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WANL-TME-2720

SEPTEMBER 1970

DATA ITEM S-54

STARTUP, SHUTDOWN,
AND THROTTLING

TRADE STUDY NO. 714

MASTER

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ABSTRACT

WANL Trade Study 714 compared four throttling approaches with a no-throttling base case. After considering various functional and technical design considerations, primary and alternate throttling recommendations were made: perform fixed-drum throttling only within SSCV capabilities, accepting a variable throttle point with reactor life, or if a fixed throttle point is required, a valve should be added to the pump discharge line to allow fixed-drum throttling.

The startup portion of the study compared three high specific impulse startups with a middle of the map startup. Applying the same considerations as the throttling portion of the study, the middle of the map startup was recommended.

The study recommended that shutdown should be performed without moving control drums, and the shutdown demand should follow a profile determined by the need to minimize cooldown propellant usage. The study also recommended the maximum chamber pressure ramp should not exceed 50 psi/sec, and the maximum chamber temperature ramp should not exceed 150°R/sec.

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I. SCOPE

This study evaluates throttling, startup, and shutdown of the Nuclear Subsystem (NSS). Previous studies ^{(1, 2)*} made a similar evaluation of the hot-bleed-cycle NSS, but a re-examination became necessary when SNPO-C Change Order 70-1 ⁽³⁾ was implemented. SNPO-C Change Order 70-1 dictated the change to the full-flow cycle, the reduction of nominal chamber temperature to 4250°R, and the increase in engine duration to ten hours, consisting of sixty ten-minute burns. The directive states, "All trade studies need to be re-examined in the light of the full flow cycle and the increased endurance requirements. . . ." In particular, the directive states that throttling at rated temperature and the operating line for startup and shutdown are among the trade studies to be re-examined.

The study is required for updating the reference design (Category B). The reference design of November 5, 1969, is used as a calculational basis. Previous studies are updated and NSS recommendations are provided for the throttling point and for startup and shutdown transients. The results of the study were presented at the trade study meetings held at WANL on February 13, 1970⁽⁴⁾, and at ANSC on February 24-26, 1970⁽⁵⁾.

* Superscript numbers refer to references listed in Section 6.

2. IDENTIFICATION OF REQUIREMENTS

The NERVA Program Requirement Document⁽⁶⁾ (NPRD) states, "The engine shall be capable of throttling at rated chamber temperature from the engine design point of (tbd) psia chamber pressure to a chamber pressure of (tbd) psia at a maximum rate of 50 psia/sec for a duration of (tbd) minutes per thrust period, sufficient to allow optimum removal of delayed neutron power production at rated chamber temperature.... Optional modes of bootstrap startup shall be provided. One mode shall provide highest possible integrated specific impulse, within the (thermal) stress limitations of the reactor structure(s), during the starting transient. The temperature rates shall be optimized. This mode shall follow the reactor structural (temperature) limits up to the rated temperature and maintain this temperature to rated thrust..... during the major portion of the transient ramps, the engine shall have the capability and controllability of 150°R/sec chamber temperature and 50 psia/sec chamber pressure rate." While the NPRD also calls for a startup mode yielding the highest possible integrated thrust during the startup transient, no advantage was shown by previous work^(2,7) except in the case of suborbital startup. A requirement for a suborbital start does not exist in the NPRD at this time. For this reason, the high thrust startup mode was not included in this study.

Trade Studies 706⁽¹⁾ and 707⁽²⁾ made the following recommendations for throttling, startup, and shutdown:

"...any throttling in the final design should be that which is available when the most reliable and best performing NSS is determined based upon rated condition considerations."

"...only one method of startup be required and that the one method of startup be on the center of the map path (essentially constant reactivity)."

"...a center of the map shutdown mode be established as the means of satisfying the NPRD-1 requirement."

Subsequent direction was provided by SNPO-C Technical Directive 69-35⁽⁸⁾, dated August 5, 1969, which stated:

"...throttling should be required and that the normal startup and shutdown mode should be along the high specific impulse line that passes through the throttle point. "

Further direction was provided by SNPO-C Technical Directive 69-43⁽⁹⁾, dated September 15, 1969, which stated:

"The engine should be designed such that 60% rated power at rated chamber temperature can be achieved without drum motion at end of life. This may require optimization of the stem design and some increase in the pressure drop allocated to the stem very likely will be required. To avoid a specific impulse penalty at rated power, valves currently in the system should be re-examined to ascertain whether or not the impedance that must be added to the nozzle/reflector circuit at 60% can be removed at rated power. An SSCV capability to compensate for 2.00 corrosion at design point is desired, which is believed to be compatible with the SSCV range required to permit the throttling capability. "

3. DESCRIPTION OF APPROACHES AND SIGNIFICANT CHARACTERISTICS

Trade Study 713⁽¹⁰⁾ establishes a \$3.00 support stem reactivity requirement at the design point which may be allocated as follows:

\$2.00	Corrosion compensation
.70	Hot-critical uncertainties ($\pm .35$)
<u>.30</u>	Peak Xenon requirement
\$3.00	Total

These requirements constitute the minimum capability case used in the study. While the support stems in the 11/5/69 reference design furnish only \$2.75 at rated conditions, adjustments to the reference system may furnish the required \$3.00.

Time at the throttling point was assumed to be one and one-half minutes of a ten-minute burn. This assumption is consistent with the ten-hour/sixty-cycle requirement and the optimum throttle duration given in the ANSC presentation of January 15, 1970, on the status of Trade Study 026, Throttling, Startup and Shutdown Ramp.⁽¹¹⁾

Five throttling approaches were compared in the study:

1. Throttling to 360 psia using control drums.
2. Throttling to 270 psia using control drums.
3. Throttling without using control drums; variable throttle point with reactor life.
4. Throttling to 270 psia without using control drums; variable impedance in the pump discharge line.
5. No throttling (base case).

The study also compared the effects of a high specific impulse startup with a middle of the map startup. The high specific impulse startup is scheduled to attain

rated chamber temperature at as low a chamber pressure and flow rate as possible. The path selected was from post-bootstrap conditions to 60% rated power (270 psia chamber pressure) at rated chamber temperature and then to rated conditions at 50 psi/sec and constant chamber temperature. The middle of the map path goes from post-bootstrap conditions to rated conditions by the most direct method. This path approximately traverses a constant drum reactivity line. These startup paths are shown pictorially in Figure 1.

The NSS startup, shutdown, and throttling requirements were evaluated by performing the various startup and throttling maneuvers. A summary of the effects identified are listed below.

1. Reactivity Requirements - The \$2.00 corrosion limit may require \$2.16 additional reactivity to perform a high specific impulse startup or a throttling maneuver to 270 psia⁽¹²⁾. Increased stress and corrosion may result depending on the method of reactivity addition.

2. Fuel Corrosion - Use of the control drums for throttling reactivity addition raises the temperature of the peripheral fuel elements causing an increase in the corrosion rate which will shorten the usable reactor lifetime.⁽¹³⁾ Interelement corrosion may be affected during the throttling operation and all subsequent operations.

3. Additional Thermal Stress in Fuel - While throttling raises the stress levels in the fuel if control drums are used for reactivity addition, the major stress effects occur during a high specific impulse startup transient.^(14, 15)

4. Controller Complexity - Preliminary evaluation of the effect of digital controls concepts indicates throttling or high specific impulse startup causes no significant increase in controller complexity over that required for no-throttling or middle of the map startup. More control elements, however, must be moved over a wider range to permit throttling and high specific impulse startup.

Figure 1

5. Throttling Point Pressure - The chamber pressure at the throttling point varies from 270 psia to 450 psia at end-of-life, depending on the method of reactivity addition. (12)

6. Reliability - The requirement to throttle and to perform a high specific impulse startup may affect the overall reliability of the NSS. The use of control drums for reactivity addition affects the reliability of the peripheral fuel elements because of the increased corrosion. Additional stresses experienced when using control drums during the high specific impulse startup lower the reliability of the peripheral elements. Use of a valve in the pump discharge line for reactivity addition maintains the NSS reliability but introduces failure modes which could subsequently harm the NSS. (16, 17)

7. Safety - Different malfunction effects exist between throttle and rated conditions, e.g., an SSCV failure in the closed position can cause more severe overheating of the support stems at throttle conditions than at design conditions. Failure of the pump discharge line impedance, used in throttling, in the closed position while at rated conditions can cause a destructive reactivity insertion. (18) High specific impulse startup takes the NSS closer to its structural limits than middle of the map startup, leaving less margin for malfunction recovery.

8. Development and Qualification - Operation at an off-design condition requires significantly more systems and component analysis and testing. More reactor testing is required to qualify throttling capability.

9. Cost - The additional analysis and testing required for off-design operation leads to increased costs.

4. COMPARISON MATRICES

TABLE 4-1 COMPARISON MATRIX - THROTTLING

Functional & Technical Design Consideration	1 Throttling to 360 psia Using Drums	2 Throttling to 270 psia Using Drums	3 Throttling Without Using Drums; Variable Throttle Point With Reactor Life	4 Throttling to 270 psia Without Using Drums; Variable Impedance In PDL	5 No Throttling (Base Case)	NSS Selection
1. Reactivity Requirements	Drum Movement (\$1.01) Required at EOL	Drum Movement Required: (\$0.16 at SOL and (\$2.16) at EOL	SSA Reactivity Available \$2.00 - \$2.65 SOL \$0 - \$0.65 EOL	Increase in PDL Impedance to Supply \$0.16 at SOL (8 psi) and \$2.16 at EOL (275 psi)	No Additional Requirement	5-(1-2-3)-4 *
2. Fuel Corrosion: a) Percent Increase in Corrosion at EOL at Drum Center Line of Peripheral Elements b) Reduction in Equivalent Full Power Life (Assumes 15% Throttle Time).	86% 0.3 Hours	182% 1.5 Hours	Negligible Adverse Effects Negligible	Negligible Adverse Effects Negligible	None None	(3-4-5)-1-2
3. Additional Thermal Stress in Fuel	1.17 Times the Axial Stress With No Throttling	1.29 Times the Axial Stress With No Throttling	Negligible Adverse Effects	Negligible Adverse Effects	1.00 - Base Case	(3-4-5)-1-2
4. Controller Complexity	Preliminary Evaluation of the Effect of Digital Controls Concepts Indicates No Significant Increase in Controller Complexity; however, More Control Elements Must Be Moved Over a Wider Range to Permit Throttling.				Base Case	5-(1-2-3-4)

* Equality of ranking is indicated by parentheses. Order of design approach number indicates ranking preference.

TABLE 4-1
COMPARISON MATRIX - THROTTLING (CONT'D)

Functional & Technical Design Consideration	1 Throttling to 360 psia Using Drums	2 Throttling to 270 psia Using Drums	3 Throttling Without Using Drums; Variable Throttle Point With Reactor Life	4 Throttling to 270 psia Without Using Drums; Variable Impedance in PDL	5 No Throttling (Base Case)	NSS Selection
5. Throttle Point Pressure	360 psia	270 psia	280-235 psia at SOL 450-390 psia at EOL	270 psia	None (450 psia)	(2-4)-3-1-5 *
6. Reliability	Lowered Reliability. More Difficult to Achieve Reliability Goals Than No Throttling Case 5.	Lowered Reliability. More Difficult to Achieve Reliability Goals than Case 1.	NSS Reliability Maintained.	NSS Reliability Maintained.	Base Case	(3-4-5)-1-2
7. Safety	Failure of SSCV In Closed Position Can Cause Over-Temperature of Support Stems.	Failure of SSCV In Closed Position Can Cause Over-Temperature Of Support Stems. More Severe Problem Than Case 1.	Essentially Same As Base Case (If SSCV Fails Closed, Cannot Reach Throttle Point)	Increases Possibility of Transient Reactivity Insertion If Valve Fails Open While At the Throttle Point. (Assumes Redundancy In PDL Valve Not Added)	Base Case	(3-5)-4-1-2

* Equality of ranking is indicated by parentheses. Order of design approach number indicates ranking preference.

TABLE 4-1
COMPARISON MATRIX - THROTTLING (CONT'D)

Functional & Technical Design Consideration	1 Throttling to 360 psia Using Drums	2 Throttling to 270 psia Using Drums	3 Throttling Without Using Drums; Variable Throttle Point With Reactor Life	4 Throttling to 270 psia Without Using Drums; Variable Impedance In PDL	5 No Throttling (Base Case)	NSS Selection
8. Development and Qualification	Significantly More Analysis and Testing Required Over No Throttling. More Reactor Testing Required to Qualify Throttling Capability.	Significantly More Analysis and Testing Required Over No Throttling. More Reactor Testing Required to Qualify Throttling Capability.	Significantly More Analysis and Testing Required Over No Throttling. More Reactor Testing Required to Qualify Throttling Capability.	Significantly More Analysis and Testing Required Over No Throttling. More Reactor Testing Required to Qualify Throttling Capability.	No Effect Base Case	5-(1-2-3-4)*
9. Cost	Increased Analysis, Development and Test Costs.	Increased Analysis, Development and Test Costs.	Increased Analysis, Development and Test Costs.	Increased Analysis, Development and Test Costs.	No Effect Base Case	5-(1-2-3-4)
Overall Selection						5-3-4-1-2** [3-4-5-1-2]
* Equality of ranking is indicated by parentheses. Order of design approach number indicates ranking preference. ** Brackets denote alternate selection ranking.						

TABLE 4-2
COMPARISON MATRIX
STARTUP AND SHUTDOWN
PROFILES

Functional & Technical Design Requirements	1 High Specific Impulse Startup Through 270 psia Using Drums. No Valve in PDL.	2 High Specific Impulse Startup Using SSA. Fixed Drums. No Valve in PDL.	3 High Specific Impulse Startup Through 270 psia. Fixed Drums. Valve in PDL.	4 Middle of the Map	NSS Selection
1. Reactivity Requirements	Drum movement required (\$.16) at SOL to reach 270. \$2.16 required at EOL.	Can achieve only 280 psia at SOL. Throttle point varies throughout life.	No drum movement required through life. Reactivity supplied by PDL valve.	No drum movement required through life.	4 - (1 - 2) - 3*
2. Control Complexity	Preliminary evaluation of the effect of digital controls concepts indicates no significant increase in controller complexity; however, more control elements must be moved over a wider range to permit throttling.			Base Case	4 - (1 - 2 - 3)
3. Throttling Point Pressure	270 psia	280-235 psia 450-390 psia	270 psia	450 psia	(1, 3) - 2 - 4
4. Stress - Fuel axial stress central - fuel ΔT ratio in periphery.	SOL: 1.0 EOL: 1.2	1.0	1.0	1.0	(2, 3, 4) - 1
* Equality of ranking is indicated by parentheses. Order of design approach number indicates ranking preference.					

TABLE 4-2
COMPARISON MATRIX (Continued)
STARTUP AND SHUT DOWN
PROFILES

	1 High Specific Impulse Startup Through 270 psia Using Drums. No Valve in PDL.	2 High Specific Impulse Startup Using SSA. Fixed Drums. No Valve in PDL.	3 High Specific Impulse Startup Through 270 psia. Fixed Drums. Valve in PDL.	4 Middle of the Map	NSS Selection
5. Reliability	Increased peripheral stresses degrade reliability.	NSS reliability same as base case.	NSS reliability same as base case.	Base case.	(2, 3, 4) - 1 *
6. Safety	High Specific Impulse path takes NSS closer to structural support limits leaving less margin for malfunction recovery.	Same as Case 1.	Same as Case 1.	Effects of mal- functions similar to effects at rated conditions.	4 - (1, 2, 3)
* Equality of ranking is indicated by parentheses. Order of design approach number indicates ranking preference.					

TABLE 4-2
COMPARISON MATRIX (Continued)
STARTUP AND SHUTDOWN
PROFILES

Functional & Technical Design Requirements	1 High Specific Impulse Startup Through 270 PSIA. No. valve in PDL.	2 High Specific Impulse Startup. Fixed Drums. No valve in PDL.	3 High Specific Impulse Startup Through 270 PSIA. Fixed Drums. Valve in PDL.	4 Middle of the Map	Selection
7. Development and Qualification	Increased analysis and testing required over the middle of the map case. Cycling to off-design condition requires increase in fuel element testing.	Same as Case 1.	Same as Case 1.	Base case.	4 - (1, 2, 3)*
8. Cost	Increased analysis, development, and test costs.	Same as Case 1.	Same as Case 1.	Base case.	4 - (1, 2, 3)
Overall Selection Ranking					4 - (2-3) - 1
<p>* Equality of ranking is indicated by parentheses. Order of design approach number indicates ranking preference.</p>					

5. SELECTION OF RECOMMENDED CONCEPTS

The comparison matrices, shown in Section 4, are used to select the final recommendation from the studies concepts. The alternates are ranked for each functional and technical design consideration and are given one to five points, the first place selection receiving one point. Equality of concepts, indicated by parentheses in the selection column of the comparison matrix, gives each of equal concepts the same number of points. The concept having the lowest total score is chosen as the recommended concept. The choice must be tempered with judgment, however, for the concept with the lowest total points may not accomplish the desired aim. This effect is in evidence in the throttling selection where the base case of no throttling actually wins.

Two throttling concepts are recommended on the basis of the analyses summarized in the comparison matrix for throttling, Table 4-1: a primary recommendation with variable throttle point, and an alternate recommendation if a fixed throttle point is required. The decision to require a fixed or variable throttle point must be based on engine studies, however, and is beyond the scope of this study.

The primary throttling recommendation is reached in two steps. First, the concepts for throttling are grouped by methods of reactivity addition: use of control drums, use of support stem flow, and no throttling, the base case. Table 5-1 shows the selection rankings for the grouped concepts. Although the no-throttling case ranks first, Section 1 points out that throttling seems to be a desirable characteristic and for this reason, fixed-drum throttling is chosen for the primary throttling recommendation. The second step in the selection process is the comparison of Concepts 3 and 4, the fixed-drum throttling concepts. Table 5-2 shows this comparison to be slightly in favor of Concept 3, Throttling Without Using Control Drums; Variable Throttle Point with Reactor Life. Thus, the primary throttling recommendation is:

Table 5-1 Point Tabulation for Throttling Reactivity Addition Methods

Functional & Technical Design Consideration	Throttling Using Control Drums	Throttling Using SSCV Only (Fixed-Drum Throttling)	No Throttling
1. Reactivity Requirements	2	3	1
2. Fuel Corrosion	2	1	1
3. Additional Thermal Stress in Fuel	2	1	1
4. Controller Complexity	2	2	1
5. Throttle Point Pressure	2	1	3
6. Reliability	2	1	1
7. Safety	3	2	1
8. Development and Qualification	2	2	1
9. Cost	2	2	1
TOTAL	19	15	11

Overall Selection: No Throttling

Alternate Selection: Throttling Using SSCV Only (Fixed-Drum Throttling)

Table 5-2 Point Tabulation for Fixed-Drum Throttling Concepts

Functional & Technical Design Considerations	Throttling Without Using Drums; Variable Throttle Point in the Reactor Life	Throttling to 270 psia Without Using Drums; Variable Impedance in PDL
1. Reactivity Requirements	1	2
2. Fuel Corrosion	1	1
3. Additional Thermal Stress in Fuel	1	1
4. Controller Complexity	1	1
5. Throttle Point Pressure	2	1
6. Reliability	1	1
7. Safety	1	2
8. Development and Qualification	1	1
9. Cost	1	1
TOTAL	10	11

Overall Selection: Throttling Without Using Drums; Variable Throttle Point with
Reactor Life

Perform fixed-drum throttling only within SSCV capabilities without an added pump discharge line impedance, i.e., accept a variable throttling capability with lifetime. Throttling capability presently expected is:

Start-of-Life	End-of-Life	
280 psia	450 psia	Minimum
225 psia	390 psia	Nominal

The minimum capability case results from the SSCV requirements of Section 3. If the peak Xenon requirement and hot-critical uncertainties are removed, the nominal case results.

The choice of throttling concepts is narrowed if a requirement to throttle to 270 psia throughout life is imposed. The selection becomes one of reactivity addition method, i.e., use of control drums, Concept 2, or use of a variable impedance in the pump discharge line, Concept 4. The comparison matrix shows Concept 4 to be clearly superior, from an NSS viewpoint, particularly in the areas of fuel corrosion and thermal stress. Therefore, if a fixed throttling point throughout life is required, the additional reactivity should be provided by a variable pump discharge line impedance as recognized by SNPO-C Technical Directive 69-43.

The startup profile recommendation is based on Table 4-2, Comparison Matrix - Startup and Shutdown Profiles, and its associated selection rankings. The point tabulation, shown in Table 5-3, leads to the recommendation to perform a middle of the map startup, essentially along a fixed drum line. By performing a fixed-drum startup, peripheral stresses and control complexities are minimized. The middle of the map startup requires more propellant, though it will probably be only a few hundred pounds greater than the propellant weight required by a high specific impulse startup.⁽⁷⁾

If a requirement for a high specific impulse startup is imposed, the choice is narrowed to Concepts 1, 2, and 3. Table 5-3 shows fixed-drum concepts to be more

Table 5-3 Point Tabulation for Startup and Shutdown Profiles

Functional & Technical Design Considerations	High Specific Impulse Through 270 psia. No valve in PDL	High Specific Impulse Startup. Fixed Drums. No valve in PDL	High Specific Impulse Startup. Through 270 psia. Fixed Drums. Valve in PDL.	Middle of the Map
1. Reactivity Require- ments	2	2	3	1
2. Control Complexity	2	2	2	1
3. Throttling Point Pressure	1	2	1	3
4. Stress-Fuel axial Stress Central-Fuel ΔT Ratio in Periphery	2	1	1	1
5. Reliability	2	1	1	1
6. Safety	2	2	2	1
7. Development and Qualification	2	2	2	1
8. Cost	2	2	2	1
TOTAL	15	14	14	10

Overall Selection: Middle of the Map

desirable, particularly since they avoid the 20% peripheral stress increase of the startup using control drums. The method of fixed-drum startup, however, depends on the throttling decision. If a valve is placed in the pump discharge line for throttling, it should be used for a high specific impulse startup. If no valve is used, the startup should have a variable profile based on the available support stem reactivity. The use of control drums, though entailing increased stresses, should be considered only if no impedance is added to the pump discharge line and a single startup profile through 270 psia is required.

The shutdown profile depends on the final throttling decision. The shutdown demand should follow a line directly from the chosen throttle point with a profile determined by the need to minimize cooldown propellant usage. Shutdown should be performed with fixed control drums to avoid control complexities and minimize peripheral stresses.

The study showed that virtually all NSS problems in startup and shutdown depend on temperature rate as opposed to pressure rate. Stress problems were found to be least troublesome for a ramp of $100^{\circ}\text{R}/\text{sec}$. Past studies have shown the same result⁽²⁾, but fuel development trends indicated $150^{\circ}\text{R}/\text{sec}$ would become an acceptable rate in the future and was recommended on that basis. Stress data have shown AXM high-expansion fuel is unsatisfactory for this temperature, however, and trends in fuel development are pointing toward high-expansion and composite elements. Test data indicate $150^{\circ}\text{R}/\text{sec}$ will be difficult to attain for these fuels, and developmental work is in progress to determine if the demand temperature rate should be reduced. Until the developmental work is conclusive, however, the NSS ramp recommendations are:

The maximum chamber pressure rate should not exceed 50 psi/sec.

The maximum chamber temperature rate should not exceed $150^{\circ}\text{R}/\text{sec}$.

6. REFERENCES

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