**Westinghouse
Astronuclear
Laboratory**

SNPO-C

Records

WANL-TME-2715
SEPTEMBER 1970

DATA ITEM S-54

REACTOR CONTROLS CONCEPTS

TRADE STUDY NO. 713

MASTER

REPRODUCTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

(31)

~~CONFIDENTIAL~~

Westinghouse Astronuclear Laboratory

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Subcontract NP-1
CODE IDENT NO. 14683

WANL-TME- 2715
SEPTEMBER 1970

SPECIAL REVIEW
FINAL
DETERMINATION
Class: U
Reviewers: KAW
Class: U Date: 4-14-82

Classification cancelled (or changed to) _____
by authority of _____
by H.F.C. TIC, date SEP 11 1973

DATA ITEM S-54

REACTOR CONTROLS CONCEPTS

TRADE STUDY NO. 713

Approved by:

F. D. Retallick
F. D. Retallick, Manager
NERVA Engineering

INFORMATION CATEGORY
CRD
James C. Burk 5-18-70
AUTHORIZED CLASSIFIER DATE

DISTRIBUTION OF THIS DOCUMENT UNLIMITED

~~CONFIDENTIAL~~
~~RESTRICTED DATA~~
~~UNCLASSIFIED~~

BLANK

ABSTRACT

This report documents the work performed as Trade Study 713, Reactor Controls Concepts, and presented orally to the government on February 13, 1970. The study was conducted as a re-examination of two objectives of its parent study, Reactor Controls Concepts, Trade Study 701; namely, the definition of a reactivity control span requirement for the control drums, and a definition of the structural support assembly (SSA) rated operation reactivity control span requirement. The recommendation was that the NERVA reactor should be designed to meet a \$6 drum span and a \$3 structural support assembly span for rated condition operation.

BLANK

TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
1.0	SCOPE	1-1
1.1	OBJECTIVE	1-1
1.1.1	Definition of Drum Span Requirements	1-1
1.1.2	Definition of the Support Stem Span Requirements	1-1
1.2	BASIS OF REQUIREMENTS RECOMMENDATION	1-1
1.2.1	Reference Design Description	1-1
1.2.2	Relationship to Fuel and Reflector Trade Studies	1-2
2.0	IDENTIFICATION OF REQUIREMENTS	2-1
2.1	PRE-BOOTSTRAP REACTIVITY CONTROL: METHOD OF STARTUP	2-1
2.2	ROLE OF DRUMS FOR POST-BOOTSTRAP REACTIVITY CONTROL	2-2
2.3	ROLE OF SSCV/SSA FOR POST-BOOTSTRAP REACTIVITY CONTROL	2-2
3.0	DESCRIPTION OF SIGNIFICANT CHARACTERISTICS	3-1
3.1	CONTROL DRUM REACTIVITY SPAN REQUIREMENTS	3-1
3.1.1	Shutdown Margin	3-1
3.1.2	Cold Critical Uncertainty	3-2
3.1.3	Loss of Core Reactivity Due to Corrosion	3-3
3.1.4	Xenon Poisoning	3-9

TABLE OF CONTENTS CONTINUED

	3.1.5	AMOD Effects	3-9
	3.1.6	Thermal Conditioning Effects	3-10
	3.1.7	Dynamic Requirements	3-12
	3.2	STRUCTURAL SUPPORT CONTROL RANGE FACTORS	3-13
	3.2.1	Rated Condition Controllability Allowance	3-13
	3.2.2	Uncertainty in Hot Critical Position	3-13
	3.2.3	Xenon Poisoning Allowance	3-15
	3.2.4	Corrosion Allowance	3-15
4.0		RECOMMENDATION	4-1
	4.1	DRUM SPAN REQUIREMENTS	4-1
	4.1.1	Summation of Factors for Flight Reactors	4-1
	4.1.2	Summation of Factors for Development Reactors	4-1
	4.1.3	Recommended Drum Span for NERVA	4-1
	4.2	STRUCTURAL SUPPORT CONTROL RANGE REQUIREMENT	4-1
	4.3	SUMMARY	

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
3-1	Normalized Fuel Carbon Reactivity Coefficient	3-5
3-2	Reflector and Core Feedback Reactivity VS. Temperature (No Flow Condition Nov. Reference Design)	3-11
3-3	Lines of Constant Reactivity for SSCV at 0° Opening	3-14

LIST OF TABLES

<u>Table</u>		<u>Page</u>
3-1	Corresponding Corrosion Activity Losses	3-6
3-2	Fuel Geometry and Core Size Effect on Hot End Diffusion Corrosion and Relative Midband Corrosion	3-8
4-1	Summary of Drum Span Requirements	4-2

1.0 SCOPE

1.1 OBJECTIVE

This trade study is an update of part of the 701 trade study, "Reactor Controls Concept Trade Study," WANL-TME-1967.⁽¹⁾ Change Order 70-1⁽²⁾ changed the NERVA engine cycle from a hot bleed cycle to a full flow cycle, the mixed mean chamber inlet temperature from 4500°R minimum to 4250°R nominal and the duration from 50 minutes to 10 hours. In conformance with the instructions of this change order, two of the objectives of the 701 trade study were re-examined: drum span requirements and support stem reactivity span requirements.

1.1.1 Definition of Drum Span Requirements

The drum span represents the change in feedback reactivity of the reflector caused by the rotation of the control drums over their travel range.

1.1.2 Definition of the Support Stem Span Requirements

Reactivity adjustments may be made by varying the inventory of hydrogen in the counterflow, cluster support stem assemblies (SSA) by varying the impedance in the structural support coolant supply assembly control valve (SSCV).

The reactivity control span requirement of this system affects, in turn, the thermal hydraulic characteristics of the SSCA, the support plate and plena (SPP) and the support stem assembly. This study is limited to the determination of the reactivity control requirements of this system at rated conditions. The requirements imposed on the structural support system for off design operation (such as throttling) are covered in Trade Study 714, "NSS Startup, Shutdown, and Throttling".⁽³⁾

1.2 BASIS OF REQUIREMENTS RECOMMENDATION

1.2.1 Reference Design Description

There are a number of design choices of various NSS components which affect the reactivity characteristics of the reactor.

Detailed calculations of feedback reactivities require detailed descriptions of the system in the analytical models used. The values presented in this study were based on the NSS Reference Design as described on December 18, 1969.⁽⁴⁾ Features of this particular reference design which were important to this study's output are:

- a. The reflector design incorporates an all beryllium reflector.
- b. The reflector design provides for a drum span of approximately \$6.00.
- c. The fuel elements were assumed to be made from high expansion graphite.
- d. The NSS design was based on a 10 hour duration consisting of sixty ten (10) minute burns.
- e. The total flow (bypass and stem flow) through the structural support coolant assembly (SSCA) was held constant at 21 lb/sec at rated conditions. The bypass flow complemented the support stem flow to hold the total flow constant as the support stem flow was adjusted.
- f. The control drum drive assembly included an actuator malfunction override device (AMOD) which returns the drum with a failed actuator to the drum position for which the core is orificed.

1.2.2 Relationship to Fuel and Reflector Trade Studies

There were two other trade studies conducted simultaneously with this one which included detailed analyses of reflector and fuel alternates.^{(5), (6)} Ideally, these studies, should have been performed sequentially rather than simultaneously since the acceptance of the recommendations or modifications of the recommendations of these studies can, of course, upset the recommendation of this study. Nevertheless, the basis for the development of the recommendation on drum spans and structural support control capability remain the same and suitable modifications can be easily made.

2.0 IDENTIFICATION OF REQUIREMENTS

2.1 PRE-BOOTSTRAP REACTIVITY CONTROL: METHOD OF STARTUP

There are a number of ways that the reactor and the reactor/engine could be started. But, regardless of the operational procedure, the pre-bootstrap phase must be characterized by the following:

- a. The reactor must be brought to some power in the MW range - perhaps to 1% of total power, prior to attempting bootstrap. This will permit supporting the bootstrap operation and the following ramp up in temperature and pressure with reasonable changes in power (i.e., reasonable reactor periods).
- b. The startups must be predictable, and repeatable.
- c. The startups will have initial conditions of no flow and the drums in their most poisoned position (full-in position).

Pre-bootstrap operations could, of course, involve hydrogen flow to provide reactivity feedback to complement or supplement adjustments in reactivity caused by drum motion. On the other hand, it is not certain that requirements on predictability and repeatability could be satisfied with a "wet" start principally because the cold critical position will be changing with reactor life and operating history so when the hydrogen insertion and drums are used together, the control problem is aggravated.

For the purpose of this study it has been assumed that the entire function of providing the necessary adjustment in reactivity to take the reactor from a shutdown condition to a power in the megawatt range must be inherent in the capability of the drums.

It is concluded then that the drum span must be such that the initial criticality can be achieved, changes in criticality over the life of the reactor can be accommodated, and the excess reactivity required to change reactor power in a specified time can be provided.

2.2 ROLE OF DRUMS FOR POST-BOOTSTRAP REACTIVITY CONTROL

Drums will be required to provide the necessary control of reactivity during and after bootstrap until sufficient system pressures exist that will permit an active reactivity control through support stem flow variations.

The exact pressure at which the control function can be transferred will depend on the final design of the stems and structural support coolant supply system. It will probably be on the order of 200 psia chamber pressure.⁽⁷⁾ During the bootstrap phase, though, the drums will experience an inward motion as a result of the hydrogen insertion into the system. And during operation at or near rated conditions, the control drums are expected to be at or near their start of life hot critical position over the life of the reactor. The core will be orificed for this drum position.

Due to the nature of the full flow cycle, the start of life (SOL) hot critical position (the orifice angle) will be "inside" (smaller drum angle) than the SOL cold critical by an amount equal to the cold to hot swing. The conclusion is that the drum span requirements are established by pre-bootstrap startup requirements; i.e., there are no requirements during or after bootstrap which would appear to necessitate a drum span larger than that to satisfy the pre-bootstrap reactivity control requirements.

2.3 ROLE OF SSCV/SSA FOR POST-BOOTSTRAP REACTIVITY CONTROL

This report concerns itself with the rated condition ($T_{c_i} = 4250^{\circ}\text{R}$, $P_c = 450$ psia) reactivity control function of the SSCV/SSA system. Trade Study 701⁽¹⁾ as well as the NSS Startup, Shutdown, and Throttling Trade Study⁽³⁾ have both shown the penalties of reactivity control with drum motion at rated temperature operation. These arguments will not be repeated here. The point made in these reports is that, from the standpoint of core reliability, there is a great advantage in maintaining a fixed radial power profile at rated temperature over the life of the reactor. This can best be achieved by an operational mode which uses the SSCV for rated temperature reactivity control which in turn permits

the drums to remain fixed at a pre-selected position. The core can then be loaded and orificed for that position. This report concerns itself with the rated condition ($T_c = 4250^\circ\text{R}$, $P_c = 450$ psia) reactivity control function of the SSCV/SSA system. The reactivity control requirements for this operation are then, for the support system to provide for all the reactivity adjustments needed to satisfy the controllability requirements at rated operation and to adjust for life effects including corrosion losses. This does not preclude, however, further consideration of concepts in which small amplitude drum motions at rated conditions are employed, together with SSCV shim to keep the radial temperature profile optimized, if the need for this type of dual reactivity adjustment is established.

3.0 DESCRIPTION OF SIGNIFICANT CHARACTERISTICS

3.1 CONTROL DRUM REACTIVITY SPAN REQUIREMENTS

During reactor startup, the control drums provide a direct, controllable, predictable and repeatable method of taking the reactor beyond criticality such that the power can be increased from source level to the megawatt range to ready the reactor for supporting engine bootstrap. As previously mentioned, adjusting system reactivity by other means is possible. For example, the engine system could be designed to deliver hydrogen to the support stems to change reactivity or other methods of startup could be employed involving hydrogen feedback. But these methods had not, at the time this study was done, been analyzed or developed to demonstrate their practicality. Further, it is believed that extensive testing would be required to provide confidence in this type of startup. This thinking led to the conclusion that a basic requirement for control drum reactivity span was that it must provide the necessary adjustment in reactivity to accomplish startup independent of hydrogen contributions to reactivity feedback. This means that the drums must be able to override the start of life shutdown margin (i.e., bring the reactor critical for the first start), override the changes in cold critical due to corrosion, poisoning, and other effects, and finally, to add the dynamic reactivity required to establish reactor powers in the megawatt range in some specified time.

3.1.1 Shutdown Margin

The minimum shutdown margin for non-operating conditions has remained the same as that identified for the hot bleed cycle: \$1.50.⁽⁵⁾ During operation (periods of hydrogen flow), the shutdown margin has also remained the same: \$0.25.

There is a significant difference in the implication of this requirement for the full flow cycle compared to the hot bleed cycle:

a. The hot bleed cycle had an \$0.80 negative reactivity feedback change in going from cold critical to criticality at rated conditions. This means that the drums

would have a net outward rotation in going from cold critical to rated operation, and hence the orifice angle would lie outside the start of life cold critical. The \$0.25 shutdown constraint was related to the drum shutdown capability as the engine traverses the bootstrap profile. Introduction of hydrogen in the core during bootstrap causes an inward motion of the drums. The \$0.25 limit, then, constrains the bootstrap profile such that the drum motion during this phase of the startup stays within this shutdown limit.

b. The full flow cycle, on the other hand, is expected to have a positive feed-back change in going from cold critical to rated operation. Work performed on the reflector trade study⁽⁶⁾ has indicated that the cold to hot reactivity swing is \$0.29 for high CTE fuel and \$0.70 for composite fuel for the beryllium ring reflector design. When the hot critical uncertainty (discussed in the next section) of \$0.35 is added to this value, there is a potential of being \$1.05 more reactive at rated conditions than at cold critical. This requires a start of life drum position at rated conditions that is \$1.05 inward from the start of life cold critical position.

The drum position profile during startup including the bootstrap and ramp up phases of the startup operation have not been identified. These profiles as well as the whole concept of operation with a drum position at rated conditions close to the full in position must be further examined from a safety standpoint to verify the validity of this \$0.25 operational shutdown margin requirement.

3.1.2 Cold Critical Uncertainty

Cold critical position is that drum position related to reactor criticality with a core at room temperature and without the presence of hydrogen. Hot critical position is that drum position related to reactor criticality at rated conditions. For this study, rated conditions are those related to a chamber pressure of 450 psia and an average chamber inlet temperature of 4250°R.

This uncertainty in the actual cold critical position with respect to the predicted cold critical position for flight reactors was estimated to be ± 15 cents three sigma for the

(THIS PAGE UNCLASSIFIED)

hot bleed reactor.⁽⁵⁾ This same value has been used for this study. It is to be emphasized that this value is related to flight reactors only and does not imply that the precision in establishing the cold critical position for development reactors would be nearly as close. The 15 cents 3 sigma value is based on:

- (a) Test experience from R-1
- (b) Criticality experiments in a critical facility on the actual core (NCX), and
- (c) The use of the shim tube capability; i.e., the in-place shim assembly (ISA) concept.

The cold critical uncertainty would be ± 50 cents without the in-place shim assembly concept.

Addition of the cold critical uncertainty to the minimum shutdown margin of \$1.50 puts the nominal start of life cold critical at \$1.65 from the most poisoned position and the possibility that the drum position at cold critical (start of life) can range from \$1.50 to \$1.80.

3.1.3 Loss of Core Reactivity Due to Corrosion

The assignment of a corrosion loss is a difficult task. It is not the purpose of this study to report in detail on the corrosion characteristics of NRX cores, the use of these data for predictions of the performance of development and flight cores or the models used in these predictions. Some of these aspects are reported in WANL-TME-2674⁽⁶⁾. The solution, though, to the problem of specifying a corrosion loss reduces itself to a selection of one or three approaches:

- a. Base the corrosion allowance on that amount of corrosion permissible from a structural standpoint.
- b. Base the corrosion allowance on an estimate of achievable results of the fuel development program.
- c. Base the corrosion allowance on the assumption that defect free fuel can be developed such that the corrosion will be limited to that resulting exclusively from the mechanism of diffusion.

(THIS PAGE UNCLASSIFIED)

~~CONFIDENTIAL~~

(U) The term "corrosion allowance" as used above refers to the change in reactivity attributable to the loss of corrosion. It is not synonymous with loss of material due to corrosion since the relation between weight loss and reactivity loss depends on the distribution of the weight loss (See Figure 3-1).

3.1.3.1. Permissible Corrosion: Structural Criteria

(CRD) Fuel element structural requirements are to withstand the pneumatic and mechanical bundling loads as applied by the core periphery and to transmit the axial loading of the element to the cluster hardware. It is believed that a peak incremental weight loss of 1.5 gm/inch (average for all elements in the core) represents a threshold above which rapid deterioration must be expected and likewise probability of structural failure of elements.⁽⁸⁾ This 1.5 gm/inch represents approximately 15% of the graphite fuel element weight (excluding the uranium beads), or 18% of the free graphite in a 30 v/o composite element.

(CRD) Also, because of variations in element corrosion performance, about 16% of the elements could be expected to have incremental corrosion peaks in excess of 2 gm/inch when the core average is 1.5 gm/inch.

(CRD) Calculations were made to determine the reactivity loss (associated with maximum peak incremental weight losses of 1.5 gm/inch) for three different axial distributions of corrosion. The results, shown in Table 3-1, indicate that if the peak incremental corrosion can be limited to 1.5 gm/inch, the reactivity loss could range from around \$1.0 to in excess of \$2.5 depending on the distribution.

3.1.3.2 Permissible Corrosion: Estimate of Development Success

(U) The characteristics of the fuel being developed for 10 hour cyclic operation are very uncertain. The corrosion distribution associated with either the composite fuel or the high expansion graphite fuel is not known. WANL's judgment is, however,

~~CONFIDENTIAL~~

Figure 3-1: Normalized Fuel Carbon Reactivity Coefficient

TABLE 3-1
CORRESPONDING CORROSION ACTIVITY LOSSES*

A.	All Hot End Carbon Diffusion Loss	\$0.97	\$1.07
B.	NRX-A6 Reactor	\$2.17	\$2.39
C.	Distribution Composed of Hot End from (A) and Midband from (B) in Proportion to Maximize $\Delta \rho$	\$2.56	\$2.82

* CORROSION REACTIVITY LOSSES CORRESPOND TO PEAK
1.5 GM/INCH CORE AVERAGE INCREMENTAL LOSS (CRD)

~~CONFIDENTIAL~~

- (U) that the amount of weight loss per element will exceed that due to diffusion only and that the distribution will not be as advantageous as the diffusion model. Weight losses corresponding to reactivity losses on the order of \$2.00 seem to be a reasonable estimate.

3.1.3.3 Permissible Corrosion: Defect Free Fuel

- (CRD) Table 3-2 gives the results of calculations made to determine fuel geometry and core size effects on hot end diffusion corrosion for 10 hour operation. Notice that the maximum incremental corrosion is less than 1.5 gm/in. for all but the 37 Hole Hybrid type fuel and the reactivity loss is on the order of 75 cents.

3.1.3.4 Corrosion Loss Selection

- (U) Basing the corrosion compensation requirement on the defect free fuel element presents a considerable risk. It would mean that drum size, reflector size, and support stem reactivity adjustment requirements would be based on the hope that fuel development goals would, in fact, be achieved. Bear in mind that so far as the core functional performance is concerned, development of a completely defect free element is not required. That is, its ability to transfer the required thermal power to the propellant and at the same time meet its structural requirements are not contingent on the development of a defect free element.

- (U) On the other hand, considering the various possible combinations of corrosion distributions, a \$2.00 corrosion loss appears to be a reasonable requirement for flight reactors.

- (CRD) However, because there are uncertainties in both the corrosion weight loss distribution and in the ability of the element to withstand high incremental corrosion (>1.5 gm/in) it is possible that extended endurance may be obtained with more than \$2.00. At least, it would seem to make sense to be able to operate development reactors even if the reactivity loss due to corrosion exceeded \$2.00. On this basis, a reactivity compensation for ground tests is set at \$3.00.

~~CONFIDENTIAL~~

TABLE 3-2
FUEL GEOMETRY AND CORE SIZE EFFECT ON HOT END DIFFUSION
CORROSION AND RELATIVE MIDBAND CORROSION

Design Alternate (1)	Hot End Diffusion Corrosion (a, b) For 10 Hour Operation					Relative Mid-Band Corrosion(c)	
	GMS-HE Per Elem. (2)	Maximum Gms/In. (3)	Relative Gms Carbon Removed Per Unit Bore Area (4)	Percent Carbon Removed from Min. Web Dim. (5)(d)	Reactivity Loss - \$ (6)	GMS-MB Per Elem. (7)	MB - \$ (8)
1. (Std. Int-Exp. Graph)	14.7	1.17	1.0	17.2	0.70	10.0	0.78
2. (Std. H-Exp. Graph)	14.6	1.17	1.0	17.5	0.70	10.0	0.78
3. (Std. Hybrid)	14.6	1.17	1.0	19.7	0.76	10.0	0.78
4. (37 Hole Hybrid)	20.6	1.66	0.87	26.0	1.02	16.0	1.17
5. (Std. Composite)	14.6	1.17	1.0	19.7	0.78	10.0	0.85
6. (Single-ch. Carbide)	----	----	----	----	----		
7. (Zig-Zag Comp.)	14.6	1.17	1.0	19.7	0.78	10.0	0.85
8. (HV-Comp. Long)	17.0	1.13	0.92	19.7	0.86	12.6	1.08
9. (Std. H-Exp. Graph. Large)	15.8	0.96	0.84	14.4	0.68	14.6	1.12

- a) PEWEE -2 development coating profile, i.e., 3.1 mils thickness at hot end.
b) Defect free hot end corrosion based on carbon diffusion loss only.
c) Mid-band corrosion proportional to bore surface area and fuel length with a ten gram loss assumed for the reference element.
d) Assuming carbon is removed equally from the circumference of the bore, then incremental grams lost can be related to an annular region from which carbon has been removed and having a certain depth dimension from the bore wall. The percent carbon removed from an interior web is defined as the ratio of this distance to the minimum web thickness.

3.1.4 Xenon Poisoning

An additional factor which can affect the cold critical position is the amount of xenon poisoning. The requirement, insofar as the drums are concerned, is to be able to override the poisoning, whatever it is, over the life of the NSS.

The reactivity worth of the poisoning depends on operating history, the time a restart is required after the previous burn, nuclear characteristics of the core and reflector, and drum position. At the time this study was done, it was estimated that if a restart was required about 10 hours after a 1 hour run near the end of the 10 hour life such that the drums must assume, during the dry start period, their least poisoned position, the poisoning effect would be approximately 70 cents.⁽⁹⁾ It was concluded that a detailed analysis of the selected reflector design in connection with specific mission analysis data would be required to establish a more precise allowance for xenon poisoning.

The value used for the hot bleed, 50 minute reactor, was 30 cents based on a startup 10 hours after a 50 minute burn. So for this study, it was estimated that from 30 to 70 cents should be assigned to the xenon poisoning allowance.

3.1.5 AMOD Effects

Since the reactivity characteristics of the full flow cycle reactor are such that the drum position at rated conditions at the start of life (the "orifice angle") is inside the start of life cold critical, the result is that the drums will have a reactivity insertion capability of about \$4.00 beyond the orifice angle. Studies on the hot bleed cycle⁽¹⁾ showed that control drum actuator failures resulting in a drum going to the full out position, would at least compromise the reliability of the core if they would not be unacceptable.

To circumvent control drum actuator failures, an actuator malfunction override device (AMOD) has been added to the reference design. This mechanism is functionally characterized by the ability to disengage the actuator from the control drum drive shaft and through the release of stored energy (a spring), reposition an out of phase (compared to the drum bank) control drum to a preselected position corresponding to the orifice angle.

Reliability studies indicate that at least one drum should be considered fixed at the orifice angle due to AMOD activation.⁽¹⁰⁾ This means that the remaining seventeen drums must satisfy the reactivity adjustment requirement during startup at end of life which normally would be achieved by the motion, as a bank, of all eighteen (18) drums. This being the case, and with an assumed \$4.00 reactivity adjustment requirement beyond the orifice angle, and additional \$0.25 is required.

3.1.6 Thermal Conditioning Effects

The critical position prior to introduction of propellant flow can be affected by the temperature state of the reactor core and reflector. Cold critical is defined as the critical position of the drums with all the reactor components at room temperature (approximately 540°R). The reflector and core feedback reactivities as a function in their average temperatures is shown in Figure 3-2⁽¹¹⁾. The algebraic sum of these feedback reactivities for particular core and reflector temperatures will affect the critical position by a corresponding amount. The effect, then, on "cold critical" position is:

a. Temperatures below room temperature: Reactor equilibrium temperature of approximately 200°R appears to be a reasonable lower limit. The net effect on core/reflector reactivity as shown in Figure 3-2, is an increase in reactivity of approximately 15 cents. It has also been estimated that the drum worth goes down by approximately 2 1/2%.

At the start of life condition, with the cold critical normally about \$1.65 out from the most poisoned position, the effect due to the change in drum worth would be to run the drums to a position corresponding to 1.025 times \$1.65 or \$1.69. But the increase in the core/reflector feedback of 15 cents would place the drums at \$1.54. For this case, then, there is no requirement to expand the drum span due to thermal effects.

At the end of life, with cold critical close to, say, \$4.50, the effect would be $0.025 \times \$4.50 = 0.15$ or a minus 4 cents.

Figure 3-2: Reflector and Core Feedback Reactivity VS. Temperature
(No Flow Condition Nov. Reference Design)

The conclusion is that there is no requirement to expand the drum span due to the effects of temperature below room temperature.

b. Temperatures above room temperature: An engine prestart operation may be required during the cooldown phase of operation. The cooldown operation will be controlled in such a manner as to maximize the specific impulse. In so doing, a deliberate attempt will be made to operate both the reflector and core at or near their temperature limits which are 750°R and 1500°R , respectively. If these temperatures exist and if no attempt is made to thermally condition the reactor prior to going critical, the drum span must be increased by approximately 75 cents. (The NPRD specifies that the engine must be capable of being restarted "at any time." Depending on how this is interpreted, there may not be time to perform the required thermal conditions).

Data from cooldown studies indicate, however, that the reactor can be conditioned effectively to nearly restore room temperature condition prior to a restart.

c. The conclusion is that for flight reactors, the effect of reactor thermal conditions can range from 0 to 75 cents.

3.1.7 Dynamic Requirements

It has been assumed for this study that engine pre-conditioning (sometimes referred to as "warmup") involves an operational phase characterized by:

a. Initial Conditions

- (1) Control drums in the full in position
- (2) TPA speed is zero
- (3) SSCA is in the closed position
- (4) Initiation of the function by the receipt of the engine pre-start command

b. Final Conditions

- (1) The reactor is supercritical on approximately a 2 second period
- (2) The nuclear power has increased such as to cause a 100°R rise in the average core temperature

The time interval that has been assigned to this function is 45 seconds. Now it takes some time to move the drums from the zero position to the critical position. This time will depend on the drum velocity limit and the critical position. For example, a 105° critical position and a $10^\circ/\text{sec}$ velocity limit means that to take the drums to their critical position requires 10.5 seconds, leaving 34.5 seconds for changing the power from a little more than source level to that yielding the 100°R in temperature.

The ratio of power at which sensible heat is detected to source power is 4.65×10^9 ⁽¹²⁾. This is approximately equal to 21 e-folds. The initial five (5) e-folds are covered due to subcritical multiplication and supercritical operation out to the position of about 15 cents beyond the cold critical. This would require a drum position, say, of 120° , take 12 seconds, and leave 33 seconds to increase the power the remaining 16 e-folds. This would, in turn, require a stable reactor period of + 2 seconds. ⁽¹³⁾ From the in-hour formula, a positive reactivity insertion of 70 cents is required to provide the 2 second period.

3.2 STRUCTURAL SUPPORT CONTROL RANGE FACTORS

3.2.1 Rated Condition Controllability Allowance

Rated Operation is defined as operation within a box on the T_c , P_c map rather than at a point on the map. The dimensions of the box represent the controllability tolerance on both P_c and T_c . Figure 3-3 illustrates this idea. The $\pm 2\%$ tolerance on the thrust (from the NPRD) amounts to ± 9 psia on chamber pressure; and the $\pm 3/4\%$ lsp tolerance permits a variation in the mixed mean chamber inlet temperature of $\pm 52^\circ\text{R}$. The figure also shows the required change in reactivity adjustment needed in the SSCV/SSA system to facilitate operation within the box without drum motion. It is concluded that a value of 10 cents be assigned to satisfy this requirement.

3.2.2 Uncertainty in Hot Critical Position

The uncertainty in the hot critical position used in this study is the same as that used in the Reactor Controls Concept Study for the hot bleed cycle. This uncertainty is

Figure 3-3: Lines of Constant Reactivity for
SSCV at 0° Opening

the RSS of the cold critical uncertainty (± 15 cents, 3 sigma) and the cold to hot swing (± 30 cents, 3 sigma) which yields an uncertainty in the hot critical position of ± 35 cents, 3 sigma. The significance of this is that the total reactivity control span of the stems must include 70 cents for this factor. This will permit reactor operation with the drums at their pre-selected orifice angle with the SSCV/SSA shimming out the uncertainty in the hot critical.

3.2.3 Xenon Poisoning Allowance

If the stem reactivity worth is to be used for rated operation temperature control, the reactivity span must be able to compensate for the xenon poisoning allowance discussed in the drum span requirement section, 3.1.4, since the poisoning will not burn out in the time it takes to go from the pre-start period to rated conditions.

There are some subtleties to this problem that had not, at the time this study was terminated, been fully investigated.

a. The xenon poison buildup is not homogenous in the core but does, in fact, peak near the periphery of the core. Adjustment of stem flow is, primarily, a pseudo-homogenous adjustment in reactivity. But since the power distribution will be upset by the regional xenon poisoning effect, stem flow adjustment may not be the best way to override this effect. It may be that a combination of stem flow and drum position adjustments should be used for overriding the reactivity loss due to xenon poisoning. On the other hand, the functional requirements of the control system would be expanded and this may offset any advantage in using the stem/drum combination.

b. It may not make sense to add the entire corrosion compensation requirement with the maximum xenon override requirement since this suggests that the operational history will be such that the maximum xenon poisoning will occur near the end of life when the corrosion is at or near the \$2.00 level.

3.2.4 Corrosion Allowance

The SSCV/SSA reactivity control capability at rated conditions must include the

capability to compensate for the loss of reactivity due to fuel corrosion. The specific value assigned to this factor must be consistent with that used in the development of the drum span: \$2.00.

4.0 RECOMMENDATION

4.1 DRUM SPAN REQUIREMENTS

4.1.1 Summation of Factors for Flight Reactors

Table 4-1 presents a summary of the drum span requirements. It shows that depending on how the thermal conditioning and the xenon poisoning factors are to be treated, the drum span requirement for flight reactors could vary from \$5.05 to \$6.20.

4.1.2 Summation of Factors for Development Reactors

Table 4-1 also presents a summary of the drum span requirements for development or ground test reactors. The difference between this list of factors and that for the flight reactor is that the xenon poisoning and thermal conditioning allowances have been deleted since it can be argued that the ground tests can be scheduled to obviate the need for including these factors. At the same time, the corrosion loss factor has been set at \$3.00 for the reasons stated in section 3.1.3.4. The drum span requirement for ground test reactors then becomes \$5.75.

4.1.3 Recommended Drum Span for NERVA

With a flight reactor drum span requirement ranging from \$5.05 to \$6.20 and a development reactor drum span requirement of \$5.75. The recommendation is to size the reflector and drum span for \$6.00.

4.2 STRUCTURAL SUPPORT CONTROL RANGE REQUIREMENT

The nominal SSA reactivity span of the reference design discussed in section 1.2.1 is \$2.75. Optimum reactor operation at rated temperature requires a flat temperature distribution at the core exit (whether the active temperature control is on the drums or the SSCV). It is recommended that the structural support be assigned a requirement of \$3.00 consistent with achieving this operational goal.

TABLE 4-1
SUMMARY OF DRUM SPAN REQUIREMENTS

	Flight Reactors	Development Reactors
1. Maximum SOL Cold Critical	1.80	1.80
A. Cold Critical Uncertainty (3σ)	$\pm .15$	$\pm .15$
B. Shutdown Margin, Minimum	1.50	1.50
2. Corrosion Loss	2.00	3.00
3. Xenon Poisoning	.30 to .70	0.0
4. Actuator Malfunction Allowance	.25	.25
5. Thermal Condition Allowance	0.0 to .75	0.0
6. Dynamic Requirement	.70	.70
	<hr/>	<hr/>
Total Requirement	\$5.05 to \$6.20	\$5.75

If updated cycle conditions, detailed studies of the SSCV/SSA uncertainties and variations, and final selection of SSA design configurations preclude a \$3.00 range, adjustments in reactor operation will have to be made to exploit the range that is available.

4.3 SUMMARY

This study has re-examined the drum and support stem recommendations of Trade Study 701. Introduction of the 10 hour endurance requirement and the full flow cycle along with an expanded understanding of the structural support requirements (and capability to meet that requirement) has led WANL to recommend a change in the control drum span requirement from \$4.00 to \$6.00 and an SSCV/SSA span from approximately \$1.25 to \$3.00 at rated conditions.

5.0 REFERENCES

- 1) WANL-TME-1967, "Reactor Controls Concept Trade Study," May, 1970
- 2) Letter, R. W. Schroeder to Dr. W. O. Wetmore, October 1, 1969;
Subject: Change Order 70-1, Contract SNP-1
- 3) WANL-TME-2720, "Data Item S-54: Startup, Shutdown, and Throttling,"
Trade Study No. 714
- 4) WANL-TMI-1995. "10 Hour NSS Reference Design," December 18, 1969.
- 5) WANL-TME-2673, "Reflector Concepts, Trade Study 763, Phase I,
February, 1970.
- 6) WANL-TME-2674, "Fuel Element Concepts, " Trade Study 759, March, 1970.
- 7) DRM 51440, "SSCV and Other Reactivity Mapping Data for the 10 Hour
Reactor," J. K. Saluja, December 29, 1969.
- 8) Letter, TD-70-021, "R-1 Corrosion Reactivity Requirement, " February 5, 1970.
- 9) Nuclear & Radiation Design Preliminary Estimates, Verbal Communication.
- 10) DRM 52049, "Reliability Analysis for the Control Drum Drive Assembly,"
January 30, 1970.
- 11) Letter NRD-70-31, "Additional Drum Span Implied by Restart Conditions, "
January 29, 1970.
- 12) DRM 51430, "Reactivity Requirements for Startup Dynamic, " J. K. Saluja,
September 17, 1969.
- 13) Letter, CSD&A-102, "Verification of 70 Cents Dynamic Drum Span Requirement
of Trade Study 713," R. A. Schatz to R. P. Rose, February 20, 1970.

(3)

TITLE Trade Study No. 713 Reactor Controls Concepts	
	DOCUMENT NO. WANL-TME-2715	DATE September 1970
ABSTRACT This report documents the work performed as Trade Study 713, Reactor Controls Concepts, and presented orally to the Government on February 13, 1970. The study was conducted as a re-examination of two objectives of its parent study, Reactor Controls Concepts, Trade Study 701; namely, the definition of a reactivity control span requirement for the control drums, and a definition of the structural support assembly (SSA) rated operation reactivity control span requirement. The recommendation was that the NERVA reactor should be designed to meet \$6 drum span and a \$3 structural support assembly span for rated condition operation.		
DATA ITEM NO. S-54	SECURITY CLASSIFICATION OF DOCUMENT
CDRL LINE NO.	TOTAL NO. OF PAGES 31	
KEY WORDS Reactivity Control Span, Structural Support Assembly Span, Drum Span Requirements, Support Stem Reactivity Span Requirements		
AUTHOR/EDITOR W. J. Severson		PREPARING DEPT. Systems Analysis
W Form 59943 DOCUMENT INFORMATION SUMMARY		

 Fold
or Cut

 Fold
or Cut

1
2
3

$\frac{1}{2} \times 10^{-10}$

254

10.0.0110