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		SHEET <u>1</u> OF <u>21</u>				Analysis	
SUBJECT (120)						DEPARTMENT (13)	
RELIABILITY CONSIDERATIONS FOR FUEL ELEMENT TRADE STUDY NO. 769						Reliability	
						DATE (6)	REACTOR
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DOCUMENT REFERENCES (DWGNO/PART NO/COMPUTER CODES/DRMS/MTLS SPECS/CORRESPONDENCE)							
1. DRM 52607	2.	3.	4.	5.			
6.	7.	8.	9.	10.			
1. PURPOSE 2. ASSUMPTIONS/METHODS 3. CONCLUSIONS (USE CONTINUATION SHEET IF NECESSARY)							
<u>PURPOSE</u>							
To document the Reliability effort in support of the fuel element trade study developed in the spring of 1970.							
<u>ASSUMPTIONS/METHODS</u>							
It was decided at the outset of the trade study that the Reliability effort would concentrate on systems considerations, while providing support to Reactor Design in preparation of a comprehensive Failure Mode Listing for the fuel element at the component level. Reliability generated an Intercomponent Interactions Matrix and a System FMECA for the fuel elements. The design alternates were then systematically evaluated against each of the FMECA modes. The evaluation is summarized in the Reliability Considerations Comparison Matrix for Fuel and Core.							
<u>CONCLUSIONS</u>							
The Reliability preference based on information available at this time rates the composite design (Alternate No. 2) best, with the hybrid design (Alternate No. 6) second and the High Void Composite design (Alternate No. 7) a close third, (all are externally coated). The uncoated designs are rejected because of unacceptably high surface corrosion, while the graphite designs are rejected because coating damage and/or structural damage would result in unacceptably high corrosion losses.							
APPROVALS		INFORMATION CATEGORY			SECURITY CLASS		
R. L. Eisner <i>R. L. Eisner</i> 6-9-70		<i>Unclassified</i>			UNCLASSIFIED		
PREPARED BY <i>R. L. Eisner</i> DATE 6/19/70		CLASSIFICATION <i>Unclassified</i> DATE 6/19/70					
APPROVED BY _____ DATE _____		AUTHORIZED CLASSIFIER _____ DATE _____					

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INTRODUCTION

The Reliability objectives in support of the fuel element trade study are:

1. To generate a detailed listing of failure modes at the component level, to gain assurance that no subtle differences between the design alternates are overlooked.
2. To generate an extensive listing of failure modes and effects at the system level, to gain assurance that no subtle differences in system effects arising in cores based on the different design alternates (and combinations of alternates for various core components) are overlooked.
3. To compare the design alternates with respect to the potential problems identified at the component and system levels, and thereby derive a quantitative Reliability order of preference for use in selection of the most desirable fuel type.

Accomplishment of the first objective resulted in a listing of nearly sixty distinct failure modes. It was judged to be impractical to attempt to analyze all of them for the present trade study. Accordingly, Reactor Design condensed the listing to achieve a manageable, yet adequate, coverage which is presented in their trade study FMA DRM (Reference 1). In so doing, they assumed that the quality and inspectability considerations could be the same for each type of element. The full comprehensive FMA listing for the fuel element will be issued independently of any trade study work, as DRM 52610. It is expected that that document will be upgraded and revised as the fuel development program matures and as analysis of the fuel failure modes becomes more sophisticated.

To accomplish the second objective, Reliability drew up an Intercomponent Interactions Matrix (Figure 1) which, together with the component failure mode listing, provided the base from which the System Failure Mode Effects and Criticality Analysis (System FMECA, Table I) was derived. This System FMECA considers the system failure mode effects and interactions of the core as a whole involving the fuel.

To accomplish the third objective, the seven design alternates were systematically evaluated with respect to each of the system FMECA* modes, making use of quantitative analysis and experimental data wherever possible, and relying on best available engineering judgement where necessary. The evaluation is summarized in the Reliability Considerations Comparison Matrix (Table II). It constitutes the basis for the Reliability order of preference of the design alternates. System effects must ultimately be understood in terms of the underlying component failure modes and mechanisms. This will eventually be done through development of a sophisticated model, which is far beyond the scope of the present trade study. The ACTION/STATUS SHEET (Table 1 A) appended to the System FMECA is used to request analysis of the important system failure modes and to document the status of such analyses. The state of knowledge at the time of the trade study is thereby summarized.

The Tables and Matrices are explained in detail in the discussion which follows. Finally, this report contains extensive discussion of those factors where, because of substantial uncertainty at this time, new information could have significant impact on the Reliability preference. This especially concerns corrosion attributable to progressive degradation of the bore coating with cycling.

DISCUSSION OF TABLES AND MATRICES

The Intercomponent Interactions Matrix (Figure 1) (See Page 4) was drawn up for consideration of intercomponent interactions effects in a systematic way. Listed first in each block (underlined) are the normal interactions between components which occur when all components are operating properly. These are largely interfacial friction effects. Next considered are the effects expected if a particular component has experienced some kind of failure. These effects generally involve a change in environmental conditions for neighboring components.

A matrix of this sort will prove useful later on in the program, for trade studies involving components for which a substantial amount of quantitative analysis is included in the FMA. It will then be possible to consider the tendencies of certain design alternates of a given

MATRIX FOR CONSIDERATION OF INTERCOMPONENT INTERACTION EFFECTS

Effect Of	Upon	CORE PERIPHERY	FUEL ELEMENT	CENTRAL ELEMENT	CHESH
CORE PERIPHERY		Interfacial corrosion reduces axial flow impedance. Low axial impedance accelerates corrosion.	Friction stresses. Interfacial H ₂ flow causes surface corrosion. Flow impedance failure causes thermal shock cracking, resulting in rapid corrosion.	None	None
FUEL ELEMENT		Friction stresses. Broken fuel element or pinhole causes rapid corrosion of pyrofoil, resulting in wrapper leakage. Longitudinal ratcheting causes ring corrugation. Circumferential ratcheting lowers axial flow impedance.	Interelement friction. Broken elements or pinholes cause increased surface corrosion of neighboring F/E.	Interelement friction. Broken F/E or pinhole causes surface corrosion of C/E. C/E broken by friction corrodes badly if interstitial H ₂ is "unsaturated".	Broken F/E tip can load CHESH. Ejected coating fragments can form WZrC eutectic on tungsten parts.
CENTRAL ELEMENT		None	Interelement Friction	None	Interface forces. (Breakage of CHESH can be serious if protection cup is threatened.) Broken C/E makes no difference to CHESH unless liner insulation corrodes away and liner blows out.
CHESH		None	None	Interface Forces	None

Normal interactions are underlined.

Other (abnormal) interactions constitute "Configurational" discrepancies for consideration when reiterating the FMA.

One matrix must be considered for each combination of alternates.

FIGURE 1

INFORMATION CATEGORY	
<i>unclassified</i>	
<i>AB</i>	<i>6/19/70</i>
AUTHORIZED CLASSIFIER	DATE

REQUESTED BY:	
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component to increase or reduce probability of occurrence for particular failure modes of other interacting components and thereby derive a more meaningful quantitative reliability figure of merit for various design alternates considering combinations of alternates in the core as a whole. As far as the present trade study is concerned, the intercomponent interaction effects must be judged qualitatively. The qualitative effects are strong enough to clearly favor a non-corrodible core periphery and external coating of the fuel elements no matter which fuel is used.

The system FMECA (Table 1) lists system level failure modes for the core and indicates: (a) the effect of the failure mode on the fuel, (b) the failure interactions between the core and other components, (c) the effect of failures on the NSS system, (d) mission criticality category of the mode, and (e) means of detection of the failure mode.

Four classes of failure modes, involving the fuel within the core subsystem, are listed. These are: (1) basic fuel modes which consider failures of fuel elements not caused by other components in the core and not directly affecting other components, (2) interaction modes where effects of the fuel elements upon other components in the core are considered, (3) interaction modes where failures of other components in the core affect the fuel, and (4) control malfunction or transient modes.

The component effect and system effect entries are self explanatory, however the intensity, extent, or rate of the various modes and effects (i.e., a degree of severity) is generally not explicitly stated. Some discussion is therefore appropriate here, to explain how such 'severity' factors were considered and how the mission criticality ratings were deduced.

First it should be recognized that the system FMECA in this trade study is used primarily to identify interactions and potential, significant effects. Accordingly, we have listed failure modes which have significant system effects other than the major effect of gradual reactivity loss. Most of these system effects individually do not require abandoning the mission and going to emergency mode operation, though they do imply reduced reliability.

Thus they must be rated Category IIA. (The criticality categories are those of ANSC flight safety contingency analysis document S019-001.) Most of the modes also entail some increase in corrosion rates. Therefore, if they occur in combination, or if the occurrence of certain individual modes (e.g., involving broken elements) is rather widespread, it may be necessary to go to emergency mode operation because of an excessive overall rate of reactivity loss, if for no other reason. Degradation effects such as overall reactivity loss due to corrosion cannot be assigned Category III unless they exceed some predetermined limits of extent or rate of increase, which would preclude continued normal operation. Thus we have assigned to Mode 1, Category IIA. (A nominal amount of reactivity loss is expected and the NSS is designed to accommodate for it.) Category III has been assigned to a mode where engineering judgement indicates that it could lead to irreversible degradation through an accelerating chain of events (generally embodying regenerative feedback effects) which would cause extensive damage to the core, within minutes, such that normal operation would no longer be possible. For example, loss of radial impedance of the core periphery is considered to be a Category III failure for a corrodible periphery. That is to imply, the criticality category assigned to a mode really envisions the probable effect(s) stemming directly from occurrence of the mode, even though in some cases normal operation could continue for a few minutes before the first system symptoms would appear. Mode No. 8, "broken element tip" was rated Category III on the premise that the component effect had occurred, i.e., that a long fragment had gotten by the CHESH. Although that event is highly improbable, given that it has occurred, the possibility of impact on the nozzle with attendant damage cannot be dismissed.

Action/Status Sheet (Table 1 A) Supplement to FMECA

As indicated in the introduction, the analysis of the many possible sequences of events starting with elementary failure modes of individual fuel elements and culminating in a system level failure mode will not be available for some time. However, there does exist a significant body of analysis and experimental observations which allows one to draw meaningful inferences as to the comparative behavior of the trade study alternates with respect to the modes listed in the System FMECA. The Action/Status Sheet supplement to the

FMECA (Table IA) is intended to reference that body of knowledge, and to indicate some of the reasoning behind the assessments shown in the Comparison Matrix (Table II). Simultaneously, the Action Sheet indicates where there are knowledge gaps, and lists the steps planned to fill those gaps.

It will be noticed that not all of the modes entered in the System FMECA are treated in the Action Sheet: Mode 3, 'local fragmentation', is not expected to be analyzed in the foreseeable future for several reasons. First, such analysis would be very complex and furthermore, 'in graphite elements, the mode has low probability of initiation and would lead simply to Mode 2a1, while in composites, downstream coating damage resulting from any such fragmentation would not lead to gross accelerating corrosion. Mode 4 has been omitted because of the decision to develop a non-corrodible core periphery. Modes 6 and 7 are not discussed because they are Category I type failures (which require further failure events to give rise to a significant system effect.) Mode 8 is very improbable because of the low stresses at the tip which, moreover, are not oriented in a way to give rise to lengthy axial fragments.

The Comparison Matrix (Table II) summarizes the evaluation of the fuel element design alternates against the most significant failure modes identified in the System FMECA, and indicates the order of preference of the alternates with respect to each consideration. The concept indicated first under a selection sequence is the one judged least likely to allow system failure via the corresponding mode; that listed last is judged to entail the greatest risk of system failure. There are three major categories for Reliability Considerations. These are: (a) "Core Reactivity Loss", where the risks of abnormally high corrosion rates are evaluated for structurally sound elements, (b) "Structural Modes", where the risks of system failure are evaluated as related to specific types of loss of structural integrity, and (c) "Interaction Modes", where risks of system failure stemming from interactions between the fuel elements and other core components are evaluated. The effects of control transients are included in this group. The circled numbers represent figures of merit with respect to these major categories of Reliability Consideration. The highest figure of merit denotes highest reliability with respect to the particular group of considerations.

The figures of merit are derived in the following manner: In each ranking sequence, a score of one point is assigned to the last ranked concept(s), a score of two points to the next to last, etc. If there are no ties, the first ranked concept is assigned seven points. Under each major category, a total score is obtained for each concept by adding its scores assigned from each of the ranking sequences. When these total scores are normalized to add up to 1, the normalized values constitute the figures of merit. The figures of merit obtained for the three major categories are then directly averaged with equal weight to yield an overall Reliability Figure of Merit. In view of the fact that a number of the structural modes culminate in failure by excessive reactivity loss through severe corrosion, it could be asked whether it is justified to list these separately, in addition to the "Core Reactivity Loss" consideration. That is to say, perhaps undue weight has been given to reactivity loss. This is believed not to be the case. Rather, this built-in weighting of reactivity loss simply reflects the high importance of corrosion resistance in the fuel. Note that the "Core Reactivity Loss" evaluation considered structurally sound elements only.

It will be noted that the order of the numerical reactivity loss entries is not reflected in the figures of merit under Core Reactivity Loss nor in the associated ranking of the concepts. The reason for this departure is that the reactivity loss numerical entries are based on extrapolated test data which does not consider the accelerating coating degradation expected at the hot end in graphite elements after a dozen or so cycles. The figure of merit, on the other hand, anticipates significant improvement in the capabilities of composite elements with further developmental effort, and specifically considers fundamental physical mechanisms which should account for basic differences in long term cyclic capability of graphite and composite elements. (These mechanisms are discussed further in the next section of this report.) The reactivity loss figure of merit was thus obtained from estimates of the relative probabilities of the design alternates for providing 10 hour/60 cycle operation, considering the improvement potential. The estimates were made by Thermal Design personnel most familiar with the corrosion behavior of the fuel elements. Reliability must emphasize the considerable uncertainties in these estimates; however, in view of present experimental evidence discussed in the next section, the ranking sequence appears far less uncertain than do the numerical values of the figures of merit.

DISCUSSION OF UNCERTAINTIES

Corrosion Behavior

General corrosion, in fuel elements having a sound carbide coating on the flow channels and on the external surfaces, is rate-limited by the diffusion of carbon through the coating. This process is fairly well understood, and constitutes the basis for ultimately developing long-lived fuel elements. Were the coating to remain intact, corrosion would not be a problem in a 10 hour reactor. Reliability considerations are therefore concerned with what happens when the coating is degraded so that transport processes far more rapid than solid state diffusion come into play and allow increased corrosion rates.

There are two types of coating degradation that are generally discussed, mid-band and hot end. The former, which peaks near station 20, comes about from mismatch of thermal expansion coefficients between coating and matrix, coupled with the difference in temperatures prevailing during coating deposition and during fuel operation. Specifically, cracks form in the coating during cooling after deposition, when the coating contracts more than the matrix. During operation, the cracks close up at stations where the service temperature reaches or exceeds the deposition temperature. The service temperatures at "mid-band" are lower than the deposition temperature, and therefore the cracks remain partially open. By going to higher CTE's in the matrix (AXM flour), to achieve a better match with the coating, and carefully choosing deposition conditions, this problem has been significantly alleviated in graphite elements but has not really been overcome. It appears that the degree of adherence of the coating to the matrix is an important variable which is not yet fully understood or controlled, so that some mid-band cracks are always found in the coating. Early corrosion tests of up to two hours duration on composite elements, where there is excellent coating-to-matrix adherence, surprisingly revealed greater mid-band corrosion than did Pewee II high CTE graphite elements. More recent tests on composite elements made with Robinson coke, designed to give a better coating-matrix CTE match, showed virtually no mid-band corrosion. These tests, however, were run at somewhat lower temperature and power levels than our usual tests. Unfortunately, no comparative tests have been run on graphite elements under these less severe conditions. Other recent tests at LASL used composite elements with 35 volume percent carbide,

instead of the reference composition of 30 volume percent, to achieve a higher matrix CTE. These tests were run at conditions fully comparable to our standard corrosion tests in severity, and showed no mid-band corrosion in six hours of 10 minute cycles. Going to higher percentages of carbide in the composite fuel, however, introduces a number of other problems, in addition to a weight penalty. At any rate, it appears that with additional development effort significant progress can be made towards overcoming the mid-band corrosion problem in composite elements.

The presence of hot end coating defects can be deduced from the fact that the incremental weight loss at the hot end after about 10 cycles exceeds that expected from diffusion limited corrosion. The excess, which peaks at about station 45, becomes progressively larger as the number of operational cycles is increased, and appears to develop sooner in graphite elements than in composite. Post mortem examinations of graphite elements which have been corrosion tested for 6 ten minute cycles reveal that the coating is no longer adherent beyond about station 30, that there are numerous cracks in the coating, and that there are "cross-hatch" grooves under the coating where extra corrosion has occurred. The grooves appear to be related to the coating cracks. There is not yet a good model to explain how the hot end coating defects develop. The degree of coating adherence and the creep-relaxation properties of the coating are important factors which are not yet adequately characterized for detailed analysis. On the other hand, once the defects occur, the consequences can be foreseen. While the cracks which form during cooldown after deposition of the coating are expected to close up at the hot end during operation, they probably will not close perfectly. If the original fracture surfaces of a coating crack do not reunite in exact registry, true closure will be prevented by their asperities. Exact registry upon closing becomes more unlikely with successive cycles because of anelasticity and relaxation effects. As a result, carbon atoms will diffuse rapidly over the crack interface. Such diffusion is much faster than diffusion through the bulk of the coating, which involves vacancy exchange mechanisms of relatively high activation energy. The activation energy for diffusion over the interface of an imperfectly closed crack is expected to be comparable to that for surface diffusion, which is somewhat lower than that for grain boundary diffusion. Analysis is planned to determine the increase in corrosion rates expected from such rapid diffusion paths.

Once coating defects develop, whether in mid-band or at the hot end, hydrogen will attack the carbon at the base of the openings and eventually undermine the coating toward the edges. As the area of the corrosion pocket increases, the rate of carbon removal increases so that the process tends to accelerate. If, on the other hand, the extent of undermining is limited by a network of carbide phase, the area of locally exposed graphite will not be able to increase as rapidly. The strongest evidence so far available of the superior potential of composites to resist accelerating degradation after coating damage has occurred, is illustrated in Figure 19 of DRM 52571, where pieces of carbide-coated graphite and composite (each with a scratch in the coating) are pictured after being subjected to a flow of 4000°R hydrogen for ten minutes. No degradation of the composite piece is evident, while the coating on the graphite piece has been extensively undermined and a substantial amount of material has disappeared. Therefore, we would expect the defect-related corrosion to become progressively worse in graphite after a few hours, and would not expect the composite to be nearly as bad. If long-duration multiple cycle tests on composite elements bear out this expectation, our present ranking sequence would remain valid.

It should be pointed out here that composite elements are expected to be considerably more resistant to erosion as well as to corrosion, as indicated by the evidence cited above. This could be a significant advantage when erosion is the key reactivity loss mechanism. Consider, for example, emergency mode operation of a core which has suffered considerable coating damage. Corrosion rates are very low at the reduced operating temperatures, but the propellant flow is still rapid and turbulent, so that loss of graphite can continue by erosion.

Structural Failures

It will be recalled that, in the first fuel element trade study, there was considerable concern with the high probability of incidence of thermal stress cracks in the high CTE graphite elements as indicated by Q tests. The structural analysis, performed for Trade Study 759 (of the combined stress from power generation, coating matrix interaction, and interelement friction) had not been extended to calculation of failure probabilities via the stress-strength overlap method. The reliability estimates therefore relied heavily on the Q test results. This was the basis of the

overriding Reliability preference for those alternates designed to minimize the in-plane thermal stress. Q tests performed over the course of the past year have continued to produce failures at much lower power levels than had been anticipated. Recent analyses of those tests have led to apparent inconsistencies which force us to conclude that our present understanding of the Q test is deficient. Therefore, Q test results have not been taken as a basis for reliability estimates in the present trade study. Instead, the detailed structural analysis was improved and used for stress-strength overlap calculations of the probability of stress exceeding the corresponding material strength. (This was conservatively taken as the probability that a crack would actually propagate from channel to surface). The present results indicate that there is a better than 94 percent chance that a core of high CTE graphite will not develop a single broken element and only a 0.1 percent chance that as many as two elements would break. It is expected that between five and ten elements, at most, will break in a core of the present composite coated fuel design.

One possibly significant uncertainty in the present trade study which must be pointed out concerns the materials properties of the composite. The strength properties have been found to be proportional to the density, and the density has so far been quite variable, not only from batch to batch, but also from region to region in any element. Predictions of stress induced structural failure were based on best estimates of the mean and standard deviation obtained from limited strength data, on material of standard density. They may therefore be subject to revision. Nevertheless, with a non-corrodible periphery, the NSS (using composite fuel) should be able to tolerate a few broken elements, so revised probabilities of cracking are not likely to have much impact on the trade study selection.

Missing Consideration of system phases

SYSTEM FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS - WORKSHEET

COMPONENT/SUBSYSTEM: Core Subsystem (Fuel, Central, Periph., CHESH)

PREPARED BY: R.L.E.

DRM No. 52058

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REFERENCE OR DRAWING: 940J385 Plus Fuel Alternates

DATE: _____

Mode Ident. No.	FAILURE MODE	COMPONENT EFFECT (Effect on fuel and/or interaction with other core components)	SYSTEM EFFECT	Crit. Cat.	MEANS OF DETECTION
	<u>BASIC FUEL MODES:</u>				
1	Overall Reactivity Loss Due to Corrosion	Gradual reduction in effective cross section of each element as corrosion continues	Gradual reactivity loss compensated by SSCV adjustment. Not a failure until \$1.00 total loss occurs and normal restart is not possible.	IIA	SSCV position
2	Local Intense Loss of Carbon				
	a. Individual Element or Cluster leaks fresh H ₂ to interstices	Accelerates corrosion of adjacent elements or clusters	Same as for Mode No. 1	IIA	No means specific to the mode
	b. Entire Aft End becomes "spongy"	Elements may crush radially (Highly improbable if total reactivity loss is less than \$2)	Possible blockage of propellant paths and ejection of lateral support components	III	No means specific to the mode
3	Local Fragmentation	Erosion of coating downstream by small fragments carried into channel, leads to Mode 2.a.	Same as for Mode No. 1	IIA	Flashes in exhaust
	<u>INTERACTION MODES</u>				
	A. Core Periphery				
4	Broken, badly corroded or pinholed elements (or joint failure in hybrid fuel) near periphery	Wrapper corrodes rapidly (unless of non-corrodible design) until penetrated, after which degradation of peripheral fuel accelerates	Same as for Mode No. 1	III for corrodible wrapper, IIA otherwise	LSS seal chamber pressures and temperatures
	B. Central Element				
5	a. Broken, badly corroded or pinholed elements	Adjacent central element corrodes rapidly, due to fresh hydrogen, leading to penetration from surface and to corrosion of insulating sleeve	May lead to eventual overheating of liner which could rupture and provide fresh hydrogen for more extensive corrosion to accelerate reactivity loss	IIA	None, unless near core T/C
	b. Transient stresses in central due fuel axial expansion on startup	Interstitial H ₂ has access to insulating sleeve, which will corrode	May lead to eventual overheating of liner which could rupture and provide fresh hydrogen for more extensive corrosion to accelerate reactivity loss	IIA	None

TABLE I

SYSTEM FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS - WORKSHEET

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COMPONENT/SUBSYSTEM: Core Subsystem (Fuel, Central, Periph., CHESH)

PREPARED BY: R. L. E.

REFERENCE OR DRAWING: 940J385 Plus Fuel Alternates

DATE: _____

Mode Cont. No.	FAILURE MODE	COMPONENT EFFECT (Effect on fuel and/or interaction with other core components)	SYSTEM EFFECT	Crit. Cat.	MEANS OF DETECTION
	C. CHESH				
6	Broken element tip	Added loading on CHESH	Risk of nozzle damage if subsequent corrosion allows large segments of tip to get by pedestal	I	None
7	Element Coating Loss, Flakes ejected from element	Possible eutectic formed with tungsten CHESH causing local melting	Reduced reliability of protection cup. Increased risk of stem rupture by CHESH failure	I	None
	D. Nozzle				
8	Broken element tip	Possibility of long fragments getting by CHESH and striking the nozzle wall	Possible puncture of nozzle causing reduction in core inlet pressure and loss of propellant	III	None
	FAILURES OF PERIPHERY AFFECTING THE FUEL				
9	Wrapper corrodes and allows increased flow and higher partial pressure of H ₂ adjacent to peripheral F/E	Increased corrosion rate of peripheral F/E, increasing gaps to further reduce axial flow impedance. Leads to mode 4	Same as for Mode No. 1	IIA	None specific to the mode
10	Wrapper tears and allows cold gas to impinge on peripheral F/E causing cracks via thermal stress	Rapid corrosion of graphite materials in vicinity of the fault as a result of fresh hydrogen leakage from F/E flow channels via cracks. Leads to mode 4	Same as for Mode No. 1	III for cor- rodable wrapper IIA other- wise	LSS seal chamber pressures

TABLE I (Cont)

SYSTEM FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS - WORKSHEET

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COMPONENT/SUBSYSTEM: Core Subsystem (Fuel, Central, Periph., CHESH)

PREPARED BY: R. L. E.

REFERENCE OR DRAWING: 940J385 Plus Fuel Alternates

DATE: _____

Mode cont. No.	FAILURE MODE	COMPONENT EFFECT (Effect on fuel and/or interaction with other core components)	SYSTEM EFFECT	Crit. Cat.	MEANS OF DETECTION
	<u>FAILURE OF CLUSTER HARDWARE AFFECTING THE FUEL</u>				
11	Clogging of orifice(s)	Hot channels leading to bead migration (graphite fuel), melting of coating. Leads to mode 2a	Same as for Mode No. 1	IIA	None specific to the mode
12	Increase flow through isolated stem due to loss of impedance of stem orifice	Increased temp. and gradients at local cluster. Leads to mode 2a	Same as for Mode 1	IIA	None specific to the mode
13	Decreased flow through isolated stem due to local obstruction	Decreased temp. and gradients in local F/E, but in- creased temp. and gradients elsewhere in core due to compensation	Same as for Mode 14	IIA	None specific to the mode
	<u>MALFUNCTION OF CDDA AFFECTING THE FUEL</u>				
14	Isolated Drum Roll-Out	Changes in temp. and gradients at local peripheral F/E. Leads to mode 2a, possibly to modes 4 and 5	Average power level maintained by SSCV compensation. Increase above normal occurs in rate of reactivity loss. (Since temp. will be non-uniform, average corrosion rates will be higher because of exponential increase with temp. i.e., hot elements extra corrosion overbalances reduction in corrosion at cooler elements.)	IIA	Drum position indicator
15	Isolated Drum Roll-In	Changes in temp. and gradients at local peripheral F/E. Temps. and gradients elsewhere in core must in- crease due to SSCV compensation	Same as for Mode 14	IIA	Drum position Indicator
16	Transient Drum Roll-Out	Increased temp. and gradients at peripheral F/E in general. Increased probability of thermal stress cracks Leads to mode 4	None unless Mode 4 occurs which is compensated by by SSCV adjustment	I, IIA or III	Drum position indicator
TABLE I (Cont)					

SYSTEM FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS - WORKSHEET

DRM No. 52058
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COMPONENT/SUBSYSTEM: Core Subsystem (Fuel, Central, Periph., CHESH) PREPARED BY: R. L. E.
REFERENCE OR DRAWING: 940J385 Plus Fuel Alternates DATE: _____

Mode Ident. No.	FAILURE MODE	COMPONENT EFFECT (Effect on fuel and/or interaction with other core components)	SYSTEM EFFECT	Crit. Cat.	MEANS OF DETECTION
	<u>MALFUNCTION OF SSCA AFFECTING FUEL</u>				
17	Overall reduction in stem flow below desired level	Compensation must come from drums rolling out from orifice angle, so as to increase temps. and gradients at periphery. Leads to mode 2a, and possibly to mode 4	Same as for Mode 14	IIA	SSCV and/or CDDA position
18	Transient SSCV flow changes	No effect unless total flow changes at rate faster than encountered in normal ramps. It must be assured through safeguards designed into the control loop, that such transients are promptly neutralized. Otherwise, serious damage could occur to any fuel through either the high thermal stresses associated with rapid temperature changes, or through the high temperature levels reached if excessive power levels are maintained for a significant time.	None if transient is promptly neutralized, otherwise, reliability is degraded through increased probability of occurrence of Modes 2 through 8.	I	SSCV position indicator

TABLE I (Cont)

SYSTEM FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS *** ACTION/STATUS SHEET

COMPONENT/SUBSYSTEM: Core Subsystem

PREPARED BY R.L.E.

DRM No. 52058

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REFERENCE: 940J385 Plus Fuel Alternates

DATE: _____

FAILURE MODE	PHASE	ACTION REQUIRED	STATUS
1. Core Corrosion Reactivity Loss	SS	<ol style="list-style-type: none"> Determine cyclic capability of graphite and composite elements for hot end and midband, based on electrical tests at LASL and WANL. Predict by analysis surface corrosion, bore corrosion, defect corrosion, pinholing and the additional corrosion resulting from broken or pinholed elements. Analyze statistically available test data and relate to R-T reactor conditions. 	<ol style="list-style-type: none"> Tests planned, scopes written. Testing to start after PW-II production. Testing will continue throughout reactor development program. Initial analyses completed - DRM No. 52260. <ol style="list-style-type: none"> Externally uncoated elements are unacceptable Pinholes larger than 5 mils diameter grow rapidly causing increased surface corrosion External coating eliminates severe surface corrosion, attenuates pinhole and defect corrosion and protects adjoining elements Composite elements have significant advantages in resisting corrosion due to defects, cracks and breakage <p>Development of prediction methods will continue.</p> Analysis completed - DRM No. 52571, DRM No. 52261 <ol style="list-style-type: none"> Graphite more susceptible to hot end cyclic degradation Composite requires improvement in midband corrosion

TABLE IA

SYSTEM FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS *** ACTION/STATUS SHEET

COMPONENT/SUBSYSTEM: Core Subsystem

PREPARED BY R.L.E.

DRM No. 52058

REFERENCE: 940J385 Plus Fuel Alternates

DATE: _____

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FAILURE MODE	PHASE	ACTION REQUIRED	STATUS
2a1. Intense Loss of Carbon in One or Multiple Elements	SS	Analyze effect of loss of individual elements by corrosion on core structural integrity	Required for reference design
2a2. Intense Loss of Carbon in One Cluster	SS	Analyze effect of loss of one cluster by corrosion , on core structural integrity	Required for reference design
2b. Aft End Becomes "Spongy"	SS	Obtain properties data and strength tests on intact corroded fuel elements. Analyze probability of aft end collapse.	Required for reference design
5a. Central Element Corrosion due to Broken or Pinholed Fuel	SS	Analyze corrosion depths in central element versus time	1. Initial analyses completed, DRM No. 52261. Coated central elements prevent failure for over 5 hours. Composite impedes rapid corrosion from damaged coatings. Liner damage very unlikely due to cold stem flow and additional time to penetrate insulating sleeve (>4 hours). Further analysis in progress.
5b. Central Element Break due to Startup Stresses	SU	Analyze transient stresses in central element with bundling forces, temperature ramps and consideration of C.T.E. of fuel and central.	1. Required for PDR analysis. Thermal and structural transient analyses not available.
9,10 Core Periphery Leakage or Penetration causing Peripheral Fuel Fracture	SS	1. Analyze the corrosion rates of peripheral elements with leakage in the core periphery area 2. Analyze the gradient stresses due to large local wrapper penetration	1. Initial analysis completed, DRM No. 52260. Corrosion through fuel web (for a 1" uncoated defect) takes 3 to 5 hours beyond station 25 in graphite. 2. Required for PDR analysis.

TABLE IA (Cont)

SYSTEM FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS *** ACTION/STATUS SHEET

COMPONENT/SUBSYSTEM: Core Subsystem

PREPARED BY R.L.E.

DRM No. 52058

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REFERENCE: 940J385 Plus Fuel Alternates

DATE: _____

FAILURE MODE	PHASE	ACTION REQUIRED	STATUS
11. Clogged Orifices or Screens	SS	1. Analyze margins in temperature between the 3σ operating temperature and the coating eutectic temperature or matrix phase change	1. Analysis completed, DRM No. 52261. Greatest margin for hybrids and lowest for high void elements.
12, 13 Individual Stem Steady State Flow Abnormalities	SS	1. Analyze local temperature and stress effects due to local stems taking higher and lower flows than predicted	1. None completed. Not a major effect for fuel trade study.
14, 15 Isolated Drum Roll-out or Roll-In	SS	1. Analyze the thermal and structural effects of an individual drum malfunction that is not compensated for by AMOD system	1. Completed analyses for Trade Study No. 701. Upgrading for selected fuel may be required for PDR reliability analysis. Requires double failure.
16, 17 Transient Drum System Roll-Out or Roll-In	SU SD SS	1. Analyze transient responses in fuel (thermal/structural) due to drum system transients. This should be done for selected reference design.	1. Fuel alternates were ranked for susceptibility to thermal stress cracking in the fuel trade study. Studies on reference design are required for PDR.
18. Transient in SSCV	SU SD SS	1. Analyze transient responses in fuel due to SSCV transient. This should be done for selected reference design.	1. Same as for drum system transients.

TABLE IA (Cont)

NOMENCLATURE RELIABILITY CONSIDERATIONS FUEL AND CORE	COMPARISON MATRIX OF DESIGN APPROACHES							SELECTION (Ranking Sequence)
	TABLE II <div>ASTRONUCLEAR LABORATORY</div>							
	1	2	3	4	5	6	7	
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	Composite	Composite External Coated	High Expansion Graphite	High Expansion Graphite External Coated	Hybrid	Hybrid External Coated	High Void Composite External Coated	
I. BASIC FUEL MODES								
A. Core Reactivity Loss	(.139)	(.222)	(.028)	(.083)	(.111)	(.195)	(.222)	
1. Present fuel (5 hr)	\$2.58	\$2.18	\$2.91	\$2.54	\$2.17 Assumes no joint corrosion	\$1.72 Assumes no joint corrosion	\$2.56	2, 7, 6, 1, 5, 4, 3
2. Estimated improvement potential	High	High	Low	Low	Intermediate	Intermediate	High	
B. Structural Modes	(.139)	(.206)	(.079)	(.145)	(.115)	(.164)	(.151)	
1. Probability of transverse crack initiation in matrix	0.9 ₄ ⁶	0.9 ₂ ⁶	0.9 ₅ ⁴	0.9 ₄ ⁷	0.9 ₄ ⁶ (Aft)	0.9 ₂ ⁶ (Aft)	0.9 ₂ ⁸	3, 4, 1, 5, 7, 2, 6
2. Corrosion of broken element transverse surface	Matrix inhibits corrosion	Matrix inhibits corrosion	52 mils/min at Station 45	52 mils/min at Station 45	Aft matrix inhibits corrosion	Aft matrix inhibits corrosion	Matrix inhibits corrosion	2, 6, 4, 7, 5, 1, 3
3. Corrosion of neighboring elements from broken, pinholed or badly corroded elements	Inhibited by carbide matrix	Inhibited by coating and carbide matrix	Corrosion into adjacent elements	Coating inhibits corrosion	Same as 1 forward, same as 3 aft	Same as 1 forward, same as 3 aft	Same as 2	2, 7, 6, 4, 1, 5, 3
4. Radial crushing of core aft end	No problem for \$1.00 loss	No problem for \$1.00 loss	Less desirable than composites	Less desirable than composites	No problem for \$1.00 loss	No problem for \$1.00 loss	Least desirable of all because of thin web	6, 2, 4, 5, 1, 3, 7
5. Same very badly corroded individual elements (spread in corrosion data ratio of 90 percentile to mean value)	4/3 (bare corrosion)	4/3 (bare corrosion)	3/2 (corrosion)	3/2 (bare corrosion)	4 ⁺ /3	4 ⁺ /3	4/3	2, 7, 1, 6, 5, 4, 3
6. Hybrid joint or aft joint failure	No joint	No joint	Aft joint cyclic capability not demonstrated	Aft joint cyclic capability not demonstrated	Joint may have structural failures	Joint may have structural failures	No joint	1, 2, 7, 6, 5, 4, 3

NOMENCLATURE RELIABILITY CONSIDERATIONS FUEL AND CORE	COMPARISON MATRIX OF DESIGN APPROACHES TABLE II (cont'd.) <div style="text-align: center;"> ASTRONUCLEAR LABORATORY </div>							SELECTION (Ranking Sequence)
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	1 Composite	2 Composite External Coated	3 High Expansion Graphite	4 High Expansion Graphite External Coated	5 Hybrid	6 Hybrid External Coated	7 High Void Composite External Coated	
II. INTERACTION WITH OTHER COMPONENTS A. Core Periphery (Non-Corrodiile) 1. Leakage or penetration of periphery causes fuel elements to crack and corrode. B. Central Elements 1. Corrosion of central element due to broken fuel element 2. Transient central stresses C. Orifices or Screens 1. Clogged orifices or screens cause local overheating of fuel (Temp margin $\downarrow$) D. CDDA, SSCA and stem steady-state abnormalities 1. Local temperature increases E. Control Transients 1. Higher fuel stresses Overall Reliability Figure of Merit	(.115) Inhibited by carbide matrix Lowest risk Low margin due to high elastic modulus 304 ϕ R Excessive surface corrosion High susceptibility to thermal shock cracking 0.131	(.158) Matrix inhibits corrosion Lowest risk Lowest margin due to high elastic modulus and high friction 313 Small increase in corrosion Highest susceptibility to thermal shock cracking; external coating contributes tensile component to matrix stress 0.195	(.130) 52 mils/min at Station 45 Crack surface regression Liner protected for over 5 hours as long as C/E coating is intact Highest margin due to low elastic modulus, low friction 253 Excessive surface corrosion Best thermal shock resistance 0.079	(.137) 52 mils/min at Station 45 Crack surface regression Liner protected for over 5 hours as long as C/E coating is intact High margin due to low modulus of elasticity 253 Excessive defect corrosion at aft end Not quite as good as 3, since external coating contributes tensile component to matrix stress. 0.122	(.151) Aft matrix inhibits corrosion Liner protection better than for concepts 3 & 4 Low margin due to high elastic modulus at aft end 469 Excessive surface corrosion Intermediate between 1 and 3 0.126	(.165) Aft matrix inhibits corrosion Liner protection better than for concepts 3 & 4 Low margin due to high elastic modulus and high friction 469 Small increase in corrosion Intermediate between 2 and 4 0.175	(.144) Aft matrix inhibits corrosion Lowest risk Low margin due to high elastic modulus and high friction 169 Small increase in corrosion High void design reduces thermal shock stress 0.172	2, 7, 6, 4, 1, 5, 3 (1, 2, 7) (5, 6) (3, 4) 3, 4, (5, 1) (7, 6, 2) order of preference 5, 6, 2, 1, 3, 4, 7 2, 7, 6, 1, 5, 4, 3 3, 4, 7, 5, 6, 1, 2