil	310
Transmission	311
Pots & bearings	310
Housing	316
Shaft forward end	503
Shaft aft end	596

Figure 9-1. Nodal Pattern for CDDA Analytic Model

Figure 9-1A. Steady State Temperatures, Normal Mode, Design Rated Condition, SOL, Graphite Core.

Figure 9-2. Flow Schematic of CDDA

Figure 9.2A. Channel and Plenum Location for CDDA Analytic Model.

W59831-1

Figure 9-3. Graphite Core, Startup, Start of Life, Normal Mode, Coolant Flow Rate vs Time

M59832-1

Figure 9-4. Graphite Core, Startup, Start of Life, Normal Mode, Coolant Pressure Drop Across Actuator vs Time

M59832-1

Figure 9-5. Graphite Core, Startup, Start of Life, Normal Mode, Temperature Rise in Actuator Coolant Flow vs Time

W50031-1

Figure 9-6. Graphite Core, Shutdown, Start of Life, Normal Mode, Coolant Flow Rate vs Time

MS9832-1

Figure 9-7. Graphite Core, Shutdown, Start of Life, Normal Mode, Coolant Pressure Drop Across Actuator

Figure 9-8. Graphite Core, Shutdown, Start of Life, Normal Mode, Temperature Rise in Actuator Coolant Flow vs Time

W59832-1

Figure 9-9. Graphite Core, Shutdown, Start of Life, Normal Mode, Actuator Housing Temperature vs Time

Figure 9-10. Graphite Core, Startup, Start of Life, Normal Mode, Actuator Housing Temperature vs Time

10.0 STRUCTURAL SUPPORT COOLANT ASSEMBLY

10.1 INTRODUCTION

Input to be supplied by ANSC Data Item S-31.

10.1.1 STRUCTURAL SUPPORT COOLANT VALVE

10.1.1.1 INTRODUCTION

Input to be supplied by ANSC Data Item S-31.

10.2 STRUCTURAL SUPPORT COOLANT VALVE ACTUATOR

10.2.1 INTRODUCTION

This chapter describes the thermal and fluid flow analysis performed on the Structural Support Coolant Valve Actuator (SSCVA). The primary function of the SSCVA is to control the operation of the Structural Support Coolant Valve (SSCV).

The SSCVA is part of the contract end item described as the NERVA Nuclear Subsystem (NSS) and is listed as an Engineering Critical Component CC-677576 in CEI Specification No. CP-677555A. This ECC Specification establishes the thermal and hydraulic design requirements for the SSCVA critical components.

10.2.1.1 Description of the SSCVA

The following design features are given in EC-677576.

"3.3.1 General Design Features

The SSCVA consists of an electrical stepper motor actuator mechanism, a coupling for connecting the actuator to the Structural Support Coolant Valve and Actuator."

Supplemental descriptive information follows:

a. Actuator Housing

The housing serves as both the frame of the actuator, mounting all of the component subassemblies, and as a pressure vessel, capable of containing the system coolant pressure. The housing also accomplishes the electrical interfacing function with the controller by means of an electrical connector and the mechanical mounting interfacing function with the valve housing by means of three belts and indexing dowels.

b. Motor

The motor is of the type generally referred to as a "stepper", since its rotor motion is usually incremental, responding to discrete pulse excitation of the stator, and would only be continuous when slewing at synchronous speed. The rotor has

twelve radially salient poles of permanent magnet material, alternately polarized. The motor stator has 24 poles, which establish a step angle of 15° , with a two phase power winding. Auxiliary coils wound on the stator act in conjunction with the rotor permanent magnets to supply step response feedback signals.

c. Transmission

A two stage epicyclic transmission (EPIC) carries motor torque to the actuator output shaft and, with a ratio of 150/1, reduces the incremental motion of the valve to one tenth degree. This transmission is comprised of two internal ring gears and a duplex pinion.

d. Potentiometer

The stepper motor and transmission, which comprise the drive elements of the actuator, position the valve under varying load and environmental conditions without dependence on closed loop position feedback, and are augmented by diagnostic position instrumentation. This is provided by two potentiometers monitoring the output shaft. They are electrically independent by virtue of having separate power supplies. Used in conjunction with a count of the stepper motor pulse feedback, there is thus provided triple redundancy of position information for use in diagnosing and correcting malfunctions.

e. Coupling Shaft

Actuator output torque is carried to the valve through a crown spline coupling shaft. Misalignment of valve and actuator axis of up to one degree are compensated for in this coupling.

f. SSCVA Controller

The actuator controller utilizes digital techniques to interpret binary coded control signals transmitted from the EPIC for motor stator phase control. The mode of control is primarily open loop in nature, although step detection techniques are utilized to signal completion of a rotor incremental step to the EPIC.

10.2.2 SUMMARY OF RESULTS AND CONCLUSIONS

Thermal analyses have been performed for the Structural Coolant Valve Actuator (SSCVA) shown in Drawing 940J150 in an NSS with a graphite core. The analyses are applicable to the performance requirements in the Critical Component Specification EC-677576. The analyses were performed using a finite element TAP-B computer code model of the SSCVA using heating rates for both a shielded and unshielded configuration. The environment applicable to the SSCVA analysis consists of thermal radiation to outer space from the housing external surface and of conduction from the housing support flange and drive shaft to a cryogenic propellant feed line. There was no forced convection cooling applied to the SSCVA in this analysis, i.e., all the heat generation was passively dissipated by radiation and conduction only.

Results of the analysis are summarized in Table 10.1-1. For the shielded case during steady state rated operation, temperatures range from a maximum of 456°R in the rotor to 240°R in the housing. For the unshielded case during steady state rated operation, temperatures range from a maximum of 815°R in the rotor to 454°R in the housing. Since the SSCVA is not convectively cooled, the maximum temperature coincides with the maximum heating rates that occur at rated power. Consequently, SSCVA temperatures during throttled, startup or shutdown operation will be lower than at rated steady state.

In conclusion, a step 4 detailed analysis has been performed for the SSCVA. The analysis was performed using a three dimensional steady state computer model for the SOL design rated condition. Results of these analyses indicate that this ECC meets the thermal/hydraulic requirements for operation as specified in EC-677576.

10.2.3 APPLICABLE REQUIREMENTS AND COMPATIBILITY OF THERMAL PERFORMANCE WITH THE NSS SPECIFICATION

The requirements and design conditions stated in this Section are specified in EC-677576, Section 3, issued on November 30, 1970.

The following requirements are applicable:

"3.1.1.1.1 Operational Modes

The SSCVA shall support and/or accommodate all operational modes and their respective operational requirements as defined in 3.1.1.1.1 (Operational Modes) and specified in 3.1.1.1.5 (Operational Requirements) of CP-677555 with no degradation of performance below that specified below."

The SSCVA thermal analysis was performed for SOL steady state rated performance, which represents the worst steady state operating condition. The Induced Thermal Environment Specified in EC-677576 was calculated and is presented in Section 10.2.2 of this chapter. The analysis performed on the SSCVA resulted in no degradation of performance below that specified in CP-677555A.

10.2.4 METHOD OF ANALYSIS (DESIGN PRACTICES)

This section presents the design practices used by Thermal Design to obtain the thermal and fluid environment within the SSCVA. The analytical procedures and the analytical models used to implement the design practices are described. In addition, a discussion of the maturity of the input data and the validity of the analysis are given. The detail analysis is within the framework of the overall computational network discussed in Chapter 2 and is designated a Step 4 calculation.

10.2.4.1 Analytical Procedures

In this subsection, the analytical procedures selected for the evaluation of the thermal-hydraulic model are presented. The justification for using the procedure, the assumptions used in the analysis, and the computer codes selected to evaluate the analytical model are discussed. The analytical procedures are consistent with the overall thermal design procedures presented in Chapter 2.

10.2.4.2 Analytical Model

The procedure used in the derivation of the analytic model is the same as the procedure followed for the CDDA because the SSCVA is the same component as the CDDA. The SSCVA model is shown in Figure 10.2-1. Therefore the discussion of Section 9.4.2.1 is applicable to the SSCVA with the following exceptions:

- (1) No coolant flow is used for the SSCVA, therefore the fluid boundary conditions do not apply. In the SSCVA thermal model, the nodes are thermally coupled by conduction, if they are in physical contact, or by thermal radiation, if separated. There is no convective cooling of the SSCVA.
- (2) The heat generated in the SSCVA is removed from its external surface by thermal radiation to outer space and by conduction from the housing flange and drive shaft to the cryogenic propellant line.

10.2.4.3 Compatibility of Analytical Model with the Design

By comparing the analytical model configuration with the SSCVA as shown in Drawing No. 940J150, it is observed that a good representation of the actuator mechanism resulted.

10.2.4.4 Boundary Conditions

The environment applicable to the SSCVA analysis consists of thermal radiation to outer space from the housing external surface and conduction from the housing support flange and drive shaft to a cryogenic propellant feed line. There was no forced convection cooling applied to the SSCVA in this analysis, i.e., all the heat generation was passively dissipated by radiation and conduction only. The Thermal Environment applicable to the SSCVA analysis is shown on Table 10.2-2.

10.2.4.5 Maturity of Input Data

The subsection describes the major input data and the maturity of these data required in addition to the analytical model to perform the SSCVA thermal-hydraulic performance calculations.

10.2.4.5.1 Material Properties

The maturity of properties data for the SSCVA and the manner in which the thermal properties vary are briefly discussed in Section 2.4.3.2. Table 10.2-3 lists the materials used in the major components and the specification identification of the material. The thermal properties used are reported in the E-105 Data Item.

10.2.4.5.2 Heating Rates

The heating rates used in this analysis of the SSCVA in an NSS with a graphite core were obtained from the results of analysis reported in the S-100 Data Item. Configurations for both shielded and unshielded cases were analyzed.

10.2.4.6 Validity of Analysis

The general methods and techniques used in the analysis of the SSCVA have been used for all the thermal analyses of the components reported in this Data Item. The adequacy of these methods has been demonstrated in their application to the NRX Technology program and to numerous component test analyses. In the NRX-A6 reactor test, a side-by-side actuator test was performed to obtain data on the effects of a radiation environment on the component and its operation. Although the CDDA design differs from that used in the NRX-A6 side-by-side test, the analysis techniques applicable to that reactor test are used in this Data Item.

10.2.5 RESULTS, ANALYSIS, AND INTERPRETATION

This section presents the results of the analysis performed on the graphite core to determine the thermal and fluid environment of the SSCVA at various steady state and transient conditions.

10.2.5.1 Composite Core

The radiation environment of the SSCVA is more severe when the NSS employs a graphite core than a composite core; therefore, the analysis of the SSCVA was performed using heating rate data and a thermal-hydraulic environment corresponding to a NSS with a graphite core.

10.2.5.2 Graphite Core

The SSCVA detailed step 4 thermal and fluid analysis was made for the SSCVA subcomponent environment with the graphite core during normal mode operation including SOL rated performance.

10.2.5.2.1 Steady State Performance

The subcomponent temperatures for the SSCVA are summarized in Table 10.2-1 and illustrated in Figure 10.2-1A and Figure 10.2-1B. The values which are shown for the rated performance at design conditions are considered to be the worst case for the SSCVA. The reason for this is that heat is transferred by radiation to outer space and by conduction cooling

through the housing flange and drive shaft. There is no coolant used within the SSCVA housing to cool the subcomponents. Because of this lack of coolant flow, the internal temperatures will not be subject to the temperature fluctuations that would be caused by a rapid change in coolant temperature and flowrate. Consequently, the most severe thermal environment will occur at the condition of maximum internal heat generation, i.e., design rated performance. Consequently, there is no discussion of throttled, startup or shutdown operation in this chapter, since they are considered less limiting than rated steady state .

The thermal analysis of the SSCVA was performed for both a shielded and unshielded configuration. For the shielded case during steady state rated operation, temperatures range from a maximum of 456°R in the rotor to 240°R in the housing. For the unshielded case during steady state rated operation, temperatures range from a maximum of 815°R in the rotor to 454°R in the housing. The housing temperature is low because it radiates to deep space, whereas the rotor and other components within the housing radiate to each other; thus the internal component temperatures will be higher than the housing.

In this analysis, it was assumed that heat transfer from the SSCVA housing occurs by radiation to deep space. This is a reasonable simplifying assumption, since the resulting analysis indicates the component temperatures are relatively low. Further refinement of the calculational model could be performed to account for such things as more detailed definition of the surrounding thrust and engine structures and for solar heat flux.

In conclusion, this section has described the thermal characteristics of the SSCVA with a graphite core for SOL rated conditions. Because of the lack of any coolant flow, radiation to outer space and conduction to the propellant pipe line were considered as modes of heat transfer.

TABLE 10.2-1 COMPONENT TEMPERATURES, GRAPHITE CORE,
RATED PERFORMANCE SOL NORMAL MODE

Component	Temperatures With Shielded Configuration	Temperatures With Unshielded Configuration
Motor Shaft	456°R	815°R
Field Coil	424°R	747°R
Transmission	334°R	654°R
Pots and Bearings	365°R	695°R
Housing	240°R	454°R

TABLE 10.2-2
SSCVA THERMAL ENVIRONMENT
GRAPHITE CORE, RATED PERFORMANCE, SOL, NORMAL MODE

TABLE 10.2-3. MATERIALS USED IN SSCVA ANALYSIS

<u>COMPONENT</u>	<u>MATERIAL</u>	<u>SPECIFICATION IDENTIFICATION</u>	<u>MATERIAL LIBRARY NO. *</u>
Field Coil	Copper	QQ-C-502	6
Motor Shaft	Stainless Steel	QQ-5-763CL304	47
Transmission	Stainless Steel		47
Pots	Plastic		-
Housing	Stainless Steel	QQ-S-763CL304	47
Shaft	Stainless Steel	AMS 5734	47

* Material Library Designation Used in Analytical Model See Section 2.4.3.2

Figure 10.2-1. Nodal Pattern Used for SSCVA Analytic Model.

Figure 10.2-1A. Steady State Temperature, for Unshielded SSCVA

Figure 10.2-1B. Steady State Temperature for Shielded SSCVA

11.0 NSS INSTRUMENTATION

11.1 INTRODUCTION

This chapter provides a general discussion of the type, location, and purpose of the NSS Instrumentation (NSSI) which is relevant to the thermal and hydraulic environment. Instrumentation is provided in the NSS so that the thermal-hydraulic environment can be monitored during all operational modes. Temperature and pressure data are obtained for all ECC's to enable an evaluation of their performance relative to prediction and to any applicable limits.

The NSS Instrumentation is part of the contract end item described as the NERVA Nuclear Subsystem (NSS) and is listed as an Engineering Critical Component EC-677565 in CEI Specification No. CP-677555A.

11.1.1 Description of NSS Instrumentation

The following general design features are given in EC-677565 for the NSS Instrumentation:

"3.3.1. General Design Features

The NSSI consists of pressure transducers, thermocouples, displacement transducers, strain transducers, accelerometers, neutronic instruments, and the associated pressure tubing, mounting hardware, and electrical leads to the first termination exterior to the pressure vessel. The components of the NSSI are used to measure selected parameters for the purpose of control, performance diagnostics, safety diagnostics, and collection of trend data."

11.2 SUMMARY OF RESULTS AND CONCLUSIONS

The NSS thermal environmental data applicable to the instrumentation are reported throughout the other chapters of this report. In general, instrumentation was selected to

operate within this environment and to enable monitoring of the environment to insure that the NSS operates within its specified limits.

Two specific thermal problems associated with the NSS Instrumentation have been analyzed and are discussed in this chapter. Conclusions from these two analyses are the following:

1. The cluster exit gas thermocouples should be positioned at 90° to the exit gas flow stream to minimize errors due to heat transfer from the thermocouple.

2. The recommended minimum number of instruments for the temperature measurements in the core are as follows:

Core Station 0.2"	4
Unfueled Elements (Station 26")	21
Cluster Exit Gas	21
Structural Support Material	10

This instrumentation list will be modified as the design progresses. Additional information on the NSS Instrumentation is supplied in Reference 6.

11.3 APPLICABLE REQUIREMENTS AND COMPATIBILITY OF THERMAL PERFORMANCE WITH THE NSS SPEC

The specified requirements for the NSS instrumentation as set forth in EC-677565 "NSS Instrumentation," require measurements for control, diagnostic, safety, and trend data under all operative modes. These requirements are not incompatible with any thermal performance parameters of the instrumentation.

11.4 METHOD OF ANALYSIS (DESIGN PRACTICES)

The analytical procedures applicable to the instrumentation are similar to those of the ECC for which the instrumentation is intended. Boundary conditions are obtained from TNT and are used with the detailed ECC calculational model modified to explicitly include the instrumentation. Consequently, the analytical model description, the maturity of input data, and the validity of the analysis applicable to any particular instrument would be as reported in the corresponding chapter of the ECC for which the instrumentation is intended.

Two specific problems associated with the configuration and placement of NSS Instrumentation are reported in this chapter. A discussion of the analytical methods used to evaluate these problems is presented in the next subsections.

11.4.1 Exit Gas Thermocouple Orientation Analysis

The purpose of this analysis is to determine the cluster exit gas thermocouple orientation relative to the flow stream which provides minimum error between the actual and measured gas temperatures.* Two thermocouple orientations were considered in this analysis; one orientation considers the thermocouple to be parallel to the flow stream, and the other orientation considers the thermocouple to be perpendicular to the flow stream. An estimate of the thermocouple temperature relative to the actual gas temperature is made for each orientation by applying the zero dimensional form of the energy equation to the thermocouple assembly. Energy transport mechanisms considered in the analysis include convection to the fluid, radiation between the thermocouple and nozzle walls and between the thermocouple and core, and nuclear heat generation in the thermocouple. Three different methods are used to define the convective heat transfer coefficient on the thermocouple parallel to the exit gas flow:

- a) Forced flow over a flat plate (Reference 2)
- b) The axially symmetric jet (Reference 3)
- c) A wake behind a body (Reference 4)

The convective heat transfer coefficient on the thermocouple perpendicular to the flow stream is defined by a correlation applicable to flow normal to small diameter wires. The CONFAC-1 computer code (Reference 1) was used to define the radiation shape factors for each of the thermocouple orientations.

11.4.2 Analysis to Determine Minimum Number of Thermocouples for NSS

The purpose of this analysis is to define the minimum number of thermocouples necessary to insure the required accuracy of specific measurements in the NSS.** A

*The details of this analysis are contained in TRD-68-174, Addendum 1.

**The details of this analysis are contained in DRM 53155.

statistical approach is used to define the minimum number of measurements. This approach allots the accuracy requirement of a measurement to local and systematic uncertainties which together with the number of measurements determine the accuracy of the measurement. This method is outlined in the following paragraphs.

The number of instruments is determined by the required accuracy in the measured average temperature and the uncertainties in each T/C measurement. In this analysis, engineering judgment has been used together with estimated uncertainties. For purposes of the analysis, uncertainties can be divided into two categories, systematic and local. Systematic uncertainties, such as core power level, average thermal conductivity, etc., affect all instruments at a given core station equally. Local uncertainties affect only one instrument with respect to its neighbors. Predicted local temperature variations (which are technically not "uncertainties") have been lumped with the local uncertainties for this study, since they affect the required quantity of instruments in about the same way. Increasing the number of instruments can materially reduce the impact of local uncertainties but cannot reduce the influence of systematic uncertainties.

If a requirement exists that a certain measured average temperature level be accurate to within $\pm X_R$ of the true value and there are k systematic uncertainties $\pm X_i$ then assuming statistical independence.

$$(1) \quad X_A = \left(X_R^2 + \sum_{i=1}^k X_i^2 \right)^{1/2}$$

where X_A = the allowable uncertainty in the average which can be charged to local effects. Again assuming independence of the local uncertainties, the error in the average of n measurements when each measurement is subject to local uncertainties $\pm X_j$ is

$$(2) \quad X_A = \left(\frac{\sum_{j=1}^n X_j^2}{n} \right)^{1/2}$$

Neglecting t-tests for confidence limits, therefore, the required number of instruments is

$$(3) \quad n = \frac{\sum_{j=1}^l x_j^2}{\left(x_R^2 - \sum_{i=1}^k x_i^2 \right)}$$

11.5 RESULTS, ANALYSIS, AND INTERPRETATION

In this section, a tabulation of the NSS instrumentation relevant to the thermal-hydraulic analysis is presented. Table 11-1 includes a description of the type of measurement and their purpose. The instrumentation allocation is based on previous reactor test experience and on a knowledge of the reactor environment as reported in the other chapters of this report.

Two thermal analyses have been performed for specific thermal problems associated with the NSS instrumentation and are presented in the following subsections.

11.5.1 Results of Exit Gas Thermocouple Orientation Analysis

The methods described in Section 11.4.1 were used to determine the cluster exit gas thermocouple orientation which provides the most accurate measurement. Table 11-2 gives a summary of the results of this analysis. The first entry in this table gives the convection heat transfer coefficients calculated for the parallel and perpendicular thermocouple orientations. Because of the complexity of the flow regime in the wake of a body, three different methods were used to calculate the heat transfer coefficient for the thermocouple parallel to the flow stream. All three of these calculations show the heat transfer coefficient to be much smaller for the parallel orientation than for the perpendicular orientation. The second entry in Table 11-2 gives the calculated thermal radiation view factors between the thermocouple and core and between the thermocouple and nozzle wall. Figure 11-1 shows the variation in thermocouple bead temperature (for 4550°R gas temperature) with

view factor for both thermocouple orientations. This figure indicates that the thermocouple temperature is more sensitive to view factor for the parallel orientation than for the perpendicular orientation. The third entry in Table 11-2 gives the thermocouple bead temperature at 4550°R gas temperature for both thermocouple orientations. These results show that the thermocouple perpendicular to the flow stream reads much closer to the actual gas temperature than does the thermocouple parallel to the flow stream. This is due to the high heat transfer coefficient and relative insensitivity to radiation view factor of the thermocouple oriented perpendicular to the flow stream.

The cold boundary layer buildup on the tungsten protection cup has been neglected. This condition would tend to make the thermocouple bead read even lower than the analysis shows. This problem is eliminated by bending the thermocouple 90° to the exit gas flow.

From the above results it can be concluded that the thermocouple should be positioned at 90° to the exiting gas flow.

It should be noted that although this analysis was performed for 4550°R exit gas temperature, the conclusions are also applicable to the current 4300°R exit gas temperature.

11.5.2 Results of Analysis to Determine Minimum Number of Thermocouples for NSS

This section gives the results of applying the statistical approach outlined in Section 11.4.2 to specific measurement locations in the NSS. The importance of uncertainty analysis in determining instrumentation requirements is apparent in Figure 11-2. This figure shows the results of applying Equation 3 of Section 11.4.2 for various assumed uncertainty levels. This figure indicates for given uncertainty levels, the number of instruments required to meet a specified accuracy requirement.

Table 11-3 presents the accuracy requirements, estimated uncertainty values and calculated minimum number of thermocouples for four NSS temperature measurements. The four measurements considered are the core station 0.2 fuel element temperature, the fuel exit gas temperature, the core station 26 unfueled element temperature, and the structural support (support stem or liner tube) material temperature. The accuracy requirements presented in Table 11-3 for the core station 0.2 temperature and the structural support material temperature are determined from the maximum calculated value, the temperature limit and a 99% probability of not exceeding the limit. The accuracy requirements on the fuel exit gas temperature and station 26 temperature are based on the necessary accuracy to which the operating point of the engine must be defined. The systematic errors listed in Table 11-3 are estimated values based on analysis and test results; these errors include uncertainties due to variations in parameters (such as average thermal conductivity, power level, etc.) which affect all instruments at a given core station equally. There are two values listed for the systematic errors both for the fuel exit gas temperature and for the station 26 temperature. These two values are felt to scope the range of systematic uncertainty values for each of these measurements. The allowable error due to local effects listed in Table 11-3 is simply the square root of the difference between the squares of the required accuracy and systematic error. The estimated local uncertainties listed in Table 11-3 include not only the variation due to local uncertainties in parameters affecting the temperature at the given location, but also the expected radial variations in the temperature. Finally, the minimum number of thermocouples required for each measurement is presented in Table 11-3. This number is the square of the local uncertainty value divided by the allowable error due to local effects. This analysis is based on full power conditions, but the support structure will be nearer temperature limits during cooldown when the pulse cooling will be initiated based on these measurements. There is a possibility that local variations and uncertainties would be greater during cooldown than at full power, but a very detailed model (consisting of many parallel flow paths with interconduction

between them) would be required to predict these local effects. Therefore, a requirement for ten T/C's rather than seven is recommended subject to later verification.

The final requirements for the flight engine instrumentation will come as a result of ground test reactor diagnostic measurements, post operational disassembly and post test analysis. At least three instruments should be provided for any temperature measurement worthy of including on the requirements list. This is to avoid the chance of using an erroneous reading from a single defective instrument. There is no really conclusive analysis that can prove a specific number of instruments are essential, but the quantities given below are based on reasonable assumptions and are believed to be within a few instruments of what will eventually be found necessary.

1. Core Station 0.2"	4
2. Unfueled Element (Station 26")	21
3. Cluster Exit Gas	21
4. Structural Support Material	10

[REDACTED]

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[REDACTED] Astronuclear Laboratory [REDACTED]

11.6 REFERENCES

1. Wells, K. J., CONFAC-1, TRD-68-142, Thermal Design Computer Codes Manual, dated March 1968.
2. "Principles of Heat Transfer," F. Kreith, International Test Book Co.
3. "Fluid Dynamics of Jets," S. I. Pai, D. Van Nostrand.
4. "Boundary Layer Theory," H. Schlichting, McGraw-Hill Book Co.
5. TRD-68-202, "Conduction Loss from Cluster Gas Exit Thermocouple," dated May 1968.
6. WANL-TME-2767, S-054 Data Item, Trade Study 792, NSS Instrumentation.

TABLE 11-1

PRELIMINARY NSS MEASUREMENT DATA REQUIREMENTS LIST

MEASUREMENT DATA REQUIREMENTS LIST (MDRL) Flight ISSUE DATE 11/30/70 REV. COMPONENT/SPEC. Nuclear Subsystem CP 67555(N) Page 1 of 13												
C-103												
WANL Design Criteria No.	Measurement Channel No.	Measurement Description	Core Station	Radius	Theta	Data Range Requested		Requested		PR	Snp. Org.	E- Use ***
						Normal Operational Point/Range	Set-Up Range	Accuracy *	Frequency Response			
061-A		Reflector Material Strain (Axial)	48	22.2	15°	+ 500 μ in/in		25 μ in/in	1000 Hz	D1	WANL	D
		Reflector Material Strain (Axial)	48	22.2	135	$\pm$ 500 μ in/in		25 μ in/in	1000 Hz	D1		D
		Reflector Material Strain (Axial)	48	22.2	255	$\pm$ 500 μ in/in		25 μ in/in	1000 Hz	D1		D
		Reflector Material Strain (Hoop)	48	22.2	15	$\pm$ 500 μ in/in		25 μ in/in	1000 Hz	D1		D
		Reflector Material Strain (Hoop)	48	22.2	135	$\pm$ 500 μ in/in		25 μ in/in	1000 Hz	D1		D
		Reflector Material Strain (Hoop)	48	22.2	255	$\pm$ 500 μ in/in		25 μ in/in	1000 Hz	D1		D
084-A		Reflector Standoff Bolt Strain	57.7	23.3	17°40'	0-3000 μ in/in		+ 5%	1000 Hz	D1		D
		Reflector Standoff Bolt Strain	57.7	23.3	137°40'	0-3000 μ in/in		$\pm$ 5%	1000 Hz	D1		D
		Reflector Standoff Bolt Strain	57.7	23.3	257°40'	0-3000 μ in/in		$\pm$ 5%	1000 Hz	D1		D
062-A		Structural Support Stem Load	-8.0	0	TBD	0 to 1200 LB		+ 5% FS	1000 Hz	T1		T
		Structural Support Stem Load	-8.0	TBD	TBD	0 to 1200 LB		$\pm$ 5% FS	1000 Hz	T1		T
		Structural Support Stem Load	-8.0	TBD	TBD	0 to 1200 LB		$\pm$ 5% FS	1000 Hz	T1		T
		Structural Support Stem Load	-8.0	TBD	TBD	0 to 1200 LB		$\pm$ 5% FS	1000 Hz	T1		T
		Structural Support Stem Load	-8.0	15.75	TBD	0 to 1200 LB		$\pm$ 5% FS	1000 Hz	T1		T
086-A		Core Inlet Plenum Acoustical	-1.8	0.0	0	0-160 db		+ 5 db	2-5 K Hz	D1		D
		Core Inlet Plenum Acoustical	-1.8	15.0	120	0-160 db		$\pm$ 5 db	2-5 K Hz	D1		D
		Core Inlet Plenum Acoustical	-1.8	17.0	240	0-160 db		$\pm$ 5 db	2-5 K Hz	D1		D

* Requested Accuracy at Normal Operation Point or Over Normal Operating Range

** Priority (PR): C1 - Required to safely operate Flight Engine.
 C2 - Required to safely operate Ground Test Engine.
 T1 - Required Trend Data for Flight Engine.
 T2 - Required Trend Data for Ground Test Engine.

S2 - Required ground test only data for safety and Trend Data
 D1 - Required Flight Engine diagnostic channels.
 D2 - Required ground test diagnostic channels.
 E1 - Required ground test only experimental channel for transducer evaluation.

*** End Use: C - Control D - Diagnostic E - Experimental S - Safety T - Trend Data

Core Station 0 Inch = Engine Station 101.73

TABLE 11-1 (CONT'D)

PRELIMINARY NSS MEASUREMENT DATA REQUIREMENT LIST

MEASUREMENT DATA REQUIREMENTS LIST (MDRL) <u>Flight</u> ISSUE DATE <u>11/30/70</u> REV. <u> </u> COMPONENT/SPEC. <u>Nuclear Subsystem CP 677555(W)</u> Page <u>2</u> of <u>13</u> Pages												
C-103												
WANL Design Criteria No.	Measurement Channel No.	Measurement Description	Core Station	Radius	Theta	Data Range Requested		Requested		PR **	Resp. Org.	End Use ***
						Normal Operational Point/Range	Set-Up Range	Accuracy *	Frequency Response			
088-A		Reflector Inlet Plenum Acoustical	54.6	25.7	0	0-160 db		+ 5 db	2-5 K Hz	D1	WANL	D
		Reflector Inlet Plenum Acoustical	54.6	25.7	120	0-160 db		+ 5 db	2-5 K Hz	D1		D
		Reflector Inlet Plenum Acoustical	54.6	25.7	240	0-160 db		+ 5 db	2-5 K Hz	D1		D
087-A		NSS Outlet to Turbine Acoustical	-31.0	8.0	0	0-160 db		+ 5 db	2-5 K Hz	D1		D
		NSS Outlet to Turbine Acoustical	-30.0	14.0	120	0-160 db		+ 5 db	2-5 K Hz	D1		D
		NSS Outlet to Turbine Acoustical	-29.0	20.0	240	0-160 db		+ 5 db	2-5 K Hz	D1		D
080-A		Core Support Plate Axial Vibration	-7.0	22.0	TBD	TBD	+ 15 G	+ .75 G	1000 Hz	D1		D
		Core Support Plate Radial Vibration	-7.0	22.0	TBD	TBD	+ 15 G	+ .75 G	1000 Hz	D1		D
		Core Support Plate Radial Vibration	-7.0	22.0	TBD	TBD	+ 15 G	+ .75 G	1000 Hz	D1		D
081-A		Reactor to PVCS Displacement	-30.5	9	0	TBD		+ .01	300 Hz	D1		D
		Reactor to PVCS Displacement	-30.5	9	120	TBD		+ .01	300 Hz	D1		D
		Reactor to PVCS Displacement	-30.5	9	240	TBD		+ .01	300 Hz	D1		D
040-A		Core Axial Displacement	-10.0	0.0	TBD	-.65 to +.15		+ .01	300 Hz	D1		D
		Core Axial Displacement	-10.0	12.0	TBD	-.65 to +.15		+ .01	300 Hz	D1		D
		Core Axial Displacement	-10.0	18.0	TBD	-.65 to +.15		+ .01	300 Hz	D1		D
041-A		Core Radial Displacement (Forward)	1.24	23.4	12°20'	+ .49		+ .01	500 Hz	D1		D
		Core Radial Displacement (Forward)	1.24	23.4	132°20'	+ .49		+ .01	500 Hz	D1		D
		Core Radial Displacement (Forward)	1.24	23.4	252°20'	+ .49		+ .01	500 Hz	D1		D
041-A		Core Radial Displacement (Aft)	48.29	23.4	12°20'	+ .49		+ .01	500 Hz	D1		D
		Core Radial Displacement (Aft)	48.29	23.4	72°20'	+ .49		+ .01	500 Hz	D1		D
		Core Radial Displacement (Aft)	48.29	23.4	132°20'	+ .49		+ .01	500 Hz	D1		D
		Core Radial Displacement (Aft)	48.29	23.4	192°20'	+ .49		+ .01	500 Hz	D1		D
		Core Radial Displacement (Aft)	48.29	23.4	252°20'	+ .49		+ .01	500 Hz	D1		D
		Core Radial Displacement (Aft)	48.29	23.4	312°20'	+ .49		+ .01	500 Hz	D1		D

11-11

TABLE 11-1 (CONT'D)
PRELIMINARY NSS MEASUREMENT DATA REQUIREMENTS LIST

MEASUREMENT DATA REQUIREMENTS LIST (MDRL) <u>Flight</u> ISSUE DATE <u>11/30/70</u> REV. <u> </u> COMPONENT/SPEC. <u>Nuclear Subsystem CP 677555(W)</u> Page <u>3</u> of <u>13</u> Page <u> </u>												
WANL Design Criteria No.	Measurement Channel No.	Measurement Description	Core Station	Radius	Theta	Data Range Requested		Requested		PR **	Resp. Org.	End Use ***
						Normal Operational Point/Range	Set-Up Range	Accuracy *	Frequency Response			
050-A		Reflector Inlet Plenum Pressure	52.8	25	35	1135 psia/ 20 to 1194 psia		+ 1% FS	10 Hz	T1	WANL	T
		Reflector Inlet Plenum Pressure	52.8	25	155			+ 1% FS	10 Hz	T1		T
		Reflector Inlet Plenum Pressure	52.8	25	275			+ 1% FS	10 Hz	T1		T
048-A		NSS Outlet to Turbine Pressure	TBD	TBD	35	1070 psia/ 60 to 1200 psia		+ 10 psia		D1		D
		NSS Outlet to Turbine Pressure	TBD	TBD	155			+ 10 psia		D1		D
		NSS Outlet to Turbine Pressure	TBD	TBD	275			+ 10 psia		D1		D
051-A		NSS Inlet From Turbine Pressure	TBD	TBD	TBD	668 psia/ 60 to 700 psia				D1		D
		NSS Inlet From Turbine Pressure	TBD	TBD	TBD					D1		D
		NSS Inlet From Turbine Pressure	TBD	TBD	TBD					D1		D
028		SSBL Inlet at P/V Closure Pressure	TBD	30.5	105	1080 psia/ TBD to 1387 psia		TBD	1 Hz	D1		D
		SSBL Inlet at P/V Closure Pressure	TBD	30.5	105					D1		D
		SSBL Inlet at P/V Closure Pressure	TBD	30.5	105					D1		D
052-A		Structural Support Supply Plenum Pressure	TBD	TBD	0	1125 psia/ 60 to 1200 psia		+ 1% FS	10 Hz	C1		C
		Structural Support Supply Plenum Pressure	TBD	TBD	90			+ 1% FS	10 Hz	C1		C
		Structural Support Supply Plenum Pressure	TBD	TBD	180			+ 1% FS	10 Hz	C1		C
		Structural Support Supply Plenum Pressure	TBD	TBD	270			+ 1% FS	10 Hz	C1		C
054-A		Reflector Inlet to Core Exit ΔP										
		High Leg	52.8	25	TBD	685 psia/ 679 to 798 psia		+ 1% FS	10 Hz	T1		S, T
		Low Leg	TBD	TBD	TBD							
		Reflector Inlet to Core Exit ΔP										
		High Leg	52.8	25	TBD			+ 1% FS	10 Hz	T1		S, T
		Low Leg	TBD	TBD	TBD							

TABLE 11-1 (CONT'D)
PRELIMINARY NSS MEASUREMENT DATA REQUIREMENTS LIST

MEASUREMENT DATA REQUIREMENTS LIST (MDRL) Flight _____ ISSUE DATE <u>11/30/70</u> REV. _____ COMPONENT/SPEC. <u>Nuclear Subsystem CP 677555(W)</u> Page <u>4</u> of <u>13</u> Pages												
WANL Design Criteria No.	Measurement Channel No.	Measurement Description	Core Station	Radius	Theta	Data Range Requested		Requested		PR **	Resp. Org.	End Use ***
						Normal Operational Point/Range	Set-Up Range	Accuracy *	Frequency Response			
054-A		Reflector Inlet to Core Exit ΔP High Leg	52.8	25	TBD	685 psia/ 679 to 798 psia		+ 1% FS	10 Hz	T1	WANL	S, T
		Low Leg	TBD	TBD	TBD			- 1% FS	10 Hz	T1		
057-A		Reflector Inlet to Core Exit ΔP High Leg	52.8	25	TBD	30 psid/ 0 to 50 psid		+ 1% FS	10 Hz	T1		S, T
		Low Leg	TBD	TBD	TBD			- 1% FS	10 Hz	T1		
		Final LSS Seal ΔP High Leg	TBD	19.8	TBD			+ 1% FS	10 Hz	T1		T
		Low Leg	TBD	19.8	TBD			- 1% FS	10 Hz	T1		
		Final LSS Seal ΔP High Leg	TBD	19.8	TBD			+ 1% FS	10 Hz	T1		T
		Low Leg	TBD	19.8	TBD			- 1% FS	10 Hz	T1		
053		Core Axial ΔP High Leg	-1.0	TBD	TBD	170 psid/ 30 to 220 psid		+ 2 psid	10 Hz	C1		S, T
		Low Leg	TBD	TBD	TBD			- 2 psid	10 Hz	C1		
		Core Axial ΔP High Leg	-1.0	TBD	TBD			+ 2 psid	10 Hz	C1		S, T
		Low Leg	TBD	TBD	TBD			- 2 psid	10 Hz	C1		
		Core Axial ΔP High Leg	-1.0	TBD	TBD			+ 2 psid	10 Hz	C1		S, T
		Low Leg	TBD	TBD	TBD			- 2 psid	10 Hz	C1		

TABLE 11-1 (CONT'D)
PRELIMINARY NSS MEASUREMENT DATA REQUIREMENTS LIST

MEASUREMENT DATA REQUIREMENTS LIST (MDRL) <u>Flight</u> ISSUE DATE <u>11/30/70</u> REV. <u> </u> COMPONENT/SPEC. <u>Nuclear Subsystem CP 677555(W)</u> Page <u>5</u> of <u>13</u> Pages C-103												
WANL Design Criteria No.	Measurement Channel No.	Measurement Description	Core Station	Radius	Theta	Data Range Requested		Requested		PR **	Resp. Org.	End Use ***
						Normal Operational Point/Range	Set-Up Range	Accuracy *	Frequency Response			
053		Core Axial ΔP High Leg Low Leg	-1.0	TBD TBD	TBD TBD	170 psid/ 30 to 220 psid		+ 2 psid	10 Hz	C1	WANL	S, T
056		Refl. Inlet/NSS Outlet to Turbine ΔP High Leg Low Leg	53.8 -34.0	25.0 7.0	TBD TBD	69 psid/ 0 to 75 psid		+ 1% FS -	10 Hz	C1		S, T
		Refl. Inlet/NSS Outlet to Turbine ΔP High Leg Low Leg	53.8 -34.0	25.0 7.0	TBD TBD				10 Hz	T1		T
		Refl. Inlet/NSS Outlet to Turbine ΔP High Leg Low Leg	53.8 -34.0	25 7.0	TBD			+ 1% FS	10 Hz	T1		T
		NSS Inlet From Turbine/Core Inlet ΔP High Leg Low Leg	-37.0 -2.8	3.5 TBD	0 0	40 psid/ 0 to 50 psid		$\pm$ 1% FS	10 Hz	T1		S, T
059-A		NSS Inlet From Turbine/Core Inlet ΔP High Leg Low Leg	-37.0 -2.8	3.5 TBD	120 120			+ 1% FS	10 Hz	T1		S, T
		NSS Inlet from Turbine/Core Inlet ΔP High Leg Low Leg	-37.0 -2.8	3.5 TBD	240 240			+ 1% FS	10 Hz	T1		S, T
		Structural Support Inlet/Exhaust Plenum ΔP High Leg Low Leg	-8.7 -4.5	TBD TBD	TBD TBD	50 psid/ 0 to 100 psid		+ 1% FS +	10 Hz	C1		S, T
060-A												

TABLE 11-1 (CONT'D)
PRELIMINARY NSS MEASUREMENT DATA REQUIREMENTS LIST

MEASUREMENT DATA REQUIREMENTS LIST (MDRL) <u>Flight</u> ISSUE DATE <u>11/30/70</u> REV. <u> </u> COMPONENT/SPEC. <u>Nuclear Subsystem CP 677555(W)</u> Page <u>6</u> of <u>13</u> Page C-103												
WANL Design Criteria No.	Measurement Channel No.	Measurement Description	Core Station	Radius	Theta	Data Range Requested		Requested		PR **	Resp. Org.	End Use ***
						Normal Operational Point/Range	Set-Up Range	Accuracy *	Frequency Response			
060-A		Structural Support Inlet/Exhaust Plenum ΔP										
		High Leg	-8.7	TBD	TBD	50 psid/		+ 1% FS	10 Hz	C1	WANL	S, T
		Low Leg	-4.5	TBD	TBD	0 to 100 psid						
063		Structural Support Inlet/Exhaust Plenum										
		High Leg	-8.7	TBD	TBD	50 psid/		+ 1% FS	10 Hz	C1		S, T
		Low Leg	-4.5	TBD	TBD	0 to 100 psid						
		Structural Support Inlet/Exhaust Plenum										
		High Leg	-8.7	TBD	TBD	50 psid/		+ 1% FS	10 Hz	C1		S, T
		Low Leg	-4.5	TBD	TBD	0 to 100 psid						
		Cluster Exit Gas Temperature	55.1	TBD	TBD	4300°R /		+ 50°R	TBD	C1		C
		Cluster Exit Gas Temperature	55.1			500°R to		+ 50°R	TBD	C1		C
		Cluster Exit Gas Temperature	55.1			4500°R		+ 50°R	TBD	C1		C
		Cluster Exit Gas Temperature	55.1					+ 50°R	TBD	C1		C
		Cluster Exit Gas Temperature	55.1					+ 50°R	TBD	C1		C
		Cluster Exit Gas Temperature	55.1					+ 50°R	TBD	C1		C
		Cluster Exit Gas Temperature	55.1					+ 50°R	TBD	C1		C
		Cluster Exit Gas Temperature	55.1					+ 50°R	TBD	C1		C
		Cluster Exit Gas Temperature	55.1					+ 50°R	TBD	C1		C
		Cluster Exit Gas Temperature	55.1					+ 50°R	TBD	C1		C
		Cluster Exit Gas Temperature	55.1					+ 50°R	TBD	C1		C
		Cluster Exit Gas Temperature	55.1					+ 50°R	TBD	C1		C
		Cluster Exit Gas Temperature	55.1					+ 50°R	TBD	C1		C
		Cluster Exit Gas Temperature	55.1					+ 50°R	TBD	C1		C
		Cluster Exit Gas Temperature	55.1					+ 50°R	TBD	C1		C

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TABLE 11-1 (CONT'D)

PRELIMINARY NSS MEASUREMENT DATA REQUIREMENTS LIST

MEASUREMENT DATA REQUIREMENTS LIST (MDRL) <u>Flight</u> ISSUE DATE <u>11/30/70</u> REV. <u> </u> COMPONENT/SPEC. <u>Nuclear Subsystem CP 677555(W)</u> Page <u>8</u> of <u>13</u> Pages												
WANL Design Criteria No.	Measurement Channel No.	Measurement Description	Core Station	Radius	Theta	Data Range Requested		Requested		PR **	Resp. Org.	End Use ***
						Normal Operational Point/Range	Set-Up Range	Accuracy *	Frequency Response			
064-A		Shield Material Temperature	TBD	TBD	TBD	400°R/40°R to		+ 20°R	1 Hz	C1	WANL	C
		Shield Material Temperature	TBD	TBD	TBD	1100°R		± 20°R	1 Hz	C1		C
		Shield Material Temperature	TBD	TBD	TBD			± 20°R	1 Hz	C1		C
(C) 076		Structural Support Liner Temp.	8	14	60	300-1200°R/ 200 to 1600°R		+ 20°R	1 Hz	C1		C
		Structural Support Liner Temp.	18	0	0			± 20°R	1 Hz	C1		C
		Structural Support Liner Temp.	18	4	0			± 20°R	1 Hz	C1		C
		Structural Support Liner Temp.	18	8	0			± 20°R	1 Hz	C1		C
		Structural Support Liner Temp.	18	12	0			± 20°R	1 Hz	C1		C
		Structural Support Liner Temp.	18	14	0			± 20°R	1 Hz	C1		C
		Structural Support Liner Temp.	18	16	120			± 20°R	1 Hz	C1		C
		Structural Support Liner Temp.	26	14	180			± 20°R	1 Hz	C1		C
		Structural Support Liner Temp.	38	14	240			± 20°R	1 Hz	C1		C
		Structural Support Liner Temp.	50	14	300			± 20°R	1 Hz	C1		C
075-A		Structural Support Supply Plenum Temperature		TBD	TBD	60°R/40°R to 600°R		+ 5°R	2 Hz	C1		C
		Structural Support Supply Plenum Temperature		TBD	TBD			± 5°R	2 Hz	C1		C
		Structural Support Supply Plenum Temperature		TBD	TBD			± 5°R	2 Hz	C1		C
		Structural Support Supply Plenum Temperature		TBD	TBD			± 5°R	2 Hz	C1		C
072-A		L.S.S. Seal Exit Gas Temperature	52.5	TBD	TBD	1350°R/400°R		+ 20°R	2 Hz	T1		T
		L.S.S. Seal Exit Gas Temperature	52.5	TBD	TBD	to 2000°R		± 20°R	2 Hz	T1		T
		L.S.S. Seal Exit Gas Temperature	52.5	TBD	TBD			± 20°R	2 Hz	T1		T
077-A		Structural Support Exhaust Plenum Temperature	-6.4	TBD	TBD	550°R/250°R to 800°R		+ 10°R	2 Hz	T1		T
		Structural Support Exhaust Plenum Temperature	-6.4	TBD	TBD			± 10°R	2 Hz	T1		T
		Structural Support Exhaust Plenum Temperature	-6.4	TBD	TBD			± 10°R	2 Hz	T1		T
(C) 078-A		Structural Support End Cap. Mtl. Temp.	53.5	TBD	TBD	TBD/TBD		+ 10°R	2 Hz	T1		T
		Structural Support End Cap. Mtl. Temp.	53.5	TBD	TBD			± 10°R	2 Hz	T1		T
		Structural Support End Cap. Mtl. Temp.	53.5	TBD	TBD			± 10°R	2 Hz	T1		T

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RESTRICTED DATA

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TABLE 11-1 (CONT'D)
PRELIMINARY NSS MEASUREMENT DATA REQUIREMENTS LIST

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RESTRICTED DATA

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MEASUREMENT DATA REQUIREMENTS LIST (MDRL) Flight C-103 ISSUE DATE 11/30/70 REV. COMPONENT/SPEC. Nuclear Subsystem CP 677555(W) Page 9 of 13 Pages												
WANL Design Criteria No.	Measurement Channel No.	Measurement Description	Core Station	Radius	Theta	Data Range Requested		Requested		PR **	Posp. Org.	End Use ***
						Normal Operational Point/Range	Set-Up Range	Accuracy *	Frequency Response			
079A		Support Plate Material Temperature	-6.5	0.0	TBD	300°R/150°R		+ 20°R	1 Hz	CI	WANL	C, T
		Support Plate Material Temperature	-6.5	8.0	TBD	to 800°R		+ 20°R	1 Hz	CI		C, T
		Support Plate Material Temperature	-6.5	19.0	TBD			+ 20°R	1 Hz	CI		C, T
073		Reflector Inlet Plenum Temperature	53.8	25.0	TBD	191°R/60°R		+ 5°R	2 Hz	CI		C
		Reflector Inlet Plenum Temperature	53.8	25.0	TBD	to 700°R		+ 5°R	2 Hz	CI		C
		Reflector Inlet Plenum Temperature	53.8	25.0	TBD			+ 5°R	2 Hz	CI		C
022-A		Core Inlet Plenum Temperature	-3.2	TBD	TBD	300°R/100°R		+ 5°R	2 Hz	CI		C
		Core Inlet Plenum Temperature	-3.2	TBD	TBD	to 1000°R		+ 5°R	2 Hz	CI		C
		Core Inlet Plenum Temperature	-3.2	TBD	TBD			+ 5°R	2 Hz	CI		C
		Core Inlet Plenum Temperature	-3.2	TBD	TBD			+ 5°R	2 Hz	CI		C
		Core Inlet Plenum Temperature	-3.2	TBD	TBD			+ 5°R	2 Hz	CI		C
		Core Inlet Plenum Temperature	-3.2	TBD	TBD			+ 5°R	2 Hz	CI		C
103		Control Drum Vane Material Temperature	26.0	29.7	5°	TBD/40°R to		+ 1% FS	5 Hz	CI		C
		Control Drum Vane Material Temperature	26.0	24.7	125°	1200°R		+ 1% FS	5 Hz	CI		C
		Control Drum Vane Material Temperature	26.0	24.7	245			+ 1% FS	5 Hz	CI		C
		Control Drum Vane Material Temperature	26.0	24.7	TBD			+ 1% FS	5 Hz	CI		C
037		Core Nuclear Power (Low Range)	26	28	TBD	.1 watt to				CI		C
		Core Nuclear Power (Low Range)	26	28	TBD	3000 watts				CI		C
		Core Nuclear Power (Low Range)	26	28	TBD					CI		C
		Core Nuclear Power (Low Range)	26	28	TBD					CI		C
038		Core Nuclear Power (Medium Range)	26	28	TBD	1500 watts		10%	10 Hz	CI		C
		Core Nuclear Power (Medium Range)	26	28	TBD	to 4.5 MW		10%	10 Hz	CI		C
		Core Nuclear Power (Medium Range)	26	28	TBD			10%	10 Hz	CI		C
		Core Nuclear Power (Medium Range)	26	28	TBD			10%	10 Hz	CI		C
039		Core Nuclear Power (High Range)	26	28	TBD	2.5 MW to 5000 MW		10%	10 Hz	CI		C

TABLE 11-1 (CONT'D)
PRELIMINARY NSS MEASUREMENT DATA REQUIREMENTS LIST

MEASUREMENT DATA REQUIREMENTS LIST (MDRL) Flight _____ ISSUE DATE 11/30/70 REV. _____ COMPONENT/SPEC. Nuclear Subsystem CP 677555(W) Page 10 of 13 Pages												
WANL Design Criteria No.	Measurement Channel No.	Measurement Description	Core Station	Radius	Theta	Data Range Requested		Requested		PR **	Resp. Org.	End Use ***
						Normal Operational Point/Range	Set-Up Range	Accuracy *	Frequency Response			
039		Core Nuclear Power (High Range)	26	28	TBD	2.5 MW to		10%	10 Hz	C1	WANL	C
		Core Nuclear Power (High Range)	26	28	TBD	5000 MW		10%	10 Hz	C1		C
		Core Nuclear Power (High Range)	26	28	TBD			10%	10 Hz	C1		C
095-A		Shield Gamma Dose Rate	-25.0	0.0	0	1515 MW/		+ 10%	TBD	T1		T
		Shield Gamma Dose Rate	-25.0	10.0	20	100 W to		± 10%	TBD	T1		T
		Shield Gamma Dose Rate	-25.0	25.0	40	1800 MW		± 10%	TBD	T1		T
096-A		Shield Fast Fission Neutron Flux	-25.0	0.0	0	TBD/100 W to		+ 10%	TBD	T1		T
		Shield Fast Fission Neutron Flux	-25.0	10.0	20	1800 MW		± 10%	TBD	T1		T
		Shield Fast Fission Neutron Flux	-25.0	21.5	40			± 10%	TBD	T1		T
097-A		Shield Thermal Neutron Flux	-25.0	0.0	0	TBD/100 W to		+ 10%	TBD	T1		T
		Shield Thermal Neutron Flux	-25.0	10.0	20	1800 MW		± 10%	TBD	T1		T
		Shield Thermal Neutron Flux	-25.0	21.5	40			± 10%	TBD	T1		T
099-A		Reflector Gamma Dose Rate	26.0	28.0	0	TBD/100 W to		+ 10%	TBD	T1		T
		Reflector Gamma Dose Rate	26.0	28.0	20	1800 MW		± 10%	TBD	T1		T
		Reflector Gamma Dose Rate	12	28.0	40			± 10%	TBD	T1		T
100-A		Reflector Fast Fission Neutron Flux	26.0	28.0	0	TBD/100 W to		+ 10%	TBD	T1		T
		Reflector Fast Fission Neutron Flux	26.0	28.0	20	1800 MW		± 10%	TBD	T1		T
		Reflector Fast Fission Neutron Flux	12.0	28.0	40			± 10%	TBD	T1		T
101-A		Reflector Thermal Neutron Flux	26.0	28.0	0	TBD/100 W to		+ 10%	TBD	T1		T
		Reflector Thermal Neutron Flux	26.0	28.0	20	1800 MW		± 10%	TBD	T1		T
		Reflector Thermal Neutron Flux	12.0	28.0	40			± 10%	TBD	T1		T

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MEASUREMENT DATA REQUIREMENTS LIST (MDRL) <u>Flight</u> ISSUE DATE <u>11/30/70</u> REV. <u> </u> COMPONENT/SPEC. <u>Nuclear Subsystem CP 677555(W)</u> Page <u>11</u> of <u>13</u> Pages												
C-103												
WANL Design Criteria No.	Measurement Channel No.	Measurement Description	Core Station	Radius	Theta	Data Range Requested		Requested		PR **	Resp. Org.	End Use ***
						Normal Operational Point/Range	Set-Up Range	Accuracy *	Frequency Response			
071-A		NSS Inlet From Turbine Temperature	-37.0	TBD	TBD	255°R/100°R to 300°R		+ 1% FS	2 Hz	T1	WANL	T
		NSS Inlet From Turbine Temperature	-37.0	TBD	TBD			± 1% FS	2 Hz	T1		T
		NSS Inlet From Turbine Temperature	-37.0	TBD	TBD			± 1% FS	2 Hz	T1		T
070-A		NSS Outlet to Turbine Temperature	-35.0	7.0	TBD	275°R/100°R to 300°R		+ 5°R	2 Hz	T1		T
		NSS Outlet to Turbine Temperature	-35.0	7.0	TBD			± 5°R	2 Hz	T1	T	
		NSS Outlet to Turbine Temperature	-35.0	7.0	TBD			± 5°R	2 Hz	T1	T	
074-A		Reflector Material Temperature	26.0	22.1	0	350°/60°R to 700°R		+ 10°R	1 Hz	C1		C
		Reflector Material Temperature	26.0	22.1	120			± 10°R	1 Hz	C1	C	
		Reflector Material Temperature	52.0	22.1	240			± 10°R	1 Hz	C1	C	
045		SSCV Actuator Position	N/A	N/A	N/A	TBD/0-300°		+ 0.5°		C1		C
		SSCV Actuator Position	N/A	N/A	N/A			± 0.5°		C1	C	
		SSCV Actuator Position	N/A	N/A	N/A			± 0.5°		C1	C	
		SSCV Actuator Position	N/A	N/A	N/A			± 0.5°		C1	C	
		SSCV Actuator Position	N/A	N/A	N/A			± 0.5°		C1	C	
		SSCV Actuator Position	N/A	N/A	N/A			± 0.5°		C1	C	
031		Control Drum Position	-33.0	24.5	5	TBD/0-175°		+ 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	5			± 0.5°	20 Hz	C1	C	
		Control Drum Position	-33.0	24.5	5			± 0.5°	20 Hz	C1	C	
		Control Drum Position	-33.0	24.5	25			± 0.5°	20 Hz	C1	C	
		Control Drum Position	-33.0	24.5	25			± 0.5°	20 Hz	C1	C	
		Control Drum Position	-33.0	24.5	25			± 0.5°	20 Hz	C1	C	
		Control Drum Position	-33.0	24.5	25			± 0.5°	20 Hz	C1	C	
		Control Drum Position	-33.0	24.5	45			± 0.5°	20 Hz	C1	C	
		Control Drum Position	-33.0	24.5	45			± 0.5°	20 Hz	C1	C	
		Control Drum Position	-33.0	24.5	45			± 0.5°	20 Hz	C1	C	
		Control Drum Position	-33.0	24.5	65			± 0.5°	20 Hz	C1	C	
		Control Drum Position	-33.0	24.5	65			± 0.5°	20 Hz	C1	C	
		Control Drum Position	-33.0	24.5	65			± 0.5°	20 Hz	C1	C	
		Control Drum Position	-33.0	24.5	65			± 0.5°	20 Hz	C1	C	

TABLE 11-1 (CONT'D)
PRELIMINARY NSS MEASUREMENT DATA REQUIREMENTS LIST

MEASUREMENT DATA REQUIREMENTS LIST (MDRL) Flight <u>ISSUE DATE 11/30/70</u> REV. <u>COMPONENT/SPEC. Nuclear Subsystem CP 677555(W)</u> Page <u>12</u> of <u>13</u> Page:												
C-103												
WANL Design Criteria No.	Measurement Channel No.	Measurement Description	Core Station	Radius	Theta	Data Range Requested		Requested		PR **	Resp. Org.	End Use ***
						Normal Operational Point/Range	Set-Up Range	Accuracy *	Frequency Response			
031		Control Drum Position	-33.0	24.5	85	TBD/0-175°		+ 0.5°	20 Hz	C1	WANL	C
		Control Drum Position	-33.0	24.5	85			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	85			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	105			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	105			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	105			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	125			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	125			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	125			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	145			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	145			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	145			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	165			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	165			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	165			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	185			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	185			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	205			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	205			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	205			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	225			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	225			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	225			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	245			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	245			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	245			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	265			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	265			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	265			± 0.5°	20 Hz	C1		C
		Control Drum Position	-33.0	24.5	285			± 0.5°	20 Hz	C1		C

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TABLE 11-1 (CONT'D)
PRELIMINARY NSS MEASUREMENT DATA REQUIREMENTS LIST

MEASUREMENT DATA REQUIREMENTS LIST (MDRL) <u>Flight</u> ISSUE DATE <u>11/30/70</u> REV. <u> </u> COMPONENT/SPEC. <u>Nuclear Subsystem CP 677555(W)</u> Page <u>13</u> of <u>13</u> Page <u> </u>												
C-103												
ANL Design Criteria No.	Measurement Channel No.	Measurement Description	Core Station	Radius	Theta	Data Range Requested		Requested		PR **	Resp. Org.	End Use ***
						Normal Operational Point/Range	Set-Up Range	Accuracy *	Frequency Response			
031		Control Drum Position	-33.0	24.5	285	TBD/0-175°		+ 0.5	20 Hz	C1	WANL	C
	Control Drum Position	-33.0	24.5	285	± 0.5			20 Hz	C1	C		
	Control Drum Position	-33.0	24.5	305	± 0.5			20 Hz	C1	C		
	Control Drum Position	-33.0	24.5	305	± 0.5			20 Hz	C1	C		
	Control Drum Position	-33.0	24.5	305	± 0.5			20 Hz	C1	C		
	Control Drum Position	-33.0	24.5	325	± 0.5			20 Hz	C1	C		
	Control Drum Position	-33.0	24.5	325	± 0.5			20 Hz	C1	C		
	Control Drum Position	-33.0	24.5	325	± 0.5			20 Hz	C1	C		
	Control Drum Position	-33.0	24.5	345	± 0.5			20 Hz	C1	C		
	Control Drum Position	-33.0	24.5	345	± 0.5			20 Hz	C1	C		
	Control Drum Position	-33.0	24.5	345	± 0.5			20 Hz	C1	C		

TABLE 11-2

RESULTS OF THERMOCOUPLE ORIENTATION ANALYSIS

Parameter	Thermocouple Parallel to Flow Plate	Thermocouple Perpendicular to Flow Stream
Convection Heat Transfer Coefficient (Btu/sec. in. ² °R	1) 4.1×10^{-4} laminar flow over flat plate 1.0×10^{-5} turbulent flow over flat plate 2) 5.25×10^{-4} axially symmetric jet theory 3) less than (1) above	1) 6.05×10^{-3} flow normal to small diameter wire
Thermal Radiation View Factors		
a) Thermocouple to core	0	0.43
b) Thermocouple to nozzle	1.0	0.55
Thermocouple Bead Temperature for 4550°R Gas Temperature °R	4200	4530

TABLE 11-3

DETERMINATION OF MINIMUM NUMBER OF THERMOCOUPLES FOR SOME
NSS TEMPERATURE MEASUREMENTS

Measurement Location	Required Accuracy	Systematic Errors	Allowable Error Due to Local Effects	Local Uncertainty 1σ	Minimum Required No. of Thermocouples
Core Station 0.2	174°R	130°R	116°R	216°R	4
Fuel Exit Gas	50°R	Assume None	50°R	228°R	21
	50°R	30°R	40°R	228°R	32
Core Unfueled Element at Station 26	125°R	103°R	71°R	328°R	21
	125°R	35°R	120°R	328°R	8
Structural Support Material	213°R	167°R	132°R	340°R	7

Figure 11-1. Thermocouple Bead Temperature vs View Factor

Figure 11-2. Number of Instruments Required to Give X_A Uncertainty in Mean with X_o Local Uncertainty

Astronuclear
Laboratory

	TITLE Thermal and Fluid Flow Analysis Report, Nuclear Subsystem	
	DOCUMENT NO. WANL-TME-2753	DATE
ABSTRACT Thermal and fluid flow analyses are presented to document the detailed analyses conducted to derive and establish the performance and design requirements for the Nuclear Subsystem and its Engineering Critical Components. This data item establishes and substantiates the appropriate parameters of the selected design and provides the source for steady state and transient data used in the detail thermal and structural analyses. This Data Item report gives a summary of the applicable specifications relevant to the thermal design, a description and derivation of the analytical models and methods, the maturity of the input data, the validity of the analytical methods, and the interpretation and analysis of the resulting steady state and transient data.		
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