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March 1969

Westinghouse Astronuclear Laboratory

SUMMARY REPORT ON
WESTINGHOUSE ASTRONUCLEAR LABORATORY
EFFORTS ON THRUST NULLING (U)

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SECTION 1

(U) INTRODUCTION

(U) This report summarizes the work WANL has done on reactor decay heat removal consistent with various thrust nulling concepts for NERVA. Effort has been applied over the past year in an attempt to provide information which will allow better definition of the requirements for thrust nulling and for defining various concepts (associated with the NSS) which could provide thrust nulling capabilities during the reactor after heat cooldown process. Appendix 1 is a listing of the documents concerning thrust nulling which has application to this subject. The initial WANL effort was done as part of the Engine Task Force with the first presentation by WANL at the 4 and 5 January 1968 meeting. This presentation was documented in a letter to SNPO-C, dated 21 February 1968. Subsequent investigations were made by both AGC and WANL as to other concepts or extension of the initial concept presented by WANL. The AGC studies were presented at an April 1968, Engine Task Force meeting and are documented as a Trade Study (S054-SS090205-F1), submitted to SNPO-C in support of the Nuclear Propulsion System Specification. WANL's continuing effort was presented at a June 1968, Engine Task Force meeting.

(U) Subsequent to the June meeting, an attempt was made to determine the requirement for thrust nulling. A meeting was held in July 1968, between NERVA personnel and the Manned Space Flight Center personnel at Houston. No firm requirements were identified as a result of this meeting. Further work by AGC to evaluate additional concepts to provide a thrust nulling capability have been published in September and November (Items 8 and 10 of Appendix 1) of 1968.

(U) This report is intended to compile in one place all the work done to date by WANL on the nuclear subsystem relative to thrust nulling. As directed by SNPO-C during the 23 January 1968, SNPO-C/WANL/AGC Systems Engineering meeting, features for thrust nulling primarily through the Core Structural Support System are being added to the NSS reference design. Work is also in progress to further evaluate this reference design as to its

capabilities and limitations. This analysis will include effects of other reference design changes such as elimination of the ganged drum drive, addition of high expansion fuel, and brim and wall-to-wall shielding.

(U) Specifically, this report discusses the NPRD requirements to be considered in reactor cooldown studies, a preliminary evaluation of reactor cooldown characteristics against these requirements without thrust nulling, a preliminary evaluation of a reactor cooldown concept which utilizes primarily core structural support flow collected for thrust nulling and several alternate reactor cooldown schemes applicable to various thrust nulling concepts. A summary of the characteristics is provided early in the report.

SECTION 2

(U) REQUIREMENTS

(U) The study effort discussed in this report was performed for purposes of determining how to meet requirements presently enumerated in the NPRD, dated 5 June 1968, which read as follows:

a) Section III, B. 1. d (Last paragraph)

"During the shutdown transient, impulse lost by using propellant at less than full I_{sp} shall be minimized. However, after (tbd) seconds of coolant flow, the system should provide for either using the available impulse or for dissipating the coolant flow with zero thrust. The user shall have the option of either using the available impulse or counteracting the thrust. "

b) Section III, B. 1. e.

"In the various modes of operation, the performance shall be controlled within the following 3 sigma limits:

(1) Shutdown

(a) Total impulse	$\pm 20,000 \text{ lb-sec.}$
(b) Time	$\pm 15 \text{ sec.}$
(c) Propellant Consumption, including Cooldown Propellant"	(tbd)

(U) The preliminary investigations to meet the second sentence of requirement (a) above consist of means by which hydrogen propellant can be used to extract the reactor decay heat and then directed overboard in such a manner as to allow counter-balancing of any thrust generation. In addition, means are indicated for lengthening the time between reactor cool-down pulses, for consideration in the basic mission desires that generate requirement (a). The results of this evaluation are presented in Section 4 of this report.

(U) Requirement (b) above states the need for controllability of cooldown total impulse and shutoff. At times, this requirement has been interpreted to possibly infer the need for decay heat coolant thrust nulling. Section 5 of this report deals with this requirement in a preliminary manner.

SECTION 3

(U) SUMMARY

(U) The work to date has indicated the feasibility of using hydrogen flow through the core structural support system as a means of removing the latter time portions of the core decay heat. This allows piping the effluent to a common location where it can be directed through thrust nulling devices. Investigations have been made with hydrogen flow supplied to the core structural support system by both tank pressure (30 psia) and by a pressurized supply (up to approximately 315 psia). Table 1 summarizes the results of these studies in that it shows the time at which the core structural support system could remove the core decay heat and thus allow directing the coolant flow to a thrust nulling device for various reactor run times and structural support supply pressures. These studies are considered preliminary in nature but adequate for initial use in evaluating thrust nulling requirements. Reactor Cooldown schemes that do not utilize flow through the core to the thrust chamber result in lower coolant discharge temperatures and a resultant penalty in coolant usage for the reactor decay heat cooling process. The magnitude of this penalty is dependent on the degree to which any reactor coolant scheme other than the primary one is used during the decay heat cycle. However, to allow some relative evaluation of this penalty, the energy removed per pound of cooldown hydrogen is listed in Table 1.

(U) Conclusions which can be drawn on reactor cooldown for thrust nulling as a result of the study based on present NERVA technology are as follows:

- 1) Systems for cooling down the reactor primarily through the core structural support system and collecting the coolant for discharge to thrust nulling devices cannot be used sooner than 9 times the run time if fed by 30 psia tank pressure, or in the limit case, 0.4 times the run time if feed pressures of 315 psia are used.

- 2) If a tank fed core structural support coolant system is used for thrust nulling, the time after a run when it will be capable of removing the core heat will be dependent on the finally selected tank pressure.

TABLE 1

(U) SUMMARY OF REACTOR DECAY HEAT REMOVAL CAPABILITIES
FOR CONSIDERATION IN THRUST NULLING

<u>Scheme</u>	<u>Reactor Run Time-minutes</u>	<u>Core Structural Support System Supply Pressure psia</u>	<u>Approximate Time After Shutdown at Which the Reactor Decay Heat may be Removed by this Scheme (Thrust Nulling Initiated-minutes)</u>	<u>Energy Removed per Pound of Cooldown Fluid Btu/lb</u>
Flow through core structural support only - collected for discharge to thrust nulling device.	5	30	47	1175
	50	30	420	1175
	5	315	2	1450
	50	315	17	1450
Normal Flow Path plus Nozzle Bleed for Thrust Nulling	5	30	2	4800
	60	30	5	4800

3) The use of a reactor decay heat coolant scheme which uses the core structural support system will result in a significant reduction in heat removal per pound by the coolant due to maximum temperature limitations in the reactor components. Thus extended use of thrust nulling by this scheme will result in mission penalties due to the extra coolant which must be carried.

4) From the standpoint of efficient reactor decay heat removal for thrust nulling, the most desirable scheme is one that allows use of the coolant in the primary passages of the core. Thus, thrust nulling concepts applied to the thrust chamber would minimize the amount of cooldown propellant and make it possible to go into thrust nulling at short times after shutdown on tank pressure.

(U) The capability of providing zero thrust windows during the cooldown process has also been investigated. Studies have been made which show that considerable periods of zero thrust can be provided during the cooldown process by over-cooling the reactor during a pulse, just preceding the period where zero thrust is desired. This method does not depend upon a thrust nulling device as part of the engine design.

(U) The shutdown impulse controllability requirement as given in the NPRD has been frequently interpreted to infer the need of a thrust nulling device. The work to date has indicated the possibility that this requirement can be met without a thrust nulling device by controlling and adjusting the reactor coolant discharge temperature during the pulse cooldown process.

(U) A thrust nulling device is being added to the NERVA reference design. This design incorporates core structural support system flow and parallel reflector flow with the combined flow being collected and discharged to the thrust nulling device. The capabilities of this system are presently being evaluated.

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SECTION 4

(CRD) REACTOR DECAY HEAT COOLING SCHEMES COMPATIBLE WITH ZERO THRUST REQUIREMENTS (U)

4.1 (CRD) ZERO THRUST WINDOWS WITHOUT THRUST NULLING DEVICES (U)

(CRD) One of the needs for zero thrust capability during the decay heat cooldown period is to permit operations which cannot be accomplished while the vehicle is being thrust. The reactor can be cooled to provide longer periods between cooling pulses, but at the expense of cooldown fluid. This mode, in addition to thrust nulling, should be considered to satisfy mission requirements. Figures 1 and 2 show the time between pulses for two (2) different full power running times and for several different changes in core temperatures during the pulse. Here it is assumed that if one can anticipate the need for a non-thrusting period during the reactor decay heat removal process, sufficient overcooling can be provided to allow for a subsequent longer period of time until the next pulse. As an example, Figure 2 indicates that if a zero thrust window of 30 minutes is required after 5-1/2 hours following a 50 minute full power run, such windows could be provided by controlling the preceding pulse to lower the average core temperature approximately 800°R.

4.2 (CRD) ZERO THRUST WINDOWS BY PROVIDING THE REACTOR COOLANT TO THRUST NULLING DEVICES (U)

4.2.1 (CRD) Use of the Core Structural Support System Coolant Path (U)

(CRD) The one concept for cooling the reactor and providing the coolant to thrust nulling devices which has been investigated in the greatest detail at WANL, is the concept using the core structural support assembly for providing the reactor coolant. In this concept the coolant enters through the support stem feed plenum and cools the stem, unfueled element and the fuel elements by conduction. The flow exits into a sealed support stem effluent plenum and then through a special valve which directs the flow to the thrust nulling device. In this scheme, all core cooling must be done in the support stem flow path only. A schematic of this scheme is shown in Figure 3.

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Figure 1. (CRD) Time Between Pulses - Operating Time 5 Minutes at Full Power -R-1 Reference Design (U)

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Figure 2. (CRD) Time Between Pulses - Operating Time
50 Minutes at Full Power - R-1 Reference
Design (U)

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Figure 3. (CRD) Thrust Nulling Using Support Stem Effluent (U)

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(U) Figures 4, 5, 6 and 7 show mechanical layouts of various concepts for collecting the support stem and reflector effluent and diverting it out of the pressure vessel for the purpose of thrust nulling, for several NSS configurations, all of which were considered prior to the ED and DC meeting, July, 1968. Figure 8 shows a mechanical layout for collecting the support stem effluent and diverting it out of the pressure vessel for the purpose of thrust nulling for the NSS design shown on Drawing 939J685. Figure 9 shows the mechanical layout in the same NSS reference design, but includes provision for and subsequent collection of reflector flow.

4.2.1.1 (CRD) Capability with Tank Pressure (U)

(U) The calculational approach was to determine the time when the flow rate (due to propellant tank pressure of 30 psia) could meet the requirements imposed by the heat generation rate and allowable materials temperatures. This defines the point when thrust nulling may be initiated, based on core components only. The assumptions and results for the core structural support system with tank pressure coolant fluid are shown in Table 2. Figures 10 and 11 show the point in time when thrust nulling, based on core constraints in this mode of cooldown, may be initiated after 5 minutes and 50 minutes at full power.

(CRD) Figure 12 shows a typical support stem and liner temperature distribution at the time when thrust nulling with tank pressure could be initiated. Due to the counter flow heat exchanger effect, the liner temperature is at 1700°R but the exit support stem fluid temperature is only slightly over 500°R . Subsequent evaluation has reduced the liner temperature limit. The reduction of the liner temperature limit from 1700°R to 1300°R reduces the capability of this concept in that less heat can be removed. With this lower limit the exit support stem temperature will be approximately 300°R .

4.2.1.2 (CRD) Capability with Pressurized Feed (U)

(U) A parametric study of support stem heat removal capability augmented by pressurized feed fluid was analyzed. The assumptions used for this study are shown in Table 3. Also shown in this table is a comparison of time after shutdown when thrust nulling may be

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Figure 4.(CRD) Code 4 Study Layout (U)

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Figure 5. (CRD) Code 4 Study Layout (U)

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Figure 6. (CRD) Code 4 Study Layout (U)

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CODE 4 STUDY LAYOUT

DATE	10/10/68	BY	J. L. B.
DESIGNED BY	J. L. B.	CHECKED BY	J. L. B.
APPROVED BY	J. L. B.	DATE	10/10/68
THRUST SPOILER SYSTEM			
REV. (U)			
939J530			

Figure 7. (CRD) Code 4 Study Layout (U)

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Figure 8. (CRD) Code 4 Study Layout (U)

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Figure 9. (CRD) Code 4 Study Layout (U)

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Figure 10. (U) Decay Power - Operating Time 5 Minutes at
Full Power - Design Power= 1575 MW

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Figure 11. (U) Decay Power - Operating Time 50 Minutes
at Full Power - Design Power = 1575 MW

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TABLE 2
 (CRD) SUPPORT STEM COOLING ANALYSIS (U)

MAXIMUM ALLOWABLE CORE TEMPERATURE (SUPPORT LINER MATERIAL LIMIT)	1700°R
TANK PRESSURE	30 PSIA
R-1 REFERENCE SUPPORT STEM DESIGN	
MAXIMUM ALLOWABLE SUPPORT STEM EFFLUENT TEMPERATURE	850°R
FLOW PASSAGE TO THRUST NULLING DEVICE BASED ON 0.2 MACH. NUMBER	
OTHER REACTOR COMPONENT TEMPERATURE LIMITS NOT CONSIDERED (SHOULD BE SECOND ORDER)	
<u>PRELIMINARY RESULTS</u>	
MAXIMUM SUPPORT STEM COOLING	0.5 MW
FLOW RATE AT MAXIMUM SUPPORT STEM COOLING	0.35 LB/SEC
TO THRUST NULLING DEVICE CROSS SECTIONAL FLOW AREA	40 IN ²

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Figure 12. (CRD) Typical Support Stem Temperature Distribution (U)

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TABLE 3
(CRD) ASSUMPTIONS (U)

R-1 Reference support stem design (orificed at inlet)	
Maximum allowable support stem liner temperature	1300°R
Maximum allowable support stem tube temperature	1000°R
Maximum allowable station zero unfueled temperature	1260°R
Thrust nulling pipe flow inlet Mach number	0.2
Cross sectional pipe flow area into thrust nulling device	40 in ²
Other reactor component temperature limits not considered	

TIME AFTER SHUTDOWN WHEN THRUST NULLING MAY
BE INITIATED

Inlet pressure (psia)	30	315
Full Power Operating Time		
5 minutes	2800 sec	130 sec
50 minutes	7 hours	17 minutes

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initiated for a tank pressure of 30 psia and a pressurized inlet pressure of 315 psia for two different full power run times. Figures 13 through 17 show the support stem inlet pressure, outlet pressures, flow rate, exit fluid temperature and maximum unfueled temperature versus heat removed for the pressurized SSA feed system case.

(CRD) The reason the exit fluid temperature peaks out at approximately 9000 Btu/sec. is due to a change in the temperature limiting component. Below 9000 Btu/sec., the support tube is temperature limited while above 9000 Btu/sec. the unfueled temperature at station zero limits the heat removal capability.

(U) It should be noted that in this study using a pressurized feed source as well as the study with tank pressure only, the only components evaluated with regard to the core structural support system providing heat removal capabilities were the core region. No other component limits were considered. Further evaluation may show that other NSS components are temperature limiting with no coolant flow and, therefore, may influence the results shown in this report. The studies to evaluate the other components in the NSS as well as expanding the capabilities of the concept are presently being performed.

4.2.2 (U) Thrust Nulling by Other Concepts

(U) Two basic approaches have been investigated for providing the reactor coolant to thrust nulling devices during decay heat. The first uses only the support stem coolant path. The second uses the standard flow path through the nozzle in parallel with the support stems. Two schemes on both basic approaches are possible, making a total of four flow paths for consideration. One scheme of the first approach to use only the support stem path was presented in Section 4.2.1. The other three schemes which have been considered but only for 30 psia tank feed pressures are as follows.

(U) In Scheme A the coolant is introduced to the system through the support stem feed plenum only (the first approach mentioned above). The flow exists from the support stem effluent plenum with part of the coolant passing through the core and main nozzle and the other part passing through the reflector. That portion which passes through the reflector is exhausted to balance the main nozzle thrust. This is shown in Figure 18.

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Figure 13. (CRD) Tie Tube Pressure Requirement (U)

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Figure 14. (CRD) Tie Tube Discharge Pressure Outlet Pressure (psia) versus Heat Removed (Btu/sec) (U)

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Figure 15. (CRD) Tie Tube Heat Removal Capability (U)

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Figure 16. (CRD) Tie Tube Coolant Exit Temperature (U)

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Figure 17. (CRD) Maximum Unfueled Temperature versus Heat Removed (U)

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Figure 18. (CRD) Stem Flow After Cooling Exit at Nozzle -
Scheme A (U)

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(U) In Scheme B (for which no figure is present) the flow is introduced in the normal flow path (both nozzle torus and support stem manifold; the second approach mentioned above). The flow that enters through the normal flow path passes through the nozzle coolant tubes and reflector. At the reflector exit the flow splits, part of the flow is directed to thrust nozzles external to the pressure vessel used to null the main nozzle thrust, and the other part through the core and main thrust nozzle. Very early figures indicated large quantities of cold propellant would have to be exhausted at the reflector exit to balance the main nozzle thrust and thus because of this large inefficiency in reactor cooldown relative to the other schemes no further consideration was given to it.

(U) Scheme C uses the normal flow path (through the nozzle and in parallel with the support stems; the second approach). The flow is split at the nozzle chamber, where part of the flow exists in the forward position of the nozzle or in a transition ring from the reflector to nozzle. This bleed port flow exhausted to a thrust balancing device for the main nozzle. A schematic of this scheme is shown in Figure 19.

(U) The time that thrust nulling may be initiated with these coolant schemes, the amount of decay heat that can be removed by them, the unspoiled impulse and the total fluid requirements for different power run times is shown in Table 4 for the different schemes.

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Figure 19. (CRD) Stem Flow After Cooling Flow Separation - Scheme C (U)

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TABLE 4
(CRD) PRELIMINARY SUMMARY
THRUST NULLING SCHEME DECAY HEAT COOLING CHARACTERISTICS (U)
TANK PRESSURE = 30 PSIA

	TIME AT FULL POWER Min	INITIATE THRUST SPOILER FLOW * Sec	% OF DECAY HEAT REMOVED BY THRUST SPOILER FLOW **	TOTAL H ₂ USED FOR DECAY HEAT COOLING** Lb
Normal Flow	5			2710
Path Operation	20	---	---	6560
	60			17500
Scheme A - Flow to Stems Exhausted	5	1000	30%	4320
Through Reflector	20	3200	35%	10650
and Core	60	9500	37%	24400
Scheme C -Normal	5	120	44%	2710
Flow Path plus	20	200	69%	6560
Nozzle Bleed for				
Spoiling	60	300	85%	17500

* Represents minimum time after shutdown when thrust spoiler operation can be initiated while meeting cooldown requirements.

** Assumes coolant path is through the thrust nulling device from the minimum time at which it can be initiated till the end of the cooldown cycle.

SECTION 5

(U) IMPULSE CONTROLLABILITY DURING SHUTDOWN

(U) The ability to control the energy imparted to the vehicle during the shutdown phase is dependent on the ability to predict the total decay heat produced in the reactor and the temperature at which the decay heat coolant will be ejected. If one assumes that the capability of predicting total decay heat within $\pm 10\%$ will be developed from future reactor and engine tests, then the corresponding total cooldown impulse uncertainty for a specified cooldown coolant temperature would also be 10% unless some sort of corrective action were taken. Assuming the $\pm 10\%$ error in decay heat, Figure 20 shows the resulting impulse uncertainty as a function of reactor burn time. It can be noted that the resulting impulse uncertainty due to the uncertainty of predicting reactor decay heat is considerably outside the range of $\pm 20,000$ lb-sec. (Requirement, Section III, B.1.e, NPRD.) However, since it can be shown that the total impulse is inversely proportional to the square root of the coolant temperature, it appears feasible that the total cooldown impulse uncertainty could be controlled by varying the coolant temperature during the various pulses in the cooldown process. Table 5 presents an approximate total cooldown impulse for a five (5) minute burn time for various coolant temperatures.

TABLE 5

(U) APPROXIMATE TOTAL COOLDOWN PULSES

<u>Chamber Temperature - $^{\circ}\text{R}$</u>	<u>Total Impulse - lb-sec</u>
1000	1.4×10^6
1500	1.16×10^6
2000	1.0×10^6

(U) It can be seen that the total cooldown impulse may be varied by approximately 40% by control of the average coolant temperature between 1000 to 2000 $^{\circ}\text{R}$ during the cooldown period. The 1000 - 2000 $^{\circ}\text{R}$ range of temperatures during the cooldown seems to be a

Figure 20. (U) R-1 Cooldown Total Impulse Uncertainty
versus Burn Time

reasonable one based on previous cooldown studies and experience with NRX reactors and their cooldown limitations, but is meant to be for illustrative purposes in this study. Refinement of the most applicable range would be evaluated in future analysis.

(U) Based on the possibility of varying the total cooldown impulse, a possible logic to overcome the cooldown uncertainty in total impulse has been formulated. The logic is envisioned as follows:

1) A predicted total cooldown impulse versus time based on a predicted decay heat power and an average chamber temperature (1500°R as an example) is scheduled and used as the basis for firing time.

2) For each pulse period during the cooldown, the increment of impulse obtained is monitored and used in maintaining an integrated impulse with time history to compare with predicted.

3) If a deviation of the predicted and actual total impulse history with time occurs then the subsequent pulse periods would be re-scheduled at an increased or decreased average coolant temperature. As an example, if at an early point in the cooldown process, the actual integrated total impulse shows a -10% deviation from the predicted when pulsing at a chamber temperature of 1500°R then the chamber temperature could be decreased by approximately 20% to 1200°R on subsequent pulses for corrective action. In this manner, the cooldown total impulse may be "walked along" a predicted curve and the decay heat uncertainty effect on cooldown impulse theoretically eliminated.

4) When approaching the end of the pulse cooldown period, at which time the reactor needs no further cooling to maintain all component temperatures within limit, the coolant pulse temperature may require final adjustments to lower the core temperature to an acceptable level to assure other components remain within their limits subsequent to the termination of pulse cooling while still meeting the requirements on total impulse.

(U) It appears, based on these preliminary investigations, that means of meeting the NPRD requirement for controllability of shutdown impulse can be found in the method in which reactor cooldown is accomplished without requiring thrust nulling techniques.

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SECTION 6

(U) REFERENCE DESIGN

(U) Based on direction from SNPO-C in the 23 January 1969 Systems Engineering meeting at AGC, WANL is adding features to the nuclear subsystem which will allow the decay heat coolant to be directed to thrust nulling devices. The scheme for accomplishing this is as shown in Figure 21. This system allows the reactor to obtain cooldown flow through the normal propellant inlet line, as well as the normal core structural support system. The support system effluent is collected along with the reflector effluent and directed out of the pressure vessel to the thrust nulling device.

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Figure 21. (CRD) NERVA NSS With Thrust Nulling (U)

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APPENDIX 1

(U) LIST OF DOCUMENTATION PERTAINING TO PAST WORK ON THRUST NULLING

1. Letter, Arnold to SNPO-C (Bosse) February 21, 1968, NERVA Decay Heating Cooling Thrust Requirements
2. Letter to Stinnett from Schroeder, March 26, 1968, NERVA Decay Heat Cooling Thrust Requirements (requests AGC to initiate some additional studies)
3. Memo 7830:M3671, Sheridan from Buden, April 10, 1968, Specific Impulse and Thrust Performance of the NERVA Engine
4. Engine Task Force meeting minutes, April 19, 1968, for meeting on April 16-17 Schroeder to Arnold
5. Engine Task Force meeting minutes, June 17, 1968, for meeting on June 13-14 Schroeder to Arnold
6. Trip Report from E. J. Ney, Trip to Houston, Manned Space Center, June 11, 1968, letter number WANL-TR-5891
7. Trip Report from Johnson, SNPO-W, same subject as Item 6
8. AGC letter 7830:M3853, Preliminary Analysis of NERVA Engine Null Thrust Technique dated September 18, 1968
9. WANL letter SI-004, WANL Comments on AGC letter 7830:M3853, October 1, 1968
10. AGC letter 7810:1048, Rice to Schroeder, AGC, Thrust Nulling Studies, November 25, 1968
11. AGC Trade Study, S054-SS090205-F1, September 1968
12. DRM:1017, Decay Heat Removal Capability of the Support Stem Assembly, July 9, 1968
13. DRM:1036, Support Stem Cooling Augmented by Pumped LH_2 /Support Stem, September 16, 1968