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NUCLEAR SUBSYSTEM CONTROL
AND
ITS INTEGRATION INTO ENGINE CONTROL

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NUCLEAR SUBSYSTEM CONTROL AND ITS INTEGRATION INTO ENGINE CONTROL

1. INTRODUCTION

The purpose of this memorandum is to present the current Westinghouse position with respect to the NERVA engine control system. Recommendations are given in this memorandum with respect to three aspects of the control system:

- (1) Selection of the over-all engine control system which best meets the current NERVA requirements.
- (2) Establishment of an appropriate interface between the nuclear subsystem control and the balance of the over-all engine control system.
- (3) Definition of goals for future control system development.

The criteria for the over-all NERVA engine control system are, in our opinion, the following:

- (1) The control system should be chosen to provide the maximum over-all engine reliability.
- (2) The control system should ensure adequate performance of the engine.
- (3) The control system, particularly during the developmental testing phase of the program, should be one which offers maximum feasible protection from system malfunction to the vital engine components.

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The control systems considered for the NERVA engine consist basically of a reactor power level controller and a propellant feed controller coupled by a programmer and linked by the dynamics of the over-all engine system. The over-all engine system recommended in this memorandum, in our opinion, meets the requirements of over-all engine reliability and performance and provides greater protection for the reactor in the event of system malfunction than does any competing system.

For selection of the interface between the nuclear subsystem control and the balance of the over-all engine control system, we believe that the criteria should be: first, the definition of the interface should not compromise any of the principal objectives of the over-all control system; second, the definition should be one providing the greatest latitude and flexibility to both the nuclear subsystem designer and the engine designer to achieve more reliable control systems without compromising or endangering the principal components of the system; third, the definition should be one permitting the most rapid application of detailed information on the performance of important engine components to be applied to the control system design.

As a definition of the control system interface, Westinghouse recommends that the neutron flux loop and the reactor temperature loop be made part of the nuclear subsystem with the balance of the over-all control system an Aerojet responsibility. Our analysis indicates that the over-all control system is separable into two distinct parts: one, the propellant feed controller which determines the engine propellant flow rate and thus over-all thrust output of the engine; and two, the reactor power level controller which

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determines the operating temperatures within the reactor. This division of the over-all engine control system is a natural interface between that portion of the over-all control system which is essentially associated with the over-all engine control. This interface provides the nuclear subsystem designer with a high degree of flexibility and latitude to take into account detailed reactor temperature limitations in establishing allowable outlet temperatures. Furthermore, it provides an incentive without obstacles to nuclear subsystem control loop simplification since those factors to which the reactor is sensitive are under the nuclear subsystem designer's control.

As to future developments, our recommendations are toward simpler, more reliable systems. In particular, systems which permit mission accomplishment even with some control system malfunction are desirable. Furthermore, Westinghouse believes that a system which does not depend on measurement of core outlet temperature is a highly desirable objective. The system proposed, as well as the interface definition, will, in our opinion, provide a proper framework in which to seek these objectives.

II. CONTROL SYSTEM OPERATING MODES

The engine control system must operate in the four following modes:

- (1) The nuclear startup phase in which the reactor is brought from the source level up to a level at which propellant flow can be initiated.
- (2) The startup transient period during which time the propellant flow is initiated, and the power is increased

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to the desired operating level.

- (3) The steady state power range control during which the reactor temperatures are maintained within safe limits compatible with the propellant flow.
- (4) The reactor cooldown period during which the cooldown system delivers to the engine programmer a "Flow Required" signal on the basis of limiting reactor component temperatures.

Prior agreement between Aerojet and Westinghouse has established that Westinghouse is responsible for the first mode, i.e., the nuclear startup phase. This is a natural responsibility since this phase involves only the nuclear flux loop. There has also been agreement that provision of the cooldown "Flow Required" signal is a nuclear subsystem responsibility since the signal is derived from sensors in the reactor.

This memorandum deals with the power range control system which is operative in the flow startup transient and during power operation.

III. ALTERNATE POWER RANGE REACTOR CONTROL PHILOSOPHIES

The control designer has several alternate concepts which can be used for power range reactor control. It is evident that throughout the power range of operation, the chamber pressure and temperature must be controlled within limits imposed by reactor design. There are four possible control schemes that will achieve this:

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- × (a) Derive $T_C D$ (core outlet temperature demand) from $P_C D$ (nozzle pressure demand) - See Figure 1.
- (b) Derive $T_C D$ from $P_C M$ (nozzle pressure measured) - See Figure 2.
- × (c) Derive $P_C D$ from $T_C D$ - See Figure 3.
- (d) Derive $P_C D$ from $T_C M$ (core outlet temperature measured) - See Figure 4.

✓ In addition to these, a fifth possibility would be to program independently $T_C D$ and $P_C D$ so that the desired relationship between $T_C M$ and $P_C M$ is maintained.

Control schemes (a) and (c) as well as the independent programming of $T_C D$ and $P_C D$ have been discarded by both Aerojet and Westinghouse since these systems are too dependent upon the temperature loop for the safe operation of the pressure loop, and conversely.

Control scheme (b), Figure 2, is the control system currently recommended by Westinghouse. This scheme of control has been built up in a breadboard system and its capability to control the reactor investigated utilizing an analog computer. WANL-TME-270, NERVA Engine Reactor Control System: Preliminary Synthesis and Analysis, presents in detail the result of the investigation and shows that the system has adequate control for a wide variety of initial flow transients and shutdowns.

Figure 5 shows the pressure demand programs for startup, and Figure 6

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shows the pressure demand programs for shutdown which were used to demonstrate the capability of concept (b) to control the reactor during these phases of operation. The results of the most severe flow startup transients are shown in Figures 7 and 8. The system was stable and protected the core adequately from adverse rates of change of temperature. The tie rods remained within allowable temperature limits from startup to full power.

The results from the most rapid shutdown investigated are shown in Figures 9 and 10. Again, both the core and the tie rods were adequately protected. Figures 11 and 12 show the results of large, rapid flow perturbations during startup. These curves also show that the system controlled satisfactorily and safely under these adverse flow conditions.

These latter results indicate that the system recommended by Westinghouse will protect the reactor for many feed system malfunctions with the exception of a complete catastrophic failure of the feed system.

Control scheme (d), Figure 4, is the system of control preferred by Aerojet. From our point of view, this system has the undesirable feature that any malfunction of the propellant flow control system that provides less than demanded flow could result in reactor damage or destruction. As a general principle, we believe that a system which requires a specific flow rate versus time curve does not have the reliability potential of a system which can function over a wide range of flow startup transients. Thus, in our opinion, this system is less satisfactory than the system we recommend.

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IV. ENGINE CONTROL SYSTEM INTERFACE

It has been noted previously that the control system divides rather naturally into the propellant feed loop and the temperature control loop. The examples of the preceding section illustrate this point and no further discussion will be presented in support of this point. The remainder of the discussion on the interface definition will concern itself primarily with the overwhelming importance to the nuclear subsystem designer of the reactor temperature control. The discussion will consider the close interrelationship of the reactor design conditions with outlet temperature and the many areas of reactor design which are affected by the temperature control and conversely. Because of the close relationship, it is the Westinghouse opinion that responsibility for the temperature control will ensure consideration of all of the details involved in the reactor operating limits in both design and off-design condition. In summary, it is the Westinghouse recommendation that the control system interface be established at a point which maintains the responsibility for integrity and reliability of the nuclear subsystem completely within the cognizance of the supplier of these components. As a corollary, considering present system concepts, the interface in the control system should be defined so that the nuclear subsystem developer is responsible for the system design of the temperature feedback loop.

V. REACTOR TEMPERATURE LIMITATION EFFECTS ON CONTROL SYSTEM DESIGN

A. Steady State Temperature Limitations

Under steady stabilized operating conditions there are definite acceptable and safe relationships between various system parameters which must

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be maintained by the reactor control system. These functional relationships result from detailed features of a given core design or component arrangement. For the NRX-A type design, the following system components are temperature limited and must be protected:

1. Reactor Fuel

Two factors limit the temperature that can be allowed in the fuel. The first is the surface temperature of the coolant channels which is limited by the melting point of the coating. The second factor is the loss of structural integrity of the fuel as higher temperatures are experienced.

The structural aspect of the fuel problem is strongly affected by temperature gradients both in time and spatially. Fuel element temperature gradients will vary with the reactor seal design, the pyrographite tile designs, the leakage through the inner reflector, the core bundling pressure and the method of lateral support. Changes in any of these features can affect the core temperature limitations to a degree which requires that the control system change. The reactor control system designer must be cognizant of any changes so that he can evaluate its effect on the control system on a continuing basis.

Ultimately the reactor designer will specify temperature limitations by means of three dimensional space and time temperature distributions within the core. The control designer must decide which of these conditions is limiting in the temperature loop. With present systems, the control designer must be able to relate the limiting condition in the reactor to the core outlet temperature. This involves a detailed, back-and-forth, working relationship with the reactor designers.

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When using the core outlet temperature for control, the maximum hot channel temperature in the core must be correlated to the chamber temperature through an analysis of the reactor hot channel factors including a statistical analysis of the effects of manufacturing variations on channel temperature. Examples of this type of information are contained in WANL-TME-102, which show that the control and instrument measurement errors of the chamber temperature affect the number of channels exceeding the maximum allowable fuel temperature. Figure 13, taken from WANL-TME-102, shows this relationship. As reactor design and analysis proceed, this type of information must be continually revised and updated, again requiring intimate working contact with reactor designers.

2. Tie Rods

Analysis has shown that the propellant flow rate required by the tie rods has a fixed relationship to the power level. This relationship has been defined in preliminary fashion; it will be more rigorously defined by reactor analysis as design techniques improve and as knowledge is gained from the NRX and component testing programs. WANL-TME-181, Steady State Part Power Performance of the NRX-A1 Core, discusses the restrictions on power and flow required to protect the tie rods. Figures 14 and 15 taken from WANL-TME-181, show the safe operating temperature flow and temperature power maps required by the tie rods. This information can be converted into a temperature pressure map. Since chamber temperature and pressure are the control parameters used for reactor control, this is the non-linear relationship which must be provided by the reactor control system. Figure 16, based upon information

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derived more recently than WANL-TME-181, shows the temperature pressure map which was provided for in the WANL breadboard control system referred to previously.

The fuel elements and the tie rods are the critical limiting components during power operation; however, other components which must be considered during both startup and power operation are listed below and the limiting temperature tabulated. The temperature conditions on each of these components must be precisely studied during all levels of reactor operation and reactor history.

<u>COMPONENT</u>	<u>STARTUP LIMITING TEMPERATURE °R</u>	<u>POWER OPERATION LIMITING TEMPERATURE °R</u>
Fuel	700°	4400°*
Tie Rods	700°	800°
Tie Rod Channel Liner	700°	1100°
Core Support Plate	600°	900°
Inner Reflector	700°	1000°
Barrel	600°	1000°
Outer Reflector	600°	900°
Shield	600°	1000°
Reactor Vessel	600°	900°

*Maximum nominal fuel temperature which statistically corresponds to maximum fuel "hot spot" temperature of 5700°R and a nominal chamber temperature of 4090°R.

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B. Temperature Transient Limitations

1. Core

The limiting safe rate of change of temperature of the reactor, which was alluded to previously, is a function of many reactor variables. For beaded fuel elements, the transient thermal gradients and their associated stresses developed on the elements set an upper limit on allowable rates of change of temperature in the reactor. These gradients are a function of many complex flow and temperature conditions which will require detailed analysis. Analytic techniques to define these conditions are under development and will be applied to control system design as results are available.

2. Tie Rods

Tie rod integrity is affected only by hot spots or by long duration temperature transients above the design point. The control system must be capable of preventing excessively long duration temperature excursions.

3. Other Core Components

The temperature distributions during startup in the core peripheral parts, such as the seals, filler strips and inner reflector, involve detailed analysis. The temperatures and flow conditions existing during startup introduce factors which must be considered by the control system designer, since these may affect the detailed requirements of the reactor temperature feedback system.

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C. Off-Design and Malfunction Temperature Limitations

The reactor control system must be designed to protect the reactor and maintain engine operation under as many combinations of off-design situations or system malfunction conditions as possible. One function to be performed by the reactor control system designer is to identify the conditions that may exist as a result of a malfunction and to analyze together with the reactor designer the consequence of these conditions. Between these two groups a decision can be reached on suitable modes of operation for such abnormal conditions.

Items of concern which affect the operating temperature and will require evaluation in the design of the reactor control system include:

1. Temperature and Neutron Control Loop Malfunctions

The loss of feedback signals or abnormal demand signals can cause core destruction. The WANL reference design described in WANL-TME-270 provides cutback circuits to protect against such malfunctions in the control loops. These cutback circuits amount to fixed point controllers which will hold the power or temperature at a fixed value just beyond the design point in case of feedback loop failures which amount to a loss of signal. The cutback circuits also protect the core from transients of a detrimental magnitude. Further analysis and improvement is required in the design of the reactor controller which will provide operability for as many malfunctions as possible in either the flux loop or the temperature loop.

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2. Temperature Transducer Malfunction

The most likely temperature transducer malfunction is the loss of signal. This would cause a drum position demand to be generated which would destroy the core if it were not for the possibility of adding flux cutback protection. This condition is a special case of a control loop malfunction which must be provided for in the control system design.

3. Drum Malfunctions

Drum mechanism malfunction which cause either a full out or full in failure are particularly serious and cannot be tolerated at full power and flow. For the flight controller, it would increase the probability of mission success if such failure could be detected and action taken to position the failed drum at a designated nominal operating point. There are possible drum actuator failures that might drive a single drum full in or full out. In the event of such a failure, the control system could detect the failure and reset the chamber temperature to a lower value consistent with reactor safety. This value would be determined by reactor analysis on the basis of the effect of such a failure on power maldistribution. The reactor and engine would then operate at reduced performance instead of failing catastrophically.

4. Drum Synchronization

The control drums cause neutron flux scalloping around the outer edges of the core. If the drums do not move synchronously, these flux tilts or scalloping effects are accentuated and may cause hot spots or temperature gradients which cannot be tolerated. The present limitation on

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drum synchronization is that the bank of twelve must be controlled to within 5° of each other. Consideration must be given to this problem and allowance made in the protective system for synchronizing malfunction.

In summary, the purpose of this discussion has been to point out the close and intimate relationship between reactor operating limits and the outlet temperature and the complex nature of this relationship. It has been indicated that it depends on time during the operating cycle, power level and power history. Furthermore, this relationship is acutely sensitive to changes in design and advanced analytic data. We believe these factors can be taken into account with maximum system reliability by a close working relationship between reactor design, reactor analysis, and control design and analysis. This relationship can only be effective, however, if the nuclear subsystem control design includes the temperature feedback loop.

VI. RECOMMENDED DIRECTIONS FOR ADVANCED DEVELOPMENT

While the discussion in this memorandum has generally centered around two particular control system concepts, much development and analysis is required before any of these systems can be considered adequate for a RIFT flight. To achieve the near perfect reliabilities which are required, it is entirely possible that the final system will not resemble any of those presently under consideration.

There are two fundamental flaws with the systems now being considered.

These are:

1. The systems are complex, and there is no assurance that they are capable of reliable operation. It should be the goal of the

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NERVA project to develop a system which can meet performance requirements even though failures occur in major feedback or demand signals. For example, a single control system malfunction should not prevent achievement of the mission even though the predicted reliability under these conditions may be reduced. It is our opinion that a system of this type may be achieved through an extensive program of analysis and experimentation.

2. The control system as presently conceived depends upon a measurement of the reactor outlet coolant temperature for core protection. It is evident that this measurement is not truly satisfactory to perform the function. The highest temperature in the reactor can only be deducted rather inaccurately from the core outlet temperature. To make this point, it is only necessary to note that the outlet coolant temperature is a function of the fuel element flow, the coolant flow and the seal leakage.

An additional factor which enters is the effect of core inlet temperature on the reactor hot spot temperature. It has been determined that with the same core outlet temperature, a 50° change in the inlet temperature into the reflector could cause a hot spot temperature change of 500°.

In summary, it should be an objective that the temperature feedback loop should be the one that assures that the reactor is protected.

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FIGURE 1 CONTROL SYSTEM-ALTERNATE (a)

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FIGURE 2 CONTROL SYSTEM-ALTERNATE (b)

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FIGURE 3 CONTROL SYSTEM-ALTERNATE (c)

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FIGURE 4 CONTROL SYSTEM ALTERNATE (d)

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FIGURE 5

PRESSURE DEMAND PROGRAMS FOR STARTUP

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FIGURE 6

PRESSURE DEMAND PROGRAMS FOR SHUTDOWN

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LEGEND FOR FIGURES 7 THROUGH 12

Symbol	Definition	Units
W_c	Flow rate of coolant into reactor coolant channels	lbs/sec
$\bar{n}/n_o$	Linear measure of neutron power	%
P_1	Reactor coolant channel pressure below fuel orifice	psi
P_c	Reactor thrust chamber pressure	psi
θ	Control drum actuator angular position	degrees
P_{cD}	Demanded reactor thrust chamber pressure	psi
T_2	Reactor coolant channel temperature at core exit	$^{\circ}R$
T_f	Average fueled graphite temperature	$^{\circ}R$
T_c	Mixed coolant temperature in reactor thrust chamber	$^{\circ}R$
T_{tr}	Tie rod coolant temperature at core exit	$^{\circ}R$
W_T	Total flow rate of coolant into reactor coolant channels and tie rod channels	lbs/sec
$\bar{T}_a$	Average tie rod wall temperature	$^{\circ}R$
T_{cD}	Demanded mixed coolant temperature in reactor thrust chamber	$^{\circ}R$
ρ_{KI}	Total inherent reactivity	δK
$(\bar{n}/n_o)_{th}$	Linear measure of thermal power	%
Compensation	Lead network output during decreasing T_{cD}	volts

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FIGURE 7 CONTROL PARAMETERS DURING FLOW START-UP (Sheet 1)

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FIGURE 8 CONTROL PARAMETERS DURING FLOW START-UP (Sheet 2)

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FIGURE 9 CONTROL PARAMETERS DURING SHUTDOWN (Sheet 1)

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FIGURE 10 CONTROL PARAMETERS DURING SHUTDOWN (Sheet 2)

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FIGURE 11 CONTROL PARAMETERS DURING LARGE, RAPID FLOW
PERTURBATIONS DURING START-UP (Sheet 1)

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FIGURE 12 CONTROL PARAMETERS DURING LARGE, RAPID
FLOW PERTURBATIONS DURING START-UP (Sheet 2)

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FIGURE 13 CONTROL AND TEMPERATURE MEASUREMENT ERROR--°R

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MIXED CORE EXIT TEMP. VS. CORE FLOW AS A FUNCTION OF POWER AND TIE ROD EXIT TEMP.

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FIGURE 15

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STEADY STATE PRESSURE-TEMPERATURE
RELATIONSHIP TO MAINTAIN A CONSTANT
TIE ROD COOLANT TEMPERATURE (T_{tr}).

FIGURE 16

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