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Westinghouse Astronuclear Laboratory

MASTER

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WANL-TME-2760
JANUARY 1971

DATA ITEM S-54

FUEL ELEMENTS (U)

TRADE STUDY NO. 772

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MASTER

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(41)

Subcontract NP-1
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[redacted]

TRADE STUDY NO. 772

APPROVED BY:

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ABSTRACT

This report describes the trade study made for the purpose of evaluating two fuel element design approaches and selecting a fuel element design for the R-1 reactor.

The trade study evaluates fuel elements of standard geometry configuration; i.e., geometry similar to NRX reactors. The materials of the fuel elements considered are high expansion graphite and composite.

The evaluation and selection is made through a comparison matrix in which the ability of each design approach to meet the requirements is objectively evaluated and the design approach having the highest potential to meet the functional, technical and programmatic requirements is selected.

The design of the fuel element selected for the R-1 reactor is the Composite Fuel Element. The selection is based on this design's better performance with respect to reactivity loss. The smaller reactivity loss of the Composite Fuel Element offers a better potential for meeting the required life of the R-1 reactor. Also, the Composite Fuel Element has a higher reliability and safety value.

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INTRODUCTION

The design approaches to fuel elements this report describes are two of the designs selected previously in Fuel Element Trade Study, Order of Preference, Trade Study No. 769, WANL-TME-2709, dated June 1, 1970. These designs are: composite fuel elements and high expansion graphite fuel elements of a geometry similar to fuel in NRX-reactors.

The fuel elements are components of the Nuclear Subsystem of R-1 which contains the fuel elements in an array located in the core of the reactor and consisting of 1878 fueled and 349 support elements. The fuel elements are the source of nuclear heat and serve as the heat exchanger by providing flow channels in which the hydrogen propellant absorbs this heat while passing through the fueled element on the way to the rocket nozzle. One of the components which interfaces with the Fuel Elements is the Core Periphery which surrounds the array of fuel elements, serves as a thermal barrier against the cold propellant present at the circumferential boundary and as a transmitter of lateral bundling forces from the Reflector Assembly to the array of fuel elements. The other component which interfaces with the fuel elements is the Cluster Hardware which supports the elements axially from the Core Support Plate. The geometrical relation of these components is shown in Figure 1-1.

The material of this report is presented in four sections. Section 1.0 contains definitions of the requirements for trade-off based on component specification (EC-677566), SNPO-C technical directives and programmatic factors a fuel element design must meet in order to be considered for R-1.

Section 2.0 contains descriptions and illustrations of the design approaches.

Section 3.0 presents the comparison matrix in which each design of Section 2.0 is evaluated relative to the requirements of Section 1.0. The evaluations are defined in the matrix by quantitative entries based on analyses referenced in Section 4.0 or qualitative entries based on estimates.

Section 4.0 presents a summary of the evaluation and selection. At the end of Section 4.0 is a numbered list of documents which contain the analytical material used in the comparison matrix for evaluation of the design approaches of this trade study.

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1.0 IDENTIFICATION OF REQUIREMENTS FOR TRADE-OFF

1.1 FUNCTION

The primary function of the fuel element is to provide a source of nuclear heat and to serve as a heat exchanger by providing flow channels in which the hydrogen propellant absorbs this heat while passing toward the rocket nozzle. In addition, the fuel elements provide for attachment to the support plate through the cluster hardware.

1.2 SCOPE

This section identifies the requirements which a fuel element design must meet.

These requirements are divided into three groups: the functional, the technical requirements and the non-technical requirements. The functional and technical requirements are quoted from Specification No. EC-677566, Fuel Elements (FE) (Graphite) and where applicable from Specification No. EC-677566/20, Fuel Elements (FE) (Composite) and if necessary are supplemented by interpretations in terms of specific physical properties. Requirements of Specification Nos. EC-677566 and EC 677566/20 not quoted in this section are assumed to be satisfied equally by all design approaches or are of a basic, non-tradeable type that is, all design approaches must and do meet them.

Following the functional and technical requirements are requirements which the design approaches must meet in order to satisfy contract schedules.

1.3 REQUIREMENTS

This section presents the requirements that were used to evaluate the design approaches. The paragraphs enclosed by quotation marks are the fuel element requirements obtained from Section 3.0 of the Fuel Element Specification Nos. EC-677566 or EC-677566/20. The information following these paragraphs contains the working data that were used when the appropriate EC specification values were to be determined (tbd).

1.3.1 Functional Requirements

1.3.1.1 Flow and Thermal Characteristics

"3.1.1.1.3.1.1 Flow and Thermal Characteristics. - The FE, as assembled in the NSS shall be capable of sustaining a controlled nuclear heat generation throughout the operating service life specified in 3.1.2.3.1.1.1 (Operating Service Life). The FE, as assembled in the NSS, shall be capable of accepting propellant from the core inlet plenum and transferring the nuclear generated heat to the propellant while channelling the propellant to the thrust chamber."

" 3.1.2.3.1.1.1 Operating Service Life. - The FE shall be capable of operating with all NSS components at the conditions necessary to produce a nominal mixed mean chamber inlet temperature (rated temperature) of 4250°R for a minimum of 600 minutes accumulated in multiple cycles, up to 60, of varying duration. The maximum time at Rated Performance shall be 60 minutes for a single cycle of Normal Mode Operation and (tbd) minutes for a single cycle of Single Turbopump Operation Mode. The FE shall be capable of the duty cycles defined in Table IV of CP-90290."

The above requirements are expressed in fuel element's ability to meet in addition to all the requirements of this section also the following demands:

1.3.1.1.1 Fuel Temperature

The fuel element's temperature capability shall exceed the temperature the fuel element experiences.

1.3.1.1.2 Stresses

The fuel elements shall have a positive stress margin of safety.

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1.3.1.2 Bundling Load

" 3.1.1.2.1 Bundling Load. - The FE shall be capable of withstanding the bundling loads of 3.1.1.1.3.1.2.3 (Core Bundling Function) of EC-677559."

The following paragraph is the pertinent quote from EC-677559.

" 3.1.1.1.3.1.2.3 Core Bundling Function. - To satisfy the lateral support function, the RA shall include the means to provide a radially inward pneumatic load on the core during all operating conditions. The pneumatic bundling forces shall be equivalent to an average pressure of (tbd) psi. In addition, at assembly the RA shall provide a mechanical bundling force at the Core Periphery surface. This force shall be equivalent to an average pressure of 10 psi over the forward one-seventh of the core and (tbd) psi over the aft six-sevenths of the core." Where RA stands for reflector assembly (EC-677559).

The bundling load for this trade study is 30 psi nominal. This load is conservative because, it is higher than the optimum load of 22 psi max. defined in DRM 53622, Core Bundling Pressure Optimization done concurrently with this document.

1.3.1.3 Axial Loads

" 3.1.1.1.3.1.2 Axial Loads. - Each central element shall be capable of withstanding and transmitting to the Cluster Hardware the axial loads of its adjoining fueled elements. The loads for the fueled elements and central elements are specified in 3.1.2.4.2.2 (Loads Environment)."

For fuel elements made of graphite the following applies.

" 3.1.2.4.2.2 Loads Environment. - The FE shall be designed to withstand the operating and non-operating loads environment and resulting deflections specified in Tables 11 (tbd) and 12 (tbd) (fueled elements) and Tables 13 (tbd) and 14 (tbd) (central elements)."

[redacted]

[redacted]

(U) The following paragraph is the equivalent quote from EC-677566/20 applicable to fuel elements made of composite.

(U) "20.3.1.2.4.2.2.2 Loads Environment. - The FE shall be designed to withstand the operating and non-operating loads environment and resulting deflections specified in Tables 20.11 (tbd) and 20.12 (tbd) (fueled elements) and Tables 20.13 (tbd) and 20.14 (tbd) (central elements)."

(U) The axial load for this trade study for both the graphite and composite fuel is as follows (Refer to DRM 53451, Structural Design Supporting Data for Fuel Element Trade Study, No. 772 and DRM 53450, Mean Value Cluster Deformation and Cluster Loads Versus Support Plate Bow).

Load on Fueled Element (Graphite and Composite) (U)

(CRD)	Due to Weight and Pressure Drop	μ = 85 lbs	σ = 2 lbs
	Due to Element to Element ΔT	μ = 0	σ = 32 lbs

Load on Support Element (Graphite and Composite) (U)

(CRD)	On Forward (cold) End		
	due to weight and Pressure Drop	μ = 48 lbs	σ = 5 lbs
	At Aft End (Total)	μ = 716 lbs	σ = 100 lbs

1.3.1.4 Radial Expansion (U)

(U) "3.1.1.2.2 Radial Expansion. - The FE, as assembled in the NSS, shall not cause the reactor core to expand radially more than 1.8% of the as-assembled core dimensions."

1.3.1.5 Reactivity Loss (U)

(U) "3.1.1.1.3.1.3 Reactivity Loss. - The total reactivity loss due to corrosion of the FE, as assembled in the NSS, shall not exceed $1.00 at end of life. The maximum incremental weight loss in a single element shall not exceed (tbd)."

[redacted]

(CRD) The maximum incremental weight loss in a single fuel element for this trade study is 1.5 gm/inch nominal. This value is based on experience with NRX Fuel. It represents 15% of the graphite fuel element weight and 18% of free graphite in 30 v/o composite fuel element (Refer to DRM 52445, R-1 Corrosion Reactivity Compensation Determination). This weight loss results in a 60 psi (2.3 σ) additional stress in a maximum bundled element (Reference DRM 53451, Structural Design Supporting Data for Fuel Element Trade Study, No. 772). The resulting stress increase is insignificant.

1.3.1.6 Reliability (U)

(U) "3.1.2.1 Reliability. - The reliability allocation for the FE is 0.998903. This allocation applies to the total number of fueled elements and central elements required to make up the reactor core."

1.3.1.7 Safety (U)

(U) "3.1.2.7 Safety. - The FE shall conform to the requirements of 3.1.2.7 (Safety) of CP-677555."

1.3.2 Technical Requirements (U)

(U) 1.3.2.1 Fuel Loading

For fuel elements made of graphite the following applies.

(CRD) "3.3.1.2.1 Fuel Loading. - Maximum fuel loading for the fueled elements shall be 630 mg/cc."

(U) The following paragraph is the equivalent quote from EC-677566/20 applicable to fuel elements made of composite.

(U) "20.3.3.1.2.1 Fuel Loading. - Maximum fuel loading for the fueled elements shall be (tbd) mg/cc."

(CRD) The maximum fuel loading of the composite fuel elements for this trade study is 765 mg/cc.

1.3.2.2 Weight

For fuel elements made of graphite the following applies.

"3.3.1.3 Weight. - The target weight for the FE is 3,670 pounds."

The following paragraph is the equivalent quote from EC-677566/20 applicable to fuel elements made of composite.

"20.3.3.1.3 Weight. - The target weight for the FE is 5,165 pounds."

1.3.3 Non-Technical Requirements

1.3.3.1 Development and Qualification

The required development effort is to be compatible with CY-71 to CY-73 budgetary plans. The state of the technology of fuel element production and evaluation as to suitability for use in R-1 shall be considered in the evaluation of design approaches.

1.3.3.2 Schedule (U)

The length of time required for development, qualification and production of fuel elements shall be compatible with R-1 test date of 10/15/73.

[redacted]

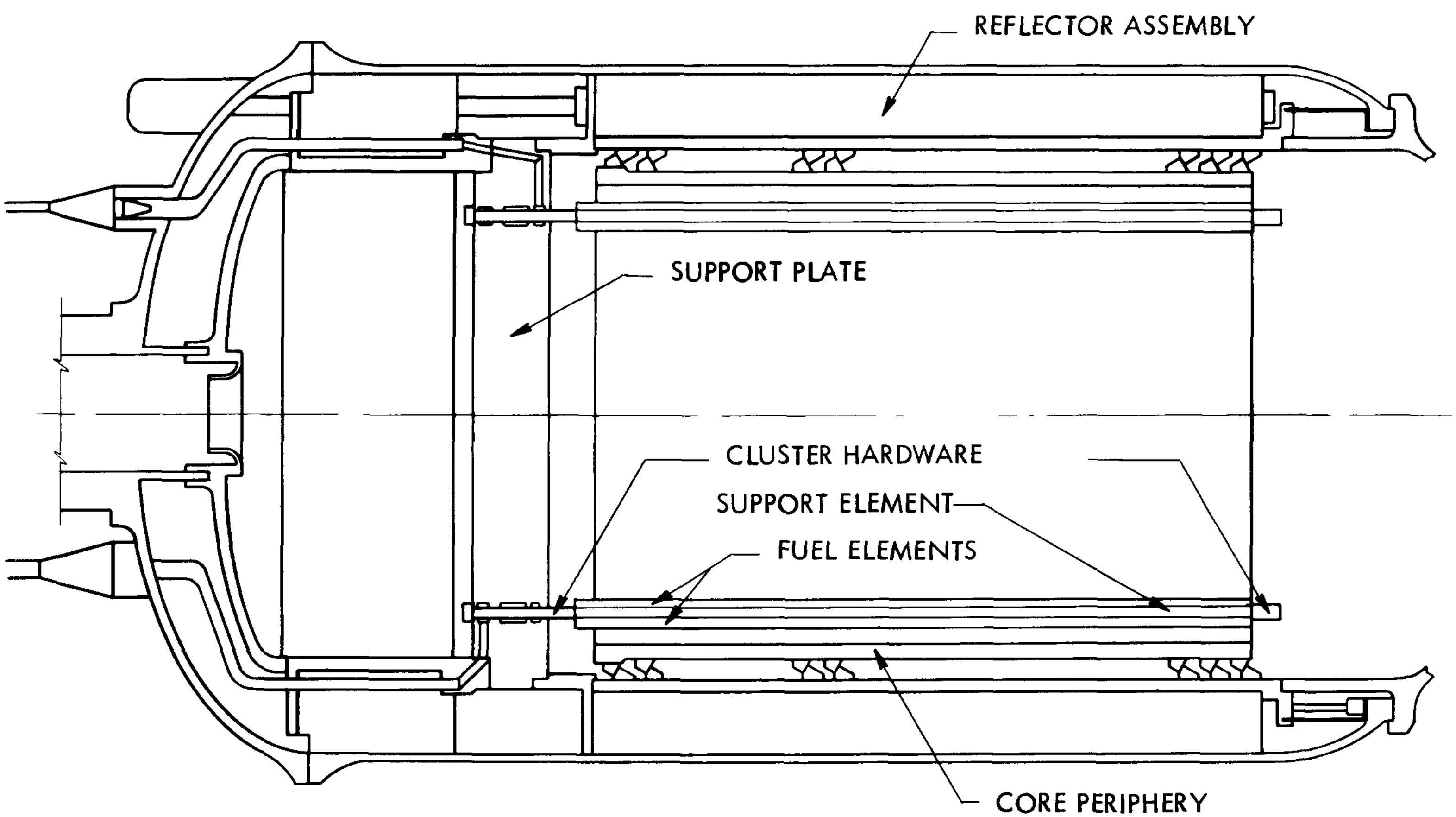


Figure 1-1. Geometrical Relation of Fuel and Support Elements to Interfacing Components in NSS (Longitudinal Cross-Section)

[redacted]

2.0 DESCRIPTION OF DESIGN APPROACHES (U)

(U) This section defines the two fuel element design concepts evaluated in this trade study. These two concepts were selected in a previous Trade Study, No. 769, WANL-TME-2709, June 1, 1970 as preferred designs.

2.1 DESIGN APPROACH 1 - COMPOSITE FUEL ELEMENT (U)

(U) The Design 1 fuel element is defined on WANL Drawing, Number 947C844 and the companion support element is defined on WANL Drawing, Number 947C843,shown in this document as Figure 2.1 and 2.2 respectively.

(C-RD) The material of this fuel element design is 30 v/o UC-ZrC-C composite defined in PDS-30253-1.

(C-RD) The support element is made of 30 v/o ZrC-C composite defined in PDS-30254-1. Brazed to the aft end of the support element is a tip made of composite material which has a creep resistance needed at the very end of the element.

(C-RD) The geometry of the fueled element of this design is 0.753 inch (nominally across-flats) hexagonal bar of 52 inches nominal length, having 19, 0.0925-inch minimum effective diameter, flow channels located symmetrically within the hexagonal cross-section and extending through the full element length. The central flow channel is equipped at the forward end with a .164 - 32 UNC x .920 deep thread which serves as an attachment to the Cluster Hardware. The configuration is basically similar to the configuration of fuel elements used in NRX and Pewee reactors.

(C-RD) The flow channel coating and external surface coating is ZrC deposited by the GEM process at linearly increasing nominal temperatures from $2472^{\circ}R$ at the forward end to $2832^{\circ}R$ at the aft end. This type of coating is selected because it offers the potential for the required corrosion protection. The coating profiles of this design are such that the resulting minimum effective flow channel diameter does not increase the core pressure drop beyond the allowable value and provides a corrosion protection. The external lateral geometry of the support element is basically the same and is compatible with the fueled element. The coating of the support element is compatible with the coating of the fueled elements and is

(CRD) deposited in the same manner as the coating of fueled elements. The support element is provided with a .5255 diameter bore which extends the entire element length and houses the Cluster Hardware i.e, the support stem, liner tube and insulation. The .562-24 UNEF thread in the forward end of the bore serves as a redundant axial support.

(CRD) The aft end of the support element is attached, by brazing during cluster assembly, to Cluster Hardware which provides the primary fuel element support. Some support elements are equipped with .100 diameter holes which serve as receptacles for instrumentation.

2.2 DESIGN APPROACH 2 - GRAPHITE FUEL ELEMENT (U)

(U) The Design 2 fuel element is defined on WANL Drawing, Number 947C617, and the companion support element is defined on WANL Drawing Number 947C618, shown in this document as Figure 2.3 and 2.4 respectively.

(U) The geometry of this fuel element design corresponds to the standard geometry defined in Section 2.1.

(U) The fuel element constituents are: pyrocarbon coated UC_2 fuel particles, specified by PDS 30050-2, dispersed through a graphite matrix whose primary constituent is specified in PDS 30139-3. Brazed to the aft end of the element is a corrosion resistant NbC-Graphite composite tip specified in PDS 30106-3.

(U) The support element is made of graphite defined in specification PDS-30256-1. The support element is also equipped with a brazed-on aft end tip defined in PDS-30106-3.

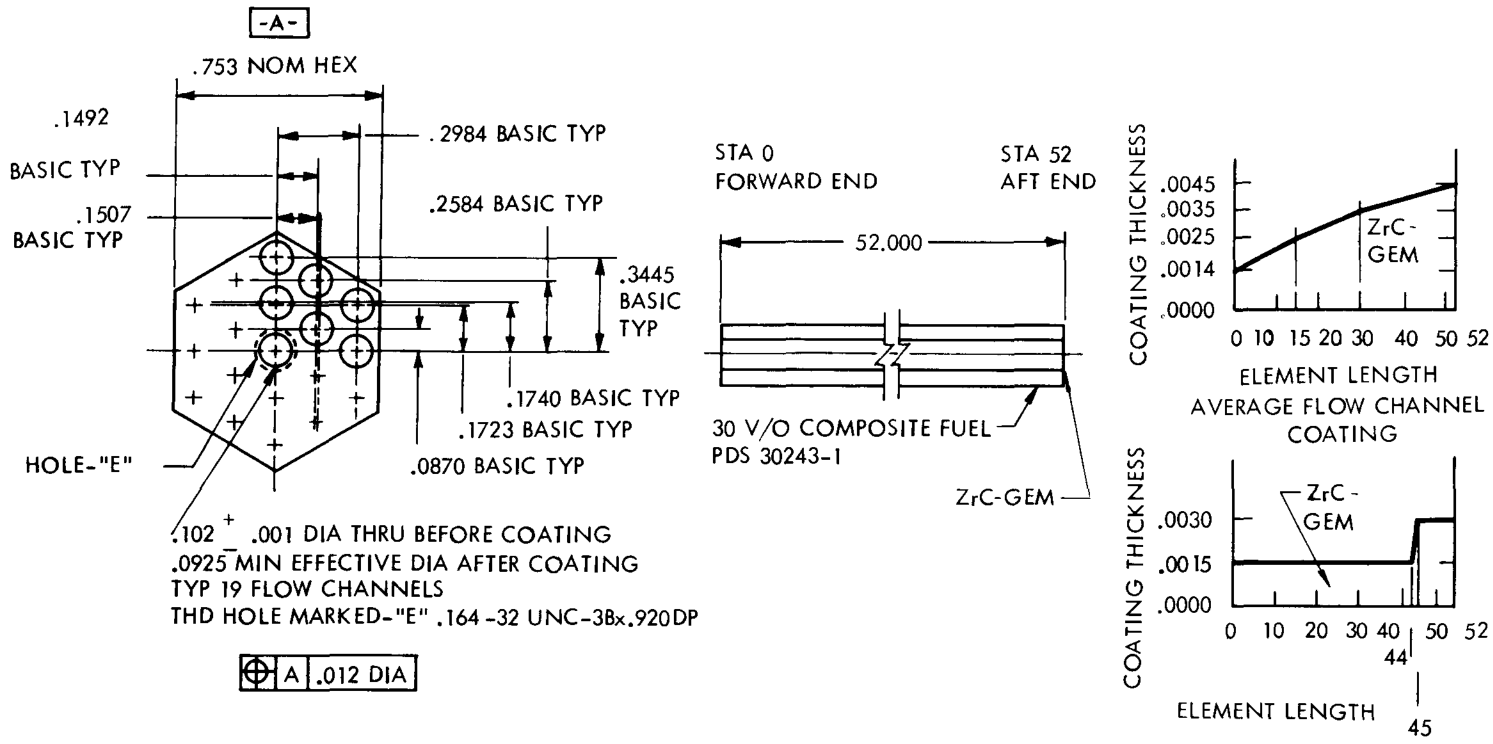
(CRD) The coating of flow channels and external surfaces of the fueled element consists of a thickness of NbC deposited by the GEM process followed by a thickness of ZrC deposited by the HED process. The temperature of coating deposition process varies linearly from 2450°R at the forward end of the element to 2900°R at the aft end of the element for the GEM-NbC and 2200°R at the forward end of the element to 3600°R at the aft end of the element for HED-ZrC.

(CRD) The flow channel coating provides a corrosion protection without undue restriction of flow. The thickness of external surface coating of Design 2 fueled element evolved from the traditional aft end coating of fuel elements used in NRX and Pewee reactor. The

(CRD)
average 0.003-inch thick coating at the aft end is presently considered to be the maximum feasible. Because ZrC coating of fueled elements needs a bead migration barrier at the aft portion of the element, both the flow channels and external surfaces are provided with NbC sub-coating. The external NbC coating extends from Station 40 to the aft end.

(U) The support element coating and geometry are compatible with fueled element coating and geometry. The coating consists of ZrC deposited by the HED process at same temperatures as the ZrC-HED process for the fueled elements.

[redacted]



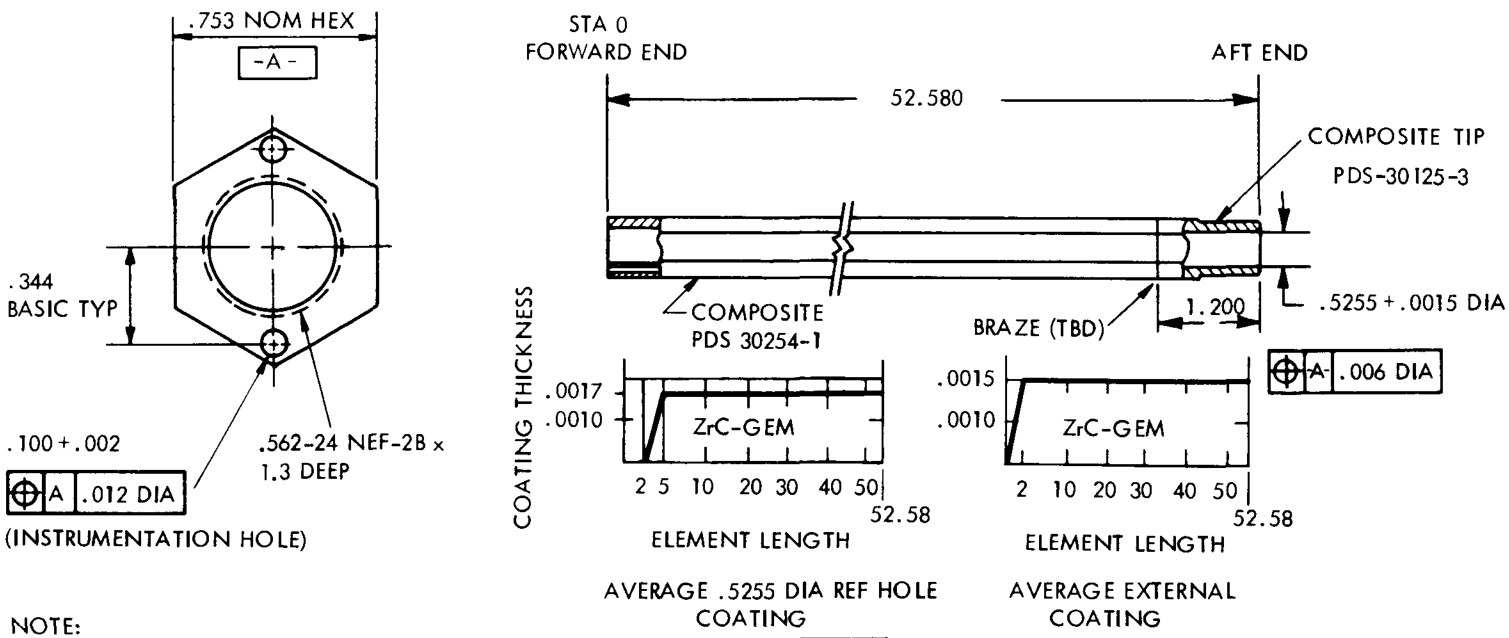
NOMINAL COATING MASSES	
FLOW CHANNELS	93 gm Zr
EXTERNAL	22 gm Zr

1 - DIMENSIONS OF COATED FEATURES APPLY
AFTER COATING UNLESS OTHERWISE SPECIFIED

Figure 2-1. Composite Fuel Element (947C844)

[redacted]

[redacted]

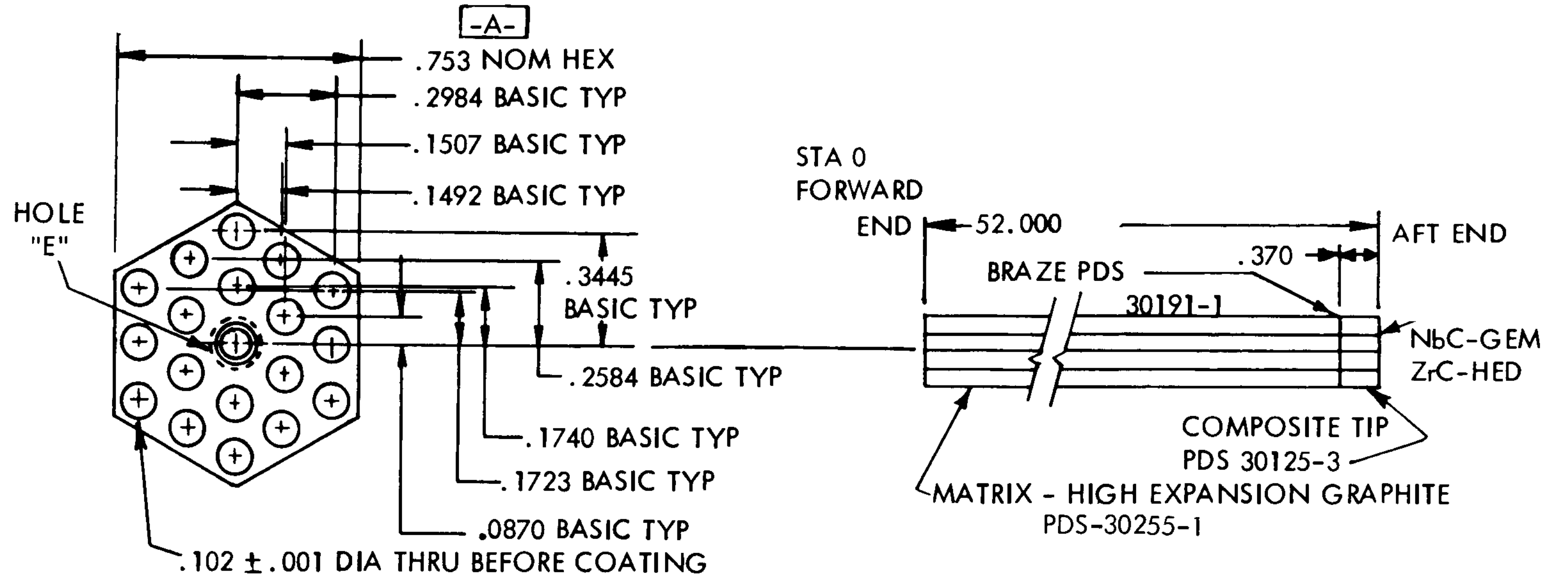


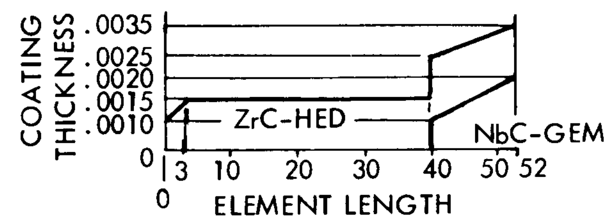
NOTE:
1. DIMENSIONS OF COATED FEATURES APPLY AFTER COATING UNLESS OTHERWISE SPECIFIED.

AVERAGE COATING MASS	
IN .5255 REF HOLE	14 GM Zr
EXTERNAL	19 GM Zr

Figure 2-2. Composite Support Element (947C843)

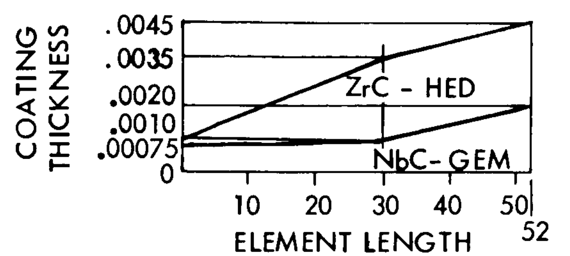
[redacted]





AVERAGE EXTERNAL COATING

NOMINAL COATING MASSES		
FLOW CHANNELS	41 GM Nb	60 GM Zr
EXTERNAL	5 GM Nb	19 GM Zr



AVERAGE FLOW CHANNEL COATING

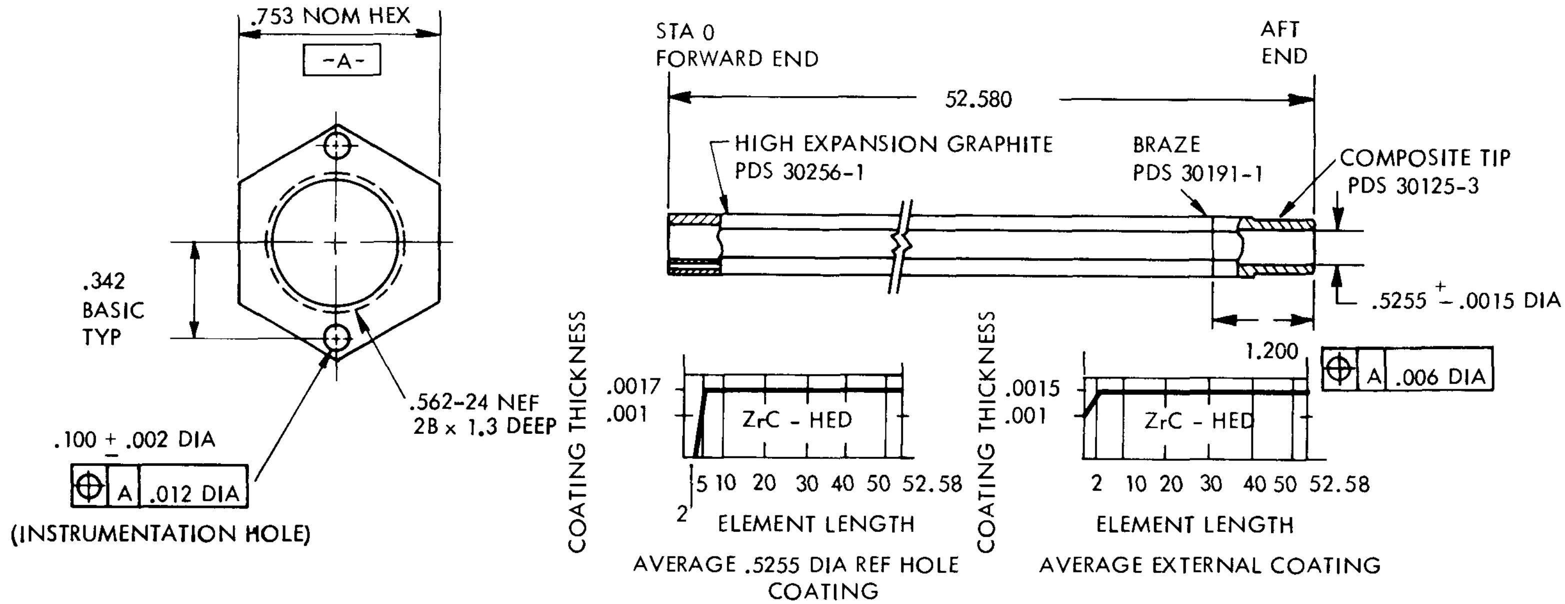
NOTE:

1 DIMENSIONS OF COATED FEATURES APPLY AFTER COATING UNLESS OTHERWISE SPECIFIED.

Figure 2-3. Graphite Fuel Element (947C617)

[redacted]

[redacted]



AVERAGE COATING MASS	
IN .5255 REF HOLE	14 gm Zr
EXTERNAL	19 gm Zr

NOTE:
1. DIMENSIONS OF COATED FEATURES APPLY AFTER COATING UNLESS OTHERWISE SPECIFIED.

Figure 2-4. Graphite Support Element (647C618)

3.0 COMPARISON MATRIX

This section describes the method of constructing the Comparison Matrix and the use of the matrix in evaluating design approaches and selecting a Fuel Element design approach.

The matrix is constructed to provide a means of evaluating each design approach described in Section 2.0 against the requirements defined in Section 1.0. Each requirement is entered in the matrix as a row heading and each design approach is entered as a column heading. All the requirements of Section 1.0 are divided among five consideration groups. The functional and technical requirements of Section 1.0 are contained in the three consideration groups: Reliability and Safety, Performance and Weight. The non-technical requirements are entered in two consideration groups: Development and Qualification and Schedule. The comparison matrixes containing these consideration groups are shown in Tables 3-1 through 3-5.

The entries in the matrixes are data and/or descriptions abstracted from appropriate DRMs referenced at end of Section 4.0. The entries define the results of analysis of each design's ability relative to a consideration.

The design approaches are evaluated against each requirement by assigning each approach on "emphasis factor" which defines the approach's standing among all the approaches for the given requirement.

The emphasis factor assignment is made under the following rule:

Emphasis Factor Criteria

Selection	Value	Rule
First Selection, a	0 to 1.0	
Second Selection, b	0 to 1.0	$b < a$
⋮	⋮	⋮
Nth Selection, n	0 to 1.0	$n <$ n01

$$\sum_{1}^{N} = 1.0$$

The emphasis factors are shown in the matrix as circled numbers.

The evaluation of each design approach's standing for each consideration group is done through average emphasis factors. Average emphasis factors are shown at the bottom of each consideration group. Average emphasis factors for each consideration group are multiplied by a specific weighting factor and this value is entered into the summary matrix shown in Table 3-6. The sum of these weighted average emphasis factors shown at the bottom of Table 3-6 for each design concept defines the overall Figure of Merit, i.e., the relative standing of each design approach's relative to all considerations. The highest value represents the best design approach relative to the consideration groups or the requirements. The following weighting factors were used:

Consideration	Weighting Factor
Reliability and Safety	.30
Performance	.25
Weight	.25
Development and Qualification	.10
Schedule	.10

[redacted]

NOMENCLATURE TABLE 3-1 RELIABILITY AND SAFETY CONSIDERATIONS FUEL ELEMENT EC-677566 & EC-677566/20	ASTRONUCLEAR LABORATORY COMPARISON MATRIX OF DESIGN APPROACHES		SELECTION
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	1 Composite Fuel Element	2 Graphite Fuel Element	
RELIABILITY (1)* (Objective: To achieve the reliability goal of .998903)	0.80	0.20	
Overall Reliability Estimate	$P_s = 0.97$	P_s = Low***	
Fuel Elements			
Failure modes leading to reactivity loss in excess of $1.00			
Principal Failure Modes**	Fuel element carbon loss at the hot end including defect corrosion and corrosion acceleration due to cyclic operation.	Fuel element carbon loss at the mid-band and hot end including defect corrosion and corrosion acceleration due to cyclic operation.	
Secondary Failure Modes	Carbon loss caused by corrosion at a relatively large number of fuel element breaks, which however, spread slowly and does not cause significant reactivity loss.	Carbon loss caused by corrosion at a relatively small number of fuel element breaks which results in corrosion of the aft portion of the element and increased external surface corrosion on adjacent elements. (Approximately one cent reactivity decrease caused by complete corrosion of the aft third of one element)	

* Superscripts in parenthesis refer to sequence numbers in the list of references in Section 4.0.

**Principal failure modes are the only failure modes having an important effect on system reliability estimate.

*** No available data which shows tendency for improved cyclic capability. Therefore, no speculation as to future potential is made.

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NOMENCLATURE TABLE 3-1 Cont'd RELIABILITY AND SAFETY CONSIDERATIONS FUEL ELEMENTS EC-677566 & EC-677566/2	ASTRONUCLEAR LABORATORY COMPARISON MATRIX OF DESIGN APPROACHES		SELECTION
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	1 Composite Fuel Element	2 Graphite Fuel Element	
RELIABILITY CONT'D			
Support Elements			
Failure modes leading to damage of cluster hardware			
Principal Failure Modes +	None	None	
Secondary Failure Modes	Transient stress cracking followed by local corrosion of element and insulating sleeve, thus exposing the liner tube.	Transient stress cracking followed by local corrosion of element and insulating sleeve, thus exposing the liner tube.	
SAFETY (2)*			
(Objective: To minimize possibility of loss of emergency mode capability)	0.36	0.64	
Most Probable Category IV** Failure Mode	Transient high temperatures preceding the emergency mode cause softening or melting of fuel and lead to structural collapse of a portion of the core.	Transient high temperatures preceding the emergency mode cause coating melting due to eutectic formation with migrated uranium, however structural collapse is caused only by excessive graphite sublimation at extremely high temperature.	
Category III b Failure Modes which could develop into category IV Failure Modes.	Mechanical failure with ejection of fragments and subsequent possible nozzle damage.	Mechanical Failure with ejection of fragments and subsequent nozzle damage	
RELIABILITY AND SAFETY AVERAGE***EMPHASIS FACTOR	0.65	0.35	

* Superscripts in parenthesis refer to sequence numbers in the list of references in Section 4.0

** For definition of Failure Categories refer to DRM 52812, Flight Safety Contingency Analysis Report

***This is a weighted average where the reliability account for 2/3 and Safety for 1/3 of the value

\+ Principal failure modes are the only failure modes having an important effect on system reliability

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NOMENCLATURE PERFORMANCE CONSIDERATIONS FUEL ELEMENTS EC-677566 & EC-677566/20 — TABLE 3-2	ASTRONUCLEAR LABORATORY COMPARISON MATRIX OF DESIGN APPROACHES		SELECTION
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	1 Composite Fuel Element	2 Graphite Fuel Element	
FLOW AND THERMAL CHARACTERISTICS			
FUEL TEMPERATURE[(3)]* (Objective: Adequate margin between fuel temperature capability and temperature the fuel experiences)	0.45	0.55	
Probability that 1 Element in the Core Exceeds the Temperature Limit	$P_f = 10^{-5}$	$P_f = 10^{-10}$	
Fuel Temperature	Maximum Nominal Matrix Temperature, 4433°R at Sta 48	Maximum Nominal Flow Channel Wall Temperature 4387°R at Sta 50	
For Uncertainties and Temperature Limit	See	Reference (3)	
STRESSES[(4)]* (Objective: Maximum margin of safety)	0.10	0.90	
Steady State Rated/Ramp-up Transient Stresses in Fuel Elements Due to: (1) Heat Generation (2) Coating Matrix Interaction (3) Interelement Friction and Temperature Difference (4) Interaction with Periphery (5) Cold End Support Attachment			
*Superscripts in parenthesis refer to sequence numbers in the list of references in Section 4.0.			

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NOMENCLATURE PERFORMANCE CONSIDERATIONS FUEL ELEMENTS EC-677566 & EC-677566/20 TABLE 3-2 (CONT'D)	ASTRONUCLEAR LABORATORY COMPARISON MATRIX OF DESIGN APPROACHES		SELECTION
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	1 Composite Fuel Element	2 Graphite Fuel Element	
STRESSES CONT'D			
Axial Stress in Fuel Element			
Calculated Maximum (2.3σ)(psi)	14000/30000	4600/5500	
Allowable (80% of 2.3σ Minimum Tensile Strength) (psi)	4750 / 4750	1930 / 1930	
Margin of Safety = $\left(\frac{\text{Allowable}}{\text{Calculated Maximum}} - 1\right)$	-.66 / -.84	-.58 / -.65	
Transverse Stress in Fuel Element			
Calculated Maximum (2.3σ) (psi)	3500 / --	1530/--	
Allowable (80% of 2.3σ Minimum Tensile Strength) (psi)	3600/--	1720 / --	
Margin of Safety = $\left(\frac{\text{Allowable}}{\text{Calculated Maximum}} - 1\right)$	+ .0285/--	+.11 / --	
Ramp-Up Transient * Stress in Support Elements due to: (1) Heat Conduction (2) Coating Matrix Interaction (3) Interaction with the Fuel Element (4) Cold End Attachment (5) Creep Bulging of the Support Element Tip	* Rated steady state margins in support element are higher than the corresponding ramp-up transient values.		

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NOMENCLATURE PERFORMANCE CONSIDERATIONS FUEL ELEMENTS EC-677566 & EC-677566/20 TABLE 3-2 (CONT'D)	ASTRONUCLEAR LABORATORY COMPARISON MATRIX OF DESIGN APPROACHES		SELECTION
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	1 Composite Fuel Element	2 Graphite Fuel Element	
STRESSES CONT'D			
Axial Stress in Support Element			
Calculated Maximum (2.3σ) (psi)	6600	1700	
Allowable (80% of 2.3σ Minimum Tensile Strength) (psi)	4950	2900	
Margin of Safety = $= \left(\frac{\text{Allowable}}{\text{Calculated Maximum}} - 1\right)$	-.250	+.71	
Transverse Stress in Support Element			
Calculated Maximum (2.3σ) (psi)	7430	4100	
Allowable (80% of 2.3σ Minimum Tensile Strength) (psi)	2950	2400	
Margin of Safety = $= \left(\frac{\text{Allowable}}{\text{Calculated Maximum}} - 1\right)$	-.603	-.415	

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NOMENCLATURE
PERFORMANCE CONSIDERATIONS
FUEL ELEMENTS
EC-677566 & EC-677566/20

TABLE 3-2 (CONT'D)

ASTRONUCLEAR LABORATORY

COMPARISON MATRIX OF DESIGN APPROACHES

FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	1 Composite Fuel Element	2 Graphite Fuel Element	SELECTION
BUNDLING LOAD AXIAL LOADS	The effects of bundling and axial loads are included in the axial and transverse stress considerations.		
RADIAL EXPANSION (5)* (Objective: Not to Exceed the Allowed Expansion) Probability of: $\alpha \Delta T$ + Creep $\geq .018$	(0.40) $P_f = 2.0 \times 10^{-4}$	(0.60) $P_f = 3 \times 10^{-10}$	
REACTIVITY LOSS (6) (11) (12)* (Objective: Meeting Required Life of 10 Hours and 60 Cycles Without Exceeding $1.00 Reactivity Loss)	(0.85)	(0.15)	
Number of 10 Minute Cycles which will not Cause Reactivity Loss in Excess of Allowable at Probability $P_s = 0.999$	Estimated present capability, 25 cycles Estimated Flight Engine capability (based on initial electrical corrosion tests) 55 cycles ($P_s = 0.97$ for 60 cycles)	Estimated present capability, 16 cycles Estimated Flight Engine capability (based on electrical corrosion tests) does not indicate an improvement over 16 cycles.	
Incremental Weight Loss of a single fuel element	0.84 gm/inch (25 cycles) 1.32 gm/inch (60 cycles)	0.52 gm/inch (16 cycles)	
FUEL LOADING MARGIN (7) * (Objective: Maximize Fuel Loading Margin while Providing Sufficient Fuel to Sustain Controlled Nuclear Fission)	(0.50)	(0.50)	

* Superscripts in parenthesis refer to sequence numbers in the list of references in Section 4.0.

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NOMENCLATURE
PERFORMANCE CONSIDERATIONS
FUEL ELEMENTS
EC-677566 & EC-677566/20

TABLE 3-2

ASTRONUCLEAR LABORATORY

COMPARISON MATRIX OF DESIGN APPROACHES

FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	1 Composite Fuel Element	2 Graphite Fuel Element	SELECTION
FUEL LOADING MARGIN CONT'D			
Maximum loading required mg/cc	765	620	
Loading Limit (Based on Present Processes) mg/cc	765 ***	630	
Margin = $= \left(\frac{\text{Loading Limit} - \text{Maximum Loading Requirements}}{\text{Maximum Loading Required}} \right)$	0.0%	1.6%	
PERFORMANCE			
AVERAGE[+] EMPHASIS FACTOR	0.525	0.475	

+ This is a weighted average where the resistance to reactivity loss accounts for 1/3 of the value

*** This is the value presently utilized in thermal analysis for this trade study. This thermal analysis indicates that the thermal requirements are met with a small margin of safety.

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NOMENCLATURE
WEIGHT CONSIDERATIONS FUEL ELEMENTS
EC-677566 & EC-677566/20

TABLE 3-3

ASTRONUCLEAR LABORATORY
COMPARISON MATRIX OF DESIGN APPROACHES

FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	1 Composite Fuel Element	2 Graphite Fuel Element	SELECTION
WEIGHT (Objective: The weight of the core shall be minimized.)	(0.40)	(0.60)	
Core Weight (13) * (Fuel Envelope Includes all Fueled and Support Elements) (lbs)	5190	3726	
Core Weight Difference Over Specified Core Weight (lbs)	+ 25	+ 56	
Shield Weight Difference Over Design 1 (lbs) (8) *	0	41	
WEIGHT			
AVERAGE EMPHASIS FACTOR	0.40	0.60	
* Superscripts in parenthesis refer to sequence numbers in the list of references in Section 4.0.			

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NOMENCLATURE TABLE 3-4 DEVELOPMENT AND QUALIFICATION CONSIDERATIONS FUEL ELEMENTS EC-677566 & EC-677566/20	ASTRONUCLEAR LABORATORY COMPARISON MATRIX OF DESIGN APPROACHES		SELECTION
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	1 Composite Fuel Element	2 Graphite Fuel Element	
DEVELOPMENT & QUALIFICATION (Objective: To develop fuel elements with maximum potential to meet the requirements of Specification No. EC-677566 and EC-677566/20 within contractual, budgetary and schedular requirements.) Development of Process and Fabrication (10)* * Superscripts in parenthesis refer to sequence numbers in the list of references in Section 4.0.	(0.50) The principal efforts required to develop the element are definition of graphitizing procedures, die design development for longer die life and minimization of extrusion defects, and definition of coating procedures and fixturing to attain profile and dimensional requirements. Additional equipment remains to be installed to achieve required production rates for graphitizing, machining, and inspection capability.	(0.50) A well-developed manufacturing technology exists at WNCO for the POCO high expansion type of bead loaded graphite element. Additional development of OD coating process and fixturing is required in addition to development of a satisfactory tip joint braze technique for 10 hour, 60 cycle capability. The bead leaching problem encountered in PW-2 which produced bore coating nodules must be resolved if R-1 coating requirements are to be met.	

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NOMENCLATURE TABLE 3-4 (CONT'D)
DEVELOPMENT AND QUALIFICATION CONSIDERATIONS
FUEL ELEMENTS
EC-677566 & EC-677566/20

ASTRONUCLEAR LABORATORY
COMPARISON MATRIX OF DESIGN APPROACHES

FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	1 Composite Fuel Element	2 Graphite Fuel Element	SELECTION
Development of Materials[(10)*]	0.40 Characterization of raw material powders ZrC, UO_2 and graphite flours are still incomplete. Development of specifications to insure reproducible lots of raw material effects on element properties are required.	0.60 Principal raw materials for the graphite element are well characterized. Purchase of reproducible lots of flour yet to be demonstrated.	
Development of Quality Control and Testing Techniques[(10)]	0.44 Standards for all phases of fuel characterization required. LASL and WANL experience in corrosion testing of composite fuel indicate no significant problems except at high powers and temperatures. Better techniques needed to non-destructively identify good and poor coatings.	0.56 Proven NDT surveillance techniques and equipment exist at WNCO except for technique to classify individual element coating quality. Corrosion test experience for graphite elements is extensive although difficulties in testing thick R-1 type coatings can be expected. A suitable tip joint surveillance test must be developed.	
*Superscripts in parenthesis refer to sequence numbers in the list of references in Section 4.0.			

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NOMENCLATURE TABLE 3-4 (CONT'D)
DEVELOPMENT AND QUALIFICATION
CONSIDERATIONS
FUEL ELEMENTS
EC-677566 & 677566/20

ASTRONUCLEAR LABORATORY
COMPARISON MATRIX OF DESIGN APPROACHES

FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	1 Composite Fuel Element	2 Graphite Fuel Element	SELECTION
Cost of Development,[(9)*] Qualification and Production of One Reactor Core of Fuel Elements	(0.51) $10,690,000	(0.49) $11,225,000	
DEVELOPMENT AND QUALIFICATION AVERAGE EMPHASIS FACTOR	0.463	0.537	

* Superscripts in parenthesis refer to sequence numbers in the list of references in Section 4.0.

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NOMENCLATURE TABLE 3-5 SCHEDULE CONSIDERATIONS FUEL ELEMENTS EC-677566 & EC-677566/20	ASTRONUCLEAR LABORATORY COMPARISON MATRIX OF DESIGN APPROACHES		SELECTION
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	1 Composite Fuel Element	2 Graphite Fuel Element	
SCHEDULE Objective: To meet R-1 Test Date of 10/15/73			
Development of Process and Fabrication (10)*	(0.55) The potential for meeting the R-1 schedule is good assuming the required manpower levels are available as required. No major break-throughs in process development are required.	(0.45) The potential for meeting the R-1 schedule is good although coating processes for the element bore and OD and a tip-braze process capable of meeting the R-1-performance requirements have not been demonstrated. Manpower availability must also be assumed.	
Development of Materials (10)	(0.50) Candidate materials with availability consistent with the R-1 schedule have been identified. Proper funding and timely decision on element selection is required at the appropriate time to achieve the required schedule.	(0.50) Candidate materials with availability consistent with the R-1 schedule have been identified. Proper funding and timely decision on element selection required to achieve the required schedule.	
* Superscripts in parenthesis refer to sequence numbers in the list of references in Section 4.0			

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NOMENCLATURE TABLE 3-5 (CONT'D) SCHEDULE CONSIDERATIONS FUEL ELEMENTS EC-677566 & 677566/20	ASTRONUCLEAR LABORATORY COMPARISON MATRIX OF DESIGN APPROACHES		SELECTION
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	1 Composite Fuel Element	2 Graphite Fuel Element	
Development of Quality[(10)]* Control and Testing Techniques	(0.45) The principal NDT methods for characterization of composite elements have yet to be standardized at WNCO. However, the potential to meet R-1 schedular requirements is good. Transfer of LASL technology plus continued implementation of WNCO effort is expected to result in an adequate capability by the end of R-1 pre-production.	(0.55) The principal NDT methods for graphite elements are well developed at WNCO Additional development is required for tip qualification. The potential to meet R-1 schedular requirements is good.	
SCHEDULE			
AVERAGE EMPHASIS FACTOR	0.50	0.50	
* Superscripts in parenthesis refer to sequence numbers in the list of references in Section 4.0.			

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NOMENCLATURE TABLE 3-6 MATRIX SUMMARY FUEL ELEMENTS	WEIGHTING FACTOR	ASTRONUCLEAR LABORATORY COMPARISON MATRIX OF DESIGN APPROACHES		SELECTION
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS		1 Composite Fuel Element	2 Graphite Fuel Element	
RELIABILITY AND SAFETY	.30	0.196	0.104	
PERFORMANCE	.25	0.131	0.119	
WEIGHT	.25	0.100	0.150	
DEVELOPMENT AND QUALIFICATION	.10	0.046	0.054	
SCHEDULE	.10	0.050	0.050	
FIGURE OF MERIT		0.523	0.477	

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4.0 SELECTION OF DESIGN (U)

(U) Based on the evaluation in Section 3.0, Design Approach I, Composite Fuel Element is recommended for the R-1 reactor. This selection is caused primarily by the higher ranking of composite elements for reliability - safety and performance.

(CRD) In both of the above categories the reactivity requirement was weighted heavily because excessive reactivity loss inescapably causes loss of effective propulsion. Of the two, composite fuel elements have much better potential for meeting the reactivity requirement. The limiting mechanism for composite fuel elements is the hot end carbon loss including the effects of coating defects and cycles on corrosion. Graphite elements are much worse in this respect. They also suffer from cyclically induced midband carbon loss.

(U) With respect to corrosion of broken elements, although composite is more likely to break, its resistance to the spread of corrosion around the break makes it unlikely that this will be a major contributor to reactivity loss. Graphite elements, on the other hand, though less likely to break, allow corrosion to spread much more widely around each break. However, the probable number of breaks is small and therefore the expected reactivity loss is small.

(U) Composites are believed to have a satisfactory potential for development into a ten-hour, sixty cycle element. This belief is reinforced by favorable results of recent corrosion tests (See Reference 11). Graphite, on the other hand is unlikely to attain this goal.

(U) Another important consideration in the selection is stress margin. Both graphite and composite elements, but particularly the latter, show negative stress margins.

(U) For a proper evaluation of these reported structural margins it is necessary to realize that they are strongly influenced by calculated stress uncertainties. The original intent in the propagation of error calculations was to obtain an evaluation based on flight engine uncertainties. The handling of materials properties uncertainties in the analysis for this trade study is an important departure from this intent, especially as it enters into the stress uncertainty determination. Estimated standard deviations reported in Materials Department DRM's were used in the analyses.

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The very large coefficients of variation* for calculated stresses which result from using these standard deviations in a propagation of error analysis are a strong indication of conservatism.

It is believed that this will not be characteristic of the fully developed, well controlled materials of the flight reactor fuel. Standard deviations of about three to five percent of the mean do not seem unattainable in this context and would result in significant stress margin improvement.

In addition, it is likely that development effort will result in more favorable mean values for some of the materials properties. For example studies of new binders underway have the objective of producing a matrix with reduced modulus of elasticity and improved strength. These factors would greatly improve the stress capability of the elements. Recent data from Los Alamos Scientific Laboratory show that process variations can favorably affect the composite fuel mechanical characteristics. This demonstrated ability to improve fuel properties is a source of optimism that structural problems can be eliminated or at least alleviated by a vigorous development program.

Analytic and experimental progress toward a better understanding of coating-matrix interaction is also expected to make a significant reduction in the conservatively calculated stress. A fully developed theory of failure well correlated with experiment could further result in substantially higher allowable stress.

The foregoing considerations temper the apparently gloomy stress situation and give confidence that satisfactory steady state stress margins for flight engine fuel can be attained.

* This is the ratio of standard deviation to mean value. In one instance it is 142%.

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REFERENCES

1. DRM 53041 Systems Reliability Supporting Data for the Fuel Element Trade Study No. 772

2. DRM 52809 Systems Safety Supporting Data for Fuel Element Trade Study No. 772

3. DRM 53426 Thermal Design Supporting Data for Fuel Element Trade Study No. 772 Probability of Exceeding Maximum Material Temperature Limits

4. DRM 53451 Structural Design Supporting Data for Fuel Element Trade Study No. 772

5. DRM 53295 Expansion of the Assembled Core

6. DRM 53431 Corrosion Supporting Data for Fuel Element Trade Study No. 772

7. DRM 53368 Nuclear Supporting Data for Fuel Trade Study No. 772

8. DRM 52853 Radiation and Shielding Input to the Fuel Element Trade Study No. 772

9. DRM 51783 Trade Study No. 772, Fuel Cost Estimate

10. DRM 51782 WNCO Contribution to Fuel Element Trade Study No. 772

11. DRM 53429 Recent Developments in Fuel Element Corrosion Performance

12. DRM 53421 An Analytical Study of Fuel Element Diffusion Corrosion

13. WANL-TME-2764 Mass Properties Analysis Report, S-047

Following are other references which contain indirect supporting material:

14. DRM 53432 Thermal Design Supporting Data for Core Periphery Trade Study No. 778 and Fuel Element Trade Study No. 772

15. DRM 51697 A Comparison of a 375 TRACK Model of a Fuel Element with the MCAP and BMI computer codes

16. DRM 53145 A Fuel Element Strip Model

17. DRM 53152 Investigation of Fuel Element Thermal Conductivity Data

18. DRM 52562 Heat Transfer Between Adjacent Fuel Elements at Different Powers

19. DRM 52913 Thermal and Hydraulic Analysis of LASL's Proposed Orificing Scheme for Corner Holes of Pewee-2 Fuel Elements

20. DRM 53452 Calculated Interstitial Core Gaps for NSS PDR

21. DRM 53453 Fuel Element Bore Coating Defect Size Estimates for PDR

22. DRM 53436 Thermal Design Supporting Data for Fuel Element Trade Study No. 772

23. DRM 52445 R-1 Corrosion Reactivity Compensation Determination

24. DRM 53439 Thermal Design Supporting Data for Trade Study No. 772. Interelement Pressure and Flow and Core Bundling

25. DRM 53622 Core Bundling Pressure Optimization

26. DRM 53450 Mean Value Cluster Deformation and Cluster Loads Versus Support Plate Bow)

27. DRM 53653 Summary of Thermal and Corrosion Supporting Data for Fuel Element Trade Study, No. 772

28. DRM 53292 Failure Mode - Mechanism - Analysis - Part Function Sheets for Fuel Elements, Composite and Graphite

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TITLE Trade Study No. 772
Fuel Elements

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ABSTRACT

This document describes a trade study of design approaches of Fuel Elements.
The trade study evaluates graphite and composite fuel elements and selects the composite fuel element design for the R-1 reactor.

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