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WANL-TME-1980
OCTOBER 1970

DATA ITEM S-54

DETERMINATION
OF NOMINAL T_c FOR
4500°R MINIMUM (U)

TRADE STUDY NO. 702

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DATA ITEM S-54

DETERMINATION OF NOMINAL T_c FOR 4500°R MINIMUM

TRADE STUDY NO. 702

By H. J. C. TIC, date SEP 10 1973

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NOV 18 1970

Attention: Mr. P. P. Ventura

Subject: Data Item S-54, WANL-TME-1980, Determination of Nominal
 T_c for 4500°R Minimum, Trade Study 702

Gentlemen:

Enclosed are ten (10) copies of Data Item S-54, WANL-TME-1980,
Determination of Nominal T_c for 4500°R Minimum, Trade Study 702.

This data item is required by the statement of work for subcontract
NP-1, Project No. 719.

Respectfully,
ORIGINAL SIGNED BY
A. C. SANDERSON
A. C. Sanderson, Manager
Program Management
NERVA Nuclear Subsystem

RAJ/paw

Enclosure: Ten (10) copies of Data Item S-54, WANL-TME-1980

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ABSTRACT

The nominal chamber inlet temperature, T_c , required for the NERVA hot bleed cycle reference engine (June 1969) to assure the NPRD-1 specified rated performance is established. The nominal T_c determined for the specified 4500°R minimum chamber temperature was 4563°R for the flight engine. This was based upon the estimated accuracy with which the true NSS exit temperature for the flight engine could be measured and controlled. It was further determined that to assure the engine minimum rated specific impulse requirement of 825 seconds would require nominal T_c of 4625°R . The NSS exit gas temperature and fuel temperature levels resulting were found to be inconsistent with the high NSS reliability requirements stipulated in NPRD-1 based upon extrapolated NRX-1 technology. This study recommends a review of these requirements and a nominal T_c for the NERVA flight engine of 4500°R .

This study report satisfies the requirements of Trade Study Index No. 702 as agreed to in a joint meeting at AGC, Sacramento on April 8 and 9, 1969.

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1.0 SCOPE

This study established the best estimate of the nominal chamber inlet temperature required to meet the June 1969 reference hot bleed cycle engine minimum performance as specified by Reference 1.^{*} The accuracy in establishing and controlling the true NSS exit gas temperature, the related NSS core temperature distributions and corresponding material temperature environments for the fuel and other NSS components were estimated. Component thermal design and performance requirements related to these temperature levels and uncertainties were established and compared with the estimated capability to provide an indication of core reliability. Design margins and/or design improvements were indicated.

* June 1969 NPRD-1 requirements for a 4500°R T_{min} and 825 sec I_{sp} minimum were eliminated by SNPO-C Technical Directives 69C-33 and 70-1.

2.0 IDENTIFICATION OF REQUIREMENTS

2.1 BACKGROUND

A nominal NSS rated power operating condition must be established due to uncertainties that are sufficiently greater than the minimum specified performance to assure meeting this minimum performance. The required performance of the NSS is established by the NPRD-1 specified minimum exit temperature (Para III B) and the engine system chamber temperature requirements. The rated power thermal operating condition for the NSS can be developed from the established nominal chamber temperature, T_c , and the NSS thermal performance. This operating thermal environment must be established before serious design evaluation can be undertaken.

This study was made to identify the nominal chamber inlet temperature and NSS thermal environment needed for the NSS component design analysis for the hot bleed cycle reference engine as specified in June, 1969. The scope of this study was outlined in Trade Study Index No. 702, jointly agreed to at AGC Sacramento on April 8 and 9, 1969 (Reference 2). The relationship of this study to other pertinent interfacing studies is indicated in Figure 2-1. Results of this study are needed to define the design requirements for the NSS components, and are input to Engine System Trade Study 001 and NSS Trade Study 701.

Significant results of this study were reviewed with SNPO-C and AGC in a joint meeting at Cleveland on July 10 and 14, 1969.

2.2 FUNCTIONAL AND TECHNICAL DESIGN REQUIREMENTS

Specific functional and technical design requirements were developed from the following

2.2.1 NPRD-1 Requirements

Paragraph III B 1, (a): ... "Performance Requirements at Rated Conditions ...

(2) minimum mixed mean chamber inlet temperature, T_c 4500°R

(4) minimum overall specific impulse, I_{sp} 825 lb sec/lb_m

and (e) "controllability within the following 3 sigma units:

Figure 2-1. Relationship of Trade Study 702 to Other Trade Studies

(2) Steady State

(a) Specific Impulse $\pm 0.75\%$

(b) Thrust $\pm 2.0\%$

(See reference 1)

2.2.2 Data Item Document S-53 Requirements

.... typical RAS Block No. 1.1.1.7.2*, column C-11: a means is required to maintain the NSS mixed mean propellant effluent temperature within the following limits at nominal rated operating conditions ...

Nominal $T_c = \underline{\text{tbd}} \pm \underline{\text{tbd}}$ or

Nominal $\Delta P_{\text{NSS}} = \underline{\text{tbd}} \pm \underline{\text{tbd}}$ PSID

(See reference 3)

2.2.3 Per Engine Systems Engineering Trade Study No. 001

.... "to obtain 825 sec specific impulse, at a nozzle area ratio of 100:1, ... chamber inlet temperature considering measurement, controls and engine to engine uncertainties for dual turbo pumps (nominal is 4625°R) . . . "

2.2.4 Per Scope of Engine System Rated Performance Definition, Trade Study No. 001

. . . "account should also be taken of the uncertainties in the operation of engine control system and uncertainties in manufacturing and component performance in order to establish minimum requirements . . . " (Reference 5, sheet 1)

2.3 PROGRAMMATIC IMPACT

This study is input to Trade Study No. 701 and subsequently feeds back into Engine System Trade Study No. 001 as noted in Figure 2-1. Resulting thermal environmental data developed in this study are input to design and performance analyses and reliability evolutions for the engine subsystems.

* This referenced fourth level RAS was eliminated by SNPO change order 69-26 of August 1969.

3.0 DESCRIPTION OF APPROACHES AND SIGNIFICANT CHARACTERISTICS

This study was conducted to permit establishment of certain design requirements related to the rated operating condition thermal environment. The study was developed to meet the basic overall objectives of defining a T_c nominal and NSS design core temperature environment for the rated operating condition. Included in the definition of T_c nominal are the following considerations:

- a. The temperature loop accuracy,
- b. the ratio of T_c measured to T_c actual mixed mean chamber temperature
- c. relationships of fuel temperatures to T_c
- d. definition of core design requirements for the NSS to assure required performance
- e. definition of fuel element capabilities required, and
- f. allocation of design tolerances and required parameter performance to the NSS subsystems such as instrumentation and control capabilities

The approach used, pertinent back-up data, and results of analysis are noted in the following.

3.1 METHOD AND ASSUMPTIONS

3.1.1 Method

The following approach and method were used in this study to establish the thermal environment for the NSS and required exit gas temperature level and uncertainty ranges:

- a. determine and list the pertinent NSS and engine control factors contributing to the uncertainty levels in establishing the true mixed mean chamber inlet temperature including control uncertainty.

- b. determine the nominal NSS core exit gas temperature required to meet the nozzle chamber inlet requirement at rated power (both for a 4500°R minimum T_c and for an engine I_{sp} minimum of 825 sec).

c. determine the uncertainty in establishing the local core exit gas temperature and distribution as a function of sampling size.

d. determine the fuel temperature environment imposed by the above for a reasonable sampling size.

e. compare the local temperature environment requirements to the fuel capability as projected for the NERVA engine.

f. establish the sensitivity of the T_c level and fuel environment to design variations such as drum reactivity control and reactivity loss with operating time.

g. establish the T_c nominal requirements as a function evaluation of the above and recommend uncertainty tolerances for control and component design for the NERVA flight engine. Establish the nominal T_c required based on these design considerations.

The relationships between the actual mixed mean chamber temperature, the nominal measured chamber temperature, T_c , and the core fuel material temperature environment to be established are shown in Figure 3-1.

3.1.2 Assumptions

Preliminary engine system data as presented in Reference 4 have been used as the Engine System Trade Study No. 001 input to Trade Study No. 702. The core fuel temperature distribution data and rated operating characteristics have been developed using the reference design (reference 6) and the steady-state rated state point analytical model with the following assumptions:

a. Rated power condition at start-of-life as presented for the Reference Design (See Table 3-1).

b. AGC supplied temperature control loop component uncertainties as presented in Table 3-2 (Page 133, Ref. 4) referred to the core exit thermocouple. (Does not include core exit thermocouple uncertainty - See paragraph 3.2 - 3(a).)

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TABLE 3-1
NOMINAL STATE POINT DATA - REFERENCE

<u>STATION</u>	<u>FLOW LB/SEC</u>	<u>PRESSURE PSIA</u>	<u>TEMPERATURE °R</u>
Pump Outlet	88.52	953.7	52.5
Nozzle Tube Outlet	67.53	736.4	203.8
Reflector Inlet	65.09	738.4	203.8
Structural Support Outlet	5.00	685.8	975.6
Structural Support Bypass	16.00	685.8	52.3
Central Shield Inlet	86.08	651.2	275.2
Core Inlet	86.08	620.0	281.5
Core Periphery Outlet	1.30	450.0	1657.3
Hot Bleed	1.08	450.0	4589.4
Chamber	85.01	450.0	4640.0

TABLE 3-2
TEMPERATURE CONTROL TOLERANCE (EXCLUDES MEASUREMENT SYSTEM)

Temperature Control Loop Signal Demand Generator	$\pm 4.5^{\circ}\text{R}$
Temperature Control Loop Reference Signal Potentiometer	$\pm 4.5^{\circ}\text{R}$
Temperature Control Loop Summing Junction Resistor Error	$\pm 4.5^{\circ}\text{R}$
Temperature Control Loop Averaging Amplifier	$\pm 4.5^{\circ}\text{R}$
Temperature Control Loop Variation Due to Drum Position Tolerance	$\pm 9.0^{\circ}\text{R}$
	RSS = $\pm 12.75^{\circ}\text{R}$
	RSS (I_{sp}) = $\pm 1.42 \text{ SEC}$ or 0.172%

c. Controllability of temperature loop as developed in Reference 7 of $\pm 25^{\circ}\text{R}$ (3σ).

d. Minimum chamber inlet temperature required by the engine system as presented in Reference 1 (NPRD-1) of 4500°R . Engine System Tolerance Study T_c minimum requirement of 4565°R , per Reference 4 Page 136, has been imposed as an additional requirement. For this study NSS temperature requirements are based upon core exit temperature as determined to meet a given chamber T_c condition. NPRD-1 test requirements (Reference 1) have not been interpreted and are, therefore, not imposed at this time. (Specification extreme* and qualification test condition).

e. PAX predicted power distributions with at least R-1 temperature distribution results incorporated.

f. Uncertainty estimates in core temperatures based on a succession of well instrumented test reactors and post disassembly analysis prior to a flight qualification engine.

g. Control drum rotation at rated conditions for ± 1.00 reactivity loss and a creep limit of 0.001 in. in the core support are acceptable (until test reactor feedback is available to extend these) and a local element corrosion equivalent to ± 2.00 reactivity loss.

h. Core exit temperature distribution persists into chamber inlet and is not mixed with bypass at the core exit plane, thus ignoring this uncertainty factor on local thermocouple measurements, while including it in establishing the true chamber temperature estimate.

i. The bias between measured temperature at the core exit plane and sampled average chamber measured level would be determinable during R-series reactor testing with well instrumented reactors.

* Extreme temperature is herein referred to as the fuel temperature for the $+3\sigma$ individual channel peak temperature, when T_c is at $+3\sigma$ level; whereas maximum design is nominal fuel temperature estimate.

j. The reliability of the core can be related to the probability of exceeding the (1) local fuel material temperature limit, resulting in fuel head migration and severe coatings degradation, and (2) overall reactivity loss limit and/or local element corrosion loss limit. Other factors such as creep limit, additional graphitization, tip brazing limit, etc., have been ignored at this point in the study.

k. A6 type fuel element performance characteristics assuming a 10 cycle capability have been developed.

l. Fuel exit temperature to maximum matrix temperature as evaluated for a 1.1 power factor limit.

Other assumptions are as noted on tables and figures and stated in the text.

3.2 NSS EXIT TEMPERATURE UNCERTAINTY

The three areas contributing to the NSS exit temperature (chamber inlet) uncertainty which must be evaluated are:

1. Accuracy of the control system hardware and instrumentation (thermocouple sensor data and control accuracy and dead band related).

2. The accuracy with which the thermocouple temperature compares to the true local temperature (heat transfer factors of convected, conducted, radiative, and internal nuclear heating).

3. The relationship between the determined average temperature as obtained from a limited number of discrete local sensors and the true mixed mean chamber temperature (due to design and reactivity effects of local variations of hot spots and channel to channel effects, regional factors such as loading zone and reactivity distributions, mixing and changes with time due to corrosion and δk changes).

The principal factors which contribute to the above are discussed separately in the following:

- a. Accuracy of Control System Hardware and Instrumentation -

The estimated reference design control system hardware accuracies were

used as provided by AGC in the Engine Trade Study Reports Meeting April 22 and 23, and presented in Reference 4, excluding dead band and measurement accuracy (gas to thermocouple). The controller hardware uncertainty total statistically to $\pm 9^{\circ}\text{R}$ (3σ). (See Table 3-2).

These controller hardware uncertainty data have been combined with an estimated controller action dead band effect of $\pm 17^{\circ}\text{R}$ (for the reference design). (A calibration error of $\pm 25^{\circ}\text{R}$ is another factor but of a bias type). The steady-state controllability precision^{*} was thus established for the study as $\pm 25^{\circ}\text{R}$ (see Reference 7 and addenda).

b. Heat Transfer Factors at Thermocouple Sensor (local actual to thermocouple sensor junction)

Evaluation of the best tolerances for typical thermocouple sensor design having sufficient lead extension into the hot stream to alleviate conduction error has indicated an uncertainty of $\pm 31^{\circ}\text{R}$ on a 3σ basis (see Reference 7). This is the indeterminate bias variance of the thermocouple sensor material temperature from the local gas temperature under operating conditions.

c. Measured Average to Actual Mixed Mean Temperature -

The contributing factors to this uncertainty are temperature and flow distribution and mixing effects due to design considerations of varying physical and nuclear features. These are broken down into (1) core bypass effects, (2) local power and flow effects, (3) regional power effects, and (4) reactivity distribution changes and uncertainties. Also imposed upon the above are effects due to corrosion and δk changes with life.

The core bypass in the lateral support region affects the relationship between the fuel average exit temperature and the chamber mixed mean temperature and the chamber mixed mean temperature. This relationship is noted in Figure 3-2 for the engine nominal T_c of 4625°R . Evaluation of the lateral support system has indicated a design bypass

* Precision is used here with regard to repeatability in contrast to accuracy which is with respect to an absolute value, including fixed or bias type errors.

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Figure 3-2. Nuclear Subsystem Schematic

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(CRD) flow rate of 1.3 lbs/sec (see Reference 8). With a 3σ uncertainty in this flow as established, the average fuel exit temperature would be $36^{\circ} \pm 12^{\circ}\text{R}$ (assume 50°R maximum). This uncertainty would be combined with random uncertainties and heat transfer uncertainty as noted in Table 3-3, but the total effect is a direct $\sim 50^{\circ}\text{R}$ diluent which must be added for the determination of fuel temperature for a given T_c nominal. The uncertainty in the individual temperature measured by a core exit thermocouple is shown in Table 3-4.

(U) The effect of the combination of these uncertainties with the uncertainty of core exit thermocouples at various locations in the core exit plane is shown in Table 3-5. The sources of these core uncertainties are discussed in Section 3.3. As noted in Table 3-6, the uncertainty effects are reduced significantly with the number of radial samples. A significant effort to establish a good radial (regional) distribution average is needed to reduce the required nominal T_c level. For the start-of-life condition, the overall uncertainty considering 5 radially located thermocouples with the present predicted distributions would be $\pm 140^{\circ}\text{R}$. With 36 thermocouples the lowest nominal T_c is 4563°R for a 4500°F minimum to account for the three areas contributing to the start-of-life rated condition chamber temperature uncertainty.

(U) Thermocouple location and related change in average radial temperature profile for a \$1.0 control drum reactivity insertion during lifetime is shown in Figure 3-3. The radial temperature variation resulting from reactivity insertion by drum control to make up reactivity lost by corrosion and/or core reactivity uncertainty is shown in Figure 3-4. As noted in this figure, and discussed later in Section 3.3, with 18 control drums and SOL position of control drums at the designed position, a \$1 reactivity insertion would result in at least a 65°R periphery fuel temperature increase.

3.3 CORE TEMPERATURE UNCERTAINTY

(U) The temperature environment within the core has a significant impact upon reliability and design considerations. Core fuel and non-fuel material temperature requirements are developed herein considering (a) the established nominal core exit

TABLE 3-3
CORE BYPASS FLOW UNCERTAINTY ESTIMATE
RATED OPERATING CONDITIONS

1.	LSS Flow Uncertainty (Ref. T.S. No. 710)	$\pm 20\%$	3σ
2.	Heat Generation Uncertainty (Ref. NRD-69-103)	$\pm 7.5\%$	3σ
3.	Heat Conduction from Core (tends to be self-correcting)	$\pm 10\%$	3σ
4.	Statistical Sum of Above	$\pm 24\%$	3σ
5.	Temperature Uncertainty Resulting	$\pm 12^\circ \text{R}$	

TABLE 3-4
INDIVIDUAL CORE EXIT GAS T/C TEMPERATURE MEASUREMENT UNCERTAINTY (3 σ) *

Heat Transfer Effects (Rad., Cond., Conv., Heat Gen.)	$\pm 31^{\circ}\text{R}$
T/C Calibration	$\pm 25^{\circ}\text{R}$
RSS	$\pm 40^{\circ}\text{R}$

* Undeterminable Bias -
random precision factors reduced by multiple points and tests

TABLE 3-5

COMBINED UNCERTAINTY IN DETERMINING CORE EXIT TEMPERATURE CONDITIONS
(WITH 36 CORE EXIT T/C)

Contributing LSS Factor	$\pm 12^{\circ}\text{R}$
Sensor Measurement Uncertainty	$\pm 40^{\circ}\text{R}$
Location Uncertainty (36 T/C)	$\pm 48^{\circ}\text{R}$
Uncertainty RSS	$\pm 63^{\circ}\text{R}$
Uncertainty Core Exit 3σ Temperature	$\pm 63^{\circ}\text{R}$

TABLE 3-6
SUMMARY OF GAS MEAN TEMPERATURE VALUES ($^{\circ}\text{R}$)

<u>Number of Core Exit T/C</u>	<u>5</u>	<u>9</u>	<u>16</u>	<u>36</u>
1. Required Nominal T_c - Engine (NSS)	4625	4625	4625	4625 (4500)
2. Nominal $T_{\text{Core Exit}}$	4675	4675	4675	4675 (4550)
3. Total 3σ Uncertainty	140	107	84	63 (63)
4. Maximum 3σ $T_{\text{Core Exit}}$	4815	4782	4759	4736 (4613)
5. Minimum NSS Mixed Mean (T_c) Guaranteed	4485	4518	4511	4560 (4437)

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Figure 3-3. Radial Exit Gas Temperature Profile 18 Continuous Drums, Fixed SSCSS

Figure 3-4. Control Drum Motion Temperature Effect for Fuel Elements Adjacent to Control Drums (No Flow Control)

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temperature level without control drum effects, (b) the uncertainty in core exit and core material temperature without control drum effects, and (c) the rated power lifetime effects on temperature levels and uncertainties in local temperature.

3.3.1 Sources of Core Temperature Uncertainty

A summary of the sources of core temperature 3σ uncertainties is presented in Table 3-7. The variation in local temperature environment has been developed by statistically adding (RSS approach) the independent uncertainty factors shown. These result in the total local effects as noted in Item 6 of Table 3-7. The uncertainty values summed for the central and periphery regions are shown both as developed after one power test (R-1) has been completed and as projected to after multiple power tests (the R and E series tests) have been completed. These uncertainties must be combined with the average core temperature requirements to establish the possible 3σ extremes.

Average temperature data for the fuel calculated for the reference hot bleed cycle design are shown in Table 3-8. Even without the uncertainty considerations discussed above, these core fuel material temperature requirements are significantly above the core exit temperature level needed to meet the chamber nominal condition. The core must also meet the NPRD-1 and CEI Specification requirements as presented in Section 2.0, with a reliability of ≥ 0.99862 (one in 725 possibility of failure). For this reason, it is obvious that the nominal temperature level required is of prime importance over the 3σ variation.

The uncertainty factors as summarized in Table 3-7 are imposed upon the average temperature requirements shown in Table 3-8 in developing the overall core temperature environment requirement. This is discussed in the following.

3.3.2 Core Material Temperature Requirement

The 3σ variations in core exit temperature level was established by considering the total effect of NSS temperature and measurement/control uncertainties as $\pm 63^\circ\text{R}$ in

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TABLE 3-7

SOURCE OF TEMPERATURE UNCERTAINTIES (3σ VALUES)

	<u>Central Region</u>	<u>Peripheral Region</u>
1.0 Element Effects		
1.1 Scan (U Assay) 1% Central 2% Peripheral	52	88
1.2 Air Impedance (No X Coat) 0.4 Mils	54	31
1.3 Orifice Step Changes on Element Basis 10°R	10	10
1.4 Combined Channel Effects	57.5	49.0
Individual Channel Effects Leading to 1.4		
1.4.1 Fuel Homogeneity	240	203
1.4.2 Orifice Coefficient (acceptance limit 50°R)	50	50
1.4.3 Hot End Support 1% Flow	52	44
2.0 Combined Element Effect	<u>95</u>	<u>106</u>
3.0 Comparison With NRX Test Data ⁹¹⁰ (3σ)		
3.1 NRX-A6 Exit Gas T/C's	+ 128°R (SOL)	+ 172°R (EOL)
3.2 NRX-A6 Station 26 T/C's	+ 156°R (SOL)	+ 179°R (EOL)
3.3 NRX-A6 Thermal Capsules	+ 242°R (Melted at Power Peak SOL)	
3.4 NRX-A5 Station 32 T/C's	+ 156°R (SOL)	+ 172°R (EOL)
3.5 NRX-A5 Station 26 T/C's	+ 166°R (SOL)	+ 135°R (EOL)
3.6 NRX-A5 Thermal Capsules	+ 141°R (Melted at Different Times During Run)	

(1)

From least-squares curve fitting, after subtracting instrument accuracy

TABLE 3-7 (Cont'd)

	<u>Central Region</u>	<u>Peripheral Region</u>
4.0 Regional Effects		
4.1 Radial Power Prediction - 4.2% (2.1%) Central 7.2% (3.6%) Peripheral	225 (113) ⁽¹⁾	322 (161)
4.2 Average Core Tin + 10°R	5	15
4.3 Local Core Tin + 10°R	27	40
4.4 Axial Power Distribution 3% at Sta. 2 Inches	7	5
5.0 Combined Regional Effects	<u>277 (116)</u>	<u>325 (167)</u>
(2.0 Combined Element Effects)	95	106
6.0 Combined Element and Regional Effects	<u>246 (15)</u>	<u>342 (198)</u>

⁽¹⁾After one power test (after multiple power tests)

TABLE 3-8

AVERAGE FUEL TEMPERATURES AT NOMINAL CHAMBER TEMPERATURE LEVELS

(Established for 4500°R Nominal, 4500°R Minimum, and 825 Second I_{sp} Minimum)

Nozzle Chamber Temperature)	4500	4563	4625
Calculated Fuel Element Temperatures (°R) ⁽¹⁾			
Exit Gas	4550	4613	4675
Peak Fuel	4695	4758	4820
Peak Channel Wall	4620	4683	4745
Fuel Tip Joint	4610	4673	4635
Central Tip Joint	4660	4723	4785

(1)

No control drum effects or uncertainties

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Section 3.2 Local exit temperature variations must be imposed upon this average exit temperature level to assess the local core material temperature environment. The temperature variations shown in Table 3-7 have been combined as shown in Table 3-9 to give the temperature increase above nominal average exit gas required for design fuel development and reliability studies. The results are presented in Table 3-10 for two nominal chamber temperature levels, 4625°R as required for the engine performance per Reference 4 and a nominal level of 4500°R , for comparison. The requirements of a minimum chamber temperature of 4500°R would stipulate temperature levels approximately 63° higher than the latter case (case II as shown plus 63°R) for a 3σ assurance as specified by Reference 1. Also shown in Table 3-10 are estimates of fuel capability as indicated from the data presented in Table 3-11. This indicates a need to re-evaluate the minimum chamber temperature requirement if the reliability specified in Reference (1) is to be met. The reason for this is seen in the following paragraphs.

The probability of a fuel element reaching the maximum temperatures indicated in Table 3-10 is related to the hot element temperature and population. The contributing factors associated with the $\pm 3\sigma$ uncertainty establishing the hot element has been shown in Table 3-7. Development of the population of hot elements has been based upon these factors as shown in Table 3-9, with the orificing criteria and drum effects as were shown in Figure 3-4. Using these referenced data, the following are obtained for the core periphery in regard to hot element population.

$$\begin{aligned} \text{First, with SSCV control, } \Delta_{\text{CD}} &= 0 \\ &\text{assumed} \\ \sigma_{\text{CD}} &= 0 \end{aligned}$$

and assuming 21 core regions per reactor (needed since regional power uncertainties and radial variations resulting predominate the uncertainty effects) it follows that for the NERVA engine:

- a. the number of elements/region = 88 and

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TABLE 3-9
 TEMPERATURE INCREASE ABOVE NOMINAL AVERAGE, $T_{EG} (3 \sigma)$

$$1. \quad T_{EG} = \sqrt{T_{C.D.}^2 + 3\sigma_T^2 + 3\sigma_E^2 + 3\sigma_{C.D.}^2}$$

ΔT_{EG} = Temperature Increase Above Nominal Average Due to Control Drum Effects and Uncertainties (3)

$\Delta T_{C.D.}$ = Nominal Increase for Worst Element for \$1 Corrosion Without Flow Control, Assuming 18 Control Drum and Orificing Criteria Illustrated in Figure 3-4

$3\sigma_T$ = Uncertainty in True Average Fuel Exit Gas Temperature

$3\sigma_E$ = Uncertainty in Element Temperature Versus Average

$3\sigma_{C.D.}$ = Uncertainty in Worst Element Temperature Due to Uncertainty in Hot-Critical Control Drum Position

		Without Control Drum Effects		With Control Drum Effects (1)	
I. At Core Center	ΔT_{EG} =	254	(164) ⁽²⁾	318	(228)
II. At Core Periphery	ΔT_{EG} =	348	(208)	436	(292)

(1) 18 Drums, No Flow Control, \$1 Corrosion Reactivity Loss, Orificing Criteria as Shown by Figure 3-4

(2) After Single Power Test (after multiple power tests)

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TABLE 3-10

COMPARISON OF FUEL TEMPERATURE REQUIREMENTS AND TECHNOLOGY

		Periphery Full Power 3 Temperatures (°R)		
	Nominal Temperature (°R)	Without Control Drum Effects	With Control Drum Effects (18 Drums, No Flow Control \$1. Corrosion Reactivity Loss)	Estimated Fuel Capability (2) (°R)
I. T _c = 4625 ± 63°R				
Exit Gas	4675	5023 (4883) (1)	5111 (4969)	
Peak Fuel Material	4820	5168 (5028)	5256 (5112)	
Channel Coating	4745	5093 (4953)	5181 (5037)	5170
Fuel Tip Joint	4735	5083 (4943)	5171 (5027)	5000
II. T _c = 4500 ± 63°R				
Exit Gas	4550	4898 (4758)	4986 (4842)	
Peak Fuel Material	4695	5043 (4903)	5131 (4987)	
Channel Coating	4620	4968 (4828)	5056 (4912)	5170
Fuel Tip Joint	4610	4958 (4818)	5046 (4902)	5000

(1) After Single Power Test (after multiple power tests)

(2) See Table 3-11 and Reference 8

TABLE 3-11
FUEL TEMPERATURE TECHNOLOGY

Materials

Melting Temperature

NbC	3500°C (6800°R)
ZrC	3420°C (6650°R)
NbC - ZrC - U Minimum (LASL)	2800°C (5530°R)

Recent Y-12 Data on Melting of Coated Specimens:

ZrC on Unfueled Carbon Softens at 2700°C (5350°R) - Flows at 2700-2900°C (5350-5710°R)
ZrC on 630 MB U/CC Fuel Softens at 2400°C (4810°R) - Flows at 2500°C (4990°R)
ZrC Over NbC on 400 MG/U/CC ZrC Softens at 2500°C (4990°R) - NbC Does Not Soften -
NbC-ZrC and UC₂ Began Mixing at 2600°C (5170°R)

Bead Migration (Not Considered a Fuel Operating Temperature Limitation):

Std. Bead - Some Bead Migrate Thru Shell (2%)	2300°C (4630°R)
All Beads Migrate Thru Shell	2460°C (4920°R)

Composite to Fuel Tip Brazed

Cycle Integrity Appears Attainable at 5000°R, Uncertainty at Higher Temperatures

b. the probability that one region in a reactor will be at the $\pm 3\sigma$ condition is number regions/number reactors (for $3\sigma = 21/725$) or one in 35.

(CRD) Thus, in one reactor out of 35 reactors, it is possible that one region of 88 elements would operate at a temperature level of $+3\sigma$ above regional nominal. In this region, it is probable that due to local uncertainties, two elements would be operating at the extreme condition of $+3\sigma_{FE} = +348^{\circ}\text{R}$ above nominal (without drum effects). For the nominal chamber temperature of 4625°R , the nominal channel coating temperature (4743°R) and peak material temperature (4820°R) are given in Table 3-10. Adding the uncertainties to the nominal temperatures results in the maximum temperatures which have been presented in this table and the population conclusions below:

a. In one power test, it is probable that approximately 88 elements in a peripheral region will reach temperatures A and two elements in this hot region will reach temperatures B as noted in the chart below obtained from Table 3-10.

b. In 35 power tests, it is probable that one peripheral region will reach temperatures C and two elements will reach temperatures D. Estimated fuel capability is 5170°R for the channel coating and 5000°R for tip braze (Reference 9).

Estimated Temperature with Uncertainties After One Power Test, $T_c = 4623^{\circ}\text{R}$

	<u>Nominal</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>
Channel Coating ($^{\circ}\text{R}$)	4745	4842	4917	5017	5093
Peak Material ($^{\circ}\text{R}$)	4820	4917	4992	5092	5168

3.3.3 Radial Temperature Distribution at Start and End of Life

(U) Fuel element nominal radial temperature distributions at start of life and end of life were shown in Figure 3-3 for a 4640°R T_c nominal, assuming a \$1 corrosion reactivity loss for the reactor fixed SSCSS. When a continuously variable flow support stem control valve is in the system, the temperatures are flat at 4690°R for all core radii. An increase

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above nominal of approximately 65°R in periphery temperature results for a \$1 reactivity loss, as indicated in Figure 3-4, at design conditions (no error in orificed drum position).

(U) Reactor control thermocouples must be capable of determining the true mixed mean chamber temperature at all times during life. Since the radial temperature distribution changes due to the control drum motion, as shown by Figure 3-4, the thermocouples must sample the gas from each radial region. The selection of the proper core location and quantity of measurements in the R and early E series reactors are vital in order to determine the radial distribution and the average temperature accurately.

3.3.4 Reliability of Core Versus Temperature (U)

(U) An indication of the sensitivity of the core reliability to temperature is presented in Figure 3-5 which shows a comparison of fuel element corrosion loss probability preliminary estimates as a function of the nominal fuel exit gas temperature. Curves 1 and 3 show similar results because they are based on two basic assumptions; a slope derived from the NRX-A6 core performance data and an assumed normalizing point meeting the reliability goal of 0.99862 at a nominal T_c of approximately 4700°R . Curve 2 was not derived on this basis, but shows the probability of a \$2 reactivity loss based upon the NRX-A6 fuel performance. With NRX-A6 quality fuel (with a 10 cycle capability), Curve 4 represents the \$1 loss probability with $T_c = 46^{\circ}\text{R}$ ($3\sigma = \pm 140^{\circ}\text{R}$). As expected, the NRX-A6 operating point of 4380°R shows a low probability of loss of \$1. Improvements in fuel technology have resulted in electrical corrosion tests indicating significantly lower than A6 fuel losses. Based on the NRX-A6 loss slope, at least a 200°R increase for 10 cycles over the demonstrated single cycle for NRX-A6 exists. On this basis, Curve 5 shows current fuel capability approaching requirements for the flight engine for 50 minutes of operation.

3.3.5 Non-Fuel Components

(CRD) Evaluation of non-fuel component limitations included those closely related to the core; the axial and lateral support systems and reflector systems. Conclusions from

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Figure 3-5. Comparison of Fuel Element Corrosion Loss Estimates

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(CRD) these evaluations are briefly noted in Table 3-12. These results indicate that with the exception of the cluster hot end support hardware (CHESH), sensitivity to the nominal T_c levels considered was not significant. Components without acceptable margin from a temperature standpoint were the central support element tip, due to braze temperature (5000°R) and creep (> 0.001 mil radial/75 min) as noted. Corrosion loss estimates for these components and the lateral support components were not significantly sensitive to the temperature levels considered, (i.e., differences in loss estimates cannot be ascertained within uncertainty ranges). It is not within the present understanding or effort available to explicitly determine the effect on reliability with this indicated insensitivity.

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TABLE 3-12

CONCLUSIONS FROM NON-FUEL COMPONENT STUDIES BEARING ON
DESIGN DEVELOPMENT REQUIREMENTS VERSUS POTENTIAL

<u>System</u>	<u>Effect</u> *	<u>Reference</u>
Axial Support System (AS)	Change in maximum and minimum support stem and liner temperatures levels caused by shift in T_c can be compensated by adjustment in support stem coolant flow.	DRM 51676
Lateral Support System & Reflector (LSS)	Insensitive to T_c .	DRM 51676 Computer Runs RAC-1001 RAC-1002
Core Periphery (CP)	Maximum wrapper temperature at ID directly proportional to T_c . Wrapper OD temperature not sensitive. Estimate negligible effect on design development since wrapper overall corrosion is primarily dependent on leakage rate.	Computer Runs RAC-1001 RAC-1002
Cluster Hot End Support Hardware	Maximum temperature directly proportional to T_c . Central support element temperature margin and braze capability may be exceeded.	DRM 51422

* Second order effect (negligible) on all systems is the slight change in internal heating caused by the change in level for different nominal T_c 's. This would, in turn, affect internal temperature differences and stresses in components.

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4.0 COMPARISON MATRIX

A trade off of the required nominal chamber temperature level for a 4500°R minimum against the significant design parameters within design prerogatives determine the number of temperature sensing locations available for determination of the core exit temperature distribution, is presented in Table 4-1. The 3σ extreme temperature levels in the fuel material possible with each of these arrangements is shown for both a 4500°R minimum T_c and a 4565°R minimum T_c (the engine requirement for the 825 sec I_{sp} minimum, Reference 4).

Since this study was established to evaluate the temperature requirements for control and NSS design and not explicitly to select these design concepts, the detailed results are not amenable to merit factor trade off matrix presentation such as would be developed for a design alternate selection trade study. However, the effect of uncertainty ranges resulting from the inaccuracy and uncertainty in pertinent design parameters has resulted in a means of establishing the measurement and controllability requirements trade off shown and the recommendations which follow in Section 5.0.

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TABLE 4-1

ESTIMATED NOMINAL T_c AND SINGLE ELEMENT
EXTREME TEMPERATURE VS. NUMBER OF T/C * -
START -OF-LIFE RATED CONDITIONS

<u>No. of T/C</u>	<u>5</u>	<u>9</u>	<u>16</u>	<u>36</u>
1. 3σ Uncertainty on T_c^{**} - ($^{\circ}\text{R}$)	140	107	84	63
2. Nominal T_c for 4500 $^{\circ}\text{R}$ Min. - ($^{\circ}\text{R}$)	4640	4607	4584	4563
3. Maximum T_c (+ 3σ) - ($^{\circ}\text{R}$)	4780	4714	4668	4626
4. 3 Uncertainty on Individual Fuel Exit Gas Due to Hot Channel Factors (periphery region) - ($^{\circ}\text{R}$)	<u>+342</u>	<u>+342</u>	<u>+342</u>	<u>+342</u>
5. Statistical Sum of (1) and (4) - ($^{\circ}\text{R}$)	<u>+370</u>	<u>+359</u>	<u>+352</u>	<u>+347</u>
6. Peak Fuel Material to Exit Gas ΔT - ($^{\circ}\text{R}$)	+150	+150	+150	+150
7. $\bar{T}_{EG}$ Exit Gas to $\bar{T}_c$ ΔT (Bypass Mixing) - ($^{\circ}\text{R}$)	+ 50	+ 50	+ 50	+ 50
8. Extreme Fuel Element Temp. for a +3 Case - ($^{\circ}\text{R}$) (Sum of (2), (5), (6), and (7))	5210	5166	5136	5110
9. Extreme with T_c Min. of 4565 $^{\circ}\text{R}$ (Ref. 4) - ($^{\circ}\text{R}$)	5275	5231	5201	5175

* Radial Rake at Core Exit (Statistically Placed Distribution)

** Includes control loop component uncertainties of $\pm 9^{\circ}\text{R}$ obtained from ANSC (Ref. 4).

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5.0 RECOMMENDATIONS

Based upon present estimates of attainable minimum temperature uncertainties and probable fuel capability, NERVA chamber inlet temperature requirements for flight units in excess of a 4500°R nominal value do not appear consistent with attaining high NERVA reliability. On this basis, a $36 T_c$ exit temperature sensing sample providing a minimum reasonable uncertainty and a requirement of a nominal chamber temperature of no greater than 4500°R is recommended. NPRD-1 performance requirements and the related NERVA component specifications should be changed to reflect this evaluation conclusion.

Investigation of the reactor temperature requirements indicates the need for an aggressive program to minimize each contributing factor to the statistical temperature uncertainty. The need for adequate NSS exit gas temperature sampling is evident from this study. The minimum of 36 thermocouple sensors is therefore recommended. The primary purpose being to minimize the core exit distribution uncertainty, and provide adequate trend data and diagnostic information as required by Reference 1.

Development of a fuel element capable of operating with exit gas temperature levels up to 5000°R is needed for the flight engine. Since the qualification testing environment is significantly higher ($\sim +2.3\ 26\sigma$ with a 99% probability plus margin for test condition),^{*} re-evaluation of the specification extreme test condition should be undertaken.

Development of a core exit gas temperature sensor capable of measuring within the accuracies developed herein, but at temperature levels to 5000°R is needed.

A definite effort toward defining statistical placement of in-core and material temperature measuring devices to reduce the temperature distribution uncertainty by

^{*}Reference letter of July 17, 1969; Subject: "Clarification of Intent of Specification SNPO-C-1, Schroeder to Wetmore.

developing better data for determining measurement to actual temperature bias during testing is required.

A significant effort is needed to assure that each reactor configuration and reactor test condition are controlled within adequate design and operating tolerances to assure the development of the statistical data required for reducing uncertainties.

The NPRD-1 requirement to demonstrate design performance may be interpreted to require a significantly higher nominal chamber temperature during R-series reactor tests than presented in this study for the flight engine (after multiple tests). This must be considered in view of probable effect upon reliability of the R reactors, especially R-1. It is therefore recommended that qualification test requirements for R-1 be based upon the NERVA flight qualification nominal T_c requirement.

6.0 REFERENCES

1. NPRD-1, "NERVA Program Requirements Document," dated March 17, 1969
2. Trade Study Index Sheet 5, No. 702, "Determination of Nominal T_c for 4500°R Minimum," dated April 25, 1969
3. Data Item S-53 Requirements Allocation Sheets, Mission "B", NSS Level, dated July 21, 1969 Issue
4. RN-PA-0018, "Systems Engineering and Trade Study Reports Meeting," Volume 1 of 2, dated April 22, 1969
5. Trade Study Index, Sheet 1, No. 001, "Engine System Rated Performance Definition," April 25, 1969, Issue
6. NERVA Reference Design, Hot Bleed Cycle, Drawing No. 939J685, Revision B, of June 1969.
7. Control Study, DRM 51414, "Actuator Performance Requirements".
8. NERVA Reference Design, Hot Bleed Cycle, Drawing No. 957A841
9. NERVA Reference Design, DRM No. 51422, "NSS Temperature Requirements and Fuel Capability," dated July 10, 1970

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TITLE Determination of Nominal Tc for 4500°R Minimum Trade Study 702	
	DOCUMENT NO. S-54 Data Item - WANL TME-1980	DATE
ABSTRACT The nominal NSS exit temperature or chamber temperature, Tc, required to assure the minimum NPRD-1 NERVA flight engine performance is established and NSS component thermal requirements are evaluated. A nominal Tc of 4500°R is recommended for NERVA since the study indicated the nominal TC of 4563 and 4625°R required to meet the respective NSS and engine performance was not consistent with high NERVA fuel reliability.		
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