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WANL-TME-1967
SEPTEMBER 1970

DATA ITEM S-54

REACTOR CONTROLS CONCEPT
TRADE STUDY (U)

TRADE STUDY NO. 701

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TRADE STUDY NO. 701

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F. D. Retallick

F. D. Retallick, Manager
NERVA Engineering

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ABSTRACT

This report presents the evaluation of twenty NSS reactivity control concepts for NERVA. The objective of the study was to compare these concepts on the basis of performance, reliability, weight, safety, development risk, and schedular impact.

The candidate concepts included combinations of type of control drum actuation (binary and continuous or analog), individually driven drums, and ganged drum systems, number of drums (12, 18, and 36), and type of Structural Support Coolant Supply System (SSCSS) flow control (non-variable, binary and continuously variable). In addition, drum span requirements were identified for various operational modes and types of SSCSS flow control.

A 36 control drum configuration, each with its own analog type actuator, was selected together with a continuously variable flow control on the SSCSS. This concept was selected because it provides the maximum reactivity control flexibility and it maximizes core reliability by minimizing temperature variations in the core both during normal operation and also in the event of inoperative control drums.

This report documents the work performed prior to August, 1969 and is limited in application to the 50 minute duration, hot bleed cycle reactor.

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1.0 SCOPE

1.1 BACKGROUND

It became apparent during the definition phases of the NSS for NERVA that it may be difficult to develop control drum actuators which would have a reliability commensurate with an overall NSS reliability of 0.997, and impossible to demonstrate that reliability (at 90% confidence). It was believed that actuator failures in 12 or 18 drum systems having relatively large drum spans (\$6.00 to \$7.00) would introduce unacceptable fuel element temperatures and temperature variations. Consequently, a trade study was identified to examine various combinations of reactivity control elements to provide an engineering basis (rather than an arbitrary acceptance of the technology program control concept) for the selection of a control concept for NERVA.

Basically, it was believed that if the drum span was limited to that actually required for operation, and if the number of drums could be increased over that used in the technology program, that the power scalloping in the core periphery would be minimized if a drum were inoperative. Further, it was believed that if a control concept could be developed which could make use of two position drums, that the actuators for this concept could be made sufficiently reliable so that one may not have to design for the stuck drum case. This study, then, was performed to evaluate these ideas such as controllability, utilization of Structural Support Assembly (SSA) flow control, reliability, weight, safety, and mechanical feasibility.

It is to be noted that this study is not an evaluation of controllers, i.e., it is not intended that the study arrive at some conclusion regarding the electronic equipment required for reactivity control. The study deals, instead, with the more basic problem of deciding how reactivity control is to be achieved by a combination of drum motion and changes in the Structural Support Assembly (SSA) flow rate (which affects the hydrogen inventory in the core).

1.2 OBJECTIVE OF STUDY

The objective of the study was to:

1. Establish the reactivity change required for operation.
2. Determine the utility of the SSCSS for reactivity control.
3. Select the type of control drum actuation (binary or proportional).
4. Select the type of SSCSS flow control (none, binary, or proportional).
5. Select the number of control drums.

2.0 FUNCTIONAL AND TECHNICAL DESIGN REQUIREMENTS

TABLE 2.1

<u>Functional Requirements</u>	<u>Technical Design Requirements</u>	<u>References</u>
(U) 1. Provide reactivity control of the NSS during full power and full temperature operation.	<p>(U) 1.1 <u>Endurance at Rated Conditions:</u></p> <p>1.1.1 <u>Flight</u> 50 minutes at rated conditions. The operating time shall be utilizable in either one cycle or multiple cycles up to ten, of varying lengths totaling a minimum of 50 minutes.</p> <p>(U) 1.1.2 <u>Prequalification Tests</u> 75 minutes at rated conditions (in multiple cycles) without deterioration of rated performance as specified in 1.1.1 above.</p> <p>(U) 1.2 The specific impulse shall be controlled within 3σ limits of $\pm 0.75\%$. ($\pm 52^\circ\text{R}$)</p>	<p>(U) SNPO-NPRD-1, June 5, 1968, pp. 2, para. III.B.1.b (1) and (2)</p> <p>(U) SNPO-NPRD-1, para. III.B.1.e (2), pp. 6</p>

TABLE 2.1 (CONTINUED)

<u>Functional Requirements</u>	<u>Technical Design Requirements</u>	<u>References</u>
	1.2.1 The permissible variation in mixed mean chamber inlet conditions shall be $\pm 52^{\circ}\text{R}$.	
	1.3 Thrust controllability shall be $\pm 2\%$.	SNPO-NPRD-1, pp. 6, para. III.B.1.3(2)
	1.4 The reliability requirement for the NSS shall be 0.997 at 90% confidence level.	
	1.5 Maximum effort should be placed on a design which eliminates single failures or credible combinations of errors and/or failures which endanger the completion of the mission flight, flight crew, launch crew, and the general public.	SNPO-NPRD-1, pp. 16, para. III.B.8.a

TABLE 2.1 (CONTINUED)

<u>Functional Requirements</u>	<u>Technical Design Requirements</u>	<u>References</u>
2. Provide reactivity control of the NSS during throttling.	2.1 The engine shall be capable of throttling at rated chamber temperature from the engine design point of 450 psia chamber pressure to a chamber pressure of (TBD) psia at a maximum rate of 50 psi/sec for a duration of (TBD) minutes.	SNPO-NPRD-1, pp. 3, para. III.B.1.c and Technical Directive 35, August 5, 1969.
3. Provide reactivity control of the NSS during engine startup.	3.1 Provide reactivity control which results in a post bootstrap startup mode which follows the high specific impulse line that passes through the throttle point.	SNPO-NPRD-1, pp. 4, para. III.B.1.d and Technical Directive 35, August 5, 1969.
	3.2 Provide reactivity control which results in a post bootstrap startup mode which provides the highest possible integrated thrust to rated operating conditions.	SNPO-NPRD-1, pp. 4, para. III.B.1.d, although Technical Directive 35 essentially eliminates this requirement.

TABLE 2.1 (CONTINUED)

<u>Functional Requirements</u>	<u>Technical Design Requirements</u>	<u>References</u>
	3.3 The engine shall be capable of initially bootstrap starting and restarting at any time.	SNPO-NPRD-1, pp. 4, para. III.B.1.d.
4. Provide reactivity control during the Emergency Mission.	4.1 The design . . . should not . . . restrict the emergency operating requirements	Technical Directive 35, August 5, 1969.
	4.2 The design shall be capable of operation at 185 psia chamber pressure and 1850°R chamber temperature.	Trade Study 711 Recommendation

3.0 DESCRIPTION OF DESIGN APPROACHES

3.1 BASIC DESIGN DECISIONS

This study involves a set of decisions relative to the type of drum actuators, number of drums, and type of SSCSS flow control. Before describing the control concepts which are combinations of these variables, it is important to understand the reactivity control requirements and capabilities associated with these reactivity control elements; namely, the drum span requirements and reactivity swing capability of the SSCSS.

3.1.1 Drum Span Selection

3.1.1.1 Design and Operational Parameters

Table 3-1 summarizes the design and operational parameters which affect the drum span requirements. By combining these parameters, a set of drum spans was developed to provide a basis for comparing the effects of these parameters and also to provide a basis for analysis of the failed or "stuck" drum case.

3.1.1.2 Static Requirements in the Control Drum Span

Table 3-2 presents a summary of the components making up the control drum span that are related to static, or steady state conditions.

A corrosion allowance of \$1.00 was used in this study as the best estimate for corrosion associated with 50 minutes of full power and temperature operation with 10 starts. ⁽¹⁾ The corresponding value for the ground test endurance demonstration of 75 minutes would be \$2.00.

The cold critical uncertainty of $\pm \$0.15$, three sigma, will be achieved by the use of the PAX/R-1 and NCX experiments followed by an in-place shim adjustment (ISA) performed on the actual NERVA reactor. ⁽²⁾

The cold to hot reactivity feedback uncertainty of $\pm \$0.30$ (three sigma) is based on NRX reactor experience. ⁽³⁾ The reactivity change in going from the ambient, or

TABLE 3-1
DESIGN AND OPERATIONAL PARAMETERS
WHICH AFFECT THE DRUM SPAN REQUIREMENT

<u>Support Stem Utilization</u>	<u>Maneuvering Capability</u>	<u>Corrosion Compensation (\$)</u>	<u>Xenon Compensation (\$)</u>
A. Fixed Orifice	A. Middle of the Map Operation	A. 0.5	A. With Xenon Override at EOL
B. Two Position SSCV	B. High Thrust Startup	B. 1.0	B. Without Xenon Override at EOL
C. Continuous SSCV	C. High I_{sp} Startup ^{sp}	C. 2.0	
	D. High I_{sp} and High Thrust Startup (and Throttling)		

TABLE 3-2

SUMMARY OF THE STATIC REQUIREMENTS IN THE CONTROL DRUM SPAN

<u>Item</u>	<u>Magnitude</u>
1. Corrosion Allowance	+\$1.00
2. Cold Critical Uncertainty	<u>+\$0.15</u> (3 σ)
3. Hot Critical Uncertainty	<u>+\$0.30</u> (3 σ)
4. Effect of Xenon Buildup on Startup	+\$0.30 (3 σ)
5. Required Shutdown Margin for Non-Operating Conditions	-\$1.50
6. Required Shutdown Margin for Operating Conditions	-\$0.25
7. Cold Flow Test and Bootstrap ⁽¹⁾	-\$1.00 (3 σ)

cold condition, to the full power, or hot condition, was calculated to be - \$0.80 for an SSCV position corresponding to a stem flow of 5 lb/sec to + \$0.50 for an SSCV position corresponding to a stem flow of 9.6 lb/sec.

The xenon-135 effect on NERVA critical drum position is dependent on operating history and the time after shutdown when a restart is attempted. The worst case is after a 50 minute run with a restart at 10.5 hours after shutdown. A reactivity loss of \$0.23 has been calculated for this case⁽⁵⁾ and \$0.30 assigned to this effect to account for uncertainties.

The shutdown margin for non-operating conditions has been assigned a value of \$1.50 minimum based on a minimum shutdown margin of \$0.50 when people are in the vicinity of the reactor.⁽⁶⁾ This means that procedural controls will be required to limit total reactivity additions of hydrogen in fueled vehicle stage, personnel, and equipment to less than \$1.00. This is believed reasonable since three people have historically been allowed in the vicinity of the reactor for a nominal reactivity addition of \$0.48, and the fuel tanks of the second stage are expected to be worth much less than \$1.00. The required shutdown for flight operation is based on operational reliability requirements rather than safety requirements.⁽⁶⁾

3.1.1.3 Dynamic Requirements in the Control Drum Span

In addition to these static requirements, a control drum dynamic requirement of \$0.70 is necessary for the power period required during autostart. Preliminary autostart studies⁽⁷⁾ identified deviations around cold critical of + \$0.90 and - \$0.60 during chilldown and bootstrap; however, it is believed that some optimization of the problem would result in a value close to the \$0.70 used in the drum span development. All other dynamic requirements can be met within this capability.

3.1.1.4 Drum Span Summary

Table 3-3 presents the throttling reactivity requirements as a function of the support stem flow rate, or SSCV position, and critical position as related to SSCV position.

TABLE 3-3

DEVELOPMENT OF THROTTLING REACTIVITY REQUIREMENTS

1. Reactivity (\$) Relative to Ambient Conditions

	SSCV Setting		
	<u>0° (5 lb/sec)</u>	<u>47.5° (9.6 lb/sec)</u>	<u>90° (17 lb/sec)</u>
A. At 100% Power and Full Temperature	-0.80	+0.50	+2.70
B. At 60% Power and Full Temperature	-1.55	-1.10	-0.30

2. Reactivity (\$) Relative to the State Point Corresponding to 100% Power and an SSCV Setting of 0°

	SSCV Setting		
	<u>0° (5 lb/sec)</u>	<u>47.5° (9.6 lb/sec)</u>	<u>90° (17 lb/sec)</u>
A. At 100% Power and Full Temperature	0.00	+1.30	+3.50
B. At 60% Power and Full Temperature	-0.74	-0.30	+0.50

3. Reactivity (\$) Relative to the State Point Corresponding to 100% Power and an SSCV Setting of 47.5°

	SSCV Setting		
	<u>0° (5 lb/sec)</u>	<u>47.5° (9.6 lb/sec)</u>	<u>90° (17 lb/sec)</u>
A. At 100% Power and Full Temperature	-1.30	0.00	+2.20
B. At 60% Power and Full Temperature	-2.05	-1.60	-0.80

The significance of the + and - signs is that the values shown are feedbacks of the system; therefore, a -0.80, for example, means that there is a negative feedback reactivity of 0.80 which must be corrected by an outward drum movement equivalent of 0.80.

Figure 3-1 illustrates how the previously discussed components are summed to give an overall drum span. The figure shown is for illustration only. Actually, a whole set of these diagrams was developed for the various cases under consideration.⁽⁴⁾

Table 3-4 presents the development of drum span requirements for a variety of SSCSS flow control concepts, and operating modes.

3.1.2 SSCV/SSA Reactivity Control Capability

3.1.2.1 SSCV/SSA Reactivity Control Capability at Full Power Full Temperature Conditions

Figure 3-2 presents the reactivity control capability associated with changing the flow rate through the Support Stem Assembly (SSA). This flow rate is controlled by positioning the Structural Support Coolant Valve (SSCV) which is part of the Structural Support Coolant Supply System (SSCSS). As the figure shows, there are limits on SSA flow which are associated with temperature limitations on the support stem material. These limits as well as other technical background on the SSA is contained in WANL-TME-1923⁽⁸⁾ and will not be repeated here.

These data show the potential flow range capability of the SSA, provided that the low temperature limitation on the support stem is eliminated or significantly reduced. The SSCSS along with its SSCV has been assumed to work in the following manner:

1. If the SSCV is fixed, i.e., it is replaced by an orifice, the orifice would be sized, in all likelihood, such that the cold critical position would coincide with the hot critical position. This would require an SSA flow of approximately 7.5 lb/sec and correspond to a valve position of 30°.

TABLE 3-4

DEVELOPMENT OF DRUM SPAN REQUIREMENTS, (\$)

<u>Support Stem Design</u>	<u>Mode of Operation</u>	<u>Cold-to-Hot Reactivity</u>	<u>Maneuvering Reactivity Requirement</u>	<u>Drum Span Requirements</u> *	
				<u>Without Xenon Override</u>	<u>With Xenon Override</u>
1. Fixed Orifice					
A. SSCV=0°	High Thrust	-0.80	0.70	4.50	4.80
B. SSCV=47.5°	No Maneuvering	+0.50	0.70	3.50	3.80
C. SSCV=47.5°	60% Throttling	+0.50	1.10	4.10	4.40
D. SSCV=47.5°	High I _{sp}	+0.50	1.60	4.60	4.90
E. SSCV=30°	High I _{sp} /Limited High Thrust	0.00	1.80	4.80	4.10
F. SSCV=30°	Fixed Drum	0.00	0.70	3.70	4.00
2. Two Position SSCV (0° to 47.5°)					
	High I _{sp} and High Thrust	-0.80	0.80	4.60	4.90
3. Continuous SSCV					
A. 0° to 47.5°	High I _{sp} and High Thrust	-0.80	0.00	3.80	4.10
B. 0° to 90.0°	High I _{sp} High Thrust				

* \$1.0 Corrosion Allowance, \$0.35 Uncertainty (Ambient and Operating), \$1.65 Minimum

Figure 3-1. Basic Drum Span Requirement Schematic Without Maneuvering

Figure 3-2. SSA δK Capability at Rated Conditions ($P_c = 450$ psia; $T_c = 4640^\circ R$)

2. If the SSCV is a two position device, its travel would be limited such that when it is at its full open position, (at rated conditions) the flow would not result in temperatures below the minimum stem temperature limit of 200°R which would mean that the nominal maximum flow would be such that the maximum would not be more than 9.6 lb/sec. The corresponding nominal minimum flow would be 5.2 lb/sec to insure that the 1000°R upper temperature operational limit would not be violated. This would result in nominal SSA hydrogen reactivity swing of \$1.08. The uncertainties would be +\$0.20, - \$0.30.⁽¹⁰⁾ For this study, then, it was concluded that the binary SSCV has a reactivity swing of \$1.00.

3. If the SSCV is an analog flow control element, it would have the full flow range capability of 4.96 lb/sec minimum to 17.7 lb/sec maximum (at rated conditions). The valve's actual travel at rated conditions would have to be limited to that yielding a flow of 9.6 lb/sec to keep from violating the lower stem temperature limits, but the valve could be further opened to reduce the SSCSS/SSA impedance at off design conditions where less flow impedance does not give flow rates which will violate temperature limits. The overall SSA hydrogen reactivity swing, including nuclear, thermal, and instrumentation uncertainties is $\$1.25 \pm .25$.⁽⁹⁾⁽¹⁰⁾ For this study, it was assumed that the SSCV had a reactivity control range of \$1.25 at rated conditions.

3.1.2.2 SSCV/SSA Reactivity Control Capability at Off Design Conditions

Figure 3-3 presents the reactivity control capability at various SSCV positions for various points on the P_c and T_c map. These data were developed by TNT calculations on a three region (or cluster) model.⁽⁹⁾

3.2 CANDIDATE CONTROL CONCEPTS

Table 3-5 summarizes the control concepts considered in this study. Each concept can be identified by the type of control drum actuation, the number of control drums, the type of SSCV and finally, by the method used to achieve chamber temperature (T_c) controllability.

TABLE 3-5

CONTROLS CONCEPT COMPARISON MATRIX

Concepts					Characteristics					
Type of Control Drum Actuation	Number of Drums	Type of SSCV	Method of T _c Controllability		Performance	Reliability	Weight	Safety	Devel. Risk	Schedule
			Mid-Map Oper.	High I _{sp} Throt.						
Individual Analog	12	Analog Binary Orifice	Drums Drums Drums	SSCV N/A N/A						
	18	Analog Binary Orifice	Drums Drums Drums	SSCV N/A N/A						
	36	Analog Binary Orifice	Drums Drums Drums	SSCV N/A N/A						
Binary	36	Analog Orifice Orifice Orifice Orifice	SSCV None Pc Changes 2 Analog Drums SK Drums	SSCV N/A N/A N/A N/A						
Ganged Analog	12	Analog Binary Orifice	Drums Drums Drums	SSCV N/A N/A						
	18	Analog Binary Orifice	Drums Drums Drums	SSCV N/A N/A

Figure 3-3. Reactivity Control Capability at Various SSCV Positions for Various Points on the P_c and T_c Map

3.2.1 Type of Control Drum Actuation

Basically, this study considered two types of actuators for the control drums: binary and analog. For completeness, the matrix includes ganged analog drum drives as well as individually driven drums. This study does not select, for example, an electric motor type actuator versus a pneumatic actuator; only continuously variable position versus two position.

3.2.2 Number of Drums

Because it requires considerable effort to calculate azimuthal power variations at the core periphery, translate these power factors into fuel temperatures, operate on these temperatures to compute fuel stresses and further to compute failure probabilities for each of these temperatures and stresses, it was necessary to select a set of number of drums that would bracket the problem and at the same time provide a reasonable limit to the work involved. The NRX and XE reactors had 12 drums. The reference R-1 has 18. Preliminary studies had been made on the feasibility of getting as many as 36 drums into an assembly, and it looked workable. Therefore, these three numbers of drums were chosen, (i.e., 12, 18, and 36,) for comparison.

For the binary drum cases, the power scalloping was excessive for even the 36 drum case; therefore, fewer drums were judged to be impracticable.

3.2.3 Type of SSCV

Three functional types of SSCV were considered:

3.2.3.1 Orifice

This concept is a fixed impedance SSCSS which is referred to in this study as an orifice. The orifice could be sized to satisfy several different criteria as Table 3-4 suggests. The basic characteristic of this concept is, however, that the reactor would have a single reactivity characteristic and the feedback associated with the SSA hydrogen

inventory would be similar to the NRX' and the reactivity would be controlled by the control drums exclusively.

3.2.3.2 Binary

A binary control concept for SSCSS/SSA flow means a two position control on SSCSS impedance resulting in two discrete flows for any given point on the P_c and T_c engine map. Intuitively, this concept is the simplest. It requires no careful positioning of the valving elements and would potentially permit the use of devices as simple as a solenoid for valve actuation. Further, a redundant valving arrangement (required to meet reliability requirement of the SSCSS) is believed to be less complicated for the binary flow control than the continuously varying SSCSS impedance control.

3.2.3.3 Analog SSCV

The analog SSCV was considered in this study because it offers the potential of reactivity control during reactor lifetime at rated conditions without attendant drum motion. Further, it broadens the operating area on the engine map over which startups and shutdowns can be achieved without violating the temperature limits of the support stem.

3.2.3.4 SSCV Bypass Flow

Although not essential to the basic scope of this trade study, the question of SSA bypass flow is an important one. WANL evaluations⁽¹¹⁾⁽¹²⁾ have resulted in the conclusion that bypass flow is required from the Nuclear Subsystem (NSS) standpoint. (This is true regardless of which of the three SSCV concepts is ultimately employed). A total flow rate of approximately 21 lb/sec for the SSA and bypass flow is recommended.

Historically, the concept of having an SSCSS bypass flow which would complement the flow to the SSA was initially employed to keep the flow to the nozzle constant as the flow to the SSA is varied. Since this early requirement for a bypass flow

was established, however, the flow range of the SSA has been reduced to about 5 lb/sec at rated conditions and, consequently, the actual effect on engine performance and the nozzle is perhaps not so pronounced as it was when the SSA flow range was on the order of 10 lb/sec or more. Additional work on temperature limitations of the stems could result in higher ranges than the 5 lb/sec, and thus it is desirable to assure that this flexibility remains in the design.

Basically, the desire for a bypass flow is related to the desire to maximize core reliability. The logic of this is as follows:

1. Of the subsystems within the NSS, the core has been allocated the lowest reliability requirement. This allocation has been made with the knowledge that the NERVA exit gas temperature requirements are such that little margin exists between these temperatures and unacceptable fuel element temperatures. The significance of this is that maximum design consideration must be applied to reduce variations in core inlet temperatures which affect the core temperature distribution and to reduce deflections in the core support structure which affect stresses in the core components.
2. Of the three support plate designs, the three-plenum configuration which mixes bypass flow with the support stem effluent prior to discharging this effluent into the reflector discharge flow offers the best chance of minimizing variations in core inlet temperature. Assuming equal mixing effectiveness in regions outside the support plate, the three-plenum design would give a maximum local or radial coolant temperature variation at the core inlet plenum of 10°R , while the corresponding two-plenum design gives a ΔT of 100°R and the single-plenum design, 74°R . Since the trade study, "Allowable Variations of Reflector Inlet Temperature," established a limit of 16°R for core inlet temperature variations attributable to non-mixing of support stem effluent, the three-plenum design is believed to present a ready method for meeting this requirement. The other support plate designs would require extensive testing to evaluate their potential for design improvements to meet this requirement.

3. During operation, the core behaves as a unit rather than as individual elements or clusters. So far as practicable, the deflection of the Core Support Plate should match the curvature of the aft surface of the core. The curvature of the aft surface can be determined from the expansion of a monolithic core subjected to an axial temperature gradient. A preliminary estimate of the Core Aft Surface Deflection, at steady state, is .055 inch. The calculated deflection of the three-plenum support plate is .025 to .037 inch depending on SSA flow rate; the deflection of the two-plena plate is 0.128 to 0.151 inch; and the deflection of the single plenum plate is 0.065 to 0.085 inch. Minimizing the variation of plate deflection from core curvature minimizes the variation in stem loads and in turn increases the reliability of the support stems. Based on calculated deflections, the three-plenum support plate or the single-plenum plate provide more reliable designs than the two-plenum support plate.

3.2.4 Method of Chamber Temperature Control

3.2.4.1 Operating Modes

There are, generally speaking, three operating modes which have some influence on the controls concept selection.

1. Mid-map operation. This operational mode would consist of startups and shutdowns along a single path between the post-bootstrap point (1000°R and 60 psia Pc) and rated conditions (4640°R and 450 psia). Any of the controls concepts is compatible with this operational mode.

2. Throttling and high specific impulse startups. These operations have been studied from the NSS standpoint in Trade Studies 706 (NSS Throttling) and 707 (NSS Startup and Shutdown). The initial recommendation of these studies was that these modes be deleted because there were significant penalties to the NSS during these operational modes due, primarily, to the requirement for drum motion beyond the orifice angle which results in excessive core peripheral temperatures. After integrating this

information, however, with engine studies, it was decided to let these modes remain as requirements.⁽¹³⁾ The main constraint on this operational mode was, however, that throttling and high I_{sp} starts would be achieved without drum motion beyond the orificed angle.

This operational mode is not compatible with the orifice type SSCV. The reason is that all reactivity control must be obtained by drum motion. And because the core orificing is based on rated conditions, these off-design conditions mean that the reactivity additions which are required will come at the expense of core peripheral temperatures. The same is true, although to a lesser degree, with the binary type of SSCV.

The consequence of this is that if we consider the result of the studies and government reviews leading to TD 69-35, we essentially eliminate all the concepts except those involving an analog SSCV.

3. High thrust starts. This operating mode involves a startup profile along the TPCV limit line (on the P_c , T_c map) to approximately 450 psia at 50 psi/sec followed by a chamber temperature ramp at 150°R/sec to rated. This mode was deleted by TD 69-35 and will not be discussed further.

The most general mode, insofar as controls concept selection is concerned, is the mid-map mode as all the identified concepts are candidates.

3.2.4.2 Drum Control

Drum control is assumed for all the analog drum concepts because it can be found regardless of the type of SSCV. Where an analog SSCV is used with analog drums, the temperature control could be on either. Trade Study 756 will study the advantages and disadvantages of one method versus another. Such a decision does not directly affect the controls concept selection, however.

3.2.4.3 Other Methods of T_c Control

Because the binary drum concept coupled with an orifice type SSCV appeared

attractive from the simplicity viewpoint, several concepts were identified for comparison. These concepts can be distinguished by the method of Tc control as follows:

1. No Tc shimming. This concept involves no attempt to shim reactivity to compensate for corrosion or other effects which tend to cause engine operation off the design point. Operation would continue until a certain temperature error develops at which time another drum would be stepped out. This results in the largest swing in chamber temperature of all the schemes under consideration.

2. Tc control by change in Pc. This concept involves adjusting the chamber pressure to account for changes in reactor power while keeping chamber temperature constant.

3. Analog drum shimming. This concept would combine 34 binary operated drums with 2 analog drums. The analog drums would be used to interpolate between reactivity adjustments caused by binary drum motion. Basic reactivity changes would be achieved by binary drum motion coupled with analog drums for vernier control on reactivity between succeeding binary drum movements.

4. The last concept involves binary drums of different worths. The idea is that as changes in reactivity of the system require corresponding changes in drum reactivity such changes could be minimized for the binary drum case if, for example, a low worth drum was turned in (to the 0 degree position) and a larger worth drum was turned out (to the 180 degree position). The change in reactivity would then be approximately equal to the difference in drum worths.

4.0 COMPARISON MATRIX OF CONTROLS CONCEPTS

4.1 OVERALL COMPARISON OF CONCEPTS

Table 4-1 presents a summary of the comparisons made on each of the concepts. Note that for each general characteristic, an overall ranking is shown which is an attempt to numerically compare the concepts for that particular characteristic. The following paragraphs present the input to each of these characteristics.

4.2 CHARACTERISTICS USED FOR CONCEPT COMPARISON

4.2.1 Performance

4.2.1.1 Scope of Controls Studies in 701 Trade Study

Despite the title of the 701 Trade Study, its objective has not been to select a reactor controller. That objective will be taken up in Trade Study 756, Reactor Controller Selection Trade Study. The control system analysis and design activities performed in support of the 701 study have been limited to the objective of helping to select a control drum and SSCV concept. Each proposed configuration required that a controller be designed to demonstrate that NERVA performance requirements could be met, and that controller complexity considerations did not govern the choice of drums and SSCV.

4.2.1.2 Survey of Controllers Considered

In evaluating the various combinations (Figure 4-1) of analog drums, binary drums, analog SSCV, binary SSCV, and fixed SSCV, a large number of controllers was evaluated. Virtually all of them indicated ability to meet the performance requirements for NERVA, with only minor variations in controller complexity. Several different systems involving binary drums were studied. Each of them was capable of performing the required NERVA maneuvers such as throttling and high I_{sp} starts. All controlled with low static errors except the system which used no vernier reactivity adjustment. Analog drums with either analog, binary, or fixed SSCV can also be integrated into simple control

Analog Drums

{ Analog SSCV
Binary SSCV
Fixed Orifice

Binary Drums
(Sequential)

{ Analog SSCV
Orifice

{ No Vernier
Vernier via Pc Changes
Vernier via Analog Drums
Vernier via Mini Binary Drums
Vernier via Oscillating Binary Drum

Figure 4-1. Controllers Studied for 701 Trade Study

TABLE 4-1A
CONCEPTS PERMITTING THROTTLING AND HIGH I_{sp} STARTS

TYPE OF CONTROL DRUM ACTUATION	NO. OF CONTROL DRUMS	TYPE OF SSCV	STEADY STATE TC CONTROL	PERFORMANCE					RELIABILITY				WEIGHT				DEVELOPMENT RISK				SAFETY		SCHEDULE				OVERALL RANKING	COMMENTS
				TC CONTROL- LABILITY	HI ISP SOL START CAPABILITY	HI THRUST START CAPABILITY	EASE OF AUTOSTART	OVERALL RANKING	SYSTEM RELIABILITY	DRUM FAILURE ADAPTABIL.	SSCV FAILURE ADAPTABIL.	OVERALL RANKING	CDDA WEIGHT	SSCSS WEIGHT	PNEUMATIC RELATED WEIGHT	OVERALL RANKING	EASE OF CONTROLS DEV.	ACTUATORS	REACTOR INTERNAL	OVERALL RANKING	E-MODE CAPABILITY	SCHEDULAR EFFECTS OF CONTROLS	SCHEDULAR EFFECTS OF ACTUATORS	SCHEDULAR EFFECTS OF REAC. INT.	OVERALL RANKING			
ANALOG	12	ANALOG	DRUMS	+ 25°R	P _c =270 min VARIABLE	N/A	ALL SYSTEMS PERMIT AUTO START WITH EQUAL EASE	10	.9994/10	.0999/0	.966/5	0	139	300	442	8	9	4.1	10	10	5	10	6	8	8		CANNOT TOLERATE STUCK DRUM.	
		BINARY	DRUMS	+ 25°R	P _c =270 min VARIABLE	N/A		10					139	300	442	8	9	4.7	10	10	7	10	6	8	8		CANNOT TOLERATE STUCK DRUM.	
		ORIFICE	DRUMS	+ 25°R	P _c =315 min VARIABLE	N/A		1	.982/5.3	.09984/0	N/A/10	0	139	50	408	10	10	4.9	10	10	10	10	6	8	8		PERIPHERY TEMPS. ABOVE LIMITS DURING THROTTLING.	
	18	ANALOG	DRUMS	+ 25°R	P _c =270 min VARIABLE	N/A		10	.9993/9.9	.760/2.8	.966/5	2.8	209	300	655	6	9	3.4	7	8	5	10	6	10	8.5			
		BINARY	DRUMS	+ 25°R	P _c =270 min VARIABLE	N/A		10	.9978/8	.713/2.7	.9976	2.2	209	300	655	6	9	4.0	7	8.5	7	10	6	10	8.5			
		ORIFICE	DRUMS	+ 25°R	P _c =315 min VARIABLE	N/A		1	.9992/6.6	.715/2.7	N/A/10	1.8	209	50	612	8	10	4.2	7	9	10	10	6	10	8.5		REQUIRES DRUM MOTION PAST ORIFICE ANGLE; CONCEPT ELIMINATED.	
	36	ANALOG	DRUMS	+ 25°R	P _c =270 min VARIABLE	N/A		10	.9992/9.4	.99912/10	.966/5	9.4	415	300	1250	1	9	7	3	8	5	10	8	8	8.5	PREFERRED CHOICE MEETS ALL REQMTS.		
		BINARY	DRUMS	+ 25°R	P _c =270 min VARIABLE	N/A		10	.9979/8	.99056/6.6		5.28	415	300	1250	1	9	7.6	3	8	7	10	8	8	8.5			
		ORIFICE	DRUMS	+ 25°R	P _c =315 min VARIABLE	N/A		1	.9927/7	.9905/6.5	N/A/10	4.6	415	50	1220	3	10	7.6	3	8	10	10	8	8	8.5		REQUIRES DRUM MOTION PAST ORIFICE ANGLE; CONCEPT ELIMINATED.	
BINARY	36	ANALOG	SSCV	+ 25°R	P _c =270 min VARIABLE	N/A		10	.9982/8.1	.989/5.9	.989/5.9	4.8	310	300	245	8	8	4.7	3	6	1	8	8	8	8			
		ORIFICE	NONE	+ 75°R	P _c =315 min VARIABLE	N/A		1			N/A/10	.8	310	50	245	10	9	5.5	3	8	6	8	8	8	8		ALL SCHEME INCOMPATIBLE WITH HI ISP START AND THROTTLING. CORE MUST BE ORIFICED FOR ALL DRUMS OUT. TEMP GRADIENTS ARE THEN TOO HIGH FOR NORMAL OPERATION WHEN SOME DRUMS ARE IN.	
			P _c CHANGES	+ 250°R ± 7.5 psia	P _c =315 min VARIABLE	N/A		1	.871/2.7	.869/3.0	N/A/10	.8	310	50	245	10	9	5.5	3	8	6	8	8	8	8			
			2 ANAL DRUMS	+ 25°R	P _c =315 min VARIABLE	N/A		1	.871/2.7	.869/3.0	N/A/10	.8	310	50	245	10	9	5.5	3	8	6	8	8	8	8			
			SEMI-VERNIER W/ Δ SP DRUMS	+ 25°R	P _c =315 min VARIABLE	N/A		1	.871/2.7	.869/3.0	N/A/10	.8	310	50	245	10	7	5.5	3	7	6	8	8	8	8			
GANGED ANALOG	12	ANALOG	DRUMS	+ 25°R	P _c =270 min VARIABLE	N/A		10	.999/44/10	.0999/0		0	358	300	306	7.5	9	8.6	3	9	3.5	10	10	6	9	BEST SYSTEM IF STUCK DRUMS NOT CONST.		
		BINARY	DRUMS	+ 25°R	P _c =270 min VARIABLE	N/A		10				0	358	300	306	7.5	9	9.2	3	9	5.5	10	10	6	9			
		ORIFICE	DRUMS	+ 25°R	P _c =315 min VARIABLE	N/A		7	.982/5.3	.09984/0		0	358	50	272	9.5	10	9.4	3	9.5	8.5	10	10	6	9		WILL NOT MEET HI ISP AND THROTTLING REQUIREMENT; WITHOUT LARGE SPAN.	
	18	ANALOG	DRUMS	+ 25°R	P _c =270 min VARIABLE	N/A		10	.99943/10	.760/2.8		2.8	468	300	442	5.6	9	9.2	3	9	3.5	10	10	6	9	Second Best System If Stuck Drums Not Const.		
		BINARY	DRUMS	+ 25°R	P _c =270 min VARIABLE	N/A		10	.9978/8.0	.713/2.7		2.2	468	300	442	5.6	9	9.8	3	9	5.5	10	10	6	9			
		ORIFICE	DRUMS	+ 25°R	P _c =315 min VARIABLE	N/A		7	.992/6.6	.715/2.7		1.8	468	50	408	7.5	10	10.0	3	10	8.5	10	10	6	9		WILL NOT MEET HI ISP AND THROTTLING REQUIREMENT; WITHOUT EXCESSIVE FUEL TEMPS.	

TABLE 4-1B

CONCEPTS FOR "MIDDLE OF MAP" OPERATION

TYPE OF CONTROL DRUM ACTUATION	NO. OF CONTROL DRUMS	TYPE OF SSCV	STEADY STATE T _C CONTROL	PERFORMANCE					RELIABILITY				WEIGHT				DEVELOPMENT RISK				SAFETY		SCHEDULE				OVERALL RANKING	COMMENTS
				T _C CONTROL-LABILITY	HI ISP START CAPABILITY	HI THRUST START CAPABILITY	EASE OF AUTOSTART	OVERALL RANKING	"SYSTEM" RELIABILITY	DRUM FAILURE ADAPTABIL.	SSCV FAILURE ADAPTABIL.	OVERALL RANKING	CDDA WEIGHT	SSCSS WEIGHT	PNEUMATIC RELATED WEIGHT	OVERALL RANKING	EASE OF CONTROLS DEV.	ACTUATORS	REACTOR INTERNALS	OVERALL RANKING	E-MODE CAPABILITY	SCHEDULAR EFFECTS OF CONTROLS	SCHEDULAR EFFECTS OF ACTUATORS	SCHEDULAR EFFECTS OF REAC. INT.	OVERALL RANKING			
ANALOG	12	ANALOG	DRUMS (SSCV FOR COR)	+25°R	N/A	N/A	ALL SYSTEMS PERMIT AUTO START WITH EQUAL EASE	10	.9994/10	.0999/0	.966/5	0	139	300	442	8	9	4.1	10	10	7	10	6	8	8		CONCEPT WILL NOT TOLERATE SINGLE DRUM FAILURE.,	
		BINARY	DRUMS	+25°R	N/A	N/A		10					139	300	442	8	9	4.7	10	10	8	10	6	8	8		CONCEPT WILL NOT TOLERATE SINGLE DRUM FAILURE.	
		ORIFICE	DRUMS	+25°R	N/A	N/A		10	.982/5.3	.09884/0	N/A/10	0	139	50	408	10	10	4.9	10	10	10	10	6	8	8		CONCEPT WILL NOT TOLERATE SINGLE DRUM FAILURE.	
	18	ANALOG	DRUMS (SSCV FOR COR)	+35°R	N/A	N/A		10	.9993/9.9	.760/2.8	.966/5	2.8	209	300	655	6	9	3.4	1	8	7	10	6	10	8.5			
		BINARY	DRUMS	+25°R	N/A	N/A		10	.9978/8	.713/2.7	.9976	2.2	209	300	655	6	9	4.0	1	8.5	8	10	6	10	8.5			
		ORIFICE	DRUMS	+25°R	N/A	N/A		10	.992/6.6	.715/2.7	N/A/10	8.8	209	50	612	8	10	4.2	7	9	10	10	6	10	8.5			
	36	ANALOG	DRUMS (SSCV FOR COR)	+25°R	N/A	N/A		10	.9992/9.4	.99912/10	.966/5	9.4	418	300	1250	1	9	7	3	8	7	10	8	8	8.5	PREFERRED CHOICE MEETS ALL REQMTS.	OPTIMIZES CORE RELIABILITY	
		BINARY	DRUMS	+25°R	N/A	N/A		10	.9979/8	.99056/6.6		5.28	418	300	1250	1	9	7.6	3	8	8	10	8	8	8.5		BETTER SCHEME THAN ORIFICE LESS REDUCED RELIABILITY THAN ABOVE.	
		ORIFICE	DRUMS	+25°R	N/A	N/A		10	.9927/7	.9905/6.5	N/A/10	4.6	418	50	1220	3	10	7.6	3	8	10	10	8	8	8.5		BEST OF ALL ORIFICE SSCV SCHEMES.	
BINARY	36	ANALOG	SSCV	+25°R	N/A	N/A		10	.9982/8.1	.989/5.9	.989/5.9	4.8	310	300	245	8	8	4.7	3	6	1	8	8	7	8		SOME DRUM MOTION AT RATED IS REQUIRED; EXCESSIVE THERMAL EFFECTS.	
		ORIFICE	NONE	+75°R	N/A	N/A		1			N/A/10	.8	310	50	245	10	9	5.5	3	8	4	8	8	7	8		CONCEPT REJECTED. CANNOT MEET REQUIREMENT ON ISP CONTROL.	
			P _C CHANGES	+25°R ± 7.5 psia	N/A	N/A		10	.871/2.7	.869/3.0	N/A/10	.8	310	50	245	10	9	5.5	3	8	4	8	8	7	8		DRUMS REQUIRED FOR CORROSION COMP. CARRIES BASIC DISADVANTAGE OF BINARY DRUM.	
			2 ANAL DRUMS	+25°R	N/A	N/A		10	.871/2.7	.869/3.0	N/A/10	.8	310	50	245	10	9	5.4	3	8	4	8	8	7	8		DRUMS REQUIRED FOR CORROSION COMP. CARRIES BASIC DISADVANTAGE OF BINARY DRUM.	
			SEMI-VERNIER W/ΔBk DRUMS	+25°R	N/A	N/A		10	.871/2.7	.869/3.0	N/A/10	.8	310	50	245	10	7	5.5	3	7	4	8	8	7	8		DRUMS REQUIRED FOR CORROSION COMP. CARRIES BASIC DISADVANTAGE OF BINARY DRUM.	
GANGED ANALOG	12	ANALOG	DRUMS	+25°R	N/A	N/A		10	.99944/10	.0999/0		0	358	300	306	7.5	9	8.6	3	9	5	10	10	6	9	BEST SYSTEM IF STUCK DRUMS NOT CONSID.	SYSTEM WILL NOT TOLERATE STUCK DRUM.	
		BINARY	DRUMS	+25°R	N/A	N/A		10				0	358	300	306	7.5	9	9.2	3	9	6	10	10	6	9		SYSTEM WILL NOT TOLERATE STUCK DRUM.	
		ORIFICE	DRUMS	+25°R	N/A	N/A		10	.982/5.3	.09984/0		0	358	50	272	9.5	10	9.4	3	9.5	8	10	10	6	9		POWER SCALLOPING UNDESIRABLE.	
	18	ANALOG	DRUMS	+25°R	N/A	N/A		10	.99943/10	.760/2.8		2.8	468	300	442	5.6	9	9.2	3	9	5	10	10	6	9	SECOND BEST SYSTEM IF STUCK DRUM NOT	BEST OVERALL SCHEME, BUT GANGING MECH. INVOLVES SOME RISK.	
		BINARY	DRUMS	+25°R	N/A	N/A		10	.9978/8.0	.713/2.7		2.2	468	300	442	5.6	9	9.8	3	9	6	10	10	6	9			
		ORIFICE	DRUMS	+25°R	N/A	N/A		10	.992/6.6	.715/2.7		1.8	468	50	408	7.5	10	10.0	3	10	8	10	10	6	9		POWER SCALLOPING UNDESIRABLE.	

systems which satisfy NERVA performance requirements. Actually, variations in core reliability operated to select a drum and SSCV concept; core stresses influenced reliability to favor analog over binary drums, and the need to prevent drastic power factor changes with lifetime and during maneuvers led to selection of an analog SSCV concept.

What is covered in more detail is the performance that can be obtained from the analog drum/analog SSCV combination, during throttling and high I_{sp} starts.

4.2.1.3 Startup and Throttling

1. High I_{sp} Profile Capability - Figure 4-2 is a map of stem reactivity for a chamber temperature of 4640°R . It is taken from the CAM model of the reactor system. Specific numbers may be slightly different from those developed using more detailed models, but the conclusions are not affected by the differences. The vertical scale is total feedback reactivity including temperature effects and propellant reactivity both within and outside the stem. Notice that at 450 psia the reactivity span between 0 and 100% open is around \$2.50 while at 100 psia the span is virtually zero. Increasing pressure certainly increases reactivity, but changing valve position has no effect at low pressure.

At start of life, if the system is orificed such that the SSCV is closed at the design point, a throttling operation at constant drum position would consist of decreasing chamber pressure while opening up the valve to maintain a horizontal line on this map. This would permit throttling to around 250 psia, according to this model.

The dotted line is the locus of points above which stem flow exceeds 10 lb/sec. At 450 psia this also represents the 200°R low temperature limit on the stems, but below design pressure the 200°R line falls under the 10 lb/sec line since less flow is required to overcool at lower power. Lacking a good 200° line, the flow line is used as a limit recognizing that it is slightly optimistic. After \$1.00 corrosion, this line shows that one could throttle to 425 psia, but if the uncertainties are considered, one clearly should not expect to throttle at the end of life.

Figure 4-2. Map of Stem Reactivity at $T_c = 4640$

Work is in progress at WANL to reexamine the overcooling limit. If removal of the low temperature limit can be justified, it will be possible to utilize this upper corner. This still requires starting out on the low end of the valve in order to reach 60% throttling at the start of life, and at the end of life would expect to throttle to about 350 psia. The numbers may be somewhat optimistic if a substitution of a more radiation resistant material is necessary. In any case, the ability to throttle will vary continuously throughout life from startup to startup, unless a throttling point above 350 psia is selected.

2. Temperature Controller on Drums - Figure 4-3 is a block diagram of one controller which satisfied NERVA performance requirements utilizing analog drums and analog SSCV. In this concept, the temperature controller acts through the control drums. The controller is a simple integral controller which acts to reduce temperature error to zero in the steady state. For large changes in temperature, the same device programs drums out at a rate which is proportional to the rate of change of temperature demand. The reactor requirement* that drums not exceed the orificed angle during startup or throttling is accommodated by programming the SSCV according to pressure demand. This program is also a function of the overcooling limits and the amount of corrosion. In the steady-state, the SSCV is positioned to maintain the drums at the orificed angle.

Figure 4-4 is a startup at the start of life, using this system. Very low temperature errors are observed with an overshoot of only 70° . Notice that SSCV speed of about 50 degree/sec is required and that very little drum movement takes place. The 50 degree/sec is directly related to the 50 psi/sec pressure rate. Notice also that design temperature is reached at 315 psia.

Figure 4-5 is a throttling run using this same system. Again note very small temperature errors during throttling and notice that we are able to throttle to 270 psi, although we could not go through this point on the startup. The difference is accounted for by the reactor dynamic requirement for more reactivity during the power buildup. The reactivity came from the increase in chamber pressure.

* See para. 3.2.4.1, pp. 3-16

Figure 4-3. Temperature Control Concept for High I_{sp} Profiles

Figure 4-4. High I_{sp} Startup with Temperature Control on Drums

Figure 4-5. Throttling at Start of Life with Temperature Control on Drums

3. Temperature Control on SSCV - An alternative approach to temperature control which also appears to satisfy NERVA requirements is to use the SSCV directly for reactivity control, and to confine the normal role of the drums to startup and shutdown. As it turns out, this will not significantly affect required drum worth. The shutdown margin must still be provided along with allowance for all uncertainties, for startup, for corrosion, etc. In fact, the drums and SSCV profiles do not vary significantly when the control mode is switched from temperature control on drums to temperature control on stems. This interchangeability is a feature which might be used to advantage as a malfunction response.

Figure 4-6 shows the operations one must go through at start of life to perform a high I_{sp} startup with temperature control on the SSCV.

As previously discussed, at low chamber pressure the SSCV has little effect on reactor control. When in this region, say, during and just after a bootstrap, reactor control must be accomplished through drums. In the case shown, the critical drum position at the post bootstrap point is 80° . When reactivity is lost during lifetime, that number will vary continuously by an amount equivalent to \$1.00. Thus, if the reactor is to be controlled after bootstrap and prior to pressure buildup, continuous drums must be provided.

At the post bootstrap point, the drums are switched out of temperature control and programmed to their hot critical position. At start of life, this will be about one dollar drum movement. Also at the post bootstrap point, the SSCV will be switched to temperature control with a temperature error sufficient to drive it to its limiting position where it will not really control the temperature until normal operating temperature is reached. The solid line to the left is a steady state characteristic. During this open loop transient, the system will actually follow the dashed line. Although throttling to the solid line is possible in the steady state, the lowest anticipated corner for a high I_{sp} start is about 315 psia. When the operating temperature is reached by programming P_c at a rate sufficient to achieve $150^\circ\text{R}/\text{sec}$, the valve closes down in temperature control, holding nominal chamber temperature constant as pressure is increased to the design point.

Figure 4-6. Flow Control at Start of Life

Later in life, the post bootstrap drum position approaches the hot critical position, and these characteristic drum lines move down until little or no high I_{sp} capability exists.

Figure 4-7 is a block diagram of the controller used to perform these maneuvers. It shows temperature control initially on the drums in the "start" mode, and switching to stem control in the "run" mode. Drum position is programmed to the orificed angle after the switch from "start" to "run". This same switching function activates the logic which programs the SSCV in response to chamber pressure demand. The temperature error signal acts as a trim on this program. If during any of this maneuvering the valve approaches a high or low limiting position, the "valve overrange limits" function will move drums to shim the valve back to an acceptable position. Figure 4-8 shows the performance of this system during a high I_{sp} start. The performance is essentially identical to that shown by the alternative concept of temperature control through drums.

A similar conclusion may be drawn about the data of Figure 4-9 which shows a throttling run. These two concepts will be compared along with certain others, in the 765 Trade Study which is designed to select the controller which will be used with the SSCV and drum concept selected in the 701 study.

4.2.1.4 Additional Complexity for Maneuvering

The two controllers discussed above both contained provisions for throttling and for high I_{sp} starts, the throttling point being limited throughout reactor life by SSCV range even if the overcooling limitation is removed. These provisions require explicit increases in controller complexity. Referring again to Figure 4-3, the blocks below the dotted line are just to supply the high I_{sp} capability. They are concerned with programming and limiting SSCV position to reduce drum reactivity requirements and to prevent exceeding stem limits. Without these blocks, the controller consists of two simple linear systems which, alone, could control mid-map maneuvering. Similar observations could be drawn for the alternate controller.

Figure 4-7. Temperature Control Concept for High I_{sp} Profiles

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Figure 4-8. High I_{sp} Start with Temperature Control on SSCV

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Figure 4-9. Throttling at Start of Life with Temperature Control on SSCV

4.2.2 Reliability

The reliability comparison is based on comparing relative reliability values for each concept. These reliability values were computed based on core reliabilities, SSCV reliabilities and control drum drive assembly reliabilities. The reliability of the system is determined in large measure by the reliability of the core. Core reliability was taken to be a function of temperature gradient and/or excess temperatures in the core periphery. These temperatures and temperature gradients vary from scheme to scheme depending on requirements for drum motion away from the orifice angle. In addition, the excess temperatures and/or temperature gradients associated with drums either stuck in or stuck out vary with the number of drums. The reliability discussion then requires some understanding of these temperatures and temperature gradient caused stresses.

4.2.2.1 Thermal Evaluation of Controls Concepts

The assumptions used in the thermal evaluation are listed in Table 4-2.⁽¹⁴⁾

Application of these assumptions to the controls concept problem results in the temperatures shown in Table 4-3. Taking these temperatures, probabilities of failure due to temperature levels were then computed. The assumptions used for these calculations are as follows:⁽¹⁵⁾

1. Failure probability of the core due to temperature level dependent failure modes at the nominal exit gas temperature of 4690 is 5×10^{-4} .

The arbitrary number of 5×10^{-4} is selected on the basis of the core reliability apportionment. The reliability of the core is to be 0.99862, i.e., 13.8×10^{-4} failures. Out of 13.8×10^{-4} failures it is assumed that 5×10^{-4} failures are due to temperature level.

2. If the calculated increase in exit gas temperature of at least three adjacent fuel elements in a cluster is 380°R (5070°R exit gas temperature) then there is a 50% chance that the cluster will fail and cause an NSS failure.

The exit gas temperature of 5070°R (channel wall temperature of 5170°R) was

TABLE 4-2

ASSUMPTIONS USED IN THE THERMAL EVALUATION

1. Assumptions Applying to All Concepts

A. Uncertainties in fuel element power and flow which result in hot channel temperatures are relatively insensitive to control concept and are ignored in these comparisons.

B. The core is orificed to minimize the highest fuel exit gas temperature which will occur during design full power operation.

C. Thermal conduction between fuel elements is neglected.

2. Assumptions Applying to Design Full Power Operation Temperature and Reliability Analysis

A. Nominal fuel element exit gas temperature is 4690°R .

B. A one dollar corrosion reactivity loss occurs at full power design operation.

C. The fuel temperature uncertainty caused by uncertainty in hot critical drum position is not considered in the reliability calculations.

3. Assumption Applying to Design I_{sp} Throttling

A. Throttle to 60% power at 4690° average fuel element exit gas temperature.

B. Continuous SSCV has full closed to full open capability (0° to 90°).

C. Two position SSCV has 0° and 47° positions.

D. Fixed orifice has flow of a 30° position SSCV.

E. Orifice drum positions are obtained from the drum spans specified by Nuclear Design in DRM-51502 and the orificing criteria in 1B above.

4. Assumptions Applying to Stuck Drum Malfunction

A. A single drum is stuck in the full in or full out position with the drum bank in the orifice position.

TABLE 4-2 (CONTINUED)

B. The "drum stuck out" analysis is based on the minimum difference between orifice drum position and full out drum position (without including requirements for \$0.50 contingency or \$0.30 xenon in the drum span).

C. The "drum stuck in" analysis is based on the minimum difference between orifice drum position and full in drum position.

5. Assumptions Applying to Two Position Control Drum Actuators

This system cannot be analyzed on as general a basis as the analog drum position system as the core temperatures depend on the drum span and on the programmed drum motion patterns and selected orificing scheme. Two specific cases were analyzed.

Assumptions were as follows:

Case I - Fixed Orifice

- A. Orifice size equivalent to SSCV setting of 30° .
- B. No maneuvering or throttling capability.
- C. Total drum span \$3.30 (obtained from DRM-51502 without \$0.30 for xenon and without \$0.50 contingency).
- D. Initial hot critical attained with 18 drums in and 18 drums out.
- E. Orifice for constant temperature with 33 drums out and 3 drums in.
- F. Assume that the drum stuck out is one of the drums orificed for "in" position.
- G. Assume drum stuck "in" is adjacent to drum at the full in position.

Case II - Continuous SSCV

- A. Continuous SSCV has full closed to full open capability (0° to 90°).
- B. Throttling only to capability of SSCV.
- C. Total drum span \$3.10 (obtained from DRM-51502 without \$0.30 for xenon and without \$0.50 for contingency).
- D. Initial hot critical attained with 27 drums out and 9 drums in.

TABLE 4-2 (CONTINUED)

- E. Assume the drum stuck out is orificed for the in position.
- F. Assume the drum stuck in is adjacent to drum at the full in position.
- G. Orifice for constant temperature with 27 drums out and 9 drums in (DRM-51669 and 51699), or for all drums out (DRM-51696).

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TABLE 4-3
TEMPERATURE SUMMARY FOR CONTROLS CONCEPTS

SSCSS	Fixed Orifice or Two Position SS Flow Control			Continuously Variable Flow Control With Maximim Range			Binary Actuators With	
							Fixed Orifice	Continuous SSCV
No. of Control Drums	12	18	36	12	18	36	36	36
<u>Normal Operation:</u>								
Full Power Maximum FE Exit Gas Temp Level (°R)	4758	4754	4752	4690	4690	4690	4773	4765
3 Uncertainty in Above (°R)	180	134	120	0	0	0	120	0
Last FE Row at T (°R)	200	200	175	0	0	0	280	135
Last Row FE Exit Gas Below 4690	340	210	175	0	0	0	790	250
<u>Throttling (60%)</u>								
Peripheral Element Exit Gas Above 4690°R	Two Position SS Fixed Orifice		172 515	150	115	100	None	0 ⁽¹⁾
Ele-to Ele ΔT (°R)	Two Position SS Fixed Orifice		300 50	50	50			0 ⁽¹⁾
<u>Drum Stuck Out</u>								
Worst Element Exit Gas Above 4690	580	320	80	300	170	50	120	0
Ele-to-Ele ΔT (°R)	220	150	30	120	80	20	60	0
<u>Drum Stuck In</u>								
Worst Element Exit Gas Below 4690	1260	640	495	850	430	153	790	790
Ele-to-Ele ΔT (°R)	360	360	120	230	230	75	280	280

(1) Assume throttling only to capability of SSCV

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- (CRD) obtained from the NbC -ZrC coating deterioration which was observed to occur in recent Y-12 tests of a 400 MGU/CC loading fuel. NbC - ZrC and UC_2 starts mixing at $5170^{\circ}R$ (DRM 51577, page 15). The calculated temperature increase from the control concepts work include only the effect of drum motion and SSCV motion. Hot channel effects cause more elements to operate above nominal temperature, and these effects are not included.
- (CRD) 3. It is known from tests that the fuel element deterioration is exponential with temperature level.
- (CRD) The exponential behavior is due to the basic equation of graphite corrosion and equation of diffusion mechanism of the hot end corrosion. Both are proportional to $e^{-A/T}$, i.e., approximately exponential with temperature over a limited range. Figure 4-10 gives an estimated total weight loss versus exit gas temperature for R-1 fuel. It is assumed that at the nominal temperature of $4690^{\circ}R$ and 50 minute operation, the total weight loss per element will be 14 gm/element ($\sim 1.00 \Delta$ reactivity). The slope of line is taken from NRX-A6 reactor correlations.
- (U) The resulting probabilities of failure are given in Table 4-4. For a different apportionment, the probability numbers of Table 4-4 will change, but the order for the various control concepts will not change.

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Figure 4-10. Estimated Total Weight Loss Versus Exit Gas Temperature for R-1 Fuel (at Nominal Temperature of 4690°R and 50 Minute Operation, 10 GMS/Element Hot End and 4 GMS/Element Mid Band is Assumed) (CRD)

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TABLE 4-4
PROBABILITIES OF FAILURE

SSCV	Fixed Orifice or Two Position SS Flow Control			Continuously Variable Flow Control with Maximum Range			Binary Actuators with	
							Fixed Orifice	Continuous SSCV
No. of Control Drums	12	18	36	12	18	36	36	36
<u>Normal Operation:</u>								
Probability of Failure from Temp. Level	.000714	.000714	.000714	.0005	.0005	.0005	.001246	.00104
<u>Drum Stuck Out:</u>								
Probability of Failure from Temp. Level	.9 ₉	.28	.000754	.9 ₉	.0145	.000512	.001386	.00104
<u>Drum Stuck In:</u>								
Probability of Failure from Temp. Level	.000714	.000714	.000714	.0005	.0005	.0005	.001246	.00104
<u>Throttling (60%)</u>								
Probability of Failure from Temp. Level	Fixed Orifice SS	.9 ₉	.028714	.0145	.00386	.00274	----	.00104 ⁽¹⁾
	Two Position SS							

(1) Assume throttling only to capability of SSCV)

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4.2.2.2 Core Stress Evaluation of Control Concepts (U)

(U) The evaluation of the control concepts, insofar as core stress is concerned, involves determining the stresses in the peripheral elements for each concept, given the temperatures and temperature gradients described in 4.2.2.1, and then determining the probability of cracking of peripheral elements, given these stresses and a type of fuel (i.e., low expansion or high expansion matrix material). More specifically, this evaluation is aimed at generating a probability of a fuel element developing a transverse crack. Such cracks, or broken elements, are considered a failure.⁽¹⁶⁾

(U) The element axial stress, ΔT is the summation of the heat generation stress, the stress caused by the temperature difference between the average core temperature and the average element temperature, and the stress caused by the temperature gradient across the element. After determining this stress, the probability of not cracking the element was computed using the Weibull expression:

(CRD)
$$P_S = e^{-\int \left(\frac{\sigma_T - \sigma_N}{\sigma_o} \right)^m dV}$$

For fueled graphite:

$$\sigma_N = 0.0$$

$$\sigma_o = 3000 \text{ psi at room temperature}$$

$$\sigma_T = 6000 \text{ psi at } 5000^\circ\text{R; the change in } \sigma_o \text{ being a parabolic function}$$

$$m = 8.0$$

(U) Figure 4-11 presents the results of these calculations for high expansion fuel. The method used to determine the probability of failure for the core (as opposed to a single element, as shown in Figure 4-11) is given in Table 4-5.

Figure 4-11. Probability of a Cracked Element

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TABLE 4-5

STEPS IN PROBABILITY ANALYSIS

1. Divide peripheral elements into groups (sets).
2. Determine the probability of cracking for a single element in each set.
3. Determine probability of no cracks in total assembly.
4. Determine probability of not more than X cracked elements in total assembly.

An example of this method is given in Table 4-6, and the summary for all the cases, for high expansion fuel is given in Table 4-7.⁽¹⁷⁾

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TABLE 4-6
PROBABILITY OF AT LEAST X FAILURES
CONTROL CONCEPT

Fixed Orifice Flow Control, Normal Operation , 12 Drums

	<u>Set A</u>	<u>Set B</u>	<u>Set C</u>
No. Elements	84	84	168
ΔT Across Element ($^{\circ}R$)	200	50	---
$\bar{T}_{\text{Core}} - \bar{T}_{\text{Element}}$ ($^{\circ}R$)	340	125	---
Uniform Axial Stress Maximum (psi)	1150 (540)**	1150 (540)	---
Total Axial Stress Maximum (psi)	2640 (1680)	2000 (1150)	---
Probability at Least 1 Cracked Peripheral Element	---	---	.6014 (.01726)
Probability at Least 2 Cracked Peripheral Elements	---	---	.2331 (.03178)
Probability at Least 3 Cracked Peripheral Elements	---	---	.06467 (.04349)

* C = A + B

** AXM Fuel (Low Expansion Fuel)

TABLE 4-7
SUMMARY FOR CONTROLS CONCEPTS
PROBABILITY OF A CRACKED PERIPHERAL ELEMENT (U)

Fuel Type: AXM SSCSS	Fixed Orifice or Two Position SS Flow Control			Continuously Variable Flow Control with Maximum Range			Binary Actuators with Fixed Orifice Continuous SSCV	
No. of Control Drums	12	18	36	12	18	36	36	36
Normal Operation	.6014 ⁽¹⁾ (.2331) ⁽²⁾	.5116 (.1708)	.4904 (.1467)	.02285 (.052096)	.02285 (.052096)	.02285 (.052096)	.9562 (.8168)	.04667 (.001023)
Drum Stuck Out	.5735 (.2085)	.4955 (.1501)	.4797 (.1390)	.003193 (.054138)	.002989 (.053893)	.002866 (.052901)	.9466 (.7874)	.025009 (.032710)
Drum Stuck In	.7651 (.4176)	.6171 (.2470)	.5174 (.1648)	.2340 (.02596)	.09473 (.08395)	.01023 (.045825)	.9562 (.8150)	.2008 (.01842)
Throttling (60%)			.1965 (.02079)	.0047 (.041798)	.0047 (.041798)	.0047 (.041798)		.02285 (.052091)

(1) Probability of at least one cracked peripheral element

(2) Probability of at least two cracked peripheral element

4.2.2.3 System Reliability Comparison

The objective of the system reliability studies was to compare the relative reliability of the concepts; i.e., the reliability figures generated in this study are not intended to reflect the actual system reliability.⁽¹⁸⁾

The philosophy used in developing this relative reliability comparison was to combine the system reliability (based on the joint probability of success for the components considered in this study) with the reliability of the system, given that an actuator has failed.

The following basic model of the system was assumed because the reliabilities of all other NSS components are common or inconsequential to all control concepts under consideration.

Assumptions related to this model were:

1. Through the use of computer supervised redundancy, it is believed that a Reactor Control Redundant Complex (RCRC) can be built to achieve reliabilities on the order of 9_5 to 9_6 for a mission time of 10^4 hours.⁽²²⁾ It is concluded, then, that this block can be deleted from the calculations since its effect on the system reliability is nil.
2. The criteria for core failure is the temperature caused deterioration for three adjacent elements or the cracking of a single element.
3. The probability of temperature induced core failure at normal temperatures is set at 5×10^{-4} .
4. The failure rates for the SSCV&A and control drum actuators are 20×10^{-6} and 8.4×10^{-6} .
5. The major problem with the "control drum drive assembly" is the actuator.

Thus, the block diagram shown above reduces to:

Sample calculations for the individually driven drum concepts and the ganged drive concepts are shown in Tables 4-8 and 4-9. The sample ranking plot shown in Figure 4-12 illustrates the method used to rank the candidates. Similar ranking plots were obtained for the one failed actuator calculation, the failed SSCV calculations, and the 60% throttling and high expansion fuel calculations.*

Figure 4-13 is included to provide some visibility of the significance of a single control drum actuator failure. The top of each line represents the system reliability, i.e., the joint probability of success, and the lower points on the line represent the failed state system reliabilities, i.e., the joint probability of success, given that an actuator has failed.

Table 4-10 presents the results of the calculations described above. Note that the system reliabilities shown for the one failed actuator (or drum in the case of the ganged drive system) are based on the worst case. For the 12 and 18 drum systems, this is the "out" position. For the 36 drum system the worst position is "in" which means that stresses are the basic problem. If the fuel were high expansion, it could very well turn out that the full in failed position would be the worst for all cases.

A note of explanation relative to the SSCV failed state: A SSCV failed in the out position requires drum motion in to accommodate for the change in reactivity. This drum motion depresses the temperatures in the periphery causing higher than normal axial stresses in the peripheral elements. Likewise, if it is planned to have an analog SSCV, for corrosion compensation, for example, and the core is orificed on that basis,

*

Probabilities of core failure due to stresses were used based on low expansion fuel since the high expansion fuel failure probabilities were too large and biased the problem.

TABLE 4-8

EXAMPLE SHOWING DERIVATION OF RELIABILITY COMPARISON FIGURES FOR ANALOG ACTUATORS AND ANALOG SSCV

The Reliability Model Configuration is:

		12 drum sys.	18 drum sys.	36 drum sys.
For Normal System Unreliability (Q) We Have:	Q of Single Actuator X (N)	.00010	.00015	.00030
	Q of SSCV	.00002	.00002	.00002
	Q of Core	<u>.00051</u>	<u>.00051</u>	<u>.00051</u>
	System Q =	.00063	.00068	.00083
Allowing the Failure of One Drum in an "IN" Position, the Degraded Unreliability is:	Q of Single Actuator X (N-1)	.00009	.00014	.00029
	Q of SSCV	.00002	.00002	.00002
	Q of Core	<u>.01580</u>	<u>.00272</u>	<u>.00057</u>
	System Q =	.01591	.00288	.00088
Allowing the Failure of One Drum in an "OUT" Condition, the Degraded Reliability is:	Q of Single Actuator X (N-1)	.00009	.00014	.00029
		.00002	.00002	.00002
		<u>.99</u>	<u>.760</u>	<u>.00054</u>
	System Q =	.99	.7598	.00085
Assuming a Throttling Capability to 60%, the Normal System Reliability is:	Q of Single Actuator X (N)	.00010	.00015	.00030
	Q of SSCV	.00002	.00002	.00002
	Q of Core	<u>.01451</u>	<u>.00387</u>	<u>.00275</u>
	System Q =	.01463	.00404	.00307

TABLE 4-9

EXAMPLE SHOWING THE GANGED DRIVE CONCEPT USING ANALOG SSCV AND ANALOG ACTUATORS:

The Reliability Model Configuration of the Reference Design is:

For Normal "Ganged Drive" System	(1) Actuators	=	$.9_8^6$
Reliability - 18 Drum - 9 Actuators	(2) Decouplers	=	.999982
Concept	(3) Pulleys & Bearings	=	.999982
	(4) Shear Pins	=	$.9_{18}^1$
	(5) Bands	=	.99999334
Ganged Actuator System Reliability	$(1 \times 2 \times 3 \times 4 \times 5)$	=	$.999_9^{57}$
Ganged Actuator Q		=	.000043
SSCV Q		=	.00002
Q Core		=	.00051
			<hr/>
			.000573

Ganged System Reliability = .99943

TABLE 4-10

SYSTEM RELIABILITY SUMMARY

Type of Control Drum Actuator	No. of Control Drums	Type of SSCV	SYSTEM RELIABILITY					RANKING		
			Normal Oper.	1 Failed Actuator	Failed Drum Pos.	SSCV Failed	Failed SSCV Pos.	Normal Oper.	1 Failed Actuator	Total
	12	Analog Orifice Binary	.9994 .982	.09999 .09984	OUT OUT	.966 ----	OUT	10 5.3	0 0	0 0
Analog	18	Analog Orifice Binary	.9993 .992 .9977	.760 .715 .713	OUT OUT OUT	.966 ---- .99765	OUT OUT	9.9 6.6 8.0	2.8 2.7 2.7	27.7 17.8 21.6
	36	Analog Orifice Binary	.9992 .9927 .9979	.99912 .9905 .99056	IN IN IN	.966 ---- .99787	OUT OUT	9.4 7.0 8.0	10 6.5 6.6	94 45.5 52.8
Binary	36	Analog Orifice	.9982 .871	.989 .869	IN IN	----		8.1 2.7	5.9 3.0	47.8 8.1
				One Failed Drum					One Failed Drum	
GDDS	12	Analog Orifice Binary	.99944 .982	.09999 .09984	OUT OUT	.966 ----	OUT	10 5.3	0 0	
Analog	18	Analog Orifice Binary	.99943 .992 .9978	.760 .715 .713	OUT OUT OUT	.966 ---- .99765	OUT OUT	10 6.6 8.0	2.8 2.7 2.7

Figure 4-12. Normal Case Ranking Plot

Figure 4-13. Adaptability to Drum Failures

* Assumes No SSCV Malfunction

a failure of the valve in the full in position means that the entire corrosion compensation must be accommodated by drum motion. This will also increase the probability of failure.

A redundant SSCV is proposed to increase the probability of success. Further, it is assumed, so far as the ranking of the candidate concept is concerned, that single failures which could cause failures of the SSCSS system will be identified through fault tree analysis or other methods and eliminated. Consequently, the final ranking of the system did not include the SSCV failed state reliability.

4.2.3 Weight Comparison

Weight comparisons of the controls concepts have been made by summing weights that are peculiar to a particular concept. Table 4-11 lists the basis for these weight comparisons. The values and assumptions came from a number of sources⁽¹⁹⁾⁽²⁰⁾⁽²¹⁾ and are consistent with information contained in other related trade studies.

Figure 4-14 is included to show, at least schematically, what is involved in providing a redundant SSCV. Even if the SSCV was a binary valve, a parallel series combination would be required and the system would look similar to that shown.

Table 4-12 presents the weights (in lb.) for each of the systems along with the ranking for each concept. The rankings change somewhat depending on whether the actuators are pneumatic or electric. The rankings with pneumatic actuators were used in the final selection matrix.

4.2.4 Safety Evaluation

A relative safety evaluation was made independently for each drum concept considered (analog, binary, or ganged) and for each stem system flow control concept (orifice, binary, or analog SSCV) in the trade study matrix.⁽²³⁾ Numbers proportional to the estimated safety hazard were assigned to each drum and each flow control concept in turn, and the appropriate pairs of numbers were added to give the overall estimated safety hazard, on a 1-10 basis, of each candidate concept. A safety failure is the loss of the emergency mission following loss of the primary mission, so that astronaut loss or

TABLE 4-11
BASIS FOR WEIGHT COMPARISONS

Actuator Weights, Each	Analog	8 lbs
	Binary	5 lbs
Drive Shaft Weight, Each		3.6 lbs
SSCSS Weight: (Based on Redundant Valving Elements and Actuator)	Orifice System	50 lbs
	Binary or Analog	300 lbs
Drive Gas Weight Flow, Each (215 psia and 250°R)	Analog	.0063 lb/sec
	Binary	.002 lb/sec

System Assumptions

1. Analog Actuator Exhaust is Ducted to the Propellant Tank for Pressurant.
2. Drive Gas Must be Supplied from the Storage Tanks for 108 Seconds Before Dome Pressure is Sufficient to Provide Gas Supply.
3. Vessel Closure Weight is Independent of Number of Drums.
4. Reflector Weight is Independent of Number of Drums.
5. Electric Power Supply Weight is 300 lb/kwh.
6. PSS Weight Penalty \$50 lb/lb Drive Gas Weight.

Figure 4-14. Schematic of SSCSS with Redundant SSCV's

TABLE 4-12
CONTROLS CONCEPTS WEIGHT COMPARISON

TYPE OF ACTUATOR	NO. OF DRUMS	TYPE OF SSCV	ACTUATOR WT.	DRIVE SHAFT WT.	GANGING MECH. WT.	TOTAL CDDA WT.	SSCSS WT.	GAS SYSTEM WT.	ELECT. ACT.	TOTAL WEIGHT WITH GAS ACT.	TOTAL WEIGHT WITH ELECT. ACT.	RANK WITH GAS	RANK WITH ELECT.
ANALOG	12	Ana.	96	43	0	139	300	442	100	881	539	8	7
		Bin.	96	43	0	139	300	442	100	881	539	8	7
		Orif.	96	43	0	139	50	408	100	597	289	10	10
	18	Ana.	144	65	0	209	300	655	150	1164	659	6	5.5
		Bin.	144	65	0	209	300	655	150	1164	659	6	5.5
		Orif.	144	65	0	209	50	612	150	871	409	8	8.5
	36	Ana.	288	130	0	418	300	1250	300	1968	1018	1	1
		Bin.	288	130	0	418	300	1250	300	1968	1018	1	1
		Orif.	288	130	0	418	50	1220	300	1688	768	3	4
BINARY	36	Ana.	180	130	0	310	300	245	--	855	855	8	3
		Orif.	180	130	0	310	50	245	--	605	605	10	6
GANGED ANALOG	12 (8 Act)	Ana.	64	43	251	358	300	306	100	964	758	7.5	4
		Bin.	64	43	251	358	300	306	100	964	758	7.5	4
		Orif.	64	43	251	358	50	272	100	680	508	9.5	7.5
	18 (12 Act)	Ana.	96	65	307	468	300	442	150	1210	918	5.6	2
		Bin.	96	65	307	468	300	442	150	1210	918	5.6	2
		Orif.	96	65	307	468	50	408	150	926	668	7.5	5.8

population exposure results. The safety hazard number is proportional to the estimated probability, at vehicle launch, that such a safety failure will occur during the flight.

Separate evaluations were made for mid-map only and for high I_{sp} operation because of the greater safety problems with a malfunctioning SSCV in high I_{sp} operation. Because both the sets of safety hazard ratings go from 1 to 10, they do not reflect the increased safety penalty associated with high I_{sp} operation.

The analog stem flow control system considered in the evaluation matrix is the system with a single variable SSCV which must be at least partially open during high I_{sp} operations. SSCV redundancy and pulse-cooling systems that bypass the SSCV can reduce the variable SSCV safety hazard from that shown here.

It is assumed that the SSCV runout rate will be limited so that the reactivity addition rate in an SSCV malfunction can always be over-ridden by the drums in temperature control, to prevent a power excursion.

Whether 12, 18, or 36 control drums are used was not considered to be a safety problem in that the number of drums will not affect successful completion of the emergency mode. The operating temperature of the emergency mode is to be sufficiently low (nominally 1850°R) that negligible additional corrosion will occur at the core hot spot with a drum frozen out in either the 36, 18, or 12 drum configurations. The estimated relative safety hazards are as follows:

Mid Map Operation

Drums

Analog	1
Ganged	3
Binary	7

High I_{sp} Operation

Drums

Analog	1
Ganged	2.5
Binary	5

Mid Map Operations

SSCV

Orifice	0
Binary	2
Analog	3

High I_{sp} Operation

SSCV

Orifice	0
Binary	3
Analog	5

4.2.4.1 Safety Implications of Candidate Drum Actuation Concepts

With the redundancy of individual analog actuators on each drum (ganged drum system), single and double actuator failure full out (and in) do not endanger the emergency mission, so this is the most desirable drum system for safety. However, ganging the analog actuators introduces an additional failure mode of freezing the ganging system (and also of possible decoupling). Freezing will result in emergency mission loss if it occurs during coast, and whether shutdown and cooldown for intact disposal can be performed with drums frozen in the run position has not yet been determined.

Binary drums have an inherent failure mode in which all the drums step out together, rather than sequentially as designed. For a system with n drums, this gives n times the design maximum reactivity addition rate. For the 0.1 sec stepping time of the reference 36 drum \$7 binary drum system, the reactivity addition rate (\$70/sec average) is in the range of the KIWI TNT destructive test. While larger stepping times could be used up to the limit of the reactivity ramp rates required for NSS performance, this failure mode is inherent in any reactivity control system in which the individual control elements move one at a time rather than as a bank. For the reference 36 drum systems and a 60 ¢ / sec control requirement (10° / sec at 90° with a \$7 drum span), this gives a \$15/sec reactivity insertion rate, which is still in the destructive range. A safety system can probably be designed to prevent this failure mode with high reliability, and with attendant penalties, but this nevertheless remains a potentially very serious safety problem for binary drum systems.

4.2.4.2 Safety Implications of Candidate SSCV Concepts

Safety implications of the various alternatives for stem-system flow control were studied. The conclusions are as follows:

1. There is a safety requirement that the full engine operating cycle of the Emergency Mission including startup, run, shutdown, cooldown, and intact disposal can be performed with the single variable SSCV frozen at any point in its range. With the SSCV frozen in the maximum open position, the low temperature limits of the support stem system are exceeded at the full-thrust operating point and at all areas on the operating map that are acceptable as Emergency Mode operating points (Figure 4-15). If the maximum stem flow is restricted to 10 lb/sec at the operating point (47° SSCV angle) this restriction is considerably pared.

2. When the SSCV is open to the nominal 10 lb/sec or 16 lb/sec positions (or with an orifice for nominal 10 lb/sec flow, a TPCV runout could produce a reactivity excursion that would outrun the drums and would reach $6000^\circ\text{R } T_c$ in less than one second unless corrective action is taken.

With high I_{sp} startup and shutdown or throttling, these additional potential safety problems occur:

1. Malfunctions in moving the SSCV to maintain adequate SSA cooling during the high I_{sp} startup and shutdown or throttling become a safety problem.

2. During high I_{sp} startup and shutdown or throttling, an SSCV run-in to the minimum flow position will produce excessive temperatures in the support stem system.

Other safety considerations are as follows:

1. The NSS vulnerability to a partial loss-of-flow accident is a function of the safety margin in the support stem flow before the malfunction. It is not directly dependent upon whether the NSS is running at the full-thrust operating point or throttled at high I_{sp} .

Figure 4-15. NERVA Constraint Map

2. A single two-position SSCV would increase the system reliability but would not eliminate these basic safety problems. However, two parallel two-position SSCVs would reduce the safety problems associated with failure in the extreme positions of a single valve.

3. Use of a fixed orifice to control support stem flow would eliminate all safety problems involving a mispositioned SSCV. If the flow is orificed to allow high I_{sp} startup and shutdown, however, the high NSS vulnerability to a TPCV runout is extended to the full engine run time.

From safety considerations alone, fixed orifice control of coolant flow and mid-map only operation of the NSS are the most desirable. The flow would be orificed somewhat above 5 lb/sec at full power in order to meet, with a liberal safety margin, the stem system cooling requirements in steady state at all points in the mid-map startup and shutdown profiles, but also to keep the stem reactivity small in order to keep the NSS vulnerability to a TPCV runout small. The cooldown line from the tank and the SSCV would bypass this orifice for increased stem-system cooling during cooldown and pulse cooling.

If variable flow control is required for the support stem system, the SSCV should be redundant with an order of safety preference as follows:

1. A fully redundant quad-valve system with monitors for individual valve malfunctions. (See Figure 4-14)

2. Dual two-position valves that would eliminate the safety problems associated with single valve failure in either of the extreme positions of the reference design.

The relative safety hazards (10 worst) and the corresponding safety preferences (10 best) for the Control Concepts evaluation matrix are given in Table 4-13.

TABLE 4-13

RELATIVE SAFETY HAZARDS AND SAFETY PREFERENCE

<u>Drums</u>	<u>SSCV</u>	<u>Mid-Map Operation</u>		<u>High I_{sp} Operation</u>	
		<u>Safety Hazard</u>	<u>Safety Preference</u>	<u>Safety Hazard</u>	<u>Safety Preference</u>
<u>Analog</u>					
	Orifice	1	10	1	10
	Binary	3	8	4	7
	Analog	4	7	6	5
<u>Ganged</u>					
	Orifice	3	8	2.5	8.5
	Binary	5	6	5.5	5.5
	Analog	6	5	7.5	3.5
<u>Binary</u>					
	Analog Trim	10	1	10	1
	Other Trim	7	4	5	6

4.2.5 Development Risk

4.2.5.1 Reactor Design Considerations

As part of this trade study, a preliminary evaluation of the design feasibility of a 36 individually driven control drum configuration was performed.⁽²⁵⁾

Reflector and Lateral Support Systems

A drum span of \$6.00 to \$7.00 was assumed for this study on the basis of meeting all PDR requirements. Additionally, a 3g lateral support system was assumed.

Three reflector configurations were considered corresponding to the short slotted beryllium ring reference design and two alternate designs representing the aluminum frame and the graphite inner reflector as shown on the following study layouts.

1. Multiple Slotted Beryllium Ring Reflector with 36 Drums, Drawing 914E514
2. Aluminum Flanged Cylinder Reflector with 30 Drums, Drawing 914E515
3. Aluminum Flanged Cylinder Reflector with 36 Drums, Drawing 939J884

From these study layouts, it can be concluded that 36 control drums are feasible for the short slotted beryllium ring reflector with coil springs for the lateral support and the graphite barrel reflector with leaf spring.

For the aluminum frame design, 36 control drums are possible only if leaf springs are used with metallic pins. This design would also be limited to 8 rows of seal segments. In order to utilize coil springs in an aluminum frame, the maximum practical number of control drums must be limited to 30.

These studies were made independent of the type of control drum drive and do not reflect the additional potential complexities (believed to be within attainable design practice) of increased shield penetrations and re-routing of the support plate plena feed and discharge lines and instrumentation leads internal to the pressure vessel if dome mounted actuators are utilized.

Control Drum Actuators

Study layouts have been made to determine the feasibility of mounting 36 actuators. Three mounting configurations were investigated: proportional actuators dome mounted; two-position actuators internally mounted; and actuators side mounted on the pressure vessel circumference.

Thirty-six dome mounted actuators are feasible if scaled down in size to an output of approximately 100 in-lb (this is acceptable on the basis of expected bearing friction). However, all dome fluid and instrumentation penetration must be moved from the actuator mounting circle (this is shown on 939J685, Rev. B).

Two-position actuators located inside the pressure vessel and side mounted actuators circumvent the dome and shield penetration problems, but must be radiation hardened to operate without shielding (this is believed to be a major problem if proportional actuators should become necessary). In all cases, a 36 actuator configuration is feasible, but requires a departure from the reference design actuator.

The development risk associated with various numbers of drums and types of reflectors is shown in Figure 4-16.

4.2.5.2 Actuator Considerations of Various Controls Concept

The actuator considerations involve the risk associated with achieving actuator reliability requirements which differ from concept to concept, and an assessment of problems posed by space limitation or other types of mechanical problems. Table 4-14 presents a summary of the SSCV actuator considerations.

Table 4-15 presents the ranking of the SSCV options from an actuation point of view.

Figure 4-16. Development Risk

TABLE 4-14

SSCV ACTUATOR DEVELOPMENT CONSIDERATIONS

	<u>Analog</u>	<u>Binary</u>	<u>Orifice</u>
Reliability	Apportioned Actuator Failure Probability 50×10^{-6}	Apportioned System Failure Probability 80×10^{-6}	Apportioned System Failure Probability 80×10^{-6}
Mechanical Design	Most Complex Actuator	Simple On-Off Actuator or Solenoid Actuator	No Actuator

TABLE 4-15

DEVELOPMENT AND SCHEDULAR RATING

	<u>Analog</u>	<u>Binary</u>	<u>Orifice</u>
Reliability Weight 80%	6	9	10
Mechanical Design Weight 20%	6	9	10
Combined Weighted Total	6	9	10

Table 4-16 presents a summary of the control drum actuator development considerations. The entries in the table are self explanatory other than the notation, perhaps, that the ganged drive systems as well as the analog 36 systems are considered to have the characteristics that an actuator failure is allowed. The position is that indeed, the 36 drum system, as well as the ganged drive systems, can tolerance a stuck drum (or failed actuator) without materially affecting the probability of completing the mission. Table 4-17 presents a ranking of the various options of control drum actuation concepts. Table 4-18 summarizes the combined control drum and SSCV actuation rankings for each of the control concepts.

TABLE 4-16

CONTROL DRUM ACTUATOR DEVELOPMENT CONSIDERATIONS

	<u>Analog 12</u>	<u>Analog 18</u>	<u>Binary 36</u>	<u>Binary 34 + Analog 2</u>	<u>Failed Actuator Allowed</u>		
					<u>Analog 36</u>	<u>Ganged 12</u>	<u>Ganged 18</u>
Reliability	Each Actuator Apportioned Failure Probability ₆ 5.61×10^{-6}	Each Actuator Apportioned Failure Probability ₆ 3.7×10^{-6}	Each Actuator Apportioned Failure Probability ₆ 1.88×10^{-6} Relatively Simple Actuator	Each Actuator Apportioned Failure Probability ₆ 1.88×10^{-6} Two Actuators To Develop	Each Actuator Apportioned Failure Probability ₆ 230×10^{-6}	Each Actuator Apportioned Failure Probability ₆ 1700×10^{-6} (Based on 8 of 9 Operating)	Each Actuator Apportioned Failure Probability ₆ 8000×10^{-6} (Based on 10 of 12 Operating)
Mechanical Design	No Space Problems	No Space Problems	Space Limited Due to Number of Drums Simple Actuator	Space Limited Due to Number of Drums Two Actuators to Develop	Space Limited Due to Number of Drums	No Space Problems	No Space Problems

TABLE 4-17

CONTROL DRUM ACTUATOR DEVELOPMENT RANKING

	FAILED ACTUATORS ALLOWED						
	<u>ANALOG 12</u>	<u>ANALOG 18</u>	<u>BINARY 36</u>	<u>ANALOG 2+ BINARY 34</u>	<u>ANALOG 36</u>	<u>GANGED 12</u>	<u>GANGED 18</u>
RELIABILITY WEIGHT 80%	2	1	4	3	8	9	10
MECH. DESIGN WEIGHT 20%	10	10	6	3	4	10	10
COMBINED WEIGHTED TOTAL	3.6	2.8	4.4	3.0	7.2	9.2	10

TABLE 4-18

CONTROL DRUM AND SSCV ACTUATORS DEVELOPMENT RANKING

Control Drum Weighted 80%	<u>Analog 12</u>	<u>Analog 18</u>	<u>Binary 36</u>	<u>Analog 2 + Binary 34</u>	Failed Actuator Allowed		
					<u>Analog 36</u>	<u>Ganged 12</u>	<u>Ganged 18</u>
SSCV Actuator Weighted 20%							
Analog	4.1	3.4	4.7	---	7.0	8.6	9.2
Binary	4.7	4.0	---	---	7.6	9.2	9.8
Orifice	4.9	4.2	5.5	5.4	7.8	9.4	10.0

5.0 CONCEPT SELECTION

5.1 ADVANTAGES AND DISADVANTAGES OF BASIC OPTIONS

5.1.1 Binary vs. Analog Drum Actuators

5.1.1.1 Advantages of Binary Drum Actuators

Binary actuators were given serious consideration as control drum actuators for NERVA because they were believed to be extremely simple devices compared to a precisely positioned analog, or variable actuator. Their advantage lies in this simplicity. They are lighter in weight, and would simplify the equipment configuration above the forward closure. If a binary actuator of the type studied in T.S. 754 were used, it would not require ducting the actuator exhaust flow to the top of the propellant tank as the actuator would operate on pump discharge fluid and exhaust to either the reflector inlet or the dome, depending on where the actuator was located. In addition, one may anticipate that such actuators would have a reliability advantage of from 2:1 to 10:1 over an analog actuator. But fault tree analysis performed to date has not shown a clear reliability advantage. Further, even if the reliability advantage was significantly better than 10:1, failures are somewhat meaningless because binary drums will operate off their orificed angle anyway.

5.1.1.2 Disadvantages of Binary Drum Actuator

The primary difficulty with binary actuators is that it is impossible to ideally orifice the core with the present reactivity control range of the SSCSS/SSA system. As noted in Section 3.1.2.1 the reactivity control range of the analog SSCV of \$1.25 has been used for this study. This reactivity control range can be used for corrosion compensation but not corrosion compensation and adjustments for hot critical uncertainties as well. This means that for the presently understood limitations on reactivity adjustments of the SSCV, it is not possible to establish a start of life (SOL) drum position configuration coincident with the orifice angle (or orifice drum configuration, in this case). The

significance of this is that the drum or drums which is (are) positioned away from the position for which the core is orificed leads to excessive stresses if the orificing were done for all drums out; excessive peripheral temperatures if some drums were orificed in. And essentially 36 "failed" drums (compared to 36 analog drums operating as a bank) if the core were orificed for all the drums being at the midpoint. The fact is that the binary drum system will always introduce excessive core temperatures and temperature distributions (compared to analog drums moving as a bank) unless two things can be satisfied:

1. All temperature control at or near rated temperature can in fact be accomplished by the SSCV. That is, there is a unique drum configuration when the engine is operating at or near design temperature. This certainly is not possible for any of those concepts involving binary drum actuators and orifice type SSCVs.

2. The reliability of the binary drum drive assembly is such that mispositioned drums become incredible.

5.1.1.3 Binary vs. Analog Drum Actuators Summary

The discussions in 5.1.1.1 and 5.1.1.2 are summarized in Table 5-1. The conclusion is that analog actuated drum control concepts are preferred over those concepts employing binary actuators.

5.1.2 Comparison of SSCV Types

5.1.2.1 Advantages and Disadvantages of the Orifice

Selection of a controls concept embodying a fixed impedance SSCSS would provide the lightest weight (by 250 lb) and inherently the simplest system. The basic problem with this is that all reactivity control must be accomplished by drum rotation. Consider an orifice corresponding to an SSCV position of 47.5° (SSA flow = 7.5 lb/sec). The drum span required to provide high I_{sp} startups and throttling as well as corrosion compensation would be approximately \$5.00.

TABLE 5-1
BINARY VS. ANALOG DRUM ACTUATORS

Advantages of Binary

1. Lighter Weight per CDDA.
2. Does Not Require Ducting Low Pressure Exhaust and Coolant to Top of Propellant Tank.
3. Expected to Have Reliability Advantage Over Analog Actuator from 2.1 to 10.1.
4. Simplified Equipment Configuration Above Forward Closure.

Disadvantages of Binary

1. Impossible to Ideally Orifice Core With Present SSCV Reactivity Control Range.
Drum Positions Deviating from Orificed Positions Yield:
Excessive Stresses if Orificing for all Drums Out.
Excessive Temp. if Some Drums Orificed In.
Excessive Temp. and Stresses if all Drums Orificed Midway
2. Maximizes Problem of Obtaining Average Chamber Inlet Temperature Measurements.
3. Limits Flexibility in Conducting Cold Critical Experiments.

Further, since the orifice angle would be at a drum position corresponding to about \$2.45 from the full in position, drum rotation of \$2.50 beyond the orifice angle would be required. This would correspond to maximum peripheral temperatures ("into the drum") of 860°R above the normal, which are clearly unacceptable. Even if high I_{sp} starts and throttling were not required, (which they are) the SOL and EOL temperature distributions within the core would not be the same. And the fact that these temperature distributions exist, means that the probability of localized accelerated corrosion and cracking of elements will be higher than the SSCV schemes which will provide flat or nearly flat temperature distributions over the entire core life.

5.1.2.2 Advantages and Disadvantages of the Binary SSCV

The binary SSCV provides more flexibility than the orifice. This limited flexibility could be achieved in a variety of ways. For example, a two position SSCV could be set up such that its minimum flow would correspond to the 30° SSCV position (which would be intended to make the cold critical coincident with the hot critical drum position), use the drums for corrosion compensation, but reposition the SSCV to the 90° position for throttling and high I_{sp} starts. Another way would be to use the binary SSCV for corrosion compensation and drum motion for throttling. For this case, it would likely be preferable to insert, say, 50¢ with SSCV motion rather than the full \$1.00 worth.

The point is that providing some adjustment in reactivity in the SSAs will lessen the effects of reactivity adjustment via drum rotation only. But drum motion would still be required for removing cold critical and cold to hot uncertainties and corrosion compensation with corresponding reductions in core reliability. In addition, while a binary system would likely weigh as much as an analog SSCV, its total flow swing would be less.

5.1.2.3 Advantages and Disadvantages of the Analog SSCV

The advantage of the analog SSCV is that it maximizes the flow swing available for reactivity control. Even if the present SSA design with its temperature limits remains unchanged, the analog SSCV is the only type of SSCSS/SSA system which can exploit

its capability for reactivity control. If it turns out that the temperature limits can be relaxed, or the SSA is redesigned such that this flow swing is increased, the analog SSCV will be able to take advantage of it. The orifice and, quite likely, the binary SSCV will not.

This ability to trim SSA flow with an analog SSCV means, of course, that the possibility of reactor operation with flat core exit gas temperatures exist; and throttling and high I_{sp} starts can be achieved without drum motion beyond the orifice angle at rated temperature.

The disadvantages of the analog SSCV are related to its weight, control complexity and malfunctions. While it is not expected to weigh significantly more than a binary system, it will weigh about 250 lb. more than the orifice SSCV. With respect to controls complexity, it will require some sort of temperature override to exploit the full SSCSS flow swing since the present reactivity swing is based on flow changes between temperature limits. The malfunction problems have been discussed elsewhere in this report, but basically the problems that if the SSCV should fail in its full open position, the SSA materials temperature will be too low at rated and perhaps even at the E Mode operating point; likewise, if the SSCV fails to move off its minimum flow position as required, excessive peripheral temperatures will result. The position taken here is that a redundant system will be required and steps will have to be taken to reduce to a tolerable level the probability of these failure modes.

5.1.2.4 SSCV Summary

The advantages and disadvantages of the candidate SSCV concepts are summarized in Table 5-2.

The judgment is made here that because an orifice does not permit throttling and high I_{sp} starts and because a binary system offers no real important advantage compared to an analog SSCV, that a controls concept with an analog SSCV should be selected. Further, this is the only system that can provide for corrosion compensation without drum movement.

TABLE 5-2
SSCV

	<u>Advantages</u>	<u>Disadvantages</u>
Orifice	<ol style="list-style-type: none"> 1. Lightest Weight 2. Slightly Simplified Controls. 3. Inherently the Safest of all SSCV Schemes. 	<ol style="list-style-type: none"> 1. Results in Core Reliability Penalty. 2. Prohibits High I_{sp} and Throttling Capability.
Binary (Two Position)	<ol style="list-style-type: none"> 1. Permits Increased Flow Through SSA During Throttling and High I_{sp} Starts. 2. Can be Used to Reduce Drum Motion for Corrosion Compensation. 3. Simplified Scheme for Redundant Configuration. 	<ol style="list-style-type: none"> 1. Requires Drum Motion for Removing Cold Critical and Cold to Hot Uncertainties and Corrosion Compensation With Corresponding Reduction in Core Reliability. 2. Less Total Flow Swing Than Analog Actuated SSCV. 3. Adds ~250 lb to NSS Weight.
Analog	<ol style="list-style-type: none"> 1. Maximum Flow Swing Available for Reactivity Control. 2. Offers Possibility of Reactor Operation with Flat Core Exit Gas Temperatures. Maximizes Core Reliability. 3. Minimizes Drum Span for High I_{sp}, High Thrust, and Throttling Operation. 	<ol style="list-style-type: none"> 1. "Full Open" Failure Will Yield Too Low SSA Material Temperatures at Rated. 2. Will require Some Sort of Temperature Override to Exploit Full SSCSS Capability. 3. Failure of Valve Will Yield Excessive Core Periphery Temperatures and Temperature Gradients Since Drums will be Required to do SSCV Function. 4. Adds ~250 lb. to NSS Weight.

5.1.3 Comparison of Number of Control Drums

Only one significant advantage has been identified for the 36 drum configuration; that is, that it will result in tolerable core peripheral temperatures and temperature gradients if there is a stuck drum. The disadvantages of the 36 drum system as compared to the 18 drum system are listed in Table 5-3. The task, so far as selection of a 36 drum versus an 18 drum system, is clearly a job of assessing just how significant is the stuck drum advantage.

The probability of failure for three adjacent elements due to a control drum stuck in the full out position is shown⁽¹⁴⁾ in Figure 5-1. With a drum span of \$4.00, and an orifice angle of \$2.45 from the full in position, the reactivity difference, full out to the orifice angle, would be \$1.55. Figure 5-1 indicates that there would be a 60% chance of failure for the 18 drum system, and about 0.003 percent chance of failure for the 36 drum case or better than four orders of magnitude less. For the case of a control drum stuck in, a lot depends on the specific fuel thermal expansion characteristics.

For high expansion fuel, the chances of cracking a single fuel element is about one in a hundred for the 36 drum case and one in ten for the 18 drum case. For low expansion fuel, the chances of getting cracked elements is reduced but the difference, so far as number of drums is concerned, is about the same.

The above discussion leads one to the conclusion that failed drums are clearly unacceptable for the 18 drum case and would obviously be unacceptable for the 12 drum case. Selection of the 36 drum concept provides, then, a design which eliminates single failures which could endanger the completion of the mission.

For this reason, then, a 36 drum system is preferred over the 18 drum system. Now whether the actual number of drums should be 30, say, instead of 36, the answer is not so clear. Figures 5-2, 5-3, and 5-4 which are crossplots of data from Reference 26, would seem to indicate that the more drums, the better.

Figure 5-1. Probability of Failure for 3 Adjacent Elements Due to a Control Drum Stuck in Full Out Position

TABLE 5-3
COMPARISON OF 36 AND 18 DRUM SYSTEMS
(ANALOG ACTUATORS)

ADVANTAGES OF 36 DRUM SYSTEM OVER 18
 DRUM SYSTEM

1. Results in tolerable core peripheral temperatures and temperature gradients if there is a "stuck" drum.

DISADVANTAGES OF 36 DRUM SYSTEM OVER 18
 DRUM SYSTEM

1. Higher weight by 400 to 800 lbs.
2. Higher probability of having a stuck drum (factor of two).
3. Results in increased mechanical complexity of reactor internals, particularly, reflector and lateral support.
4. Higher cost.
5. Increased complexity of equipment external to P/V.

Figure 5-2. Element to Element ΔT for a Control Drum Stuck in Full Out Position vs. Number of Drums

Figure 5-3. Element to Element ΔT for a Control Drum
Stuck in the Full In Position vs. Number of Drums

Figure 5-4. Temperature Effect of a Control Drum Stuck in Full Out Position versus Number of Drums

5.2 TRADE OFF MATRIX

Section 5.1 considered advantages and disadvantages of the various basic selections and concluded that the controls concept should include 36 analog drums with a full range analog type SSCV. There was, aside from these comparisons, an attempt made to perform an actual trade of one characteristic against another and to arrive at a numerical selection of a concept.

5.2.1 Trade Off Methodology

Referring back to Table 4-1, it is seen that each concept is ranked, numerically, for each characteristic with 10 being best and 1, poorest. The ranking for each characteristic was then multiplied by a weighting factor. Then each concept's total ranking was obtained by summing the products of the ranking times their weighting factor. The concept with the highest sum is the preferred selection.

Unfortunately, there is no formula for assigning "importance" to any specific characteristic. The fact is that no scheme or concept is acceptable if it is unacceptable so far as any of the individual characteristic is concerned. Likewise, a concept which appears to be best in all respects is clearly the preferred choice. The problem, then, is to arrive at something meaningful for those cases which lie within these extremes. Admittedly, it is a somewhat arbitrary sort of process, but based on discussion with the customer, the weighting factors shown in Table 5-4 were used.

TABLE 5-4

The Characteristics	Weighing Factor
A. Reliability	30
B. Performance	25
C. Weight	25
D. Safety	10
E. Development Risk	5
F. Schedule	5
	<hr/> 100%

5.2.2 Trade Off Results

This numerical ranking was applied to the concepts for mid-map operation. The reason is that all the concepts are workable from a performance point of view for mid-map operation and they are not for the high l_{sp} start and throttling operational mode. For example, all the concepts which have an orifice are not actually candidate concepts for the high l_{sp} start operational modes. So in this sense, a selection for mid-map operation represents the most general case. Table 5-5 shows the results obtained by applying the method discussed in section 5.2.1. It turns out that the ganged drive concepts look the most attractive if one does not consider the failure of drums to be caused by rotating the ganging mechanism. Such failures are, however, not incredible. And therefore, applying the single failure criterion, most of the other concepts rank better. There are additional problems with the ganging mechanism which are important but difficult to assess; namely, the real reliability of the bands and the safety problem associated with ganging mechanism jamming should bands break. This sort of uncertainty makes it difficult to justify recommending a ganged drive concept.

The next best concept is the 36 analog drums with an analog SSCV. Its preference is not a clear one with respect to the concepts which use an orifice type SSCV. But based on the way these numbers were put together, it is the best. More importantly, it is a concept which will meet all the functional and technical requirements. The concepts employing an orifice for an SSCV will not. So it turns out that the selection made for the most general case (mid-map operation) is a selection that is suitable for the more restrictive case and is also consistent with the selection made by examining the advantages and disadvantages of the basic choices.

5.3 CONTROLS CONCEPT SELECTION RECOMMENDATION

The NSS recommendation of a controls concept is summarized in Table 5-6. The justification for this recommendation is summarized in Table 5-7.

TABLE 5-5
MID MAP OPERATION RANKING SUMMARY

	TYPE OF DRUM	CONTROL DRUMS	TYPE OF SSCV	PERFORMANCE		RELIABILITY		WEIGHT		DEVELOPMENT RISK		SAFETY		SCHEDULE		TOTAL LESS RELIABILITY	TOTAL
				RANK	PTS. AT 25%	RANK	PTS. AT 30%	RANK	PTS. AT 25%	RANK	PTS. AT 5%	RANK	PTS. AT 10%	RANK	PTS. AT 5%		
ANALOG	12		Ana.	10	250	0	0	8	200	10	50	7	70	8	40	605	605
			Bin.	10	250	0	0	8	200	10	50	8	80	8	40	620	620
			Orif.	10	250	0	0	10	250	10	50	10	100	8	40	690	690
	18		Ana.	10	250	3.0	90	6	150	8	40	7	70	8.5	43	553	643
			Bin.	10	250	2.2	66	6	150	8.5	45	8	80	8.5	43	566	632
			Orif.	10	250	1.8	54	8	200	9	45	10	100	8.5	43	638	692
	36		Ana.	10	250	9.5	282	1	25	8	40	7	70	8.5	43	428	710
			Bin.	10	250	4.8	144	1	25	8	40	8	80	8.5	43	438	582
			Orif.	10	250	4.6	138	3	75	8	40	10	100	8.5	43	508	646
BINARY	36		Ana.	10	250	4.8	144	8	200	7	35	1	10	8	40	535	679
			Orif.	1	25	.8	24	10	250	9	45	4	40	8	40	400	424
			Orif.	10	250	.8	24	10	250	9	45	4	40	8	40	665	689
			Orif.	10	250	.8	24	10	250	8	40	4	40	8	40	660	684
			Orif.	10	250	.8	24	10	250	8	40	4	40	8	40	660	684
			Orif.	10	250	.8	24	10	250	8	40	4	40	8	40	660	684
	12		Ana.	10	250	0/10	0/300	7.5	187	9	45	5	50	9	45	587	587/887
			Bin.	10	250	--	---	7.5	187	9	45	6	60	9	45	587	660/777
			Orif.	10	250	0/5.3	0/159	9.5	237	9.5	47.5	8	80	9	45	660	660/819
GANGED ANALOG	18		Ana.	10	250	218/10	84/300	5.6	140	9	45	5	50	9	45	530	614/830
			Bin.	10	250	2.2/0	66/240	5.6	140	9	45	6	60	9	45	540	608/760
			Orif.	10	250	1.8/0	54/198	7.5	187	10	50	8	80	9	45	550	604/748
			Ana.	10	250	0/10	0/300	7.5	187	9	45	5	50	9	45	587	587/887
			Bin.	10	250	--	---	7.5	187	9	45	6	60	9	45	587	660/777
			Orif.	10	250	0/5.3	0/159	9.5	237	9.5	47.5	8	80	9	45	660	660/819

TABLE 5-6

CONTROLS CONCEPT SELECTION RECOMMENDATION

	High I_{sp} and Throttling Operation	Mid -Map Operation
Drum Span	\$4.00	
Use of SSCSS	Corrosion Compensation, Throttling and High I_{sp} Starts.	Corrosion Compensation.
Number of Drums	36	36
Type of Drum Actuation	Analog	Analog
Type of SSCV	Analog	Analog
SSCV Flow Range at Rated	5 - 17 lb/second	5-17 lb/second
Temperature Control	Drums/SSCV	Drums
Throttling Capability	Variable with Run Time, 60% Maximum.	N/A
Startup Mode	High I_{sp} Mode, Variable with Run Time.	Mid-Map, Single Mode

TABLE 5-7
CONCEPT SELECTION JUSTIFICATION

1. Analog Actuated Control Drums:	• Selection of Binary Actuators Means That During Normal Operation There Will be Regions in the Core with Maximum Temperature Gradients and Corresponding Reliability Degradation. • Analog Actuators Maximize Core Reliability by Minimizing Temperature Scallop.
2. 36 Drums:	• Temperature Scallop is Minimized in the Event of Inoperative Drums - for Whatever Reason. Minimizes Criticality of Control Drum Drive Unit Meeting Reliability Requirements.
3. Continuously Variable SSCV:	• Provide Maximum Control Flexibility. • Maximizes Core Reliability by Ability to Compensate for Corrosion. • Provides Capability of Throttling Without Corresponding Excessive Exit Gas Temperatures. • For A Given Throttling Requirement, the Drum Span is Minimized; Thus Consequences of Inoperative Drums are Minimized.
4. Operating Drum Span of \$4:	• Represents Present Estimate of Minimum Drum; Minimizes Consequences of Inoperative Drum.
5. Design Drum Span of \$6:	• Reflector Thickness Accommodates \$6 Drums. • If Further Analysis Modifies \$4 Estimate, Span will be Available by Changing Actuator Stop.

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APPENDIX A

DEVELOPMENT OF DRUM SPANS

This trade study recommends that the NERVA reactor design proceed on the basis of a \$4.00 drum span but that the drums and reflector be designed for a \$6.00 span. This appendix provides the support for that recommendation.

It was concluded, in Section 5, that the controls concept should consist of 36 analog actuated drums with a full range, analog actuated SSCV. It is further understood that high I_{sp} starts and throttling (at rated temperature) will be required.

There are two ways to examine this problem. Consider first Figure A-1. The left hand stack up of drum span components represents a drum span which will provide assurance that the NSS can be started on a two second period at anytime during its life. With a nominal cold critical of \$1.65, the actual SOL cold critical may be \$1.80. To get on a 2 second period (prior to the introduction of an amount of hydrogen flow that would produce positive reactivity feedback) the drums will nominally move to a \$2.35 position (which could be \$2.20 or \$2.50 depending on which way the cold critical error happened to be). At the end of life, however, the cold critical may be at the \$3.25 position rather than the \$1.65 nominal because (1) the core may have lost \$1.00 worth of reactivity due to corrosion (2) xenon poisoning may be at its worst (\$0.30 worth), and (3) one drum may be inoperative (R-Mode, which is worth about 15¢). Thus to cover all contingencies and to assure a predictable start, a drum span of \$3.95 is required.

The other parts of Figure A-1 illustrate drum positions at the post bootstrap point and the design point. These points illustrate that drum reactivity exceeding the orificed angle is used only during transients. If reactivity in excess of the SOL hot critical requirement is not provided, the transient reactivity requirement could theoretically be satisfied by initially running the drums out to the orificed angle which at SOL will establish about the right period. At the end of life, and with maximum xenon, the reactor would not go critical without extra core chilldown followed by extra chamber pressure to provide

hydrogen reactivity as the core heats up. Bootstrap may or may not be possible. One would need an ability to predict the effects of cooldown conditions, corrosion, xenon poisoning and other environmental effects to employ this method, however. It seems wiser to recommend, in lieu of experience in these areas, a \$4.00 span which will provide the reactivity to permit a planned, repeatable start.

The drum span can also be developed in another way which is illustrated in Figure A-2. This stack up of drum span components assumes that the full range SSCV will be used for corrosion compensation and for throttling and high I_{sp} startup reactivity additions within the present capability of the SSCSS/SSA system. The additional \$1.00 for dynamic requirements is needed if one must, in every case, at any time, follow a high I_{sp} start through the 60% power point. At start of life (SOL) this would not be required and the SSCV is expected to be able to handle it above. This would not be true at end of life (EOL).

The conclusion is that a useful drum span of approximately \$4.00 is required. The next question is: If present calculations indicate a requirement for a \$4.00 drum span, which drum span should be built into the system at this time? It is recognized that just as there are uncertainties in the requirements, there are also uncertainties in calculating the actual worth of any particular drum/reflector design. If \$4.00 is actually required, one would not set out to size the drums and reflector to provide exactly \$4.00. The actual drum worth would in all likelihood be more or less than the \$4.00. (These uncertainties have not been identified as yet). Furthermore, while the \$4.00 is today's best estimate of the requirement, it does not provide for any contingency to cover, for example, unpredictable differences in the cold to hot reactivity swing.

It seems clear that some drum span should be designed into the system which will do two things: provide some contingency and also make allowances for calculational uncertainties in the determination of the actual worth of a given drum/reflector design. It has been recommended that this value be \$6.00. The question is, what is it costing the NSS in weight, for example, to build in a \$6.00 drum worth as opposed to a \$4.00 drum span?

Figure A-1. Drum Positions at the Post Bootstrap Point and the Design Point

Figure A-2. Development of Drum Span

The drum system worth (given a specific number of drums) is basically controlled by the following parameters.*

1. Control vane arc coverage.
2. Control vane B-10 surface density.
3. Control vane thickness.
4. Control vane outer diameter.

Figures A-3, A-4, A-5, and A-6 illustrate these effects.

Now, if one or several of these parameters were adjusted to reduce the drum span from a \$6.00 to a \$4.00 design, the effect on the system reactivity as shown in Figure A-7 would be +\$0.85. (This is based on a comparison of \$6.00 drums at 90° versus \$4.00 drums at 90°). This change in system reactivity could have a change in either fuel loading or reflector thickness. Figure A-8 illustrates the variation in fuel loading and Figure A-9 illustrates the effect on reflector thickness. Neither of these effects (16 mg/cc in fuel loading or 0.2 inches in reflector thickness) is felt to be significant. It is concluded, therefore, that the design of the actual drum worth should be aimed for \$6.00. This \$6.00 drum span can be reduced or limited for flight reactors by appropriate setting of actuator stops.

* D. G. Bevard, R. A. Doncals, and A. L. Mowery, "Optimization of Peripheral Reactivity Control in the NERVA Reactor," ANS 15th Annual Meeting, Seattle, Washington, June 15-19, 1969.

Figure A-3. Variation of NERVA Control Drum Span with Vane Arc, Degrees

Figure A-4. Variation of NERVA Control Drum Span with Vane B¹⁰
Surface Density

Figure A-5. Variation of NERVA Control Drum Span with Vane Thickness

Figure A-6. Variation of NERVA Control Drum Span with Control Vane Outer Diameter

Figure A-7. Variation of NERVA Drum Span with Reactivity

Figure A-8. Variation of NERVA Drum Span with the Maximum Fuel Loading

Figure A-9. Variation of NERVA Drumspace with Reflector Thickness

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