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WANL-TME-2725
JANUARY 1971

DATA ITEM S-54

REACTOR
COOLDOWN CRITERIA (U)

TRADE STUDY NO. 757

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Class:	u		

REACTOR

COOLDOWN CRITERIA (U)

TRADE STUDY NO. 757

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MASTER

INFORMATION CATEGORY	
<u>J. M. Houghton</u> 1-11-71	
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ABSTRACT

Using the tank pressure cooldown system evolved in Trade Study 703, performance calculations were made to update hot bleed results to the full flow engine; operating procedures, and instrumentation and controls requirements were defined. Other topics such as use of additional throttling valves, reactor temperature conditioning, thrust nulling, impulse controllability, and laminar flow instability were covered for the preferred alternate 2 (POSL).

The study concluded that the reference design met all requirements, and used 3213 lbs. propellant at an average chamber temperature of 1533°R (5033 lbs. propellant at 1700°R including the shutdown ramp for a 10-minute burn). The valve options of two alternates were within $\pm 10\%$ in performance but less desirable as shown in a *Comparison Matrix*.

For a $\pm 5\%$ on the decay heat uncertainty, the reactor must be capable of producing a 1455°R average chamber temperature in cooldown to meet the impulse controllability and minimum specific impulse requirements of the engine.

This study used as its model, the full flow cycle with the reference NSS model in existence during the period of November 1969 to March 1970. The significant results of this study were formally presented in February 1970 Trade Study meetings.

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1.0 SCOPE

Trade Studies 703 and 704, Reactor Cooldown and Thrust Nulling, concluded that a tank pressure system known as POSL (Pulsed-on-Separate-Limits) with alpha (radial) thrust nulling was the most desirable system of those analyzed. The original scope of this trade study was to update the hot bleed study to the full flow engine including the reactor temperature limits, associated instrumentation sensors, and criteria used in initiating, stopping, and controlling the flow. During the course of the study, two alternates, other than POSL, evolved which employed different engine valve arrangements to control the flow to the NSS which remained unchanged.

Basically this trade study is a continuation of Trade Studies 703 and 704, using the system selected therein as a basis of comparison. It is not a complete systems trade study in the true sense of the word but a study of operational procedures and a refining of the previous data.

The trade study is an input to the ANSC Trade Study 022⁽¹⁾.

2.0 IDENTIFICATION OF REQUIREMENTS FOR TRADE OFF

The general requirements for the shutdown/cooldown phase of operations stem from the NERVA Program Requirements Document (NPRD)⁽²⁾. The functional requirements are six in number:

1. Maintain structurally acceptable stress levels.
2. Maintain structurally acceptable temperature levels.
3. Optimize shutdown chamber temperature ramp rates.
4. Minimize impulse lost when operation is at less than full rated specific impulse.
5. Provide the option of either using the available impulse or for dissipating the coolant flow with zero thrust.
6. Maximum effort placed on a design which eliminates single failures.

The technical requirements are related to impulse controllability and reliability.

1. Controlled within the following 3 sigma limits.
  - a. Total impulse $\pm 20,000$ lb-sec
  - b. Time to end of cooldown ± 15 sec
  - c. Propellant consumption including cooldown (TBD)
propellant
2. Engine reliability of 0.995 at 90% confidence

3.0 DESCRIPTION OF POSSIBLE DESIGN APPROACHES

The NSS model is the Reference Design of WANL ECP-006⁽³⁾ used for analytic studies in the period of November, 1969 to March, 1970. The structural support coolant supply system shown is the preferred selection of Trade Study 760, as presented in the WANL Trade Study Review Meeting of February 13, 1970.

The Throttle Stem/Throttle Reflector (TS/TR) concept uses a continuous flow adjustment, approximately proportional to power. The highest possible performance within reactor temperature limits is achievable with this system. Total flow is controlled by one CSCV and the flow split between the nozzle-reflector and structural support is controlled by reverse flow through the SSCV. The feasibility and/or limits of low flow valve throttling must then be established for both the CSCV and SSCV. A flow schematic of this system is shown in Figure 3-1.

A side issue with this concept, as with the other two concepts, is to determine the effects of the structural support bypass flow during cooldown. This flow reduces chamber temperature, but it could be needed to cool the support plate.

The second concept is the reference concept of Trade Study 703, Pulsed-on-Separate-Limits (POSL), and is a slight modification of TS/TR requiring the same combination of valves. Flow to the stems is continuous and flow to the reflector is governed by the on-off action of an SSBV. Its amount may be adjusted by the position of the SSCV and/or the CSCV. Valve throttling limits and bypass flow effects are also to be established.

The third concept, On-Off Stem/Throttle Reflector (OS/TR) requires an additional set of valves and a slight rearrangement in piping. As shown in Figure 3-2, stem flow is controlled by forward flow through the SSCV and reflector by the RCV. This concept is proposed for a reflector temperature limited system.

Although the above three concepts form the major set of analysis for this trade study, several sets of analyses generally common to all concepts also were made. The cooldown restartable component temperature limits were again studied as a result of the influence in

Figure 3-1. Flow Schematic for Alternates 1 and 2

Figure 3-2. Flow Schematic for Alternate 3

Trade Study 703⁽⁴⁾. The relation of these limits to instrument location and their use in control were determined. A shutdown calculation was needed to obtain proper initial conditions for the following cooldown calculations. Reactor thermal conditioning flow and time in preparation for a restart from maximum cooldown material temperature levels were obtained. Finally, thrust nulling flows, exit gas temperatures and pressure drops for radial thrust nozzles (System Alpha of Trade Study 703) were computed for power levels less than 350 KW.

4.0 COMPARISON MATRIX

NOMENCLATURE		W ASTRONUCLEAR LABORATORY COMPARISON MATRIX OF DESIGN APPROACHES			SELECTION
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS		TS/TR 1 Throttle Stem/Throttle Reflector	POSL 2 Pulsed-On-Separate-Limits	OS/TR 3 On-Off Stem/Throttle Reflector	
Weighting Factor					
10	NSS Reliability	Acceptable temperature and stress levels	Acceptable temperature and stress levels	Acceptable temperature and stress levels, required additional PDL valves	10, 10, 9
10	NSS Safety	No single failure modes	No single failure modes	No single failure modes	10, 10, 10
9	Cooldown Performance, Total Cooldown Propellant Used - lb	2980	3213	3500	9, 8, 7
8	Impulse Controllability	More throttability, higher chamber temperature	Base	Same	8, 7, 7
7	Thrust Nulling	Meets requirements for radial nulling	Meets requirements for radial nulling	Meets requirements, independent reflector flow control	6, 6, 7
4	Valve requirements	Very high degree of valve throttling, continuous control	Base	Additional valves in pump discharge line for reflector flow control	1, 4, 2
3	Stem Bypass Flow	10°R reduction in chamber temperature	Reduces cooldown valve cycling by 10-20%, decreases chamber temperature by 10°R	10°R reduction in chamber temperature	2, 3, 3
5	Laminar Flow Instability Problem	Must accept potential instability for continuously throttled flow	Not a problem for core flow	Must accept potential instability for continuously throttled reflector flow	1, 5, 1
5	Reactor Thermal Conditioning	Same	Base	Cannot control reflector flow independent of core flow	4, 4, 3
3	NSS Weight	Same	Base	Same (has additional engine valves)	3, 3, 2
6	Cooldown Instrumentation and Control	Continuous flow adjustment to achieve pseudo steady state operation	Simple valve operation but has stem temperature overshoot	Requires fast response for stem circuit, continuous reflector flow adjustment.	6, 5, 5
TOTAL 70				TOTALS	60, 65, 56

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5.0 SELECTION OF APPROACH

The following sections correspond to the functional and technical design requirements in the comparison matrix of Section 4.

NSS Reliability

Since the Failure Mode and Criticality Analyses (FMECA) generated for the flow systems used for alternates 1 and 2 (Figure 3-1) show no difference, the same weighting factor was used (10). The requirement for two additional valves, RCV, for alternate 3 (Figure 3-2) reduced the weighting factor to (9). The FMECA's are given in Appendix A.

NSS Safety

All systems rank equal for the reason that there are no internal NSS changes from system to system. No single point failure modes exist.

Cooldown Performance

Maintaining acceptable temperature and stress levels during the shutdown and cooldown operations is a functional requirement which must be satisfied by all three approaches. Since only the control of flow is different for each approach, and not the internal NSS flow path, it is a matter of providing proper control parameters and associated temperature limits to the engine controller. Each system's flow is controlled to make temperatures acceptable.

The basis of the following cooldown analyses is the decay power resulting from the following run profile for which the delayed power term is multiplied by 1.05 to produce the high side of the decay power uncertainty. This run profile including pump tailoff is the reference defined by ANSC.⁽¹⁾

- 1) 28 second startup to 1452 MW, 4196^oR and 438.3 psia chamber conditions
These chamber conditions are estimations of nominal minus three standard deviations.
- 2) 10 minute hold
- 3) 4 second ramp to throttle point
- 4) 30 second throttle hold at 4196^oR and 270 psia chamber conditions

- 5) 11 second powered ramp to 2600°R and 160 psia chamber at which time drums are stepped to zero.

This run profile provides the initial conditions at the end of pump tailoff from which the required cooldown analysis can proceed.

The decay power is calculated by PRECUR, a program which solves by finite difference the reactor kinetic equations for 10 group decay precursors and 6 group delayed neutron precursors. These precursor concentrations are used as input to the TNT-PAM cooldown performance calculations starting at the throttle point.

It is worth repeating a finding of Trade Study 703⁽⁴⁾ regarding shutdown. The shutdown reported herein is a fast shutdown ($\sim 125^\circ/\text{sec}$). Reference 4 shows that up to 800 pounds of propellant can be saved by ramping the drums to zero from the throttling point and slowing down the chamber temperature ramp to approximately $80^\circ\text{R}/\text{sec}$, resulting in a far more efficient shutdown.

Figure 5-1 gives the power fraction-time profile during the first 127 seconds (673 to 800 seconds after startup), including both fission and decay portions. Figure 5-2 gives the absolute magnitude of the power down to 10 KW, or the end of cooldown.

The fuel element exit and lateral support exit temperature are shown in Figure 5-3 during the shutdown/tailoff time period. The corresponding reactor flow rates are given in Figure 5-4. The increase in flow occurring at 696 seconds is caused by the combination of continually decreasing chamber temperature and the initial fast decrease in power with a gradual decrease after the prompt fission goes to near zero. After the temperature demand is constant, the flow reaches a maximum and monotonically decreases thereafter.

Material temperatures for the structural support tube and liner are shown respectively on Figures 5-5 and 5-6. Gas temperature at the turnaround and exit are shown on Figure 5-7 for the shutdown/tailoff period.

TOTAL THERMAL 1 FISSION 2 DECAY 3

20 MINUTES AT FULL POWER ~~SHUTDOWN~~
POWER

INDEX NO.

001-R1

Figure 5-1. Fraction of Design Power During Shutdown

Figure 5-2. Power Profile of Run

FUEL-AVERAGE 2 LATERAL SUPPORT 3 20 MINUTES AT FULL POWER --SHUTDOWN-- CHAMBER TEMPERATURE	INDEX NO. 001-R1

Figure 5-3. Fuel and Lateral Support Exit Temperatures During Shutdown

CHAMBER 1 CORE 2 REACTOR 3 SUPPORT SYSTEM 4 BYPASS 5

20 MINUTES AT FULL POWER - SHUTDOWN
FLOW RATES

INDEX NO.

001-R1

Figure 5-4. Reactor Flow Rates During Shutdown

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~~GROUP 1 EXCLUDED FROM AUTOMATIC DOWNGRADING AND DECLASSIFICATION~~

STATION 44.9-1   STATION 29-2   STATION 8.9-9   STATION 4-4

30 MINUTES AT FULL POWER - SHUTDOWN
STRUCTURAL SUPPORT TUBE TEMPERATURES

INDEX NO.

001-R1

Figure 5-5. Structural Support Tube Temperatures During Shutdown

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~~RESTRICTED DATA~~
~~GROUP 1 EXCLUDED FROM AUTOMATIC DOWNGRADING AND DECLASSIFICATION~~

STATION 44.2-1 STATION 20-2 STATION 2.2-2 STATION 4-4

30 MINUTES AT FULL POWER - SHUTDOWN	INDEX NO.
STRUCTURAL SUPPORT LINER TEMPERATURES	001-R1

Figure 5-5. Structural Support Liner Temperatures During Shutdown

TURN AROUND-AVERAGE 1 EXIT-AVERAGE 2

20 MINUTES AT FULL POWER SHUTDOWN
STRUCTURAL SUPPORT FLUID TEMPERATURES

INDEX NO.

001-R1

Figure 5-7. Structural Support Exit and Turnaround Fluid Temperatures During Shutdown

A series of steady state runs were made to scope the valve throttling requirements of TS/TR. This continuous flow system has the potential of having the highest average chamber temperature. However, these runs determined that continuous flow requires source pressures (downstream of valves) of less than 5 psia 1 hour after shutdown and 1 psia 10 hours after shutdown to operate both the reflector and stems near their respective temperature limits. During the cooldown phase approximately 2900 pounds of propellant are required. This method may put unrealistic requirements on the throttling valves, and this method produced only a 10 percent propellant savings compared to the alternate systems discussed herein.

The OS/TR, on-off stems/throttle reflector, has its principal advantage during the low power cooldown. When the stems cease to be the limiting component, the reflector limit causes a reduction in chamber temperature. The stems can be cooled by conduction and radiation to the core coolant and do not require direct convection cooling. This results in approximately 15-20 percent savings in propellant during this phase of operations. However, the on/off stem cannot be used during the high power cooldown without serious degradation of chamber temperature, or very frequent on/off cycles (< 1 sec). This system is then a degenerate case of the normal pulsed cooldown discussed in Reference 4 for this phase of cooldown and requires approximately 30-40 percent more propellant. This results in a net 0-10 percent increase in propellant over the reference cooldown to be discussed in the following paragraphs, and has the added disadvantage of requiring another set of valves in the pump discharge line.

The reference cooldown system, POSL, at the start of this trade study was derived from Trade Study 703⁽⁴⁾ and is the system for which all of the following detailed calculations were made.

The TNT Performance Analysis Model (PAM) with core/reflector conduction was used for the cooldown calculations. At the termination of the full power point, the SSCV was positioned at its minimum flow value and the bypass was wide open. These positions were held throughout pump tailoff, after which the SSA bypass valve was set to its maximum impedance position and the SSCV was set wide open.

Cooldown calculations using the POSL method were initiated at 800 seconds (all times refer to time from startup, and include full power and throttling burn). In the time period from 800 seconds to 2000 seconds, several methods of control were attempted in order to maximize chamber temperature and minimize the support stem temperature overshoot problem described in Trade Study 703⁽⁴⁾. The following conclusions are made from these runs:

1. If the SSA bypass is permitted to remain wide open, (minimum impedance) approximately 40 percent of the total flow takes this path when the reflector overlay pulse is on. Consequently there is not sufficient flow in the reflector during the pulse to reduce its material temperatures substantially, necessitating frequent pulsing to keep chamber temperatures above 1500°R.
2. With the SSA bypass valve at its maximum impedance, it still takes 20 percent of the total flow (2.5 lb/sec). The support plate temperatures never exceed 450°R with this flow, even between pulses when up to 640°R stem effluent is in the plena.
3. The reflector pulse overlay may be initiated by any component reaching its temperature limit, not just the reflector. These temperature limits are tabulated in the Instrumentation and Control Section in Table 5-4. The reflector flow is shut off when the chamber temperature reaches 1500°R. As a result of the above calculation, it was determined that the SSA bypass flow is not necessary for support plate cooling during this portion of the cooldown.
4. The minimum reflector pulse duration recommendation is ten seconds to avoid rapid valve cycling. This time period is long enough to achieve a small amount of reflector material cooling without much degradation of chamber temperature.
5. The following technique is proposed to minimize the stem temperature overshoot in the period following pump tailoff. With the SSA bypass shut off and flow to both the reflector and stem paths, the cooldown valve is throttled to maintain a chamber temperature greater than 1650°R and all components within

their temperature limits. When the downstream valve pressure reaches 12 psia, the reflector flow is terminated and the system is on stem flow only. As the stem approaches its temperature limit (within 50°R) both the reflector valve and the cooldown valve are opened wide. The stem and liner temperatures continue to rise for approximately 20–30 seconds before reaching their maximum. The reflector pulse may be throttled, but is terminated when the chamber temperature reaches 1600°R . The chamber temperature will continue to drop below 1600°R on stem flow alone and the stem flow (cooldown valve) must be throttled continuously to avoid dropping below 1500°R . Reflector pulse duration is approximately 70 seconds and stem-flow-only pulse duration is approximately 240 seconds. This cycle continues for 20 to 25 minutes for the reference burn.

6. The technique of (5) above requires a very fine control valve for the CSCV, one that is capable of throttling flow on tank pressure from 2.5 lb/sec wide open to 0.1 – 0.2 lb/sec during stem flow only. If stem flow is not throttled during this period, the stem temperature overshoot problem is aggravated so that the system (liner) temperature lag is increased by approximately threefold to 150°R . Simultaneously, the average chamber temperature is decreased. A simple calculation was made to scope the magnitude of the change. If the overlay pulse schedule is held constant and the stem flow rate is held constant at the wide open valve position of 0.4 lb/sec, the average chamber temperature decrease is 200°R . In reality the overlay reflector pulses would be rescheduled and would mitigate this change. Because of the above two reasons, it is recommended the stem flow be throttled with at least 1.8 lb/sec to the reactor with wide open valves.
7. When the reflector temperature limit initiates the pulse, a switch from continuous stem flow to normal pulsed cooldown operation is made. This occurs at 2300 seconds. Even though initial chamber temperatures of 1700°R are achievable, the average is approximately 1450°R .

The total cooldown performance evaluation is measured by two parameters, chamber temperature and chamber flow. The calculations performed to date have not yielded what are considered to be optimum profiles. That is, by readjusting some of the control parameters as cooldown valve closure rate or stem pseudo temperature limit, the next calculation will show improvement. Thus, the optimal solution is approached asymptotically. A summary of the cooldown performance is given in Table 5-1.

The data shown in Figures 5-8 and 5-9 are estimates of the best attainable chamber temperature and flow within the component temperature limit constraints. These are based on the actual PAM cooldown calculations shown in Figures 5-10 and 5-11. A comparison of Figures 5-8 and 5-10 shows an improvement of approximately 150°R . Three calculational changes are necessary to achieve this. First, the pseudo stem limit is raised from 1100 to 1300°R (only 50°R overshoot anticipated). Second, the cooldown valve throttling rate (pressure reduction rate) is increased from 1%/sec to 3%/sec, and third the throttled pressure lower limit is reduced to 12 psia, rather than 15 psia.

To illustrate the above, additional data companion to Figures 5-10 and 5-11 are listed below for POSL.

1. Plenum Pressures - Figure 5-12
2. Stem Material Temperature - Figure 5-13
3. Liner Material Temperature - Figure 5-14
4. Stem effluent temperature - Figure 5-15
5. Maximum beryllium reflector temperature - Figure 5-16

In the time between 2300 seconds and 1.3 days, the reflector is the limiting component, and its station 26 measured temperature is to be used for the pulse initiating feedback control parameter. Heat conduction from the core rather than internal heat generation is the reason the 750°R limit is reached. When this condition arises, continuous flow through the stems is no longer advantageous. The continuous stem flow technique is abandoned in favor of the normal cooldown (on/off pulsing through both stem and reflector paths). Chamber temperature in excess of 1400° may be achieved. Thus, 40%

TABLE 5-1

COOLDOWN SUMMARY FOR 10 MINUTE BURN FOR POSL
(1.05 DECAY HEAT POWER FACTOR, 30 SECONDS THROTTLING)

	<u>SHUTDOWN/TAILOFF</u>	<u>CONTINUOUS STEM FLOW</u>	<u>NORMAL PULSING</u>
APPROXIMATE TIME AFTER STARTUP - SECONDS	662-800	800-2300	2300-115000 (1.33 DAYS)
FLOW PATHS UTILIZED	NORMAL REACTOR	COOLDOWN LINE TO STEM OR STEM/ REFLECTOR	COOLDOWN LINE TO NORMAL REACTOR
LIMITING PARAMETER	NONE ⁽¹⁾	STEM	REFLECTOR
CHAMBER TEMPERATURE RANGE - °R	4250-1625	1850-1500	1600-1400
AVERAGE TEMPERATURE - °R	2190	1650	1450
HEAT REMOVED - BTU × 10 ⁻⁶	13.33	7.95	9.50
PROPELLANT USED - LBS (TOTAL = 5033 LBS)	1820	1341	1872
PERCENT OF TOTAL HEAT REMOVED	43	26	31
PERCENT OF TOTAL PROPELLANT USED	36	27	37

(1) SHUTDOWN/TAILOFF SHOULD BE PROGRAMMED TO OPERATE STEM NEAR LIMIT WITH OPEN SSCV.

Figure 5-8. Chamber Temperature During Continuous Stem Flow for POSL

Drums in at 673 sec

Figure 5-9 CHAMBER FLOW DURING CONTINUOUS STEM FLOW FOR POSL

FUEL-AVERAGE 2 LATERAL SUPPORT 3	
10 MINUTES AT FULL POWER **COOLDOWN**	INDEX NO.
CHAMBER TEMPERATURE	001-R1

Figure 5-10. Fuel Element and Lateral Support Exit
Temperatures During Early Cooldown

CHAMBER 1 CORE 2 REACTOR 3 SUPPORT SYSTEM 4 BYPASS 5

10 MINUTES AT FULL POWER --COOLDOWN--	INDEX NO.
FLOW RATES	001-R1

Figure 5-11. Reactor Flow Rates During Early Cooldown

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PUMP 1 REFLECTOR INLET 2 DOME 3 CORE INLET 4 CHAMBER 5	INDEX NO.
10 MINUTES AT FULL POWER - COOLDOWN	001-R1
PLENUM PRESSURES	

Figure 5-12. Reactor Plenum Pressures During Early Cooldown

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STATION 44.8-1 STATION 28-2 STATION 8.3-3 STATION 4-4

10 MINUTES AT FULL POWER **COOLDOWN**
STRUCTURAL SUPPORT TUBE TEMPERATURES

INDEX NO.

001-R1

Figure 5-13. Structural Support Tube Temperatures During Early Cooldown

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STATION 44.9-1 STATION 28-2 STATION 8.9-3 STATION 4-4

10 MINUTES AT FULL POWER ~~and~~ COOLDOWN
STRUCTURAL SUPPORT LINER TEMPERATURES

INDEX NO.

001-R1

Figure 5-14. Structural Support Liner Temperatures During Early Cooldown

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TURN AROUND-AVERAGE 1   EXIT-AVERAGE 2

10 MINUTES AT FULL POWER **COOLDOWN**	INDEX NO.
STRUCTURAL SUPPORT FLUID TEMPERATURES	001-R1

Figure 5-15. Structural Support Exit Gas and Turnaround Fluid Temperatures During Early Cooldown

10 MINUTE FULL POWER BURN, 1.05 DECAY POWER

Figure 5-16. Maximum Beryllium Reflector Temperature

of the cooldown fluid is used at lower chamber temperatures because of the reflector limit. This reflector limit is based on current property data which indicates loss of toughness caused by high temperature long-time annealing.

As mentioned previously, the reflector becomes limiting after 2300 seconds because of the conduction heat flux from the core. The actual time for this switchover point from continuous stem flow to normal pulsed cooldown may be delayed with a corresponding decrease in propellant used because the PAM Model was used for this assessment. The PAM has a single channel core and single channel reflector model. It would be expected to overestimate the conduction effect. From earlier studies with the three channel model, the peripheral channel ran considerably cooler than the average because of the orificing and radial decay power distribution.

Various options are available for the operation of the SSA bypass valve. It was initially thought that flow in the bypass plenum was necessary to cool the support plate. If this flow is off during the low power cooldown, there are two effects, both of which are rather minor. It is estimated that the chamber temperature increase may be 10°R and that the valve cycling duty is decreased by 10–20%. It does, however, require additional valves to eliminate this flow. Although the support plate model is only three nodes, it is adequate for these calculations because calculated temperatures are over 200°R below the limit.

The modeling of the turbine bypass line used the impedance equations of the Common Analog Model (CAM) and permitted flow in both legs of the parallel redundant valves. With this configuration and a tank pressure of 30 psia, total system flow is 2.5 lb/sec with 7–10 psi across the turbine bypass line. This is the major impedance in the system. Detailed analysis was not made for only one active turbine bypass line during cooldown. The results presented on stem temperature overshoot and laminar flow instability require further assessment for this case.

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Impulse Controllability

The impulse controllability aspects of each of the three systems are only slightly different. The current method as documented by ANSC in Trade Study 022⁽¹⁾ is to predict a cooldown thrust profile on the basis of nominal decay power and a chamber temperature approximately 10% less than that reported herein. If decay power is other than nominal, the chamber temperature can be modulated up or down by 10% (for $\pm 5\%$ in power or Q) to achieve continuous impulse control and stay within reactor temperature limits. An alternative method is to operate at maximum achievable temperature regardless of the power level but base the impulse prediction on the $-5\% Q$ and maximum T_c . At the end of the cooldown, the remaining impulse necessary to complete the mission can be added by bringing the reactor critical and using the idle mode for makeup. This does not sacrifice propellant as does the reference impulse control mode.

A comparison of the three can be made only on their ability to control impulse and thus chamber temperature for the reference scheme described above. TS/TR with its infinite throttability and higher chamber temperature is best. The other two rank approximately equal since POSL has a higher temperature and OS/TR has greater throttability in low power cooldown. If the idle mode were selected for impulse control, there would be no basis for choice.

The flow integral and chamber temperature given in the previous section on performance were used in ANSC Trade Study 022. Thrust profiles were calculated in which the specific impulse was varied from 410 to 461 seconds to correspond to -5% and $+5\%$ in decay heat uncertainty. Allowing for a $50^\circ R$ uncertainty in the calculations, a minimum specific impulse of 400 seconds and $1180^\circ R$ for the $-5\% Q$ and capability of at least 444 seconds and $1455^\circ R$ for the $+5\% Q$ are recommended for inclusion in the NSS specification.

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Thrust Nulling

- (U) Although thrust nulling is not a feature of the reference design, the requirement to have this capability does exist. As a result of Trade Study 703, the radial thrust nulling system was selected for further study. Previously, the main emphasis was on ability to thrust null early, and on high performance. No calculations were done in the very low power range where it is anticipated that thrust nulling will be used in a mission.
- (U) With certain assumptions, radial nulling (cooling of core on stem flow only) lends itself to an explicit analytic solution. The derivation of the steady state temperature distribution equations is given in Appendix B. The pressure drop equation is a standard form of the integrated momentum equation for compressible fluid having a perfect gas equation of state. Plenum, inlet, and internal NSS piping losses are also included.
- (CRD) Figures 5-17 to 5-19 give the maximum achievable performance by holding the liner at its maximum allowable temperature of 1750°R . Inlet conditions are assumed to be saturated gaseous hydrogen operating in a zero gravity field. Figure 5-17 gives the total flow as a function of power and time. The inflection point occurs at the turbulent-to-laminar transition. Exit plenum gas temperature and the product of average pressure times pressure drop ($\bar{P} \Delta P$) are given in the next two figures.
- (U) For thrust nulling between 75 KW and 10KW, the following example is given. Using the POSL cooldown described previously to 75 KW and then nulling continuously to 10 KW, 6142 lb of hydrogen are consumed. If only cooldown is considered, 5033 lb are used, or a difference of 1109 lb attributable to nulling, in addition to the loss of the impulse which would have been obtained from 264 lb of cooldown fluid, instead of no impulse from 1373 lb of thrust nulling fluid. This analysis is somewhat oversimplified in that it is not transient, does not consider reflector flow, and is only an estimate of cooldown performance since no detailed PAM calculations have been made in this very low power range.

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Figure 5-17. Support Stem Flow Rate for Radial Thrust Nulling

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Figure 5-18. Support Stem Exit Temperature for Radial Thrust Nulling

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$\bar{P}\Delta P$
(PSI)²

Figure 5-19. Support Stem (NSS) Pressure Drop Parameter for Radial Thrust Nulling

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Valve Requirements

From the cooldown analysis, the following valve requirements are evident:

For TS/TR, a very high degree of throttability requires source pressure below 5 psia 1 hour after shutdown and 1 psia 10 hours after shutdown, but does provide a potential 10% propellant saving. For POSL, the valve requirements are the minimal for the alternates considered and constitutes the base line for the requirements.

For OS/TR, an additional set of valves are required in the pump discharge lines with the added disadvantage of a 10% increase in propellant consumption.

Stem Bypass Flow

From the cooldown analysis, the stem bypass flow must be set at its maximum impedance. In this position the chamber temperature is reduced by 10°R. In addition for the POSL there is a 10 to 20% reduction in the number of valve cycles.

Laminar Flow Instability

The concept of laminar flow instability (LFI) and its application to cooldown is given in Reference 4. The pressure drop-flow rate relationship at constant heat addition is parabolic. To maintain stable flow, that is, one which will return to its original value after undergoing a perturbation (in parameters like heat flux, inlet velocity, or pressure), the core must be cooled with flow rates which have positive values of $(\partial \Delta P / \partial W)_Q$. If the core is cooled with flow rates having negative values, a local flow excursion can occur. If this remains local, that is, if the flow excursion is much faster than radial conduction, the flow theoretically can go to zero. If the transfer of heat from one channel to the next can occur through the channel walls, then the point of neutral stability is decreased and stable oscillation is possible ⁽⁵⁾. The worst case, of course, is the isolated channel case rather than the coupled channel case. Time constants associated with the former are given in the literature ⁽⁶⁾ for a typical core isolated channel of 500 seconds. During this length of time significant radial heat conduction can take place, effectively increasing the time constant for a good conductor like graphite.

To assess the effects of LFI on cooldown performance, the following "rules of thumb" were used. Stable-to-unstable flow transition is represented by Figure 5-20 from Reference 7. If the flow is stable by this curve, it has $(\partial \Delta P / \partial W)_Q > 0$ and it is unconditionally acceptable. If the flow is unstable, a second rule is applied. A somewhat arbitrary, but conservative, selection of 300 seconds was made for the longest time to permit this condition to exist, when considering that the actual excursion time constant is greater than 500 seconds because of conduction.

The first rule avoids the unstable region but the second deliberately operates therein and poses the question as to what happens to the reactor if a local flow excursion occurs. One can obtain a semi-quantitative answer to this by examining the calculated data.

The core inlet temperature as a function of time is given in Figure 5-21. From this, and the chamber temperature of Figure 5-10, the minimum stable flow can be evaluated from Figure 5-20, and compared with the actual flow of Figure 5-11. Table 5-2 gives these results. The overlay reflector pulses (high flows) always result in a stable condition by approximately a factor of 2. This would remove any instability from the previous low flow period. Of the four periods tabulated as unstable, the longest is 240 seconds; the others are about 100 seconds. These do not violate the time constant rule. However, some understanding as to what might happen to core temperatures if an unstable excursion occurred can be obtained from Figure 5-22. The average rate of change of core material temperature (dT/dt) is shown as the dashed curve. It is the difference between the rate of change caused by internal heat generation $(Q''' / \rho C_p)_{\text{core}}$ and the heat extracted by the coolant $(W\Delta H / MC_p)$. During these periods of calculated instability, approximately 80-90% of the core rise is caused by internal heat generation. This indicates that even if the flow locally decreases by 55% in 240 seconds, taking the maximum case with a 300 second time constant, the core temperature increases only approximately 10% faster; nothing catastrophic. Even this is conservative because element-to-element conduction has not been considered.

Figure 5-20 Core Flow Stability Curves

Figure 5-21 Core Inlet Fluid Temperature

TABLE 5-2
SUMMARY OF FLOW AND STABILITY CONDITIONS

Time Period	Average Chamber Temperature °R	Average Core Inlet Temperature °R	Average Chamber Flow lb/sec	Minimum Stable Flow lb/sec	Comments
800-900	1680	220	2.9	2.2	Unconditionally stable
900-1020	1550	310	0.4	1.3	Unstable, See Figure 5-22 for rate of change comparison
1020-1120	1740	330	2.4	1.4	Unconditionally stable
1120-1230	1500	350	.35	1.1	Unstable, See Figure 5-22 for rate of change comparison
1230-1320	1560	370	2.0	1.1	Unconditionally stable
1320-1460	1450	375	.25	.95	Unstable, See Figure 5-22 for rate of change comparison
1460-1540	1520	390	1.9	1.0	Unconditionally stable
1540-1780	1360	415	.25	0.7	Unstable, See Figure 5-22 for rate of change comparison
1780-1850	1500	435	1.8	0.7	Unconditionally stable
1850-2310	1250	450	0.2	0.2	Stable
2310-2390	1470	490	1.6	0.3	Unconditionally stable

Figure 5-22 Rate of Change of Core Material Temperature

Reactor Thermal Conditioning

The reactor must be able to restart at any time during cooldown. Near the end of reactor lifetime (corrosion loss is \$1) and in the stage of cooldown when the worst case average core and reflector temperatures are 1500°R and 750°R , the reactor is sufficiently subcritical that drum motion alone may not be enough to bring the reactor critical for a design having \$4.50 span. A phase of startup called thermal conditioning of the reactor is necessary to reduce the negative feedback caused by the high core material temperatures. During this phase, the reactor is cooled by tank pressure flow only. Up to 75 cents in reactivity may have to be added in this manner, through the core and reflector material temperature reactivity coefficients.

The thermal time constants of the reflector and core were derived from the previous cooldown pulse calculations and extrapolated to obtain an approximate solution to the time dependent material temperatures. The change in temperature is converted to reactivity with Figure 5-23 showing this function for two flow rates 2.5 lb/sec and 0.75 lb/sec. The table on Figure 5-23 gives the initial conditions and the end conditions for two flows having the same flow integral. At Point 2, the flow is 0.75 lb/sec and reactivity change is 45 cents in 500 seconds. At Point 3, the flow is 2.5 lb/sec with a reactivity change of 30 cents in 185 seconds. Both flow integrals are 341 lb. Thus, the rate of reactivity addition is greater for the higher flow, but more efficient use of propellant for the smaller flow rate.

NSS Weight

Since the subsystem geometry remains identical, no change in the NSS weight is attributable to any of the alternates. However, alternate three does require two additional valves which would increase the weight of the total system; hence this alternate is ranked below the others.

Cooldown Instrumentation and Control

A review of the R-1 Measurement Requirements List (MRL)(and estimated flight measurement list) has been completed in order to determine its adequacy for cooldown

THERMAL CONDITIONING REACTIVITY REQUIREMENT - CENTS

Figure 5-23 Cooldown Thermal Conditioning Reactivity Requirement

application. Table 5-3 gives the instruments which will be used for cooldown, the quantity, accuracy, frequency response, and comments. General comments applicable to Table 5-3 are as follows:

- 1) Many of the temperature and pressure measurements on the R-1 MRL but not listed in Table 5-3 will be used in cooldown analysis, but are not required for the flight engine.
- 2) The chamber thermocouples are required for R-1 and flight.
- 3) R-1 and flight instrumentation will be required to undergo extended periods of operation and continued thermal cycling for up to 3 days after shutdown.
- 4) For R-1, and possibly flight, an accurate low flow measurement with corresponding run tank temperature and pressure is needed in conjunction with the program to reduce uncertainties in decay heat predictions. Another desirable measurement for ground test reactors is a post-test insertable ring of thermocouples to make an accurate measurement of chamber temperature.
- 5) A potential problem area for cooldown in Test Cell "C" is noted. A cooldown using hydrogen is necessary to simulate flight conditions. Continuous flow is possible for at least several hours but intermittent pulsing of the reactor is used during the very low powers. During this period it will be necessary to switch to either gaseous helium, or nitrogen to avoid hydrogen pulsing of a reactor which has been filled with air between pulses. Thus, complete flight simulation is not possible. Reference 1 discusses the flight simulation in ETS-1.

The number of instruments listed in consistent with the R-1 MRL but does not necessarily meet the reliability requirements for cooldown. In order to specify the number of instruments on the flight vehicle, the Mean Time Between Failure (MTBF) and a reliability apportionment for cooldown operation are needed. The NSS Instrumentation System including signal conditioning has an allocated useful life reliability of 0.99990 (Spec. No. EC-677565).

TABLE 5-3

COOLDOWN INSTRUMENT REQUIREMENTS

Measurement	Quantity		Accuracy	Frequency Response	Comments
	Gnd.	Test Flight			
1. Forward and Center Reflector Gamma Detector	2	0 (0)	TBD	TBD	Evaluate and reduce decay heat uncertainties. For flight, help determine amount of decay heat relative to nominally expected value.
2. Center Reflector Neutron Detector	1	0 (0)	$\pm 10\%$	10 HZ	Same as 1.
3. Central Shield Gamma Detector in Aft Face	4	0 (1)	TBD	TBD	Same as 1.
4. Central Shield Gamma Detector in Forward Face	2	0 (1)	TBD	TBD	Same as 1.
5. Central Shield Neutron Detector in Aft Face	12	0 (12)	$\pm 10\%$	10 HZ	Same as 1.
6. Central Shield Neutron Detector in Forward Face	2	0 (2)	$\pm 10\%$	10 HZ	Same as 1.
7. Core Exit Plenum Pressure	4	0 (4)	± 1 psi	10 HZ	Calculation of chamber temperature and/or thrust. Also decay heat calculation.
8. SSCV Position	6	6 (6)	TBD	TBD	Control flow to nozzle/reflector and/or support plate.
9. SSBV Position	2	2 (2)	TBD	TBD	Same as 8.

NOTE: Percentages refer to percent of measured value.
Numbers in parentheses are from the current flight MRL.

TABLE 5-3 (Cont'd)

COOLDOWN INSTRUMENTATION REQUIREMENTS (Continued)

	Measurement	Quantity		Accuracy	Frequency Response	Comments
		Gnd. Test	Flight			
10.	Reflector Cylinder Material Temperature	16	4 (4)	$\pm 10^{\circ}\text{R}$	1 HZ	Pulse initiation when reflector reaches limit, and quench for end of cooldown.
11.	Reflector Bolt Material Temperature	3	0 (0)	$\pm 10^{\circ}\text{R}$	1 HZ	Same as 10. Probably needed for R-1 only.
12.	Drum Vane Material Temperature	4	0 (0)	$\pm 10^{\circ}\text{R}$	1 HZ	Same as 11.
13.	Control Drum Material Temperature	4	0 (0)	$\pm 10^{\circ}\text{R}$	1 HZ	Same as 11.
14.	Support Plate Material Temperature	2	2*(0)	$\pm 10^{\circ}\text{R}$	1 HZ	Pulse initiation when support plate reaches limit. Possible flow control on SSA bypass.
15.	Central Shield Material Temperature	12	5 (5)	$\pm 20^{\circ}\text{R}$	1 HZ	Pulse initiation when shield reaches limit.
16.	Core Inlet Plenum Gas Temperature	13	0 (12)	$\pm 5^{\circ}\text{R}$	2 HZ	Flow instability evaluation. Probably needed for R-1 only.
17.	Core Fueled Element Temperature (Station 0.0)	4	4 (4)	$\pm 20^{\circ}\text{R}$	1 HZ	Pulse initiation when Station 0 reaches limit.
18.	Core Unfueled Element Temperature	45	0 (20)	$\pm 50^{\circ}\text{R}$	1 HZ	Same as 16.
19.	Support Stem Liner Temperature	7	6 (6)	$\pm 20^{\circ}\text{R}$	3 HZ	Throttle control on cooldown valve.
20.	Support Stem End Cap Temperature	4	0 (4)	$\pm 20^{\circ}\text{R}$	3 HZ	Same as 19.

* Required for cooldown - not currently included in NSS Reference Design.

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(U) The control aspects are next considered.

(CRD) For powers greater than 1 MW, the stem material temperature is the limiting component. At present there are no plans to include a direct measurement of stem temperature because of T/C installation difficulties. A temperature feedback for flow control must then rely on measured liner temperatures for position control of the valves. The maximum liner temperature (core station 44) is approximately 250°R higher than the maximum stem temperature during early cooldown operations.

(CRD) Control of each of the three systems is different. In TS/TR, the reactor flow is continuously throttled and operates in a near steady state manner with stems and reflector at their respective limit. Monitoring and valve adjustment is continuous. POSL has continuous stem cooling with overlay pulses through the reflector. Trade Study 703⁽⁴⁾ found a stem temperature overshoot with this method because the stem flow is actually reduced when reflector flow is initiated. Thus, an anticipatory controller is needed to offset this. When the liner control temperature reaches 1500°R , the stem maximum temperature is approximately 1300°R , and the reflector flow control valve should be stepped open. This allows for 50° overshoot in the stem temperature. This pseudo limit of the liner may be linearly increased to 1600°R at 1 MW power. The OS/TR system requires the same instrumentation but a faster response in the liner thermocouple because during the high power cooldown, the liner temperature rise rate is extremely high.

(CRD) Since NSS pressure levels and drops are less than the propellant tank (30 psia) and since internal heat generation is orders of magnitude less than at full power shortly after shutdown, thermal and mechanical stresses are not limiting. A summary of each major component temperature limit is given in Table 5-4. Also given is the material temperature capability, the reason for the limit and the associated uncertainty. These data are used to initiate flow, or direct and control flow to the various flow paths when the calculated value reaches its limit. In the table, the reflector shows two materials, beryllium and aluminum. At the time of the study, aluminum was the prime alternate and was subsequently selected for the design. Although no calculations were performed for the aluminum structure reflector, its limit is sufficiently close, 50°R higher, to beryllium so that the results do not change substantially.

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TABLE 5-4
COOLDOWN MATERIAL TEMPERATURE LIMITS

	MATERIAL	MATERIAL CAPABILITY (°R)	RESTARTABLE		COMPONENT LIMIT (°R)
			REASON	UNCERTAINTY (°R)	
SUPPORT STEM	INCONEL 718	1500	DUCTILITY (SNPO-C 1)	150	1350
LINER	INCONEL 625	<u>1950</u>	CARBIDING	200	<u>1750</u>
COLD END HARDWARE	SS 302	<u>1500</u>	SPRINGS	100	<u>1400</u>
SUPPORT PLATE	ALUMINUM	710	OVERAGING	---	710
SHIELD	BATH	1010	LOSS OF H ₂ FROM TiH ₂ OVERAGING OF AL	---	1010
REFLECTOR	BERYLLIUM (ALUMINUM 6061)	750 (800)	LIMITED PROPERTY DATA, INDICATION OF DEGRADATION	---	750 (800)
SUPPORT RINGS	TITANIUM	1010	HYDRIDING	---	1010

NOTE: UNDERLINING INDICATES CHANGES FROM T. S. 703 AND 704.

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6.0 REFERENCES

1. W. J. Houghton, "Post Shutdown Operations, " Aerojet Nuclear Systems Company Trade Study 022 S-54, 30 June 1970.
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3. "NSS Reference Design, " WANL-ECP-006, November, 1969.
4. D. L. Black , "NSS Cooldown and Thrust Nulling Requirements, " WANL-TMF-2749.
5. D. L. Black, "Stability of Gas Flow in Heated Convection-Coupled Parallel Channels, DRM-51453, 20 May 1970.
6. Eli Reshotko, "An Analysis of the 'Laminar Instability' Problem in Gas-Cooled Nuclear Reactor Passages, " AIAA Journal, Volume 5, No. 9, September 1967.
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APPENDIX A FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS - COOLDOWN SYSTEM

MODE IDENT. NO.	FAILURE MODE	CRITI-CALITY CATEGORY	COMPONENT EFFECT	SUBSYSTEM EFFECT	ENGINE EFFECT	MEANS OF DETECTION
I	Cooling system fails in a manner as to provide too much coolant for a normal cooldown due to the following reasons: a) A CSCV redundant valve fails to a full open condition	May be Critical <u>Probability</u> Low	Would only be of consequence during the last phases of cool-down. Could possibly use the control feature of the check valve to modulate flow.	Could overcool stems, possibly provide over-cooling of some elements	If stems damaged, may not be able to go to a full power run	By CSCV position indicator, stem temperature
II	Cooling system fails in a manner as to not provide enough coolant for a normal cooldown due to the following reasons: a) Both CSCV valves fail closed Cooling System fails in a manner as to not provide enough coolant for a normal cooldown due to the following reasons: b) Both CSCV fail closed c) Supply piping rupture	Critical <u>Probability</u> Extremely Low Critical <u>Probability</u> Very Low Very Critical <u>Probability</u> Extremely Low	Could cause stems to melt, severe thermal stresses on elements. (Only effective during total cooldown phase). SPP could buckle. Same as II.a) Same as II.a) plus may drain supply tank if occurs upstream of CSCV	May damage NSS to make it unrestartable	May not be able to go to full power	CSCV position indicator, stem temperatures, internal SPP temperatures.

APPENDIX A (CONT'D)
FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS - COOLDOWN SYSTEM

A-2

NO.	FAILURE MODE	CRITI- CALITY CATEGORY	COMPONENT EFFECT	SUBSYSTEM EFFECT	ENGINE EFFECT	MEANS OF DETECTION
II Cont'd	d) Failure of 2 bypass blocking valves to a closed position	Very Critical <u>Probability</u> Extremely Low	Would starve the support plate bypass chamber causing over-heating of the bypass plenum walls, causing buckling and deformation of the support plate. Possible cracking of elements.	May cause enough damage to negate NSS normal run	Would not be able to go to full power run. The point of operation would have to be selected in the emergency mode at a point which would not further overstress bypass plenum walls.	Valve position, SPP temperatures, normal cooldown. Reactor temperatures.
	Cooling system fails in a manner as to not provide enough coolant for a normal cooldown due to the following reasons:					
	e) Failure to the closed position of both SSCV valves	Very Critical <u>Probability</u> Extremely Low	Same as II. d)			
	f) Complete loss of tank propellant	Very Critical <u>Probability</u> Very Low	If this happens during run, explosion by cavitation of pump. If this happens just at beginning of cooldown same effects as in II. a)	Same as II. a)	Will not startup	LH ₂ level sensor, cooldown line temperatures, TP inlet temps, TP input pressure, TP output pressure
	g) Loss of support plate function	Very Critical <u>Probability</u> Extremely Low	See Support Plate System Failure	Mode Analysis		
	h) Clogging of cooldown propellant lines due to contamination	Very Critical <u>Probability</u> Extremely Low	Same as II. a)			

APPENDIX B

In order to make rapid estimates of the effect of design changes in the support stem on the maximum liner temperature and axial location of this maximum temperature in the thrust nulling mode, a simplified thermal model of the support stem was formulated as shown in Figures B-1 and B-2.

Figure B-1. Axial Section of Simplified Support Stem Model

Figure B-2. Radial Section of Simplified Support Stem Model

Assumptions:

The model as it exists at present has the following simplifying assumptions built into it.

1. There is no core flow.
2. The propellant flowing in each support stem assembly removes all of the heat being generated in the support stem structure and the unfueled and fueled regions surrounding each stem.
3. There is no axial heat conduction.
4. The radial temperature distribution is such that $T_{UF} > T_L > T_B > T_{SS} > T_A$
5. Fluid and materials properties and heat transfer coefficients are constant.

Method:

A heat balance at some arbitrary axial location x yields the following equations for the propellant temperatures $T_A(x)$ and $T_B(x)$

$$\dot{W}_p C_p dT_A = \pi D_{ss} q_{ss} dx + \pi U D_{ss} (T_B - T_A) dx \quad (1)$$

$$-\dot{W}_p C_p dT_B = \pi D_L q dx - \pi U D_{ss} (T_B - T_A) dx \quad (2)$$

where:

$\dot{W}_p$	=	propellant flow rate in each stem - lb/sec
C_p	=	specific heat of propellant - BTU/lb-°R
q_{ss}	=	heat flux from internal generation at inner surface of stem - BTU/in ² -sec
q	=	heat flux at inner surface of liner - BTU/in ² -sec
U	=	overall heat transfer coefficient between propellant in stem and in annulus
	=	$1.0 / (1/H_A + 1/H_B + l_{ss}/k_{ss})$ - BTU/in ² -sec-°R

$$\begin{aligned}
 H_A &= \text{film coefficient at inner surface of stem} - \frac{\text{BTU}}{\text{in}^2 \cdot \text{sec} \cdot ^\circ\text{R}} \\
 H_B &= \text{film coefficient at outer surface of stem} - \text{BTU}/\text{in}^2 \cdot \text{sec} \cdot ^\circ\text{R} \\
 l_{ss} &= \text{thickness of stem} - \text{in} \\
 k_{ss} &= \text{effective thermal conductivity of stem} \\
 &\quad \text{and shim tube} - \frac{\text{BTU}}{\text{in} \cdot \text{sec} \cdot ^\circ\text{R}}
 \end{aligned}$$

Rewriting equations (1) and (2) results in two coupled, linear, non-homogeneous, first order differential equations.

$$\frac{dT_A}{dx} - \alpha (T_B - T_A) = g(x) \quad (3)$$

$$-\frac{dT_B}{dx} + \alpha (T_B - T_A) = f(x) \quad (4)$$

where:

$$\alpha = \frac{\pi U D_{ss}}{\dot{W}_p C_p}$$

$$g(x) = \frac{\pi D_{ss} q_{ss}}{\dot{W}_p C_p}$$

$$f(x) = \frac{\pi D_L q}{\dot{W}_p C_p}$$

The boundary conditions are:

$$T_A(0) = T_{A0}$$

$$T_A(L) = T_B(L)$$

$$T_B(0) = T_{A0} + \frac{\pi D_L}{\dot{W}_p C_p} \int_0^L q \, dx + \frac{\pi D_{ss}}{\dot{W}_p C_p} \int_0^L q_{ss} \, dx$$

The surface heat fluxes q and q_{ss} are assumed to be of the form

$$q = a + b \sin \frac{\pi x}{L} \quad (5)$$

$$q_{ss} = c + d \sin \frac{\pi x}{L} \quad (6)$$

The spatial distribution of the decay power is taken to be the same at all times after shutdown, only the power level changes. In this case the ratios

$$\gamma = b/a \quad (7)$$

and

$$\delta = d/c \quad (8)$$

will not change and can be determined from the axial power distribution in the stems and in the liner and material surrounding the liner. With these simplifications

$$a = \frac{(Q_{AV})_{ss} V_{ss}}{\pi D_{ss} L (1 + \frac{2\gamma}{\pi})} \quad (9)$$

$$b = \gamma a \quad (10)$$

$$c = \frac{\sum (Q_{AV})_i V_i}{\pi D_L L (1 + \frac{2\delta}{\pi})} \quad (11)$$

$$d = \delta c \quad (12)$$

where:

$$\begin{aligned}
 V_{ss} &= \text{volume of the stem} - \text{in}^3 \\
 V_i &= \text{volume of the liner, or unfueled region, or fueled region} - \text{in}^3 \\
 (Q_{AV})_{ss} &= \text{average heat generation rate in the stems at some decay power level } P_1 - \text{BTU/in}^3\text{-sec} \\
 (Q_{AV})_i &= \text{average heat generation rate in the liner, or unfueled region, or fueled region at some power } P_1 - \text{BTU/in}^3\text{-sec.}
 \end{aligned}$$

Once the values of a , b , c , and d have been determined for some decay power level P_1 , these values need only be multiplied by the ratio P_2/P_1 to determine their value at some other decay power level P_2 .

The temperature distributions $T_A(x)$ and $T_B(x)$ are found from equations (3) and (4) and the boundary conditions.

$$\begin{aligned}
 T_A(x) = & -\frac{Ax^2}{2} + \frac{BL^2}{\pi^2} \sin \frac{\pi x}{L} + \frac{E^*L^2}{\pi^2} (1 - \cos \frac{\pi x}{L}) + C_1 x \\
 & + \frac{(T_{B0} - T_{A0})}{L} x - \frac{2L}{\pi^2} (E + E^*) x + T_{A0} \quad (13)
 \end{aligned}$$

$$T_B(x) = -\frac{Ax^2}{2} + \frac{BL^2}{\pi^2} \sin \frac{\pi x}{L} - \frac{EL^2}{\pi^2} (1 - \cos \frac{\pi x}{L}) + C_1 x + T_{B0} \quad (14)$$

where:

$$A = \alpha^2 \left(\frac{D_L a}{D_{ss} U} + \frac{c}{U} \right)$$

$$B = \alpha^2 \left(\frac{D_L b}{D_{ss} U} + \frac{d}{U} \right)$$

$$E = \alpha \left(\frac{\pi D_L b}{U D_{ss} L} \right)$$

$$E^* = \alpha \left(\frac{\pi d}{UL} \right)$$

$$C_1 = AL + \frac{BL}{\pi} + \frac{L}{2} (E + E^*) - \frac{(TB0 - TA0)}{2L} \\ + \frac{\pi D_{ss} C}{\dot{W}_p C_p} - \frac{\pi D_L \alpha}{\dot{W}_p C_p}$$

$$TB0 = TA0 + \left(\frac{\pi L}{\dot{W}_p C_p} \right) (\alpha D_L + CD_{ss})$$

The liner temperature $T_L(x)$, is given by

$$T_L(x) = T_B(x) + \frac{q(x)}{H_B} \quad (15)$$

The maximum liner temperature occurs at XMAX and is given by

$$T_L(XMAX) = T_B(XMAX) + \frac{q(XMAX)}{H_B} \quad (16)$$

where XMAX is the value of X which satisfies

$$\frac{dT_L(x)}{dx} = -Ax - \frac{EL}{\pi} \sin \frac{\pi x}{L} + \left(\frac{BL}{\pi} + \frac{b\pi}{LH_B} \right) \cos \frac{\pi x}{L} + C_1 = 0 \quad (17)$$

	TITLE	
	Reactor Cooldown Criteria	
DOCUMENT NO.		DATE
WANL-TME-2725		January, 1971
ABSTRACT Using the tank pressure cooldown system evolved in Trade Study 703, performance calculations were made to update hot bleed results to the full flow engine; operating procedures, and instrumentation and controls requirements were defined. Other topics such as use of additional throttling valves, reactor temperature conditioning, thrust nulling, impulse controllability, and laminar flow instability were covered for the preferred alternate 2 (POSL).		
DATA ITEM NO.	SECURITY CLASSIFICATION OF DOCUMENT	
S-54	CRD	
CDRL LINE NO.	TOTAL NO. OF PAGES	
Not Applicable	57	
KEY WORDS		
Cooldown POSL Cooldown Performance Decay heat Shutdown Laminar Flow instability		
AUTHOR/EDITOR		PREPARING DEPT.
D. L. Black		Systems Engineering
W Form 59943		DOCUMENT INFORMATION SUMMARY

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