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May, 1969

Westinghouse Astronuclear Laboratory

FEASIBILITY EVALUATION OF ALTERNATE

NSS SOURCES FOR TURBINE DRIVE GAS

(Title Unclassified)

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FEASIBILITY EVALUATION OF ALTERNATE

NSS SOURCES FOR TURBINE DRIVE GAS

(Title Unclassified)

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I. Introduction

The purpose of this study was to perform an initial feasibility study of alternate Nuclear Subsystem (NSS) sources for turbine drive fluid. Two specific concepts (structural support discharge flow and reactor peripheral flow) were to be investigated in response to an action item from the 24-27 February 1969 Systems Engineering meetings. In addition to these two concepts, the study purpose was to define any other concepts which might have applicability and to investigate and document their feasibility as to whether detailed NSS evaluations would be worthwhile.

This study was directed toward system improvement and optimization as opposed to solution of a specific development problem. Therefore, any concepts which could conceivably improve system performance (specific impulse), weight, or remove the need for a penetration of the nozzle could have potential worth to the system.

II. Study Groundrules

The following groundrules were used for the study:

1. Any concept should be considered feasible until demonstrated to be otherwise.
2. Engine performance degradation not a criterion for rejection from the NSS feasibility standpoint.
3. Lack of bootstrap startup capability not a criterion for rejection from NSS standpoint since alternate startup sources could conceivably be used.
4. The Full Flow Engine Cycle is not to be studied since that concept has been the subject of extensive separate studies and has been rejected by SNPO.
5. Current NSS ECC performance and functional requirements are valid. However, any requirements which, if changed, would make a concept feasible should be identified.
6. Turbine requirements are as transmitted by AGC (described by Figure 1). These data are for one turbopump assembly (TPA) and it was assumed that total turbine requirements would be unchanged for two TPA sharing the load.

Figure 1 indicates turbine inlet temperature and flow requirements at rated conditions as the design inlet temperature and/or pressure base conditions are varied. These data were transmitted from L. Johnson (AGC) to R. E. Thompson (WANL) by telephone on March 20, 1969. The data of Figure 1 are for constant turbine work and constant turbine exit pressure, but not constant turbine efficiency. The data do not represent flow and temperature requirement variations with a fixed turbine, but instead represent a locus of turbine design points.

III. Summary

(CRD) This study included consideration from the NSS standpoint of the basic concepts for providing turbine drive fluid at the required pressure and temperature conditions. The concepts evaluated encompass the possible sources which could be considered to be at all reasonable. The concepts evaluated included:

1. Structural support discharge flow
2. Peripheral flow
3. Core bleed
4. Separate nuclear heater for turbine drive fluid
5. Separate nuclear heater for turbine exhaust
6. Heat pipes
7. Portion of core partitioned as turbine supply
8. Fueled central elements

(U) For each concept, energy addition requirements were considered and the attainable fluid temperature was determined. Also considered in the evaluations for each concept were the magnitude of the NSS development and redesign required and the development risks associated with each concept. For each concept, at least one typical means of implementation was developed to permit representative evaluation.

(U) Each evaluation was considered to the depth necessary in order to conclude feasibility or infeasibility and to determine the worthiness of a concept for further NSS design investigations. The conclusions which resulted from these evaluations are contained in Section IV of this report.

IV. Conclusions and Recommendations

A. Conclusions

1. Structural Support Discharge Flow (Figure 5)

- (U) a. The use of structural support discharge flow is conceptually feasible from the NSS standpoint but, with the current knowledge, only at the current level of structural support discharge temperature and with the capability to vary SSA flow, and temperature, over the existing ranges.
- (U) b. Implementation of this concept would necessitate increased NSS complexity, weight and design effort required.
- (CRD) c. If further investigations were to be performed, detailed designs of the core support plate, SSA discharge flow collection and manifold system and control systems would be required in order to evaluate the effects on NSS weight and reliability. Detailed analyses of startup and shutdown transients and off-design operations would also be required.
- (CRD) d. An increase in SSA discharge temperature would require an extensive materials development program, including radiation effects testing. The materials program required, especially radiation effects tests, would introduce significant delays in availability of material data for design purposes with the possibility that the resulting design could not supply sufficient flow for the turbine.

- (U) e. Certain redundancies have been identified to be required in order to prevent loss of normal emergency operation capability in the event of single failures. Two redundant parallel structural support control valves would be required by this system because the series connection of the turbine and structural support systems imposes new requirements on the SSCV with attendant new failure modes. The necessary additional highly reliable internal NSS piping for the turbine appears to be feasible. A redundant seal configuration at the interface between the NSS piping and the pressure vessel can be provided, if required, to attain the required reliability of this new sealing requirement.
- (U) f. Because of the obviously large engine performance penalties with this lower turbine inlet temperature and the significant interactions leading to control and NSS complexity, further NSS investigations are not warranted unless engine evaluations show the performance and complexity penalties to be acceptable.

2. Peripheral Flow (Figures 8 and 9)

- (CRD) a. The use of discharge flow from a new specially fueled region outside of the core wrapper is conceptually feasible from the NSS standpoint to provide turbine drive gas at the current turbine inlet temperature of 1660°R.

- (CRD) b. Implementation of this concept would require major redesign of the core periphery and the incorporation of a seal with very stringent reliability requirements in a severe operating environment which would degrade NSS reliability.
- (CRD) c. If further investigation were to be performed, detailed designs of the core periphery, the seal between the nozzle chamber and core periphery flow, and the collection and discharge system would be required in order to evaluate the effects on NSS weight and reliability.
- (CRD) d. In order to provide the necessary protection against critical single failures, redundant seals are required between the specially fueled peripheral region and the nozzle chamber to prevent loss of turbine flow, and redundant series-parallel valves are required to control the peripheral flow rate to prevent excessively high or low pneumatic core bundling pressures and temperatures in the core periphery.
- (U) e. Because the significant design and reliability complications of the NSS are of such magnitude as to offer no apparent advantages over nozzle hot bleed port but do introduce significant development risks, further NSS evaluations are not warranted unless overall engine evaluations define a significant engine advantage.

3. Separate Nuclear Heater for Turbine Drive Fluid (Figure 11)

- (CRD) a. A separate sub-critical nuclear heater external to the pressure vessel is

- (CRD) conceptually feasible from the NSS standpoint at rated conditions to provide turbine drive gas at the desired temperature of 1660° R.
- (U) b. No changes to the current NSS have been determined, with the possible exception of shielding, to be required for implementation of this concept. The changes that are required are the addition of the nuclear heater.
- (U) c. If further investigations are performed, detailed design of the heater and its cooling would be required. Detailed nuclear design studies would be required for both design and off-design conditions and startup studies would also be necessary.
- (U) d. In order to prevent loss of normal or emergency operation capability, in the event of a single failure, the components added by this concept requiring inherent high reliability or redundancy are the heater containment pressure vessel and the fuel elements and element supports. Maintenance of the current hot bleed cycle level of turbine inlet temperature should allow implementation of the necessary highly reliable heater pressure vessel. The relatively low operating temperatures of the elements should allow the incorporation of the necessary support redundancy, although a complex design may be necessary.
- (U) e. The design complications and development risks associated with this concept are at least as great as those associated with the Full Flow Engine and thus, further NSS investigations do not appear to be warranted.

4. The following concepts were judged infeasible with current knowledge and do not warrant further NSS investigations because of the very large increases in NSS complexity, susceptibility to single failures, and the very large increases in risk of development delays and cost increases.

(CRD)

- a. Core bleed (Figure 10)
- b. Separate nuclear heater for turbine exhaust
- c. Heat pipes (Figure 12)
- d. Portion of core partitioned as turbine supply (Figures 13 and 14)
- e. Fueled central elements (Figures 15 and 16)

B. Recommendations

(U)

1. Further Nuclear Subsystem evaluations should not be performed on the three concepts determined to be conceptually feasible from the NSS standpoint, but impractical, unless overall engine evaluations indicate sufficient advantages to override the complications and risks.

(U)

2. If overall engine system evaluations determine that it is sufficiently worthwhile to use an alternate turbine drive source, a more detailed trade study should be performed to evaluate the separate nuclear heater in comparison with the hot bleed.

V. Discussion

A. General

(U) This study included consideration of the basic concepts of turbine drive fluid supply listed below. These concepts encompass the possible sources identified to date which could be considered to be at all reasonable. This study also excluded consideration of the Full Flow Engine since that alternate has been the subject of extensive separate studies and considerations.

(CRD) Concepts examined included:

1. Structural support discharge flow
2. Peripheral flow
3. Core bleed
4. Separate nuclear heater for turbine
5. Separate nuclear heater for turbine exhaust
6. Heat pipes
7. Portion of core partitioned as turbine supply
8. Fueled central elements

(U) It is obvious that many different combinations or modifications of the above concepts are possible. The feasibility evaluations of this study can be also used to consider these combinations or modifications even though they have not been specifically considered herein. However, any consideration of series connection of various heat sources must also consider the control complications introduced since in many concepts the flow or temperature must be maintained within closely prescribed limits.

- (U) Figure 2 shows the power required to raise the temperature of hydrogen from various temperature levels to the level required by the turbine. The power requirements vary from 7 to 22 MW while the turbine only extracts 5.2 MW to drive the pump. In essence the additional power over and above that extracted by the turbine is used to provide higher temperature turbine exhaust fluid for increased overall engine performance.
- (U) Figure 2 may be used as a first test in determining the feasibility of a concept by determining if sufficient energy can be transmitted. It must be recognized, however, that energy transfer cannot be the sole criteria. In many systems, other limitations (such as maximum permissible temperature) will preclude use of the energy solely to raise temperature to the desired level.
- (CRD) Figure 3 tabulates the energy addition by each of the major components. The data for this tabulation are taken from Reference A, C and D. Examination of Figure 3 discloses that of the current NSS components which have at least reasonably high temperature capability, only the structural support system and the core itself provide sufficient energy addition, and the core periphery supplies nearly enough energy.

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FIGURE 3

ENERGY ADDITION

	<u>Component</u>	<u>MW Energy Added</u>
	Brim Shield	1.0
	Nozzle Skirt Extension (added to turbine outlet fluid)	6.6
	Nozzle Skirt	7.9
	Nozzle	33.5
	Reflector	20.5
(CRD)	Structural Support System	{ 18.1 at max. temp. 19.3 at min. temp.
	Extension Shield	1.0
	Central Shield	0.8
	Support Plate (added to primary flow)	1.6
(CRD)	Core Periphery	7.2
	Core	1526.2

Data at rated conditions from References A, C and D.

V. B. Structural Support Assembly (SSA) Discharge Flow

- (CRD) The SSA discharge flow may logically be considered as an alternate source of turbine drive fluid since sufficient energy is now added to the SSA fluid, as shown by Figures 2 and 3 and the temperatures are reasonable. Feasibility was first investigated using the current SSA design, with discharge conditions as specified in Reference A, followed by an investigation of the possibility of raising the discharge temperature.
- (CRD) For this study, it was assumed that the two-plena support plate currently being evaluated within WANL could be used and that the SSA bypass flow could be deleted. This assumption was made since cycle efficiency obviously requires the highest turbine inlet temperature permissible, and the SSA bypass flow would degrade the turbine inlet temperature if it were mixed with the SSA discharge. If the separate studies determine that the two-plena support plate is not suitable or that bypass is required for other reasons, either the three-plena support plate would be used, with the bypass only cooling the plate but not mixing with the SSA discharge, or a separate manifold would be required for the SSA discharge flow.
- (CRD) In order to use the SSA discharge as turbine drive fluid, it would be necessary to collect the discharge in a manifold at the edge of the support plate and pipe the SSA discharge fluid to a port in the pressure vessel.
- (CRD) Comparison of the flow and temperature of the structural support outlet fluid conditions without mixing of the bypass flow (Reference A) with the turbine requirements of Figure 1 indicates that sufficient energy exists in the current structural support discharge

flow to supply the turbine. These comparisons are shown on Figure 4. From this figure it can be seen that, if the turbine is designed for the lower temperature higher flow conditions, more than enough energy can be supplied by the structural support system.

(CRD) If the structural support flow is used to drive the turbine, the two systems are then connected in series even though current concepts require that each of the two systems be controlled independently. Therefore, the feasibility of such a series connection to fulfill the NSS structural support control requirements was investigated.

(CRD) A current control requirement for the SSCV is to provide a reactivity change to allow the control drums to be maintained at the nominal angle even as core reactivity changes during operation at rated conditions. In order to accomplish this, it will be necessary for the SSA flow rate to be adjusted and for this flow to be relatively unaffected by turbine requirements. Figure 5 illustrates one system which could accomplish these independent control functions. Detailed investigations may well select other control solutions, but the system shown in Figure 5 is sufficient to investigate feasibility. The TPCV and SSCV would be slaved such that opening of the TPCV would cause comparable closing of the SSCV. The net result would be a relatively unaffected SSA flow. The position of the SSCV relative to the TPCV would be adjusted in order to change the SSA flow for reactivity control. The SSCV flow would bypass the turbine and would be returned to the reflector outlet to be heated to full chamber temperature with the primary flow. The SSCV flow could alternatively be returned to the turbine discharge or separately exhausted, but either of these alternates would result in system performance degradations because the SSCV exhaust is at less than full chamber temperature. Figure 5 also shows a concept for collecting the SSA discharge flow and carrying it to a port.

(CRD) Figure 6 was prepared in order to grossly determine if sufficient SSA discharge flow and energy would be available to a particular turbine over the full SSA flow range for controlled operations. A turbine designed for 600°R , 360 psia, and 6.9 lb/sec. operation (from Figure 4) was assumed. Further simplifying assumptions of constant turbine work required and constant turbine efficiency were made. With these assumptions, Figure 6 shows the turbine and bypass flows under these conditions as a function of SSA flow. Even though the assumption of constant turbine efficiency is obviously not correct and simplified equations were used, it appears that the bypass flow requirements are such as to be reasonable and feasible for control of SSA flow. Thus, control of a series SSA and turbine appears feasible. Detailed evaluation and optimization of turbine performance would be required in order to firmly evaluate feasibility.

(CRD) In the current system, the SSA inlet pressure is varied to change SSA flow while the system of Figure 5 would vary SSA discharge pressure to alter flow. With the SSCV downstream of the SSA, the fluid in the first pass of the SSA would be at close to pump discharge pressure regardless of SSA flow. The result is that reactivity swing for a given SSA flow rate range would be decreased with the SSCV downstream. Figure 7 illustrates the pressure variations in the SSA for the two SSCV locations, and it can be seen that less density change would occur between high and low flows if the SSCV is downstream. This change in reactivity swing would be small and could possibly be minimized by optimizing the orifice location for the relatively constant SSA inlet pressure.

(CRD) Consideration has also been given to the feasibility of increasing the support stem effluent temperature so as to eliminate or reduce the engine performance penalty which would result from use of turbine drive fluid at less than the current level of 1660°R. Reference F documents the design considerations and constraints for the SSA and served as a basis for this consideration of increased temperature capability.

(CRD) If only energy addition is considered, sufficient energy is now added in the reference NSS design to heat the fluid required by the turbine, at 630 psia, to the desired temperature of 1660°R. (See Figures 2 and 3) However, additional coolant flow is used by the SSA to maintain currently acceptable SSA temperature levels.

(CRD) As stated in Reference F the limiting conditions within the SSA are the maximum and minimum support stem temperatures and maximum liner temperature. At minimum SSA flow (maximum temperature) the tie tube exit temperature is essentially equal to the maximum support stem temperature, which is at its limit, and the liner is also operating at its maximum temperature limit. Thus any attempt to increase the SSA exit temperature would result in the second pass fluid (between the support stem and the liner) heating the support stem beyond its capabilities. The minimum temperature constraint on the support stem precludes insulation of the outer surface of the support stem or removal of a forward portion of the insert tube inside the support stem. If this insert tube were not included in the forward portion of the first pass or if the stem were insulated from the second pass fluid, the maximum support stem temperature would be reduced and higher SSA discharge temperature might be permitted by the SSA at rated conditions. However, off design and startup

operations would be severely compromised because, without high temperature SSA discharge flow, the first pass fluid would overcool the stem to temperatures below the minimum permissible.

(CRD) This evaluation has considered only structural integrity of the SSA. An increase in SSA discharge temperature would also affect the range of reactivity control obtainable by varying SSA flow but this is a secondary design consideration.

(CRD) Thus, it has been concluded that with the current knowledge of material temperature limits the SSA discharge temperature cannot be increased. As documented in Reference F, other materials have been considered for the SSA and no better materials have been identified. Therefore, an increase in SSA discharge temperature would require an extensive materials program, including radiation effects testing. The materials program required, especially radiation effects tests, would introduce significant delays in availability of material data for design purposes. There is also the possibility that the SSA design with new materials could not supply sufficient flow for the turbine.

(CRD) The foregoing evaluations have assumed the availability of the support stem assembly discharge flow at the temperature existing at the tie tube exit. In the current reference NSS design, the tie tube exit fluid is mixed with the SSCV bypass flow in the middle plenum of the three-plena combined support plate and plena. Use of the SSA discharge flow as a turbine drive fluid would preclude this mixing of bypass flow. It would also require the use of the two-plena support plate currently being evaluated within WANL, use of the three-plena support plate with the SSCV bypass only cooling the plate without being mixed with the support stem flow, or a separate manifold for the SSA discharge flow.

It is entirely possible that elimination of mixing of the SSCV bypass with the SSA discharge will necessitate a change in material of the support plate/plena in order to accommodate the higher temperatures. It is anticipated that one of these alternates could be used with the necessary NSS redesign to collect and distribute the SSA discharge flow.

(CRD) With any of these collection and distribution concepts, some cooling of the SSA discharge flow will occur as it is transmitted to a pressure vessel port. Detailed analyses would be required to determine the magnitude of this cooling.

(CRD) Feasibility considerations of startup, including bootstrap, have not identified any factors which would obviously preclude bootstrap or the successful completion of startup or shutdown transients. However, several factors have been identified which indicate that startup would require detailed analyses. The insulation required to protect the SSA at rated conditions also reduces the transfer of energy to the fluid during bootstrap. It is possible that the flow/power requirements during the startup transient may not be consistent with prevention of either overtemperature or undertemperature of the SSA during the transient, and detailed analysis would be required to evaluate this question.

(U) A preliminary system failure mode analysis was performed to evaluate the susceptibility, or lack of susceptibility, of this concept to significant single failures. The analysis not only attempted to identify and evaluate any new possible NSS failures whose consequences are increased, but also to determine if there would be any possible NSS failures which would no longer be of concern in this concept or any whose consequences would be reduced.

(U) It was determined that the effect of reference design NSS failures would be essentially unchanged. This could be expected since all of the reference design NSS components would be retained and would continue to be required to perform their reference design functions. The following single failures of the NSS components added by this concept were identified which would have to be prevented by design for high inherent reliability or by redundancy in order to prevent potential loss of normal or emergency operation capability.

(CRD) 1. SSCV Failure - Failure of the SSCV to the closed position would be more severe in this concept than in the hot bleed cycle NSS and would require a more complex system to prevent such failures. In the hot bleed cycle NSS, physical stops or bypass provisions can be included in the SSCV to assure that at least minimum SSA flow is provided by the valve. When the SSA discharge flow is used as the turbine drive gas, such minimum SSA flow cannot be assured. Since the SSCV would then be in parallel with the TPCV and turbine, it would be necessary for the SSCV to have the capability of fully closing under normal conditions in order to provide the turbine gas at the highest permissible SSA discharge temperature and to close for thrust nulling operations. If the SSCV were to fail fully closed, the turbine flow requirements would then determine the SSA flow under all conditions. Under those conditions, the normal turbine flow variations during transients would over-temperature the SSA. Failure of the SSCV to be slaved to the TPCV would also result in similar effects with the severity of the consequences depending upon the specific method of failure. Two parallel redundant SSCVs would be required to provide protection against such malfunctions along with the capability to sense a valve malfunction or else

the capability to actively control the SSA flow rate. If such redundancy were not provided, such malfunctions would preclude normal operations.

- (U) Failure of the SSCV to the open position would have essentially the same effects as in the hot bleed cycle with the additional effect of reducing turbine inlet temperature. Proper sizing of redundant SSCVs would tend to mitigate this effect.
- (U) 2. Turbine Supply Manifolding and Piping Inside the NSS - This manifolding and piping represents additional NSS components. These components essentially replace a portion of the turbine inlet line and have essentially the same modes of failure and consequences. Leaks in this turbine inlet piping inside the NSS could also have the additional effects of distorting core inlet conditions if the leak were such that full mixing could not occur and could also overheat adjacent components. Depending upon the location and magnitude of the leak, the effects could range from little or no effect on normal operations to complete loss of even emergency operation capability in the event of a massive rupture. While complex manifold and piping are required, the temperatures are lower than in the current turbine inlet line and it appears that reliable internal NSS turbine manifolding and piping could be developed.
- (U) 3. Turbine Drive Port Seal - The axial differential thermal expansion between the pressure vessel closure and the central internal turbine piping must be accommodated by a new sliding seal or bellows at the pressure vessel port. Failure of this seal would cause turbine drive gas to bypass the turbine and SSCV. If the leakage were less than the desired SSCV flow, no operational effects would result. However, larger leakages would

result in lowered SSA outlet and turbine inlet temperatures. Massive failures would significantly lower turbine drive gas availability. In order to prevent these adverse effects, a redundant seal configuration could be provided if required to insure the necessary reliability.

(CRD) The evaluations of this concept have shown that the current SSA could conceptually be used to supply the turbine drive fluids at current SSA discharge flow rates and temperatures. It further appears that material limitations within the SSA preclude an increase in the temperature of the SSA discharge fluid. Attendant with this concept are engine specific impulse penalties and significant increases in reactor and NSS complexity. If this concept were to be considered further, more detailed evaluations would be required of the support plate, startup and shutdown transients, reliability and single failure effects, and control systems required.

(U) Table 1 presents a summary of the NSS considerations associated with use of the SSA discharge fluid as the turbine drive gas supply.

General Advantages	General Disadvantages	NSS Advantages	NSS Disadvantages	NSS Changes Required	System Changes Required	Questions Requiring Detailed Evaluation
TABLE I STRUCTURAL SUPPORT DISCHARGE FLOW						
(1) Eliminate nozzle penetration and substitutes lower temperature pressure vessel penetration (2) Eliminate need for diluent and its pressure vessel penetration (3) Can provide turbine drive fluid during cool-down thrust nulling so as to provide pump fed thrust nulling	(1) Turbine inlet fluid is at significantly lower temperatures and more turbine flow is required (2) Series connection of structural support system and turbine causes interactions (3) Changes in structural support outlet temperature (e.g., EOL reactivity adjustment) affect turbine inlet temperature and may compromise the $\pm 3/4\%$ I_{sp} controllability requirement	(1) None identified	(1) Bootstrap flow requirements may not be consistent with structural support requirements (Detailed analyses required to evaluate) (2) Requires the use of a 2-plena support plate or redesigned support plate (3) Added piping complexity and sealing requirements (4) Addition of a new failure mode for the NSS (failure of a stem flow lowers turbine energy available) (5) SSCV or support stem failure is made more serious since it also affects the turbine drive fluid (6) Increases the SSCV control complexity because of interactions with turbine control and necessity to hold SSCV flow at NSS desired value (7) NSS changes increase the difficulty of design or decrease the NSS reliability	(1) Two-plena support plate required (2) Structural support discharge flow must be collected and discharged. (3) Provisions must be made for mixing the turbine bypass flow with the reflector outlet flow (4) SSCV control complexity probably increased. (5) If it is a requirement to raise discharge temperature, a new material must be developed for stem and liner	(1) Parallel TPCV & SSCV required (or other system to maintain support flow constant regardless of TPCV action) which will bypass the turbine with some of the support system discharge flow (2) Startup altered and bootstrap capability must be evaluated (3) Lower temperature turbine inlet fluid	(1) Can bootstrap, high thrust, and high I_{sp} be accomplished? (2) Does this system preclude meeting the I_{sp} controllability requirement (3) Detailed NSS design to be accomplished (4) Effect on NSS reliability to be evaluated (5) Control requirements to be determined and control concepts evaluated (6) Is sufficient energy available when all system uncertainties are considered? (7) Additional NSS weight to be determined

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FIGURE 5 STRUCTURAL SUPPORT DISCHARGE FLUID AS TURBINE DRIVE SOURCE

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FIGURE 7

PRESSURE WITHIN SSA (ORIFICED BETWEEN 1st AND 2nd PASSES)

V. C. Peripheral Flow

- (CRD) In this study "peripheral flow" is used to describe the flow which passes between the reflector and the core wrapper. The peripheral flow can be considered as a source of turbine drive fluid because of its reasonable temperature and flow levels.
- (CRD) Reference B information was used as the base point. From Reference B, current preliminary estimates of the mixed peripheral exit conditions are 1.33 lb/sec. flow at 1900°R. Further detailed analysis may revise these values slightly. Comparison of these conditions with the minimum turbine requirements in Figure 1 shows that insufficient energy is currently available in the peripheral flow.
- (CRD) The peripheral flow was further examined to determine if potentially feasible NSS changes exist which would make the use of the peripheral flow feasible as a turbine source.
- (CRD) Since the periphery exit temperature is currently slightly higher than required for the turbine and considering that the requirements for the core periphery would not be violated by a lower peripheral flow temperature, the feasibility of supplying 3.6 lb/sec. at 1660°R were examined. (In actuality, it would probably be necessary to supply slightly higher temperature fluid to counteract heat losses in the manifold and piping within the NSS.) The conservative assumption was made that the current peripheral flow is discharged at the desired turbine temperature of 1660°R (instead of 1900°R) and it was determined that 11.5 MW of additional energy would have to be added if the flow were increased to 3.6 lb/sec.
- (CRD) One of the requirements on the core periphery is to provide a thermal impedance which, in conjunction with other core features, limits the maximum temperature difference in any peripheral fuel element to 375°R (minimum to average material temperature) at a given core station. Because of this requirement, it does not appear feasible to add the required 11.5MW by conduction from the fueled elements inside the wrapper, since increased conduction would increase the temperature difference.

(CRD) The conceptual feasibility of adding a fueled region outside of the core wrapper was then evaluated. Conceptually, this could be accomplished by addition of full or partial elements outside of the wrapper or by fueled filler strips. On the order of 0.8 MW is added to the core propellant flow by each core fuel element in raising the propellant temperature from approximately 290°R to 4670°R . Since it is only desired to raise the peripheral fluid temperature from 290°R to 1660°R , either the flow rate per element would have to be increased or the element loading would be decreased. It would appear to be more desirable to keep the same element flow rate with decreased fuel loading, and this also results in a conservatively high assumption in terms of number of elements required. With this assumption, approximately 80 additional elements outside of the wrapper would be required. There are now 174 filler strips in the core periphery and it therefore appears that the energy addition requirements are not unreasonable and could be accomplished by some combination of fueled full or partial elements and/or fueled filler strips. However, feasibility also depends on capability of these additional fueled peripheral elements to also meet the other periphery requirements.

(CRD) If the fueled region outside of the wrapper (elements or filler strips) could be maintained at essentially the same temperature as current filler strips, the effect on the outer core elements inside the wrapper should be unchanged. Judicious selection of fuel loading and coolant channels in the peripheral units should make this possible. Again, if the peripheral units are maintained at the same temperature as the current filler strips,

- (CRD) heat conduction to the reflector through the lateral support system (LSS) should remain essentially, the same. Heat generated in the LSS seals and in the reflector would be slightly increased because of the fueled region being in closer proximity, but the power generation is low in the periphery and should not have a significant effect. Maintenance of the same axial pressure variations in the core periphery would maintain the current pneumatic bundling loads and still supply peripheral flow at an adequate pressure of 450 psia.
- (CRD) The above discussions are concerned with steady state conditions. Transient considerations are not amendable to gross considerations and require detailed evaluation in order to avoid incorrectly concluding transient feasibility or infeasibility. However, no transient considerations which would immediately make this concept infeasible are immediately apparent.
- (CRD) Figure 8 illustrates a proposed means of collecting and discharging the peripheral flow as a turbine drive source. The peripheral units could be shouldered at the aft end to provide a circular surface for the aft row of seals and to allow the coolant channels to exit above the seal. The small flow between the outer surface of the wrapper and the fueled region outside of the wrapper would be allowed to discharge into the nozzle chamber.
- (CRD) The function of the aft seal would be to seal between the turbine drive gas and the nozzle chamber. This seal must perform its function and still accommodate both radial and axial movements during operations. The reliability requirements on this seal would be extremely stringent since failure of the seal would represent a single failure

(CRD) which would prevent any subsequent engine operation. The difficulty in meeting the reliability requirement would be magnified by the high temperature environment and the radial and axial movement capabilities required. Some leakage across this aft seal would be expected during normal operations although this leakage would be minimized by maintaining the cavity above it at a pressure close to chamber pressure. If a minimum flow past this seal is required for nozzle cooling purposes, the requirements on the seal would significantly increase since failure to supply this flow would be another major failure conceivably resulting in nozzle failure. It would also be necessary to assure adequate cooling of the remainder of the sealing and ducting structure and to prevent corrosion.

(CRD) The series connection of the periphery and the turbine would cause similar problems as in the series structural support system and turbine unless suitable valves and controls were incorporated. Figure 9 illustrates a possible solution, similar to that for the SSA concept, which includes variable slaving of the TPCV and TPCV bypass. TPCV bypass is required to prevent large fluctuations of pneumatic bundling pressures with TPCV angle changes, particularly during transients. If large TPCV angle changes were made during transients and no controlled bypass was provided, the periphery pressure could approach core inlet pressure or drop very low. The variable slaving of TPCV and TPCV bypass would probably be required because of assembly to assembly variations and may have to be actively controlled to maintain proper bundling pressures. It would also provide a means of maintaining the pressure drop across the aft seal acceptably low. For this system, the bypass flow is at too low a pressure to reinject into the system and would be exhausted, which would represent a performance penalty.

(CRD) Feasibility considerations of startup, including bootstrap, have not identified any factors which would obviously preclude bootstrap or the successful completion of startup or shutdown transients. However, greater pressure drop would be introduced between the pump discharge and the turbine which would tend to degrade the bootstrap capability. This factor would require detailed evaluation. If bootstrap were infeasible, it may be possible for flow from the reflector inlet or dome to be bled for startup and then valved off when the periphery flow could sustain the turbine.

(U) As part of the evaluation of the feasibility of this concept, a preliminary failure mode analysis was performed to grossly evaluate the susceptibility, or lack of it, of the concept to significant single failures. Investigations were also performed to determine if change to this concept would tend to improve the reliability of the basic NSS components, and it was determined that the effect of reference design NSS failures would be essentially unchanged. This results from the fact that all of the current NSS components would continue to be required with the same functional and performance requirements.

(U) It was also determined that the additional NSS components required by this concept would have to provide protection against the single malfunctions listed below in order to prevent potential loss of normal or emergency operation capability.

(CRD) 1. Seal between periphery flow and nozzle chamber - Failure of this seal could result in complete loss of flow to the turbine and complete loss of subsequent normal or emergency capabilities. Therefore, completely redundant seals would be required so that a single failure could be tolerated. Design for reliability

of these components is complicated because of exposure to full chamber temperature, the necessity to accommodate radial and axial relative motions, and the necessity to assure adequate cooling of all parts that make up this system both for protection of the parts and to avoid heat transfer to the reflector.

- (CRD) 2. Bypass valve - Redundant series-parallel valves would be required in order to protect against single failures of this new valve. The need for the valve is to insure adequate but not excessive pneumatic bundling pressures and to insure that peripheral temperatures are within limits regardless of turbine flow requirements. Thus, failure of the valve to be slaved to the TPCV must be protected against. In addition, since flow through this valve is exhausted at a significant performance penalty, it will be necessary to design the system so that the minimum possible flow bypasses the turbine. It follows that minimum flow stops cannot be included without significant performance penalties, and that instead the valve should be fully closed during some normal operations. If only one valve were used, failure of the valve closed when not desired closed would raise the core bundling pressure and periphery and turbine inlet temperatures. Failures of the valve open would result in lowered bundling pressure and lowered temperatures. Thus, redundant valves would be required along with the capability to sense a valve malfunction and so prevent potentially severe consequences.

- (U) 3. Turbine drive port seal - A sliding seal or bellows may be required between

the new internal NSS turbine inlet piping and the pressure vessel in order to accommodate differential expansions. A redundant seal configuration could be incorporated, if necessary, to provide the required reliability in preventing loss of turbine flow or reduction of reflector and core flow.

(U) Leakage of the periphery flow collection and manifold system would not have a severe effect since the reflector inlet plenum is at a higher pressure than is the periphery discharge fluid. Such leakage would result in lowered turbine inlet temperature with reduced engine specific impulse but would not prevent subsequent operations.

(CRD) The evaluations described above have considered one method of collecting and transmitting heated gas from the periphery to the turbine inlet line. It is recognized that other detailed implementations can be postulated, however, the concept shown in Figure 8 is typical. Any concept must provide an assured turbine flow within limited temperature constraints, and must be highly reliable. Any concept must also accomplish these functions without compromising reactor temperature constraints or core bundling constraints. Therefore, it is believed that the evaluations of this concept are representative of peripherally heated flow in general. Table II summarizes the NSS considerations. Detailed design studies would be required for any further evaluations.

(CRD) These evaluations have shown that a specially fueled peripheral region outside of the core wrapper could conceptually supply the turbine drive gas at the desired temperature of 1660°R. The design problems introduced by this concept appear to be significant and, while they appear to be ultimately solvable, the significantly increased NSS complexity and modes of failure would strongly tend to reduce NSS reliability and would introduce significant development risks. Introduction of this concept would require major redesign of the NSS and a substantial redirection of the NSS design effort. Therefore, while this concept appears to be technically feasible, it does not appear to offer sufficient merit to warrant further investigation.

General Advantages	General Disadvantages	NSS Advantages	NSS Disadvantages	NSS Changes Required	System Changes Required	Questions Requiring Detailed Evaluation
TABLE II PERIPHERAL FLOW (with addition of peripheral fueled elements)						
<p>(1) Eliminates nozzle penetration and substitutes lower temperature pressure vessel penetration.</p> <p>(2) Eliminates need for diluent and its pressure vessel penetration</p>	<p>(1) Series connection of peripheral flow system and turbine causes interactions</p> <p>(2) Changes in peripheral flow temperature (e.g., with SOL to EOL drum angle variation) affect turbine inlet temperature and may compromise the $\pm 3/4\%$ I_{sp} controllability requirement</p> <p>(3) Necessity to provide some turbine bypass flow</p> <p>(4) Removes cool gas from hot gas side of the nozzle</p>	<p>(1) Reduced element temperature for same mixed mean chamber temperature if peripheral flow into chamber is reduced</p> <p>(2) Reduced difficulty and uncertainty in sensing mixed mean T_c allows some reduction in nominal T_c required to assure $4500^\circ R$ minimum if peripheral flow into chamber is reduced</p>	<p>(1) Complicates periphery and reflector inlet plenum by additional elements, seals, piping, and manifold</p> <p>(2) Addition of new failure mode for the NSS (failure of aft peripheral seal lowers turbine energy available).</p> <p>(3) Maintenance of proper bundling pressures may require active control</p> <p>(4) Effect of a stuck drum may be magnified because of effect on turbine drive fluid through increased local heating</p> <p>(5) NSS changes increase the difficulty of design or decrease the NSS reliability</p> <p>(6) If peripheral flow must be supplied to the chamber for nozzle cooling, another failure mode is added to the new aft seal (failure to pass enough flow to the chamber)</p>	<p>(1) Requires development of periphery elements</p> <p>(2) Requires positive sealing of periphery to nozzle</p> <p>(3) Requires additional piping and manifold</p> <p>(4) Requires a new core periphery design</p>	<p>(1) Requires constant periphery flow regardless of TPCV movement (parallel TPCV and turbine bypass control valve) to maintain proper bundling pressure</p> <p>(2) Startup altered and bootstrap capability must be evaluated</p>	<p>(1) Can bootstrap, high thrust, and high I_{sp} transients be accomplished?</p> <p>(2) Does this system preclude meeting the I_{sp} controllability requirements?</p> <p>(3) Detailed NSS redesign to be accomplished</p> <p>(4) Effect on NSS reliability to be evaluated</p> <p>(5) Control requirements to be determined and control concepts evaluated</p> <p>(6) Fluid temperature variations with drum angle and from SOL to EOL must be evaluated</p>

FIGURE 8
PERIPHERAL FLOW BLEED

FIGURE 9
PERIPHERAL FLOW

V. D. Core Bleed

- (U) When it is considered that the turbine requires a small flow (3.6 lb/sec) of intermediate temperature gas (1660°R), the possibility arises of bleeding this gas directly from the core at the desired temperature. Such a system could bleed from the core at a point where the desired turbine inlet temperature is obtained or bleed at higher than the desired temperature and mix with diluent as required.
- (CRD) No concept for bleeding at an intermediate point in the core was identified which was reasonable to consider. Any such concept quickly resolved into effectively a separate small reactor which would pre-heat the reactor flow or would result in extreme redesigns of fuel elements and methods of fuel element support. Both individual and multiple plena or extraction points were examined. Problems include the support of elements below any such plenum, the gathering of bleed gas, and the ducting of bleed gas back to the forward face of the core.
- (CRD) Figure 10 schematically illustrates a concept for bleed hot gas at nozzle chamber conditions, and diluting and extracting this gas through a central pipe penetrating the core, support plate and plena, shield, and pressure vessel. Two concentric pipes would be used with core inlet fluid used as the diluent which would pass through the annulus. Each of these pipes would have to be of irregular shape to match the adjacent fuel elements or filler strips would have to be added to change to a circular penetration. The diluent would be used to cool both pipes and then would be injected into the turbine inlet line near the chamber in order to reduce the temperature of the hot bleed gas. It appears that

(CRD) pyro-graphite insulation would be required on the O.D. of the outer pipe in order to keep the heat flux to an acceptance level. A shield plug cooled by shield inlet fluid could be included as shown to reduce the streaming due to the shield penetration.

(U) In effect, the chamber bleed system described above simply transfers the hot bleed port from the nozzle to the NSS where the port must pass through many components.

(CRD) Among other NSS problems introduced by the chamber bleed system of Figure 10 are:

- (a) Support of the turbine supply system
- (b) Provisions for differential axial and radial movement of the various NSS components with respect to the turbine supply system
- (c) Sealing of the NSS components to the penetrating turbine supply system
- (d) Inclusion of a mass of hydrogen in the center of the core which will introduce reactivity perturbations due to TPCV control movements
- (e) Minimizing of the heat transmitted from the turbine inlet line to the support plate and plena, shield, and pressure vessel.
- (f) Provision of core bundling would be complicated

(CRD) Critical single failures which would have to be protected against by design were identified by a preliminary failure mode analysis. A leak of the outer pipe would result in high core corrosion in the area of the leak. A failure of this pipe by buckling could structurally damage adjacent core elements and could result in loss of the required core bundling. Thus, a design of this component with high inherent reliability is required.

(CRD) A failure of the inner piping or of the piping to the pressure vessel interface would result in low turbine inlet temperature since any leakage would be into the turbine line. Since failure of the port at the core face would allow cold diluent flow to enter the nozzle chamber which would severely reduce performance, this component must be designed to be inherently highly reliable.

(U) Table III summarizes the NSS considerations. While the above problems could undoubtedly be solved, the complexities are such as to require introduction of many new concepts with attendant high risks in development. Thus, detailed investigations are not warranted.

(U) An extension of the system of Figure 10 is considered in Section V. H.

General Advantages	General Disadvantages	NSS Advantages	NSS Disadvantages	NSS Changes Required	System Changes Required	Questions Requiring Detailed Evaluation
TABLE III. CORE BLEED						
<p>(1) Removes necessity for hot bleed penetration of the nozzle.</p> <p>(2) Could move the turbine inlet line to the centerline and thereby reduce a significant secondary radiation source.</p>	<p>(1) Increased complexity of the turbine inlet line system.</p> <p>(2) Possible requirement to cool turbine inlet line during cooldown, with attendant complications to thrust nulling system.</p> <p>(3) Possible increase in core, reflector, and pressure vessel diameters.</p>	<p>(1) None</p>	<p>(1) Significantly complicates the core.</p> <p>(2) If the turbine inlet line is to penetrate the shield, streaming through the shield penetration must be prevented.</p> <p>(3) Introduction of different temperature level components in the core and resulting differential movements.</p> <p>(4) NSS changes increase the difficulty of design or decrease the NSS reliability.</p> <p>(5) Complicate provision and maintenance of core bundling.</p>	<p>(1) Incorporation of the turbine bleed into the core itself.</p> <p>(2) Penetrations of the support plate and shield.</p> <p>(3) Support of the turbine inlet line required within the NSS.</p>	<p>(1) Relocation of the bleed port from the nozzle to the pressure vessel.</p> <p>(2) Effectively relocates diluent bleed from the reflector inlet to core inlet.</p>	<p>(1) Can bootstrap startup be accomplished with this system?</p> <p>(2) Would the turbine line in the core require cooling during post-operation cooldown? If so, how can thrust nulling be accomplished?</p> <p>(3) What detailed NSS design and what effects on NSS reliability?</p> <p>(4) Detailed nuclear redesign of core required to evaluate the effects of the large mass of hydrogen in the center of the core.</p>

FIGURE 10
CORE BLEED

V. E. Separate Nuclear Heater for Turbine Drive Fluid

(U) As an alternate to using the core to heat the turbine drive fluid, a separate nuclear heater for the turbine drive fluid can be considered. Such a system to heat fluid extracted from the reflector inlet is shown schematically in Figure 11. The advantages of such a system would be the elimination of the necessity to penetrate the nozzle for hot bleed extraction. The fluid extraction point could be located elsewhere in the cycle with more or less heat added in the heater depending upon the fluid extraction point. Extraction at the reflector inlet would allow the startup fluid to extract heat from the nozzle for bootstrap.

(CRD) Figure 12 shows the energy addition required to raise the fluid to the turbine inlet conditions of Figure 1. The feasibility of generating this energy by a sub-critical assembly external to the pressure vessel was considered. Such a unit would make use of the leakage flux from the reflector. As a base case, the feasibility of using typical core elements was examined. Preliminary calculations by A. Mowery indicate that a one element thick layer near the outer surface of the pressure vessel would transmit 0.4 to 0.8 MW per element at rated chamber temperature depending upon the closeness to the pressure vessel surface. As in consideration of peripheral fueled units, it is only desired to raise the fluid temperature to 1660°R instead of to 4640°R . Therefore, either the flow rate per element would have to be increased or the element loading decreased. If the flow rate per element is kept constant, 80 elements are required. If 0.4 MW per element is transmitted, 50 elements are required. Thus, on the order of 80 shortened elements could be used. In either case, the quantity of elements is large but is reasonable to consider further as a heater.

(CRD) A discharge temperature of 1660°R is required. Such a temperature will not allow the heater elements to be directly adjacent to the pressure vessel surface. A separate container with a cooled surface on the pressure vessel side would be required. One conceptual

(CRD) arrangement is a one element thick annulus of elements in an annular chamber with excess flow on the inner surface to cool the inner wall so that excessive thermal radiation to the pressure vessel would not occur. Support of the elements could possibly be accomplished by a support arrangement from the aft pressure vessel flange. Support of the elements undoubtedly could be accomplished, but would require a detailed analysis and could be a major problem.

(CRD) The feasibility of providing bootstrap startup capability is questionable and would have to be investigated in detail. The only stored energy available for startup would be that upstream of the fluid extraction point and the small stored energy in the elements. In order for startup to be successfully accomplished, the heater elements would have to start generating sufficient energy to provide the required transient turbine power before the stored energy were depleted. Since the heater elements would be a sub-critical assembly, the generation of sufficient energy would be dependent upon sufficient leakage flux from the reactor. Thus, the availability of sufficient turbine energy for startup is dependent upon the flow and power transients.

(CRD) Shielding would be affected such as to increase in weight because of this nuclear heater but the detailed changes which would be introduced cannot be determined without detailed design studies. Location of fuel elements external to the pressure vessel would definitely require a brim shield, or similar shield, of at least the current size. The heater container may have to be of a material to withstand turbine inlet temperature, with the same secondary radiation source considerations as for the current turbine inlet line but with a larger mass of material involved.

(CRD) Although the elements of the heater will be operating at lower power and temperature levels than core elements, significant power generation is required and cooling would be required after shutdown. The cooldown fluid would require separate thrust nulling provisions and possibly separate cooldown control to provide efficient cooldown fluid utilization.

(U) This concept was examined to provide a preliminary failure mode analysis with respect to the susceptibility, or lack of susceptibility, to significant single failures. From this preliminary analysis it appears that, with proper design of the separate heater, the consequences of any failure in the reference design NSS would neither be increased nor decreased by a change to this concept. Since the same NSS components would continue to be required and would have to perform their reference design functions, it can be preliminarily concluded that the reference design NSS reliability would be essentially unaffected. For this conclusion to be valid, it will be necessary for the heater elements to be located such that leakage flux perturbations, such as by a stuck control drum do not significantly effect energy addition to the turbine drive fluid.

(U) Consideration can, therefore, be concentrated on the effect of single failures of the additional components associated with this concept. Such consideration shows that the design of the heater must be such as to provide protection against the following single failures in order to prevent possible loss of normal or emergency operation capability.

(U) 1. Heater pressure vessel - Rupture of the heater containment pressure vessel or significant leakage would cause loss or reduction of flow to the

turbine. However, since the turbine drive gas temperature would be no higher than in the current hot bleed system, it appears that use of the same materials and design techniques as are now used for the hot bleed turbine inlet line would provide the necessary high reliability.

- (CRD) 2. Element and element support - It appears that more than the required quantity of elements can physically be incorporated in the heater. This provides the latitude to implement the heater in multiple parallel sections, if necessary, to minimize the effects of failure of an element or element support. It further appears that the most critical failure of an element could come in contact with the heater containment pressure vessel and cause burnout of the vessel. The relatively low operating temperatures of the elements should allow the incorporation of the necessary redundancy in the element supports in order to preclude such failures, although a complex design may be required.

- (CRD) Table IV summarizes the considerations associated with this concept. This concept is conceptually feasible as a source of energy for the turbine and could provide turbine drive fluid at the desired temperature. However, it appears that the design complications, penalties, and risks associated with this concept are at least as great as those associated with the Full Flow Engine and thus, further NSS investigations do not appear to be warranted.

General Advantages	General Disadvantages	NSS Advantages	NSS Disadvantages	NSS Changes Required	System Changes Required	Questions Requiring Detailed Evaluation
TABLE IV. SEPARATE NUCLEAR HEATER FOR TURBINE DRIVE FLUID						
(1) Eliminates need for hot bleed penetration of the nozzle.	(1) Weight of the heater. (2) Some variation of turbine inlet temperature, at an operating point, with drum angle, and resulting t_{sp} variations. (3) Radiation source at a large diameter, outside the pressure vessel, which will require additional shielding. (4) Heater elements would require cooling after shutdown.	(1) None	(1) Heater elements would require cooling after shutdown and thrust nulling provisions. (2) NSS changes which would affect leakage flux could be constrained by heater requirements. (3) New element configuration required.	(1) Provision of nuclear heater in a separate flow path outside of pressure vessel. (2) Elements required for heater with lower fuel loading or higher void fraction and of a different shape.	(1) Provisions for support and shielding of the heater required. (2) Startup altered.	(1) Detailed off-design nuclear analyses required particularly to assure adequate turbine energy availability during startup. (2) Can bootstrap, high impulse, and high thrust startups be accomplished? (3) How much shield weight increase? (4) Detailed design of the heater required. (5) Nuclear analyses required to determine energy availability during off-design operations.

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FIGURE 11 SEPARATE NUCLEAR HEATER FOR TURBINE DRIVE GAS

This page is Unclassified.

V. F. Separate Nuclear Heater for Turbine Exhaust

A separate nuclear heater for the turbine exhaust fluid was examined. Such a system would have the advantage of raising the energy of the exhaust fluid so that near full chamber specific impulse could be obtained if a suitable nozzle were utilized.

Approximately 54 MW would be required to raise 3.6 lbs/sec of turbine exhaust fluid to 4500°R from the turbine exhaust conditions of Reference C.

While it may be reasonable to generate the power required to heat the exhaust fluid in a heater, no practical solution to the following problems could be identified which would not result in unreasonably large modifications to the system:

1. Containment of 4500°R fluid
2. Low density turbine discharge fluid
3. Desire to minimize radiation source from a shielding standpoint
4. Aftercooling requirements
5. Necessity to prevent overheating resulting from design uncertainties
requires active control and probably a separate critical assembly.

Consideration of the above problems leads to the conclusion that, if the turbine exhaust is to be heated, the most desirable solutions would be either a full flow (topping) cycle or a separate small reactor of the desired power level with its own nozzle. Such a small reactor could also be used to regeneratively heat the turbine supply fluid. In effect, such a small reactor would also utilize the full flow cycle with the primary output being turbine power for the main nuclear engine. Such a reactor might be attractive for clustered NERVA applications but was considered to require too extensive modifications to be feasible under the constraints of this study.

V. G. Heat Pipes

- (CRD) Heat pipes have been proposed for use as the tensile member providing support for the core with condensing end of the heat pipe dissipating the heat removed into the turbine drive fluid as shown in Figure 12. Heat pipes could also be used not as structural members, but in place of one element per cluster for the express purpose of transmission of energy from the core interior to the turbine drive fluid.
- (U) Heat pipes are not restricted to circular cross-sections and could be made in any shape required by the core. Use of heat pipes would offer the advantages of not requiring that the turbine drive fluid be passed through the core, thereby eliminating the associated sealing, piping and manifolding problems. However, other problems are introduced by the use of heat pipes. Advantages and disadvantages are listed on Table V. Regardless of whether the heat pipes replaced fuel elements or structural units, an adequate flow of coolant (turbine drive fluid) is required over the condensing ends of the heat pipes in order to prevent overheating or overcooling. Therefore, a controlled turbine bypass system would be required similar to that required for the structural support discharge system of Section V. B.
- (CRD) From Reference E and assuming a heat pipe inner radius of 0.15 inches so as to permit heat pipe replacement of tie tube, approximately 1800 feet of both input and output pipe lengths would be required to transmit the 18 MW currently removed by the structural support system at minimum flow. This 18 MW would be sufficient to match the Figure 1 630 psia turbine requirements at 1660°R if reflector inlet or outlet fluid were used. If

(CRD) each of the 349 tie tubes were replaced with a heat pipe, 5.2 feet of both input and output sections would be required on each pipe which is clearly excessive.

(U) The above data made use of maximum recommended heat flux from Reference E. In order to utilize heat pipes, higher heat flux capability would have to be developed, larger heat pipes used, and/or energy transmittal requirements reduced with attendant lowered turbine inlet temperature.

(CRD) A preliminary failure mode analysis examination of this concept for the effects of single failures has identified design consideration features which must be incorporated into the detailed design in order to prevent adverse effects due to a single failure. The effect of a failure of a single heat pipe to provide structural support should be essentially the same as for the current design which does not appear to be a critical failure. However, it would be necessary to carefully select the heat pipe working fluid so that leaks of this fluid would not cause unacceptable reactions with the hydrogen propellant or with the adjacent core elements. The multiple penetrations of the pressure vessel required for the heat pipes could be reliably sealed by a redundant seal configuration.

(U) It appears that this application, with the disadvantages listed in Table V, would introduce such significant changes as to greatly increase the development risk and further investigation is not warranted.

General Advantages	General Disadvantages	NSS Advantages	NSS Disadvantages	NSS Changes Required	System Changes Required	Questions Requiring Detailed Evaluation
TABLE V HEAT PIPES						
<p>(1) Turbine drive fluid does not pass through core eliminating hot bleed nozzle penetration</p> <p>(2) Simplified thrust nulling since turbine flow path extracts core heat by means of the heat pipes</p>	<p>(1) Undemonstrated startup and transient capabilities</p> <p>(2) Turbine fluid can be at close to pump discharge pressure level</p> <p>(3) At least a set minimum turbine flow rate required at all times to cool the heat pipes</p>	<p>(1) Eliminates current structural support system and its piping</p> <p>(2) Can be essentially constant temperature support system at off-design operating conditions by controlling turbine flow or bypassing turbine with part of the flow</p>	<p>(1) Eliminates reactivity control by structural support system</p> <p>(2) Reduction of turbine flow can overtemperature support system</p> <p>(3) Lack of prior development</p> <p>(4) Major differences from core designs developed in Technology Program</p> <p>(5) High temperature heat pipes required for adequate turbine inlet temperatures and for structural support</p> <p>(6) NSS changes increase the difficulty of design or decrease the NSS reliability</p>	<p>(1) Major redesign of entire NSS</p>	<p>(1) Turbine drive fluid supplied to condensing end of heat pipes.</p> <p>(2) Controlled turbine bypass required in order to assure constant flow at condensing ends of heat pipes to avoid system overheating</p>	<p>(1) Selection of heat pipe fluid to allow operating over the required temperature range and heat removal requirements from startup through completion of cooldown.</p> <p>(2) Can a fluid be selected which does not have excessive adverse nuclear design effects?</p> <p>(3) Can required startups and transients be accomplished?</p> <p>(4) What detailed NSS design and what effects on NSS reliability?</p>

FIGURE 12

HEAT PIPE PROVIDING
STRUCTURAL SUPPORT

V. H. Portion of Core Partitioned as Turbine Supply

- (U) In effect, the current system uses a portion of the core to supply turbine drive fluid since a portion of the core flow is extracted through the nozzle hot bleed port for the turbine. If a portion of the core were partitioned to supply only turbine drive fluid, the nozzle hot bleed port could be eliminated and it may be possible to maintain a more constant turbine inlet temperature during throttled operation. It would also provide a readily available separable source of turbine drive fluid for pump fed thrust nulling operations.
- (CRD) The peripheral flow system of Section V-C is actually one method of separate sectioning of the core for a turbine energy source. In addition, use of a portion of the core inside the wrapper could also be considered.
- (CRD) Two basic methods for collecting core flow exist: (1) collection at the aft face and (2) supply and collection by a set of counterflow tie tubes.
- (CRD) In the first method, an outer core annulus formed by the present wrapper and a new inner wrapper would be used to heat the turbine fluid supplied from the core inlet plenum. A manifold at the aft face would collect the gas for subsequent piping through the reflector inlet plenum and pressure vessel. Numerous obvious problems exist including:
- (a) Cooling and sealing of the collection manifold
 - (b) Differential movement, both axial and radial, of the core aft face with respect to the turbine drive fluid piping through the reflector inlet plenum
 - (c) Variable heating of the turbine fluid due to drum angle changes
 - (d) Variations in turbine fuel element temperature with turbine flow requirements which would in turn affect the temperature gradient across the outer primary core elements, particularly during transients.
- (CRD) Because of the problems associated with manifolding such a system, it appears that a much more practical solution would be the use of a fueled region outside of the current wrapper to supply the needed energy to the peripheral flow. Such a system is discussed in Section V-C.

- (CRD) A counterflow system would have advantages over a system which collected turbine drive fluid at the aft core face. In a counter flow system, the fluid is supplied and collected in a low temperature environment. A counterflow system can be made up of multiple counterflow assemblies so that failure of one assembly does not completely destroy the capability of the whole system. The individual counterflow assemblies could be dispersed throughout the core to minimize the effect of a large region at lower than full temperature. The current tie tube structural support system obviously is actually such a counterflow system and, as discussed in Section V. B., can be considered as a turbine energy source.
- (CRD) Other alternate forms of a counterflow system are schematically shown in Figures 13 and 14. The Figure 13 system would enclose the elements in the central chamber in order to provide one section of the core for heating while the other (b) would provide elements in the outer channel. Approximately 80 elements, or 14 clusters, would be required if current element flow rates were maintained and only approximately 0.23 MW per element would be required to be added to the fluid. In both concepts, both the inner and outer pipes would have to take the shape of adjoining elements or else filler strips or circular element segments utilized.
- (CRD) The concepts of Figures 13 and 14 would have the same problems as the core bleed concept described in Section V. D. It would also have the additional problem of support for the elements and clusters for which no obvious solution exists. It should be noted that the

(CRD) pressure drop load on the elements tends to displace the elements forward instead of aft and would require new support concepts, possibly cold end support without tie rods or tie stems.

(CRD) A preliminary failure mode analysis identified critical single failures which would have to be protected against in a detailed design of this concept. A leak in the outer pipe would result in a high corrosion rate in the core elements in the area of the leak and a failure of this component by buckling could result in loss of core bundling and failure of adjacent core elements. Since redundancy does not appear reasonable to incorporate, this component must be designed for very high inherent reliability. The fuel elements and their supports must also be designed for high reliability and designed such that failure of an individual element or support would not prevent normal or emergency operations.

(CRD) The design problems introduced by these concepts appear to be significant and no basis for solution has been developed in the Technology Program. While the design problems undoubtedly could be solved, the greatly increased NSS complexity and modes of failure would strongly tend to reduce NSS reliability and would introduce significant development risks. Therefore, these concepts were not judged feasible. The peripheral flow system of section V.C is a more practical method of core partitioning for turbine drive fluid.

FIGURE 13

CORE PARTITIONING

FIGURE 14

CORE PARTITIONING

V. I. Fueled Central Elements

(CRD) The concept of use of fueled central elements has been investigated to evaluate feasibility. Fueled central elements can be considered in two basic concepts for turbine energy addition as follows:

1. Provision of any necessary additional energy in order to raise the fluid temperature of the SSA fluid.
2. Heating of a separate and distinct flow path in order to supply turbine drive fluid heated to the desired temperature.

(CRD) As discussed in Section V. B., sufficient energy is now added in the current reference NSS design SSA, but this energy cannot be utilized in raising the temperature. Instead, sufficient flow must be passed through the SSA in order to maintain the SSA material temperature within limits. Therefore, no additional energy addition to the SSA by fueled central elements is required.

(CRD) The feasibility of the second concept involving use of fueled central elements to heat a separate flow path for turbine drive fluid was investigated. In such a system core inlet fluid would pass through channels in the central elements, be heated to the desired temperature, and then be collected and piped to a pressure vessel port for supply to the turbine.

(CRD) Collection of the central element flow at the aft (nozzle chamber) face of the core was examined with no concept identified which was even potentially practical. Extreme heat loads would exist on any collection manifolds in the nozzle chamber which would require extensive cooling both during operation and during cooldown and afterheat

removal. This high temperature manifold and collecting device would also have to accommodate the relative radial and axial movements which occur during normal operations.

(CRD) Instead of collecting the central element flow at the hot end, it would be necessary to return the flow to the forward face of the core in somewhat of a counterflow system for collection and distribution of the discharge at the forward face of the core. Figure 15 illustrates two schemes which would eliminate the need for a hot end manifold. In each of the schemes core inlet fluid would enter the first pass and be directed aft where the flow would cross to another channel which would form the second pass to return the fluid to the forward face of the core. It would be necessary to collect the exhaust flow from each of the second pass channels into manifolds and transmit this flow to a pressure vessel port. The channels in the central elements would be similar to and would replace the current instrumentation channels. In effect this type of use of fueled central elements is a variation of the core portioning discussed in Section V. I.

(CRD) In the concept illustrated by view (a) of Figure 15, the turbine flow would be directed aft along the outside diameter of the liner and would then flow outward through a drilled passage to a flow channel for further heating and return to the forward face of the core. In addition to absorbing energy for the turbine, the first pass flow would also assist in cooling the liner and would replace some of the pyro-graphite insulation.

(CRD) It was determined that the concept utilizing flow along the liner would result in radial temperature gradients far in excess of the gradients permissible in fuel elements, particularly at the core inlet. Core inlet fluid (287°R) would flow through the central bore

(CRD) and fluid above turbine inlet temperature (at least 1700°R) would flow through the channel with only a 0.030 inch web separating the two passes. In addition, large temperature gradients would be introduced in adjacent normal fuel elements both near the core inlet and at the aft end of the core.

(CRD) The concept which makes use of channels for both the first and second passes, shown in Figure 15 (b), was determined to also introduce temperature gradients in the elements far beyond current capability. In this concept, greater distances would separate the regions of high and low temperature but the thermally induced stresses would still be excessive. In addition, the alternate regions of high and low temperature would introduce circumferential temperature gradients, in the element, liner, and adjacent fuel elements that would be excessive.

(CRD) Both concepts illustrated in Figure 15 would have the same problems of collection and manifolding and would have the same problems of increasing the difficulty of maintaining adequate core bundling due to the many low temperature regions introduced into the core. Higher than normal pressure drops would also exist between the inlet of the second pass and the element surfaces.

(CRD) Figure 16 presents a view of the cluster hardware which would have to be redesigned to permit collection of the discharge flow. Examinations by Reactor Design personnel have determined that complete redesign would be required to permit collection from three or six instrumentation channels per central element. Implementation of such a manifold and the connections to each channel would introduce severe risks into the NSS design.

- (CRD) From the design considerations discussed above and the results of a preliminary failure mode analysis, the susceptibility of this concept to single failures can be evaluated. Failure of an element plug would result in severe localized corrosion of adjacent fuel elements or of leakage of the turbine drive gas onto the hot end support hardware. Leakage of a turbine drive gas collection manifold or of the piping or connection to an element would result in a reduction in turbine inlet temperature. Leakage of the piping or connection to an element would have the additional effect of reducing the flow through a central element with the possibility of overheating. Therefore, the design must permit such loss of flow. In order to provide the necessary reliability, high inherent reliability must be incorporated in the detailed design, since little redundancy could be provided, and provisions must be included to minimize the consequences of any such malfunctions.
- (U) From evaluations performed of this concept, it has been concluded that this concept is not feasible from the NSS standpoint.

General Advantages	Disadvantages	NSS Advantages	NSS Disadvantages	NSS Changes Required	System Changes Required	Questions Requiring Detailed Evaluation
TABLE VI FUELED CENTRAL ELEMENTS						
(1) Eliminates nozzle penetration and substitutes lower temperature pressure vessel penetration (2) Eliminate need for diluent and its pressure vessel penetration	(1) Increased possibility of partial loss of turbine flow supply because of multiple connections and manifolding. (2) Turbine inlet temperature would vary as the radial power profile changes from SOL to EOL, which would vary engine I _{sp}	None	(1) Extreme temperature gradients introduced in the central elements (far beyond current capability) (2) NSS reliability degraded by the high number of connections required to collect central element flow and transfer it to the pressure vessel port (3) Would require complete redesign of the cluster cold end hardware (4) Increased pressure drop from the flow channel to the outer surface at the hot end of the element	(1) Fueled central elements (2) High temperature turbine flow collection, manifolding and distribution system required and probably complete redesign of cluster support (3) Development of fueled central elements capable of very large temperature gradients required (4) Possible NSS redesign to maintain adequate bundling	(1) Pressure vessel penetration required for the turbine drive fluid	(1) Can bootstrap, high thrust, and high I _{sp} transients be accomplished? (2) Can central elements be developed to withstand the temperature gradients? (3) Effect on NSS reliability to be evaluated (including new leakage sources) (4) Can the transient variations in central element flow with transient TPCV movement be accepted?

FIGURE 15 FUELED CENTRAL ELEMENTS

FIGURE 16
CLUSTER HARDWARE

SECTION G-G

VI. References

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