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Babcock & Wilcox Assessment of the Pratt & Whitney XNR2000

Babcock & Wilcox
Space Systems Engineering

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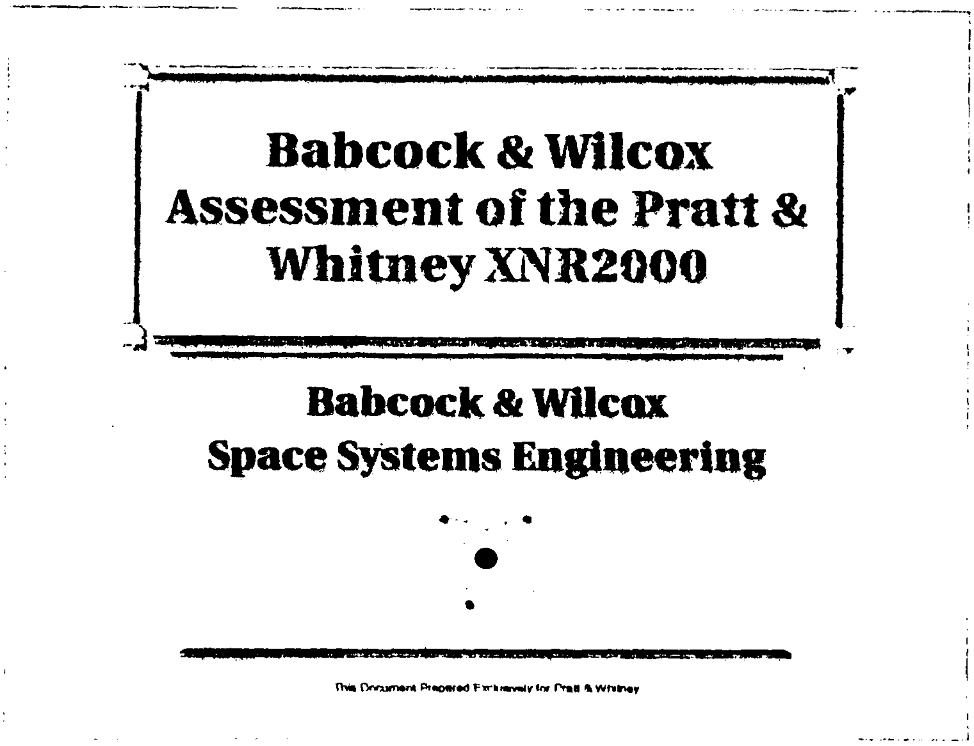

Babcock & Wilcox
Assessment of the Pratt &
Whitney XNR2000

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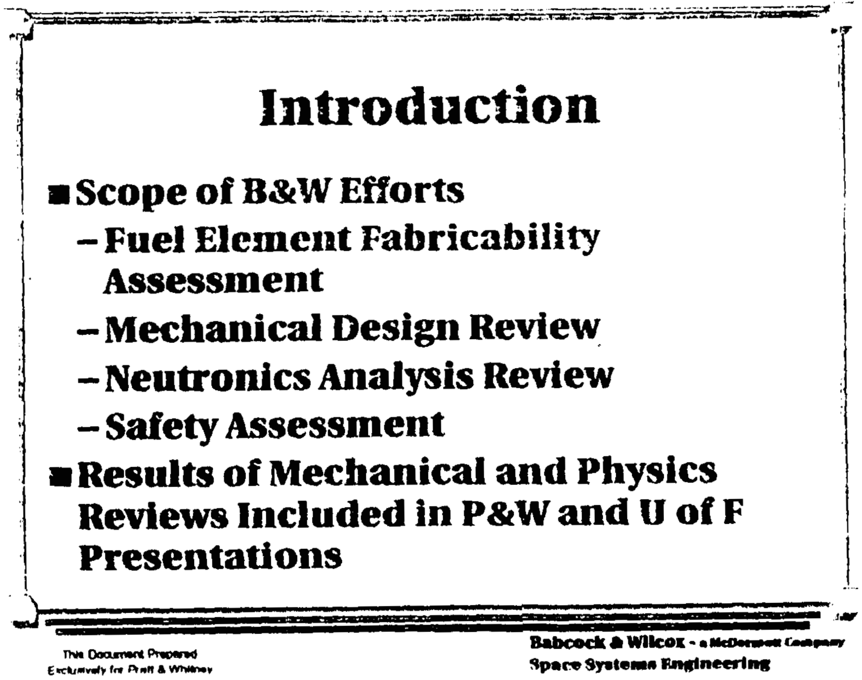
Babcock & Wilcox Assessment of the Pratt & Whitney XNR2000

Pratt & Whitney contracted with Babcock & Wilcox Advanced Systems Engineering/Space Systems Engineering to provide engineering support services for their NASA SEI Task Order Contract. Among other things, B&W is a reactor system vendor with physics, thermal hydraulics, materials, systems, mechanical engineering and manufacturing capabilities. B&W is also the operator of the only commercial facility licensed to manufacture large quantities of highly enriched reactor fuel.



Introduction

- **Scope of B&W Efforts**
  - –Fuel Element Fabricability Assessment
  - –Mechanical Design Review
  - –Neutronics Analysis Review
  - –Safety Assessment
- **Results of Mechanical and Physics Reviews Included in P&W and U of F Presentations**

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Introduction

B&W performed four subtasks for P&W as follows:

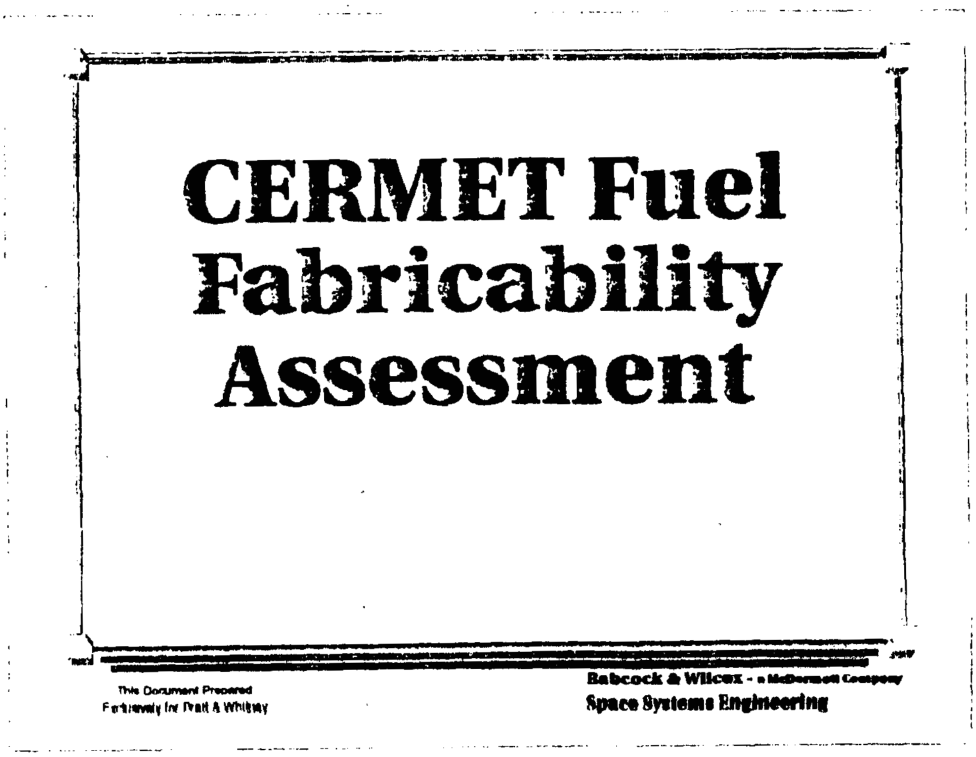
1) Fuel Element Fabricability Assessment - An assessment of the fabricability and manufacturability of CERMET fuel elements and the recoverability of the applicable technology.

2) Mechanical Design Review - An overall review of the reactor system from a mechanical engineering standpoint.

3) Neutronics Analysis Review - A review of the neutronics calculations performed for P&W by the University of Florida.

4) Safety Assessment - An overall assessment of the reactor system from a safety point of view.

The results of the mechanical and physics reviews have been integrated into the design and previously presented. The results of the fuel and safety assessments are presented here.



CERMET Fuel Fabricability Assessment

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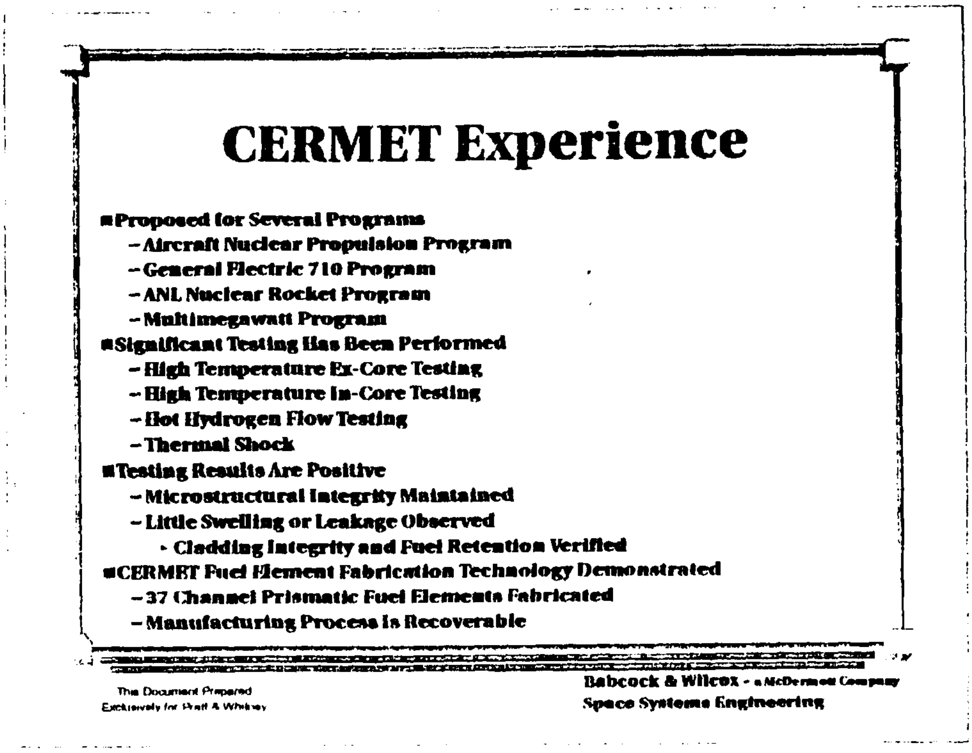
CERMET Fuel Fabricability Assessment

The fabricability of CERMET fuel elements is a major issue in the design of the XNR2000 reactor. The reactor uses both tungsten and molybdenum based UO_2 CERMET fuel elements. Most work on CERMET fabricability has focussed on tungsten based fuel elements. Since tungsten based CERMET fuel elements are more difficult to fabricate, it is reasonable to assume that if they are fabricable, then molybdenum based CERMET fuel elements will also be fabricable. The same issues and considerations that apply to tungsten based fuel elements will also apply to molybdenum based fuel elements.



CERMET Experience

- Proposed for Several Programs
  - Aircraft Nuclear Propulsion Program
  - General Electric 710 Program
  - ANL Nuclear Rocket Program
  - Multimegawatt Program
- Significant Testing Has Been Performed
  - High Temperature Ex-Core Testing
  - High Temperature In-Core Testing
  - Hot Hydrogen Flow Testing
  - Thermal Shock
- Testing Results Are Positive
  - Microstructural Integrity Maintained
  - Little Swelling or Leakage Observed
    - Cladding Integrity and Fuel Retention Verified
- CERMET Fuel Element Fabrication Technology Demonstrated
  - 37 Channel Prismatic Fuel Elements Fabricated
  - Manufacturing Process is Recoverable

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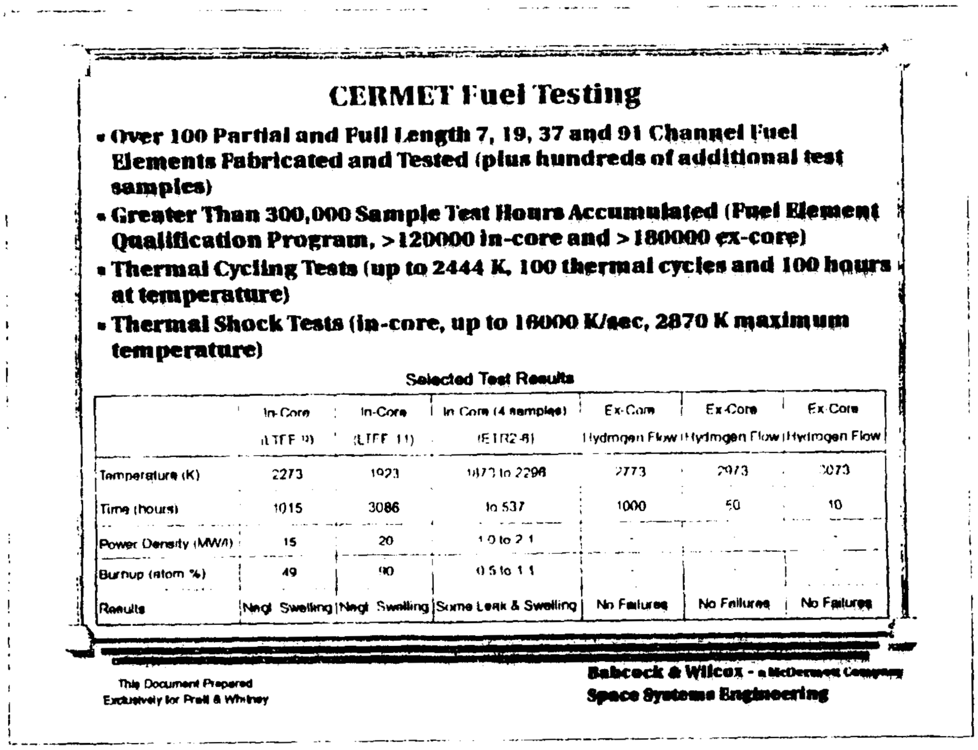
CERMET Experience

CERMET based fuel elements have been proposed for several programs in the past. The Aircraft Nuclear Propulsion program provided early experience with CERMETs. Some fuel was made and tested, but it was not a prismatic form. In the General Electric 710 program, prismatic 37 coolant channel CERMET fuel elements, similar to those proposed for use in the XNR2000, were constructed using at least two different techniques. Extensive testing was performed and documentation of these efforts is good. The Multimegawatt program demonstrated recovery of the ANL Nuclear Rocket Program technology. During the course of the 710 program and the Nuclear Rocket Program, significant testing of CERMET fuels was performed including: high temperature ex-core testing, high temperature in-core testing, hot hydrogen flow testing and thermal shock testing. The test results were positive. Little swelling or leakage was observed and microstructural integrity was maintained. CERMET fuel cladding integrity and its ability to retain the fuel was also verified.

The CERMET technology development that has been performed forms a good basis for the necessary follow-on work. The past work should be integrated with current technology, where appropriate, and a demonstration fuel element should be fabricated using depleted uranium or a surrogate fuel material.



CERMET Fuel Testing

- **Over 100 Partial and Full Length 7, 19, 37 and 91 Channel Fuel Elements Fabricated and Tested (plus hundreds of additional test samples)**
- **Greater Than 300,000 Sample Test Hours Accumulated (Fuel Element Qualification Program, >120000 in-core and >180000 ex-core)**
- **Thermal Cycling Tests (up to 2444 K, 100 thermal cycles and 100 hours at temperature)**
- **Thermal Shock Tests (in-core, up to 16000 K/sec, 2870 K maximum temperature)**

Selected Test Results

	In-Core (LTFF 9)	In-Core (LTFF 11)	In Core (4 samples) (ETR2-8)	Ex-Core Hydrogen Flow	Ex-Core Hydrogen Flow	Ex-Core Hydrogen Flow
Temperature (K)	2273	1923	1073 to 2298	2773	2973	3073
Time (hours)	1015	3086	to 537	1000	50	10
Power Density (MW/l)	15	20	1.0 to 2.1	-	-	-
Burnup (atom %)	49	90	0.5 to 1.1	-	-	-
Results	Negl. Swelling	Negl. Swelling	Some Leak & Swelling	No Failures	No Failures	No Failures

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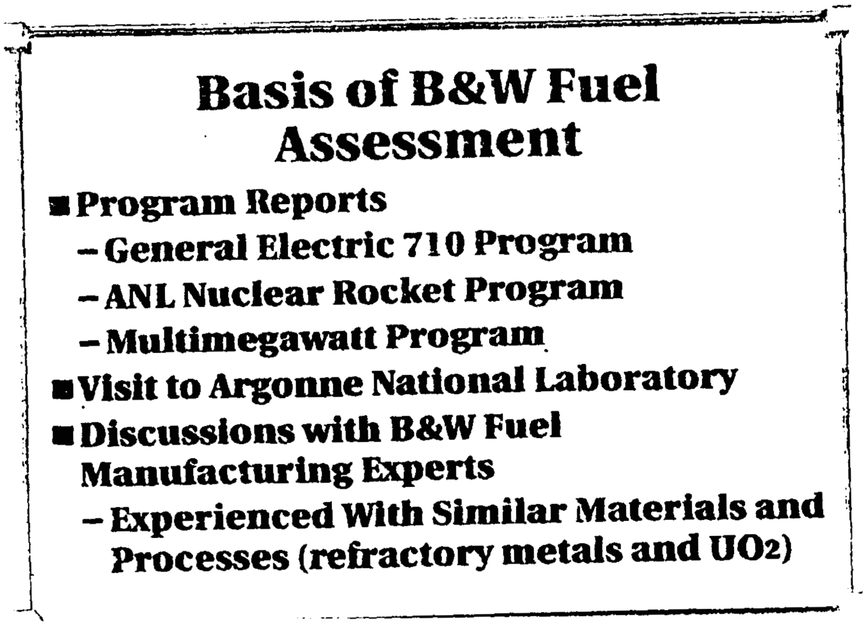
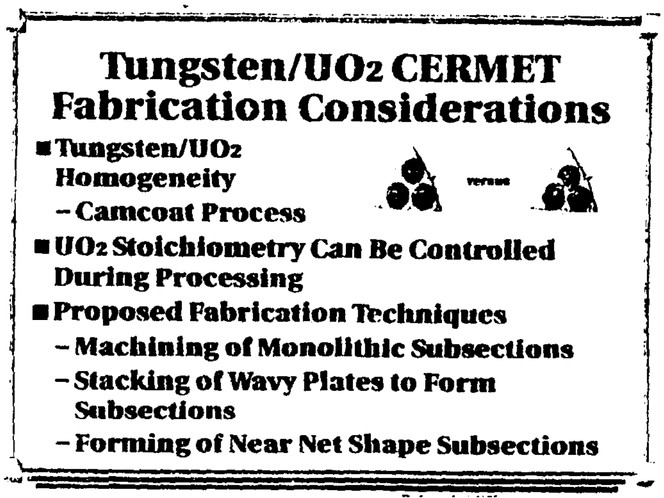


Basis of B&W Fuel Assessment

- **Program Reports**
  - **General Electric 710 Program**
  - **ANL Nuclear Rocket Program**
  - **Multimegawatt Program**
- **Visit to Argonne National Laboratory**
- **Discussions with B&W Fuel Manufacturing Experts**
  - **Experienced With Similar Materials and Processes (refractory metals and UO2)**

Basis of B&W Fuel Assessment

The B&W fuel fabricability assessment is based on written accounts of previous work, discussions with people who performed some of that work and discussions with our own manufacturing experts. The General Electric 710 program and the Multimegawatt program both left good documentation of their efforts. A trip to Argonne National Laboratory was made to talk to some of the people involved in the manufacture of CERMET fuel. B&W manufacturing personnel are experienced with refractory metals and UO_2. Discussions with B&W fuel manufacturing experts solidified confidence that CERMET fuel manufacturing technology is easily recoverable.



Tungsten/UO_2 CERMET Fabrication Considerations

- **Tungsten/UO_2 Homogeneity** versus
  - **Camcoat Process**
- **UO_2 Stoichiometry Can Be Controlled During Processing**
- **Proposed Fabrication Techniques**
  - **Machining of Monolithic Subsections**
  - **Stacking of Wavy Plates to Form Subsections**
  - **Forming of Near Net Shape Subsections**

Tungsten/UO_2 CERMET Fabrication Considerations

The CERMETs used for the XNR2000 are formed by consolidation and densification of UO_2 and tungsten (or molybdenum) powders. The UO_2 in CERMET fuel elements produced using any process must be distributed uniformly in the element. Uniformity as used here has two different meanings. First, the UO_2 loading must be locally uniform throughout the element subsection. Second, and perhaps more important, the UO_2 fuel particles must not cluster in the CERMET, but rather must be individually isolated by tungsten matrix material. This ensures that each fuel particle will be cooled adequately. Because of the differences between the behavior of tungsten and UO_2 powders, these powders must be pre-processed to ensure blending before they can be consolidated in a powder based process. It is assumed in the discussion of each consolidation process that a suitable blending process has been used prior to the actual fabrication of the element. One possible blending process is the Camcoat process developed in the General Electric 710 program.

A number of possible consolidation processes may be employed. These include, but are not limited to, pressing and sintering, hot extrusion, high energy rate forming (HERF) and heat treating, hot pressing and hot isostatic pressing (HIP). All of these processes should be capable of providing solid element subsections with little porosity in the matrix. Some of the processes, such as hot extrusion, will impart an axial texture to the element material. The acceptability of such texture must be evaluated prior to selection of a texture producing process.

In all of the above consolidation processes, the stoichiometry of the UO_2 fuel can be controlled. This is done by performing the consolidation operation in an atmosphere where the oxygen partial pressure is controlled. Typically, this involves consolidating in a hydrogen based atmosphere. Control of UO_2 stoichiometry is critical because deleterious effects occur if the fuel is either hyper- or hypo- stoichiometric.

Three CERMET fuel element subsection fabrication techniques were evaluated: machining of monolithic subsections, stacking of wavy plates to form subsections and forming of near net shape subsections. Each technique is described and a preferred fabrication technique is recommended. Machining of monolithic subsections was used in the General Electric 710 program and forming of near net shape subsections was used in the ANL Nuclear Rocket Program to fabricate fuel elements.

Fuel Element Assembly

- **Components**
  - CERMET Fuel Subsections
  - Tungsten/Rhenium Structural Can
  - Tungsten Coolant Channels
- **Assembly Options**
  - Stack Subsections In Can, Insert Tubes For Coolant Channels, HIP To Bond Can and Tubes To Fuel
  - Diffusion Bond Subsections To Each Other, HIP To Bond Fuel To Can, Form Coolant Channels By CVD Coating or Insertion of Tubes

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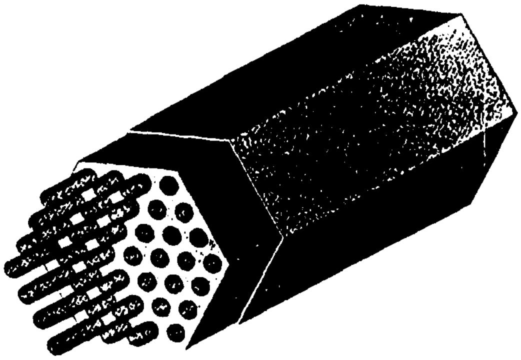
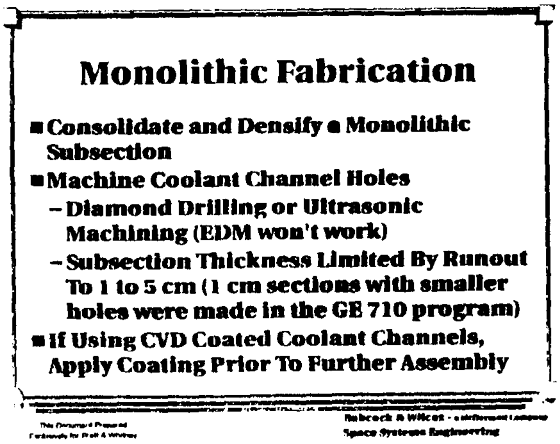
Fuel Element Assembly



Fuel Element Assembly

A complete CERMET fuel element consists of the CERMET fuel subsections, a tungsten/rhenium structural can and tungsten lined coolant channels. Final assembly of these components into full length fuel elements can be accomplished in a number of different ways. One option, used in the 710 Program, is to stack the subsections, insert tungsten flow tubes in the aligned channel holes and place the stack in the tungsten/rhenium can. A HIP operation is performed to bond the can and flow tubes to the subsection stack. With this option, the can is structural and is the sole load bearing component in the element. Another option is to coat the external surfaces of the element subsection and the ID of the coolant channels with tungsten prior to bonding a structural can onto the stack. This would eliminate the need for inserting full length flow tubes into the elements. A final option would be to bond the subsections together to form an integral fuel stack prior to bonding the stack into the can. Diffusion bonding is one possibility for the bonding process. Tungsten washers or standoffs could be used between subsections to create a plenum or transition section to minimize the effects of hole misalignments. The coolant channels can be formed as coatings on the subsections prior to assembly or by inserting tubes prior to can bonding.

Of the assembly options, bonding the subsections together prior to further assembly is preferred because it reduces the dependence on the fuel element can for structural integrity. It is not clear what technique is best for forming the tungsten flow tubes. Further technology evaluation is necessary in this area.



Monolithic Fabrication

- **Consolidate and Densify a Monolithic Subsection**
- **Machine Coolant Channel Holes**
  - **–Diamond Drilling or Ultrasonic Machining (EDM won't work)**
  - **–Subsection Thickness Limited By Runout To 1 to 5 cm (1 cm sections with smaller holes were made in the GE 710 program)**
- **If Using CVD Coated Coolant Channels, Apply Coating Prior To Further Assembly**

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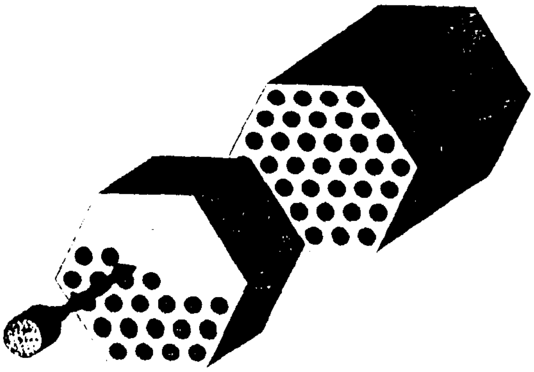
Monolithic Fabrication



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Monolithic Fabrication

In the monolithic process, the coolant flow channels are machined into a consolidated subsection. This may be done by drilling with diamond tooling or ultrasonic machining. Electrical discharge machining (EDM) is not feasible because of the high volume fraction of insulating oxide fuel in the CERMET. The maximum element subsection length which can be processed is limited by runout and depends on hole size, fuel loading, hole pitch and manufacturing tolerances. The maximum subsection length must be determined as part of the technology development. Experience with other materials suggests that this length is between 1 and 5 cm. This process was used in the General Electric 710 program to produce 1 cm thick CERMET subsections with smaller holes than proposed for the XNR2000.

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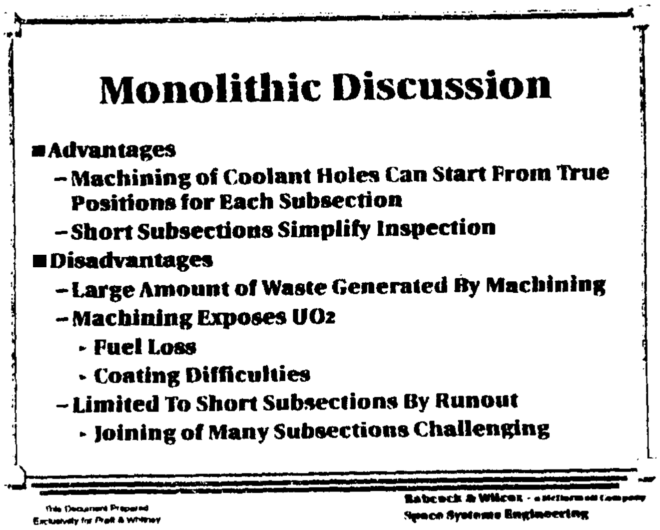

Monolithic Discussion

- **Advantages**
  - **Machining of Coolant Holes Can Start From True Positions for Each Subsection**
  - **Short Subsections Simplify Inspection**
- **Disadvantages**
  - **Large Amount of Waste Generated By Machining**
  - **Machining Exposes UO2**
    - **Fuel Loss**
    - **Coating Difficulties**
  - **Limited To Short Subsections By Runout**
    - **Joining of Many Subsections Challenging**

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Monolithic Discussion

The major advantage of the Monolithic process is that the coolant channels can be machined into the element subsections starting from true positions. Runout will increase as the depth of the hole increases, ultimately limiting the length of the element subsection which can be processed. The short length of the subsections is an advantage for inspection if the subsection flow tubes are applied as coatings before element assembly, because it will be easier to verify the integrity of the flow tube.

There are a number of disadvantages associated with the Monolithic process. As previously mentioned, subsection length is limited to between 1 and 5 cm. Stacking and bonding of the many subsections necessary to make a complete fuel element would be complicated.

Another disadvantage of the Monolithic process is that a large amount of scrap tungsten/UO_2 debris will be generated by the machining process. The uranium must be recovered from this debris. In the current design, 45% of the UO_2 initially in the consolidated fuel element subsection ends up as debris.

A final disadvantage of the Monolithic process is that the machining process exposes UO_2 fuel particles on the channel surface. This is an important effect for the following reasons. First, a significant fraction of the total amount of fuel in an element subsection will be exposed in the coolant channels. Assuming an average UO_2 particle size of 100 μm, the fraction of fuel within one-half of a particle diameter of a coolant channel is 4.9% for the current design. It is not unreasonable to assume that a large portion of the exposed fuel particles would be damaged in the channel machining process and be lost in debris, especially if fuel particles are intentionally porous (to collect gaseous fission products). This would lead to a relatively rough coolant channel surface and possibly to an unacceptable loss of fuel. A second consequence of having exposed fuel on the channel surfaces is that it may be difficult to form the coolant flow tubes by CVD. Porous or damaged fuel particles may trap halide feed material or CVD byproducts and compromise flow tube adhesion during operation. In addition, UO_2 may react with the CVD feed material or byproducts to an unacceptable degree.

Wavy Plate Fabrication

- **Consolidate and Densify "Wavy Plates"**
- **If Using CVD Coated Coolant Channels, Apply Coating To Half Channels Prior To Further Assembly**
- **Assemble Subsection**
  - **Machine Faces Flat**
  - **Clean, Stack, Align, and Load Plates**
  - **Diffusion Bond By Heating In a Controlled Atmosphere (1950 K in hydrogen)**

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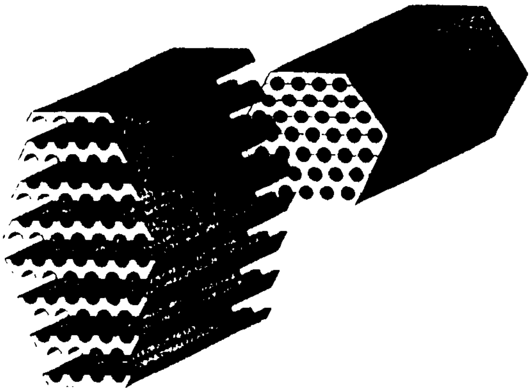
Wavy Plate Fabrication



Wavy Plate Fabrication

A fabrication technique proposed but not actually used in the General Electric 710 program was to build element subsections from flat plates. This fabrication process begins with the formation of tungsten/UO_2 powder compacts in the form of plates. Each plate would be fabricated with grooves on both of its faces. The grooves would be semicircular and correspond to one-half of a coolant channel. Stacking and aligning the plates would form an element subsection with complete, circular channels. This technique can produce elements with coolant channels arranged on a square or triangular pitch, by varying the offset between the groove patterns on the opposite faces of the plates.

After the formation of the powder compact, the plate is then consolidated by sintering. It may also be possible to perform the consolidation by hot pressing, if a suitable material for the fixturing required can be identified. Following consolidation, the plate would probably need to be ground to ensure flatness. The plate could then be coated with tungsten to form a coating on the half channels. When the plates are assembled, this coating would form the flow tube. Alternatively, the tube walls could be formed after subsection or fuel element assembly by CVD coating or insertion of tubes and HIP. After being stacked, aligned and loaded, the subsection is diffusion bonded by heating in a controlled atmosphere (1950°K in a hydrogen atmosphere for 1 hour for example).

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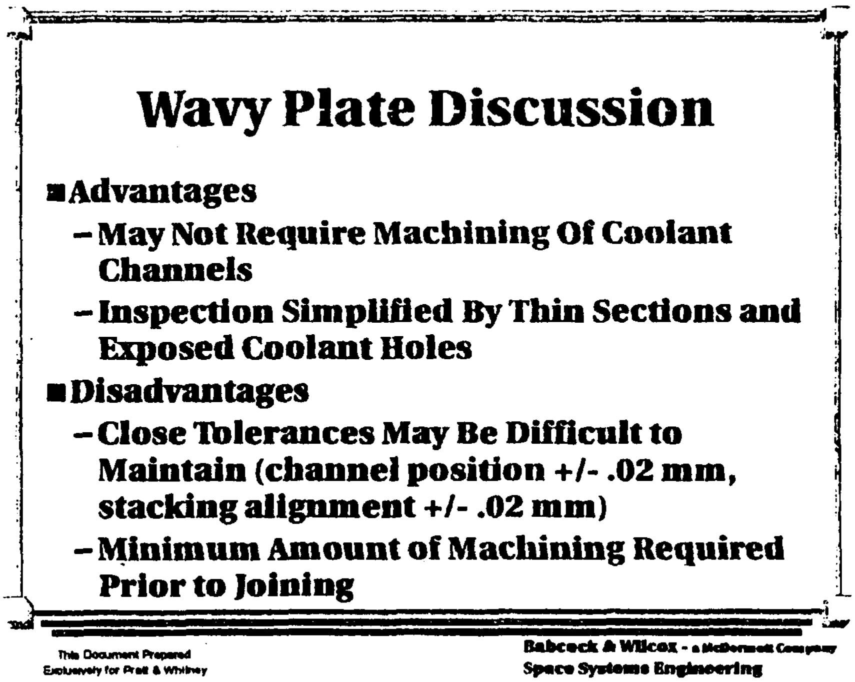

Wavy Plate Discussion

- **Advantages**
  - **May Not Require Machining Of Coolant Channels**
  - **Inspection Simplified By Thin Sections and Exposed Coolant Holes**
- **Disadvantages**
  - **Close Tolerances May Be Difficult to Maintain (channel position +/- .02 mm, stacking alignment +/- .02 mm)**
  - **Minimum Amount of Machining Required Prior to Joining**

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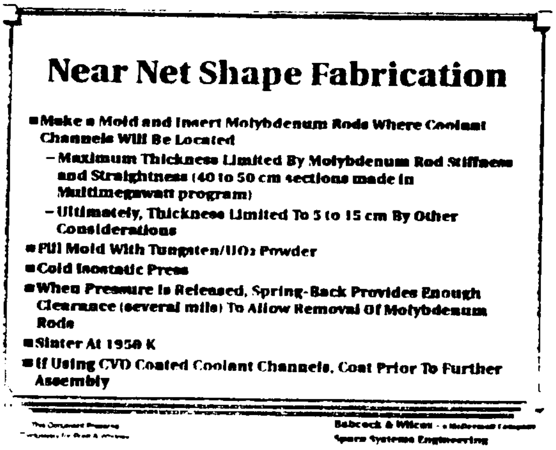
Wavy Plate Discussion

One of the major advantages of the Wavy Plate process is that the coolant channels can be fabricated without having to machine them into fully consolidated CERMET. Another major advantage is that forming the tungsten flow tubes by coating the plates prior to stacking would allow easy and detailed inspection of the integrity of the flow tube.

The major disadvantage of this process is that sintering induced shrinkage will affect the final dimensions of the plate. Accordingly, it may be difficult to maintain the required tolerances in plate dimensions. Additional difficulties may be encountered in stacking and aligning plates to form element subsections. Even if plate dimensions are such that perfect alignment is achieved, it may be difficult to maintain this alignment during the plate bonding operation. Channel position and stacking alignment tolerances will both be of the order of ± .02 mm. The tight tolerances are necessary to minimize coolant channel offsets and maximize web contact area. A final potential problem is that, if additional machining is required after consolidation, many of the disadvantages related to machining mentioned earlier may be present.



Near Net Shape Fabrication

- Make a Mold and Insert Molybdenum Rods Where Coolant Channels Will Be Located
  - Maximum Thickness Limited By Molybdenum Rod Stiffness and Straightness (40 to 50 cm sections made in Multimegawatt program)
  - Ultimately, Thickness Limited To 5 to 15 cm By Other Considerations
- Fill Mold With Tungsten/UO_2 Powder
- Cold Isostatic Press
- When Pressure Is Released, Spring-Back Provides Enough Clearance (several mils) To Allow Removal Of Molybdenum Rods
- Sinter At 1950 K
- If Using CVD Coated Coolant Channels, Coat Prior To Further Assembly

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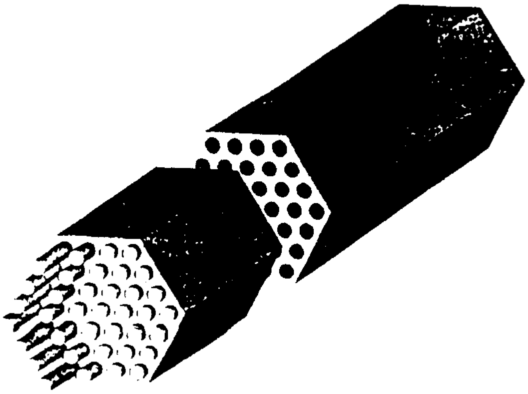
Near Net Shape Fabrication



Near Net Shape Fabrication

Fuel elements were constructed using this process in the General Electric 710 program and again during the Multimegawatt program. In this process, treated tungsten/UO_2 powder is introduced into a flexible rubber mold which contains molybdenum rods or wires. After filling, the mold is cold isostatically pressed to form a fuel element subsection powder compact. The molybdenum rods or wires are used to form the coolant channels in the compact. During mold filling, the molybdenum channel formers are held rigidly in a triangular array, with the pitch between the channel formers slightly greater than that required in the consolidated subsection, to allow for shrinkage during sintering. The key to this process is that elastic strain stored in the powder compact during isostatic pressing causes the compact to expand slightly after the pressure is removed. This spring-back effect is of a magnitude sufficient to allow the channel formers to be removed easily from the compact.

After isostatic pressing, the powder compact is sintered. The tungsten matrix can be densified to essentially theoretical density at the relatively modest temperature of 1950°K. CERMETs containing up to 61 volume percent UO_2 have been fabricated.

Segments 40 to 50 cm long were made using this process during the General Electric 710 program. The useful length may ultimately be limited to 5 to 15 cm by other factors such as channel straightness tolerances and inspectability.

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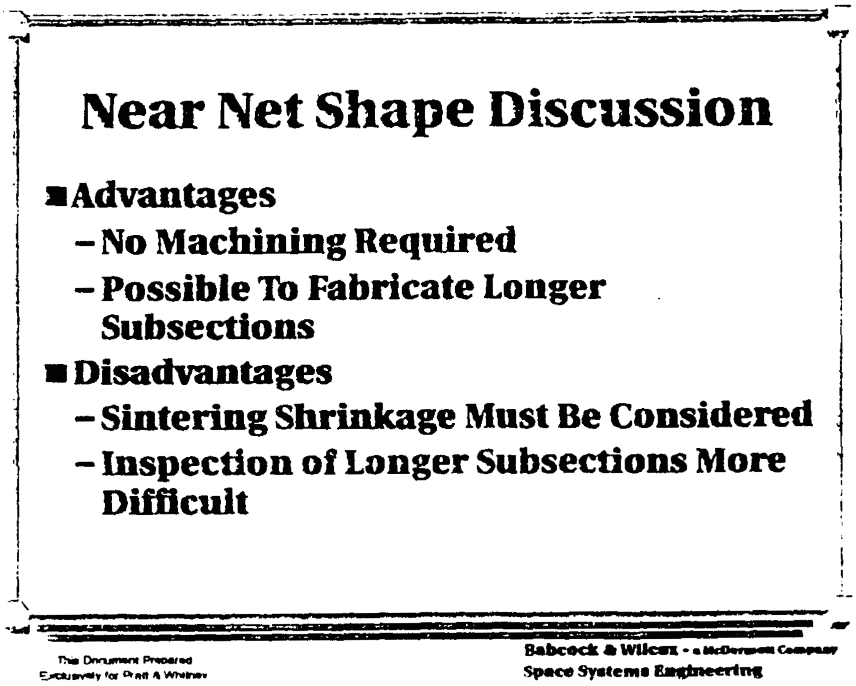

Near Net Shape Discussion

- **Advantages**
  - **No Machining Required**
  - **Possible To Fabricate Longer Subsections**
- **Disadvantages**
  - **Sintering Shrinkage Must Be Considered**
  - **Inspection of Longer Subsections More Difficult**

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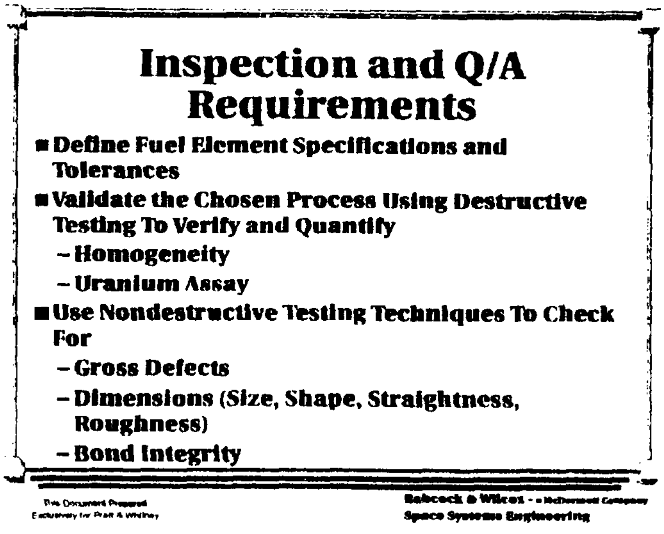
Near Net Shape Discussion

This process has two major advantages. First, a fuel element subsection is produced which is truly near net shape. Some machining of the external surfaces of the subsection may be required if inter-element spacing tolerances are tight. However, the coolant channels are formed without machining and no fuel particles are exposed in the channels. The other advantage is that this process can fabricate significantly longer element subsections which drastically reduces the number of bonds required to fabricate an integral full length element.

The major disadvantage of this process is that significant process qualification and control will have be performed to ensure that dimensional tolerances in the consolidated element subsections will be met. This work is necessary to guarantee that sintering shrinkage is reproducible from run to run during production. Process optimization may be necessary for each batch of powder used. Another disadvantage of this process is that the longer length subsections produced make inspection of the coolant channel surfaces more difficult.



Inspection and Q/A Requirements

- Define Fuel Element Specifications and Tolerances
- Validate the Chosen Process Using Destructive Testing To Verify and Quantify
  - Homogeneity
  - Uranium Assay
- Use Nondestructive Testing Techniques To Check For
  - Gross Defects
  - Dimensions (Size, Shape, Straightness, Roughness)
  - Bond Integrity

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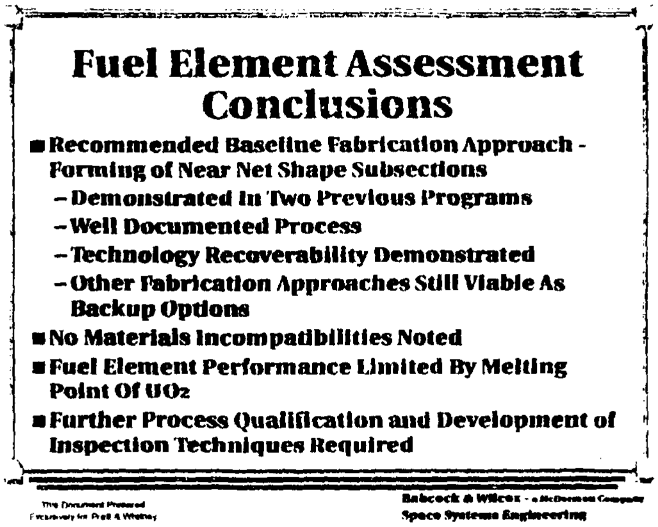
Inspection and Q/A Requirements

Significant development effort will be required in the areas of inspection techniques and quality assurance procedures. For critical items, such as fuel elements in a man-rated system, there is no such thing as an excessive amount of inspection. Manufacturing tolerances and specifications for fuel element quality must also be determined.

One obvious area for inspection is conformance to dimensional requirements. Aside from the more obvious dimensional measurements, measurements of coolant channel straightness and surface roughness must be performed. Both of these attributes would be expected to affect thermal hydraulic behavior.

Before element subsections are assembled into full length fuel elements, it will be necessary to verify that they are structurally sound. At a minimum, the porosity of the tungsten matrix should be determined and the absence of gross defects verified. Also required is measurement of the integrity of all bonds in the fully assembled fuel element. These include the bonds between element subsections, between the coolant flow tube and the CERMET fuel and between the can and the fuel element. Ultrasonic and eddy current inspection techniques can be used for these measurements.

Where direct measurements are not possible, verification has to be performed by qualifying the process. This is accomplished by running process control samples through the element fabrication process and performing destructive evaluations on them. Two measurements for which this may have to be done are UO_2 content and homogeneity of the fuel subsections. The necessity for homogeneity has already been discussed. Fuel content is required for SNM accountability. It is also necessary to verify the fuel loading of each element to ensure that the reactor will have sufficient reactivity.



Fuel Element Assessment Conclusions

- Recommended Baseline Fabrication Approach - Forming of Near Net Shape Subsections
  - Demonstrated In Two Previous Programs
  - Well Documented Process
  - Technology Recoverability Demonstrated
  - Other Fabrication Approaches Still Viable As Backup Options
- No Materials Incompatibilities Noted
- Fuel Element Performance Limited By Melting Point Of UO_2
- Further Process Qualification and Development of Inspection Techniques Required

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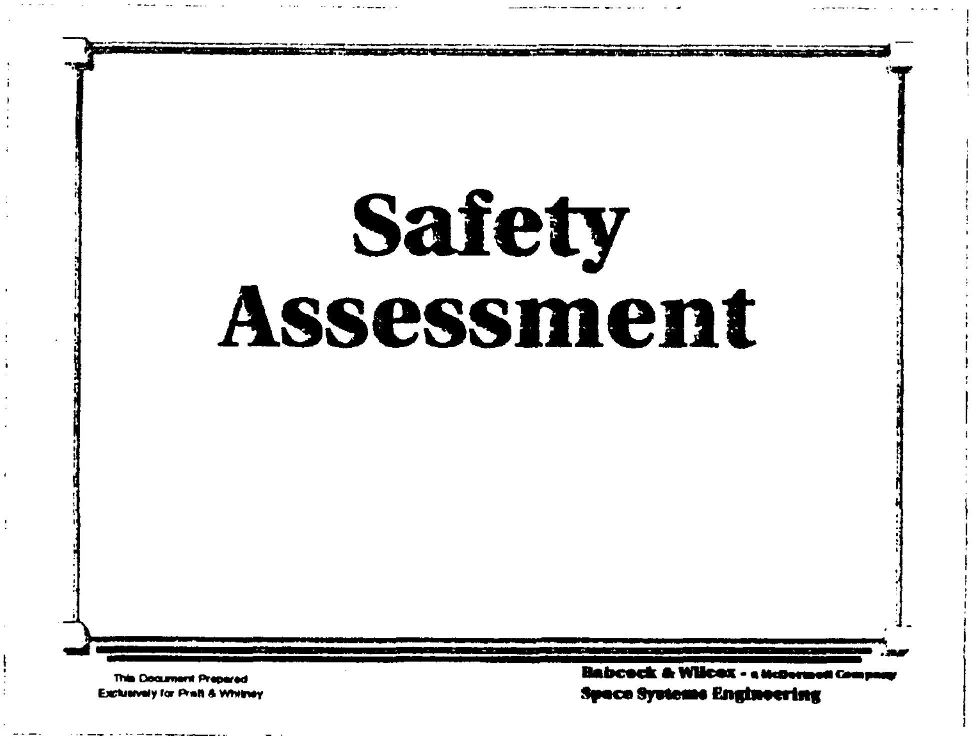
Fuel Element Assessment Conclusions

There are no insurmountable obstacles to fabrication of tungsten or molybdenum UO_2 CERMET fuel elements. XNR2000 fuel is manufacturable using demonstrated technology. There were no materials incompatibilities noted in this investigation. Fuel element performance is not limited by structural considerations but by the melting point of the UO_2. The maximum nominal fuel temperature in the XNR2000 is well below the UO_2 melting point.

The recoverability of the CERMET processing technology has been demonstrated. The development of CERMET fuel technology should not impose cost or schedule limitations.

Of the three processes considered for the fabrication of tungsten (or molybdenum) based UO_2 CERMET fuel elements, the Near Net Shape process is preferred. As discussed, this process has the potential of producing long length element subsections without having to machine the coolant channels. The process uses well known, technically simple processing steps. These steps will, of course, have to be extremely well characterized, to control sintering shrinkage and allow dimensional tolerances to be met. Finally, this process has been investigated extensively in the past and there is a significant experience base with it.

The wavy plate fabrication scheme also has potential. It should be further investigated in parallel as a backup option.



Safety Assessment

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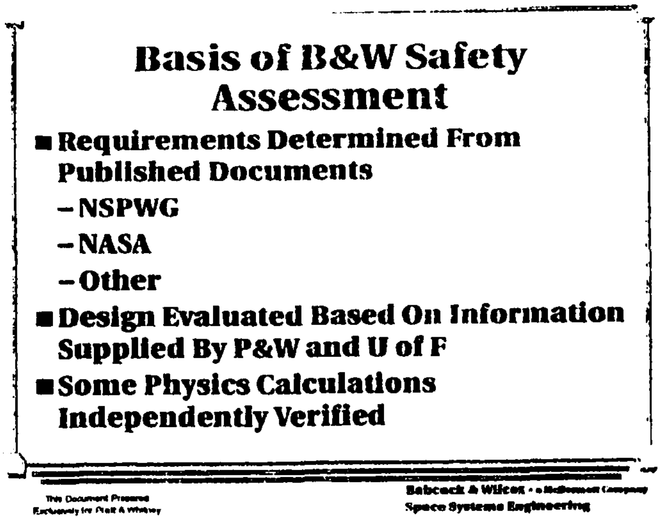
Safety Assessment

The Pratt & Whitney XNR2000 NTRE has been designed with safety as a primary consideration.

The safety of the public, mission personnel, the crew and the terrestrial and non-terrestrial environment have all been considered. The main safety characteristics of the XNR2000 are highlighted, and the effect of thrust level on safety is considered.



Basis of B&W Safety Assessment

- **Requirements Determined From Published Documents**
  - **NSPWG**
  - **NASA**
  - **Other**
- **Design Evaluated Based On Information Supplied By P&W and U of F**
- **Some Physics Calculations Independently Verified**

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Basis of B&W's Safety Assessment

The first step in the B&W safety assessment was to determine what the requirements and safety concerns for SEI NTRE systems are. Some of the documents used are listed here:

A.C. Marshall, et al; "Nuclear Safety Policy Working Group Recommendations on Nuclear Propulsion Safety for SEI"; (to be published); 1991.

Nuclear Thermal Rocket Engine Requirements, Revision 3; NASA N.P. #002; 1992.

L.W. Connell, D.L. Potter, C.C. Wong and M.W. Kniskern; "Nuclear Thermal Rocket Entry Heating and Thermal Response Preliminary Analysis"; Proceedings of the Ninth Symposium on Space Nuclear Power Systems; p. 923; January 12-16, 1992.

Occupational Safety and Health Administration, Department of Labor; US Code of Federal Regulations, 29 CFR 1910.96.

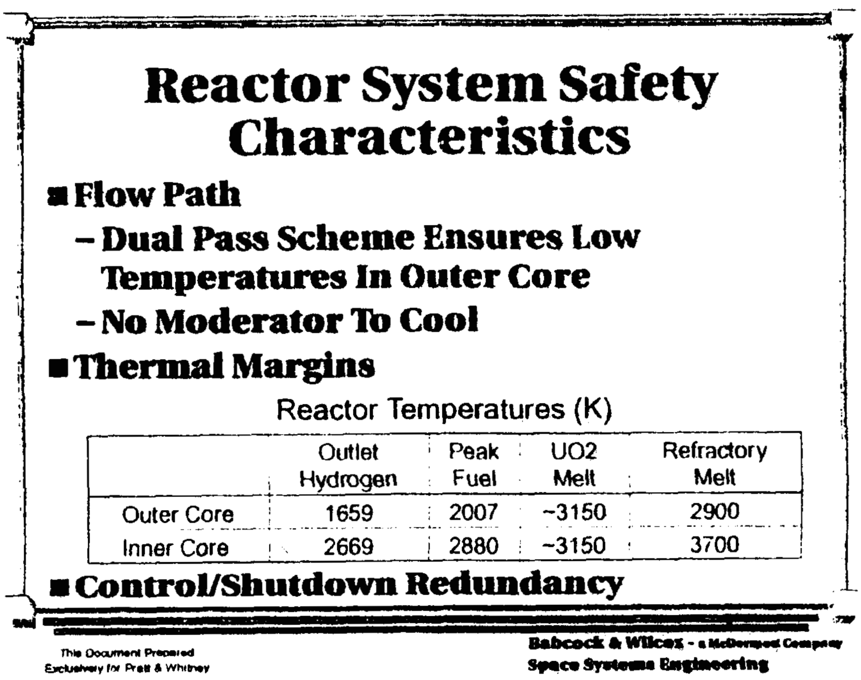
S.N. Jahahan; "The Reactor Physics Design of Gas-Cooled CERMET Reactors and Their Potential Application to Space Power Systems"; Nuclear Technology; vol. 98, p. 257; 1992.

P.M. Sforza, M.L. Shooman, D.G. Pelaccio; "A Safety and Reliability Analysis for Space Nuclear Thermal Propulsion Systems"; IAA-92-0376; 43rd Congress of the International Astronautical Federation; 1992.

D. Atkinson, et al; "Collision Damage to Nuclear Satellites"; Proceedings of the American Nuclear Society Topical Meeting on Nuclear Technology for Space Exploration; p. 843; 1992.

D. Buden; "Safety Questions Relevant to Nuclear Thermal Propulsion"; Proceedings of the Ninth Symposium on Space Nuclear Power Systems; p. 648; 1992.

The XNR2000 design was then evaluated with respect to these requirements and concerns based on information supplied by Pratt & Whitney and the University of Florida.



Reactor System Safety Characteristics

- **Flow Path**
  - **Dual Pass Scheme Ensures Low Temperatures In Outer Core**
  - **No Moderator To Cool**
- **Thermal Margins**

Reactor Temperatures (K)

	Outlet Hydrogen	Peak Fuel	UO2 Melt	Refractory Melt
Outer Core	1659	2007	~3150	2900
Inner Core	2669	2880	~3150	3700

- **Control/Shutdown Redundancy**

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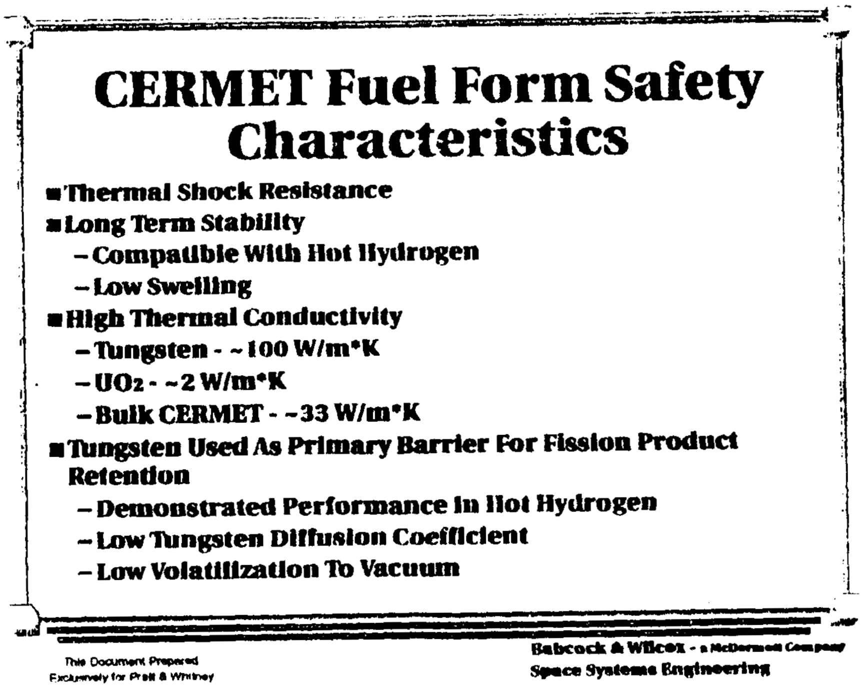
Reactor System Safety Characteristics

Safety considerations must be an integral part of the design process for any man-rated space system. Inherent safety is the preferred goal, and passive systems are preferred over active systems. The dual pass flow scheme ensures low temperatures in the outer core in a simple way. The fact that there is no moderator to cool also simplifies the flow path. The peak fuel temperature in the inner core is 2880°K (outlet hydrogen temperature of 2669°K); this compares to tungsten and UO_2 melting points of 3700°K and 3150°K respectively. In the outer core, the peak fuel temperature is 2007°K (outlet hydrogen temperature of 1659°K); the melting point of molybdenum is 2900°K. These large thermal margins provide advantages in transient and accident situations. The reflector windowing leakage control scheme proposed for the XNR2000 is simple and robust. Redundant control and shutdown systems are provided.



CERMET Fuel Form Safety Characteristics

- Thermal Shock Resistance
- Long Term Stability
  - Compatible With Hot Hydrogen
  - Low Swelling
- High Thermal Conductivity
  - Tungsten - ~100 W/m*K
  - UO_2 - ~2 W/m*K
  - Bulk CERMET - ~33 W/m*K
- Tungsten Used As Primary Barrier For Fission Product Retention
  - Demonstrated Performance In Hot Hydrogen
  - Low Tungsten Diffusion Coefficient
  - Low Volatilization To Vacuum

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CERMET Fuel Form Safety Characteristics

The XNR2000 design benefits from the inherent stability, robustness and transient tolerance of the CERMET fuel form. This may be a particular asset in the long dormant phase and in assuring operability until disposal. Tungsten and molybdenum CERMET fuels are more resistant to hydrogen erosion than carbide fuels, and therefore, lifetime is not limited by coatings technology. They also exhibit low swelling and are effective at retaining fission products. CERMET fuels exhibit excellent thermal shock resistance over a wide range of conditions. The high thermal conductivity of the fuel is advantageous in under-cooling scenarios and decay heat removal. Bulk tungsten/UO_2 CERMET thermal conductivity is in the range of 33 W/m*K, based on tungsten and UO_2 thermal conductivities of 100 and 2 W/m*K respectively. When damage thresholds are exceeded, the CERMET fuel form can handle significant degradation before failing catastrophically.

Tungsten is effective at retaining fission products. Its inherent stability, performance in hot hydrogen, low volatility to vacuum and low diffusion coefficient all combine to make it one of the best materials for this purpose. The General Electric 710 program demonstrated that the CERMET matrix alone will retain 85% of the fission products it contains. With intact tungsten cladding retention approaches 100%.

Fast Spectrum Safety Characteristics

- **Negligible Hydrogen Worth (< .2 % ρ)**
- **Less Excess Reactivity Required**
  - **Lower Delayed Neutron Fraction Makes Given Reactivity Insertion Worth More**
  - **Negligible Xenon Reactivity Effects**

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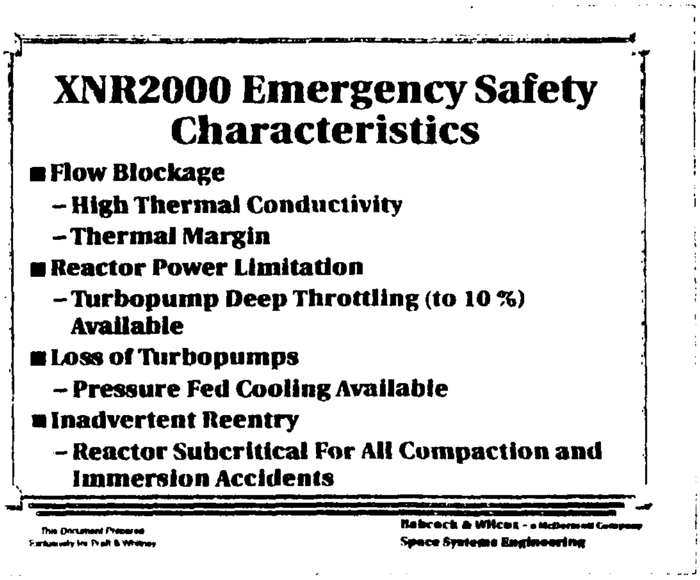
Fast Spectrum Safety Characteristics

The fast spectrum of the XNR2000 has several positive safety effects. The worth of the hydrogen in the XNR2000 is negligible (<.2 % ρ as calculated by the University of Florida and verified by Babcock & Wilcox). This is helpful at reactor startup, since there will be no large reactivity insertion due to the cold hydrogen. Little excess reactivity is required in the XNR2000. The lower delayed neutron fraction in the fast spectrum makes a given reactivity insertion worth more in terms of reactor response. Also, there a negligible xenon reactivity effect due to the fast spectrum, so there is no need to provide excess reactivity to overcome a large xenon transient.

The fast spectrum of the XNR2000 may also affect ground testing. Ground test facilities will have to be designed to handle the fast spectrum leakage from the NTRE.



XNR2000 Emergency Safety Characteristics

- **Flow Blockage**
  - **High Thermal Conductivity**
  - **Thermal Margin**
- **Reactor Power Limitation**
  - **Turbopump Deep Throttling (to 10 %) Available**
- **Loss of Turbopumps**
  - **Pressure Fed Cooling Available**
- **Inadvertent Reentry**
  - **Reactor Subcritical For All Compaction and Immersion Accidents**

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XNR2000 Emergency Safety Characteristics

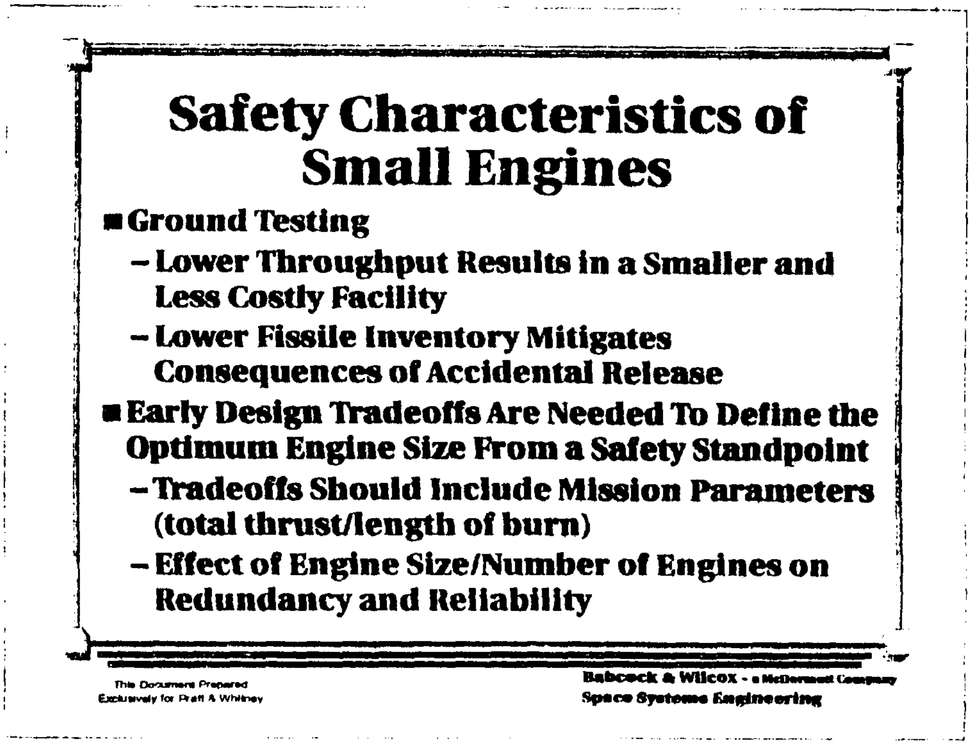
The high thermal conductivity and structural stability of the CERMET fuel is a benefit in accident situations. For partial or full flow blockage in a coolant channel, the high thermal conductivity mitigates the temperature rise. Temperatures around a blocked channel may approach or exceed the melting point of UO_2. This will not be a problem in the localized area involved. The tungsten can easily contain molten UO_2.

A loss of turbopumps accident is handled by pressure fed cooling. A high pressure reservoir will provide the hydrogen flow necessary for the critical period immediately following shutdown. After the first minute or so, the reactor can be cooled by feed tank pressure.

No NTRE currently under consideration can survive a full-power total loss of coolant accident. A low-power total loss of coolant would cause rapid shutdown of the reactor due to the negative reflector temperature coefficient. A total loss of coolant at very low power or during decay heat removal might not be catastrophic for the XNR2000 due to the robustness of the CERMET fuel.

The XNR2000 turbopumps can be throttled to 10% of full flow. This is a safety advantage for cases where the reactor power is limited for some reason. This feature allows the NTRE to provide reduced thrust at nearly full I_{sp}. This enables mission completion or full abort capability for a limited reactor power scenario.

It has been shown by the University of Florida, and verified by Babcock & Wilcox, that for all the accidents of concern in an inadvertent reentry (compaction and submersion) the reactor remains subcritical by a significant margin.



Safety Characteristics of Small Engines

- Ground Testing
  - Lower Throughput Results in a Smaller and Less Costly Facility
  - Lower Fissile Inventory Mitigates Consequences of Accidental Release
- Early Design Tradeoffs Are Needed To Define the Optimum Engine Size From a Safety Standpoint
  - Tradeoffs Should Include Mission Parameters (total thrust/length of burn)
  - Effect of Engine Size/Number of Engines on Redundancy and Reliability

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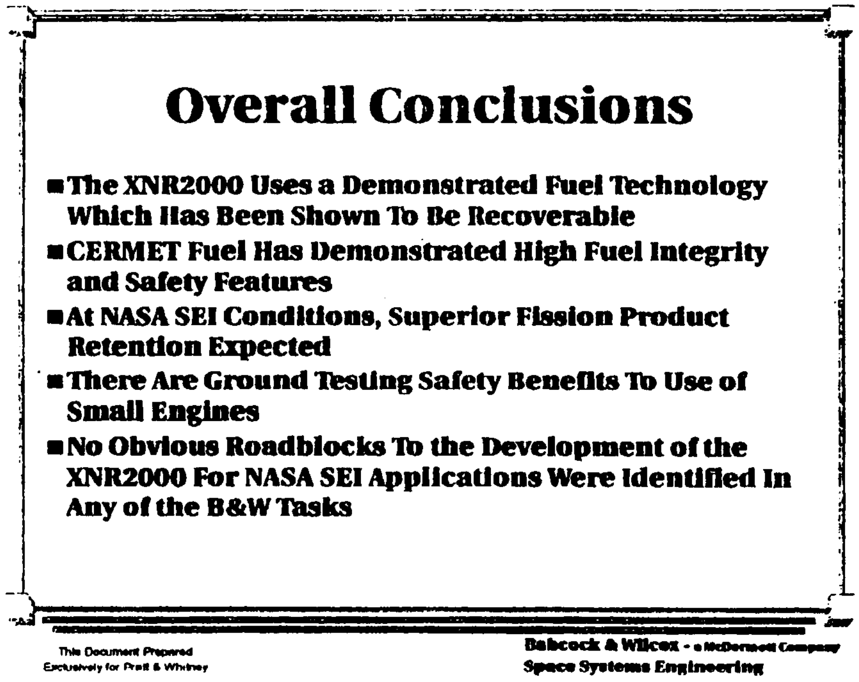
Safety Characteristics of Small Engines

The thrust levels required for SEI missions can be achieved using a few large engines or multiple small engines. It is not obvious what conclusion would be drawn from the tradeoffs for small versus large engines from an operational safety point of view. Redundancy goes up for small engines, but overall system reliability may go down.

One area where small engines have a clear safety advantage is in ground testing. Small engines will be easier and less costly to test than large engines. The test support requirements and effluent throughput will both be lower, resulting in a smaller and less costly facility. Accidents consequences will also be mitigated due to the lower fissile inventory in a small NTRE.

A detailed fault tree failure analysis will be required to determine the optimum arrangement from an overall safety point of view. This analysis should be performed as soon as possible. The tradeoffs in a safety evaluation should include certain mission parameters. For example, a lower thrust level for a longer time may result in a safety advantage. This would probably also result in a higher initial mass in low earth orbit, but this might be a worthwhile trade for increased safety.



Overall Conclusions

- The XNR2000 Uses a Demonstrated Fuel Technology Which Has Been Shown To Be Recoverable
- CERMET Fuel Has Demonstrated High Fuel Integrity and Safety Features
- At NASA SEI Conditions, Superior Fission Product Retention Expected
- There Are Ground Testing Safety Benefits To Use of Small Engines
- No Obvious Roadblocks To the Development of the XNR2000 For NASA SEI Applications Were Identified In Any of the B&W Tasks

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Overall Conclusions

B&W's overall opinion of the XNR2000 is positive. It uses a demonstrated fuel technology which has been shown to be recoverable. The CERMET fuel form has been demonstrated to have high fuel integrity and important safety features. At NASA SEI operating conditions, superior fission product retention is expected.

Ground testing considerations point to a safety advantage for small engines.

None of the B&W tasks have identified any roadblocks to the development of the XNR2000 as a viable NASA SEI NTRE.

COMPOSITE NTR ISP IS LIMITED BY BURN TIME

Thrust size	Mission burn (hr)	Design life	Composite ISP	Cermet ISP
25k	4.5	14	825	900
50k	2	8	845	900
75k	1.5	6	855	900

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Composite NTR Isp Is Limited By Burn Time

The performance level, specific impulse or propellant exit temperature, of the cermet based NTRE systems is not limited by burn time. However, the operating temperatures and consequently Isp, of the composite NTRE systems is limited by burn time due to the inherent chemical instability between the hot hydrogen environment and the carbon based fuel form.

ADVANTAGES OF DUAL PASS REACTOR

- Power/Flow Matching
- Material Temperature Matching
- Flat Radial Profiles (Mixing)
- Isolated Hot Core

900 seconds I_{sp}
Superior Fn/Wt

Advantages of Duel Pass Reactor

The primary attractive features provided by the dual pass reactor core are summarized. A flat radial power profile is provided by the dual-pass reactor due to the averaging of power distributions relative to two distinct regions. Positive flow/power matching is achievable because of the separation of the inner and outer cores. The maximum fuel element power shape factors appear in the outer core region because of the proximity of the radial reflector. However, because the outer core serves as the first pass, the coolest hydrogen propellant passes through the outer core and eliminates fuel temperature concern. Additionally, upper plenum mixing of the hydrogen serves to eliminate the outer core power peaks from the inner core fuel elements. The dual pass configuration isolates the hot inner core fuel elements from the rest of the engine system. This isolation provides material flexibility allowing the use of lighter weight Moly based fuel elements in the outer core and a Be radial reflector which provides the most reactivity worth for the weight. The most obvious benefit of the dual pass core is the reduced axial thermal gradients and consequently thermal stress loads placed on the fuel elements.

ADVANTAGES OF FAST SPECTRUM CERMET REACTOR

- Safety
  - Positive Fuel and Fission Product Retention
  - Compaction/Immersion
  - Long Life
- Simple Design
  - No H_2 Reactivity Feedback
  - Simple Support (No Tie Tube Complexity)
  - Control Flexibility
- Strong High Conductivity Fuel
  - Self Supporting
  - Dimensional Stability
  - Resistance to Thermal/Physical Shock

Advantages of Fast Spectrum Cermet Reactor

The XNR2000 builds upon the experience and database of Cermet fuels obtained in the GE710 and ANL programs. The fast spectrum Cermet fuel form was selected to meet the engine requirements of ALARA fuel and fission product release, multiple restart capability and subcriticality under credible accident scenarios. During the GE710/ANL programs the Cermet fuel form displayed tolerance to excessive temperature/power ramps due to the high strength and conductivity of the refractory metal matrix. Additionally Cermet fuel display complete compatibility in the expected hot H2 operating environment as well as cladding and fuel matrix CTE compatibility. Finally the XNR2000 is based upon a fuel form that was successfully fabricated and tested.

The selected Cermet fuel form provides a more robust, simple system design because of the elimination reactivity feedback from hydrogen moderation. A simplified support structure is possible due to the high strength of the refractory metal based fuel form.

XNR2000 CERMET NTRE
NEAR TERM RECOMMENDATIONS

- 37 hole fuel element fabrication trial
  - Near net shape
  - Wavy plate
- Refine XNR2000 baseline design
  - Mechanical design
  - Transient, off nominal
  - Reliability analysis
  - Manufacturing study
  - Health monitor/control definition
- Ensure "fast spectrum" testability in PIPET

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XNR2000 Cermet NTRE Near Term Recommendations

The near term development priorities of the XNR2000 Cermet based NTRE are listed. A 37 hole baseline fuel element should be fabricated using the near net shape fabrication technique with the many plate technique used as a backup. The preferred fabrication technique should be selected and refined to incorporate current powder metallurgy technology.

The baseline design effort should be continued and refined in the areas of mechanical design, XNR2000 manufacturing, and health monitor/control definition. Transient and off nominal studies of the XNR2000 are required as well as a reliability analysis.

The testability of the XNR2000 fast spectrum fuel form in PIPET should be established