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A TRICARBIDE FOAM FUEL MATRIX FOR NUCLEAR THERMAL PROPULSION

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Abstract – A *team from Ultramet Inc., Sandia National Laboratories and the University of Florida has been developing a new high temperature, tricarbide fuel matrix consisting of ZrC, NbC and UC using an open-cell reticulated foam skeleton. The new fuel matrix is the product of a NASA STTR project funded through Marshall Space Flight Center. The new fuel is envisioned for use in nuclear thermal propulsion systems, bi-modal reactors and terrestrial high temperature gas reactors and builds on the tricarbide fuel research in the former Soviet Union. The new fuel is mechanically robust and very efficient given its extremely high surface area, higher melting point, minimal thermal stresses, and much reduced pressure drop compared to conventional fuel types. The matrix is anticipated to operate at temperatures as high as 3000K with minimal hydrogen erosion. The foam is an engineered material in which the porosity, size and thermal conductivity of the ligaments can be controlled independently to meet specific requirements. In this article, we review the vapor phase alloying of the tricarbide to produce a homogeneous solid mixture of the constituents using TaC as a UC surrogate with the option of additional diffusion barrier layers as required. A credible reactor design and results of a new MP-CFD modeling capability using detailed simulation of the porous media are presented along with new FEM CFD simulations of a complete fuel element and core assembly. A new CVI reactor for the deposition of the tricarbide containing UC is now operational at the University of Florida. This article presents our recent experiences with UC depositions and results from hot hydrogen testing of these materials at 3000K.*

I. INTRODUCTION

Exploring the solar system while maintaining reasonable interplanetary travel times will require increases in spacecraft velocities of one to two orders of magnitude over currently achievable levels. The “packaged energy” for space propulsion systems required to achieve this goal, expressed as a combination of specific impulse (I_{sp}) and mass fraction, must increase by an order of magnitude over current chemical rocket propulsion. The primary problem is that even advanced chemical rocket systems limit maneuverability and destinations. Chemical systems will not be able to extend human space exploration much beyond the moon or Mars. One solution to this problem is to utilize more energetic fuels. Therefore, NASA's goal, as originally stated for the Advanced Propulsion Research Program managed by Marshall Space Flight Center (MSFC) and now as Project Prometheus, is to develop fission propulsion to enable rapid and affordable access to any point in the solar system.[1] The development of a new high temperature fuel matrix offers the potential for practical and high-efficiency fission propulsion systems.

Fission power enables a new propulsion growth path with two options: nuclear thermal propulsion (NTP), in which gas is heated and expanded through a nozzle; or nuclear electric propulsion (NEP), in which nuclear power is converted to electric power for an advanced propulsion system such as a plasma thruster. The I_{sp} for NTP systems can increase by a factor of 10 and the specific energy can improve by a factor of 1,000,000 over conventional rockets. NTP systems have high thrust with moderate I_{sp} (>800 sec), whereas NEP systems have lower thrust with extended I_{sp} (>5000 sec) while providing auxiliary payload power. Fission power provides more energy for instruments communications and higher data processing rates, more time for extended exploration, and more adaptability to changing mission requirements.

NASA MSFC was recently involved in a program known as the Safe Affordable Fission Engine (SAFE).[2] This program, meant to revitalize fission propulsion research, concentrated on existing nuclear technology coupled with non-nuclear testing at existing facilities. A 30-kW resistively heated prototype module, SAFE-30, underwent testing to verify heat transfer through an annular core geometry utilizing heat pipes and a 350-W Stirling engine power converter.[3] Such designs clearly have potential for lower thrust, long-I_{sp} NEP systems but are limited by their maximum operating temperature when high-thrust, shorter-pulse NTP systems or bimodal NTP/NEP systems would best meet mission requirements. The efficiency of the rocket increases if the temperature difference between the fuel and propellant is minimized. This dramatically improves thrust-to-mass ratio, reduces the amount of propellant required (tankage) for NTP systems, and can improve total available electric power for NEP systems via a high-efficiency Brayton thermal cycle or advanced Stirling engine.

Previous work at NASA and preliminary experiments at various laboratories have shown that NbC and ZrC have the best potential to meet the requirements of space nuclear reactors with respect to sustained life in hydrogen at temperatures approaching 3000 K.[4] Ultramet worked closely with Babcock & Wilcox, General Dynamics, Hercules, and others to develop NbC coating processes for a variety of components. In previous work for DOE and the Air Force, Ultramet developed processing conditions for fabrication of NbC and ZrC foam materials for potential use in particle bed reactors (PBRs) that were under development at the time by Babcock & Wilcox in support of nuclear-thermal propulsion programs such as NASA's Space Exploration Initiative (SEI) and the Air Force's Space Nuclear Thermal Propulsion (SNTP) program.[5-7]

Although both NbC and ZrC foams were successfully fabricated, only NbC foam was selected for rigorous testing due to schedule and budgetary constraints. Babcock & Wilcox subjected NbC foam specimens to hot hydrogen exposure at 3000 K for up to 30 minutes and mechanically loading at 3000 K in helium, with no observed deterioration in either case. Creep at 345 kPa (50 psi) and 3000 K was also determined to be negligible.[8]

The Prometheus project enables "Advanced Human Exploration" of the solar system, including Mars, and beyond. It specifically calls for the development of new nuclear fuels and components that are capable of extremely high temperature, very efficient operation (>925 sec I_{sp} for >1 hr). Our objective was to contribute directly to this NASA goal by demonstrating the feasibility of a revolutionary new open-cell foam fuel for space reactors. The new foam fuel can operate at extremely high temperatures using refractory materials with low neutron absorption cross-section and extended surface area. The foam fuel material consists of a tricarbide, UZrNbC, made of enriched uranium that is vapor infiltrated into an open-cell foam matrix of NbC and ZrC, a system that offers many advantages. Advanced tricarbide fuels have been proposed for nuclear thermal propulsion (NTP) applications because of their expected longer life and higher operating temperature due to their high melting temperature, high thermal conductivity, and improved resistance to hot hydrogen corrosion.[9,10] Although it is similar in composition to the Russian "twisted ribbon" fuel, the inherent foam structure has extremely high surface area and stiffness, low density (light weight), and extremely high melting point, offers reasonable thermal conductivity, should not degrade in hydrogen at 3000 K, does not clog, and retains its structural integrity at high temperature.[11]

A highly porous fuel matrix in the form of a rigid foam can be used to create high thermal efficiency, high temperature fuel elements for both propulsion and gas-cooled power reactors. Current designs, such as annular rods or pebble beds, cannot operate at extremely high temperatures and thus limit efficiency. They also do not retain there structural integrity and often sinter, change shape and lose thermal contact to the frits or coolant channels. The porous foam structure provides an extended surface area for highly efficient heat transfer and reduces density, reducing hydrogen turbopump power demands and increasing thrust-to-weight ratio.

In a NASA-funded Phase I STTR project, Ultramet teamed with Sandia National Laboratories to demonstrate the initial feasibility of the highly innovative foam fuel elements. This work included chemical vapor infiltration of the carbides into an open-cell foam skeletal structure by Ultramet and a matrix of foam densities was created for thermal/gas flow testing at Sandia. The results of flow testing, coupled with the results of thermomechanical modeling performed at Sandia, confirmed the high potential of this design following continued development. A portion of the results are presented in this article. Last year, the project obtained phase-II status. Sandia has also been involved with the development of massively parallel CFD calculations in porous media to ascertain the thermal-

aerolic properties of the foam fuel. In addition, Sandia and the University of Florida have proposed a credible baseline design of a nuclear thermal propulsion (NTP) reactor based on MCNP analysis using the new fuel. This paper presents the preliminary results of the CFD modeling effort and describes our reactor concept. In the near future, Ultramet, Sandia and the University of Florida intend to fabricate the actual UZrNbC foam fuel material. Ultramet has finalized process optimization using the TaZrNbC surrogate material and is transferring the processing technology to the University of Florida's Innovative Nuclear Space Power and Propulsion Institute (INSPI). INSPI plans to test the UZrNbC foam in a hot hydrogen environment beginning this year. Fuel element fabrication and neutron irradiation are anticipated in a follow-on program.

II. MATERIALS DEVELOPMENT

The primary goal of the program was to create the equivalent of a solid eutectic solution of a tricarbide fuel in the form of an open-celled, reticulated foam deposited on a carbide skeleton. This technology is based on Ultramet's many years of previous experience in fabricating refractory ceramic and metal foams.

II.A. Chemical Vapor Infiltration

The open-cell foam skeleton is created by starting with polyurethane foam with suitable porosity and pore density. The polymer is then pyrolyzed at elevated temperature to produce a carbonaceous foam skeleton. The carbon foam skeleton is then heated, and carefully selected gas mixtures are flowed through the foam enabling the chemical vapor to infiltrate (CVI) the foam structure and react to form the UNbZrC matrix. At sufficiently high temperatures and hold times all of the free carbon in the skeleton can be converted into metal carbide. To fabricate a non-nuclear prototype, we deposited TaC instead of UC in the matrix. Finally, a complete coating of NbC or ZrC can be CVD'd on top of the infiltrated matrix as a diffusion or encapsulation barrier to inhibit hot hydrogen erosion. In the foam, the fissile material becomes integrally connected to a structurally stable CVD foam ligamental structure. The foam matrix can have low thermal expansion, resists thermal stress and shock, and possesses good thermal conductivity, high surface area and enhanced gas permeability. It is also relatively inexpensive to fabricate (no machining) and easily scalable. The amount of moderator in the foam webbing should be insufficient to create a criticality problem during fabrication, but this issue will require further investigation before work with enriched isotopes can proceed. In our reactor concept, additional bulk moderator and absorber control drums or reflector sliders surround foam fuel annuli in a prismatic core array.

II.B. Carbide Matrix Infiltration

As noted, ceramic foam substrate fabrication begins with a reticulated vitreous carbon (RVC) foam skeletal structure. The RVC foam has an extremely high void volume (97%), combined with self-supporting rigidity. Pore densities from 3 to 100 pores per linear inch (ppi) are readily available, and Ultramet has also demonstrated the ability to effectively create higher ppi foams by compression of 100-ppi material, prior to pyrolysis, in one, two, or three dimensions. Compression can also be used to create directional properties (strength, pressure drop, etc.) if desired.

Chemical vapor infiltration (CVI), a variation of the chemical vapor deposition (CVD) process, is used primarily for coating throughout the volume of porous foam, felt, and fiber preforms. The vapor deposition process is an extremely versatile and relatively inexpensive method of molecular forming of materials that are difficult to machine or produce by conventional processes. It is a coating method that relies on the decomposition of a gaseous precursor, flowed over (in the case of CVD) or through (in the case of CVI) a heated substrate, and subsequent condensation from the vapor state to form a solid deposit. Benefits include the ability to produce deposits of controlled density, thickness, orientation, and composition. Impurity levels are typically less than 0.1%, with densities of 99.9%. In addition, CVD/CVI coating processes exhibit the greatest throwing power, or ability to uniformly deposit on intricately shaped or textured substrates. Vapor deposition of ceramic matrices within porous materials possesses distinct advantages over other methods such as slurry impregnation in that precise control of coating thickness, homogeneity, and density can be achieved. Perhaps the greatest benefit of CVD/CVI is that numerous materials can be deposited at temperatures that are one-half to one-tenth the melting point of the coating material itself.

In preparation for infiltration, the RVC foam substrate can easily be machined to near final dimensions, accounting for minor dimensional changes that occur during infiltration. In the CVI process, reactant gases, typically metal chlorides or fluorides containing the desired coating material(s), are flowed through a heated substrate, in this case the RVC foam. The compound(s) within the reactant gas stream react near the heated foam ligament surfaces to form a continuous, uniform coating over the entire substrate. NbC is deposited at 1000-1200 $^{\circ}$C via reaction of niobium pentachloride ($NbCl_5$) with methane (CH_4) and hydrogen (H_2) as follows:

$$NbCl_5 + CH_4 + \tfrac{1}{2}H_2 \; 6 \; NbC + 5HCl$$

ZrC and TaC, as well as UC, are deposited by analogous reactions. The primary deposition variables that

must be optimized are temperature, pressure, reactant concentration and flow rate, and deposition time. Ultimately, we seek to combine the three materials in a single deposit through simultaneous deposition. As discussed previously, the initial feasibility of simultaneously depositing the three carbides was demonstrated, as was the ability to apply the materials in well bonded and uncracked layers.

Since foam strength is approximately proportional to the 3/2 power of its density, a compressive strength of .3 ksi could be achieved with a density of 22% of theoretical (78% porous) for $(U_{0.1},Zr_{0.675},Nb_{0.225})C$ at room temperature. The foam thermal expansion matches that of the infiltrated materials(s). High temperature hydrogen can be used to remove the RVC foam skeleton and any free carbon in the deposit. Removal of the skeleton using hydrogen or oxygen has been demonstrated in previous work and has virtually no impact on the mechanical performance of the foam.

It is important to note that fine-grained, fully dense coatings deposited by CVD display greater stiffness and strength than do bulk materials of the same composition fabricated by powder processing. The elastic moduli of such films have regularly measured up to 25% higher than those of the bulk materials. The RVC foam is extremely well-suited as a lightweight substrate onto which very stiff coatings may be deposited/infiltrated. Since the modulus of the deposited film is so much greater than that of the vitreous carbon foam skeleton, the carbon foam has no influence on the properties of the final product; it merely acts as a "locator" for the deposited films. Ceramic foams fabricated via CVI exhibit significantly greater thermal and mechanical fracture toughness than do monolithic ceramics, which is another key benefit of the proposed reactor application: the ligamental structure severely inhibits crack propagation.

As discussed previously, a monolithic coating of ZrC will be vapor deposited over the tricarbide fuel as a diffusion barrier and will contribute significantly to the overall foam strength. The fissile material will then be integrally connected to structurally stable CVD foam ligaments. Typical of ceramic foams in general, the foam fuel will demonstrate a high level of mechanical and thermal shock resistance, relative to ceramics produced through powder metallurgy. In addition, the foam fuel will possess good thermal conductivity, huge surface area, and enhanced gas permeability. It is also relatively inexpensive to fabricate (no machining) and is scalable. Ultramet currently produces foam structures up to 46 cm (18") in diameter and 122 cm (48") long, or large batches of components that occupy the same volume. The potential clearly exists to increase reactor size and/or assemble numerous reactors for simultaneous operation.

During Phase I CVI development, 5-8 cm (2-3") diameter x 0.65 cm (0.25") thick Ta-Zr-Nb-C foam specimens with a nominally 25 μm (0.001") thick ZrC encapsulation layer were fabricated. Characterization of foam microstructures at Ultramet was performed through optical and scanning electron microscopy (SEM) of material surfaces and cross-sections. Elemental and phase analysis was performed through energy-dispersive X-ray (EDS) spectroscopy and X-ray diffraction (XRD) crystallography, respectively Mechanical properties were determined through compression testing.

II.C. Surrogate Development and Transition to Depleted Uranium

In the chemical vapor infiltration (CVI) process for a single carbide, the appropriate metal in pellet form is first chlorinated and then flowed over a heated substrate. Hydrogen and a carbon source are added to the system. Through a combination of thermal decomposition and chemical reaction, the carbide deposits on the heated substrate surface and HCl gas is removed from the reaction chamber by a vacuum system. Deposition of more than one carbide can be performed either by mixing multiple metal chloride vapor streams prior to reacting at the substrate surface or by chlorinating pre-alloyed metal pellets.

Initial tricarbide deposition work was performed on graphite substrates, prior to infiltration of foam structures. Cross-sectional optical micrographs of a ZrC-NbC-TaC coating are shown in Figure 1. Figure 1A shows the coating fracture surface, while Figure 1B shows a polished surface. The coating is fully dense (no significant porosity) and exhibits a columnar microstructure.

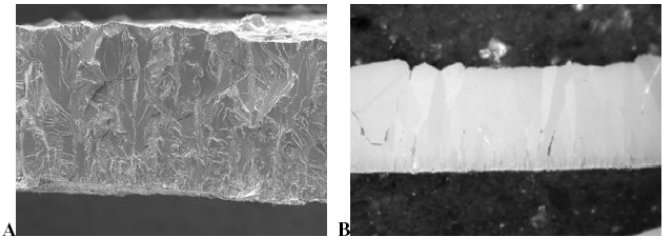


Figure 1. Optical micrographs of NbC-ZrC-TaC coating fracture surface (**A**, 90×) and polished cross-section (**B**, 60×)

Energy-dispersive X-ray spectroscopy elemental analysis was performed on coated graphite and foam structures produced in Phase I, while the phases present were determined by x-ray diffraction (XRD). The analysis showed that it is feasible to deposit the three carbides simultaneously, creating a solid solution by building at the molecular level, and to infiltrate the material into a foam structure. The XRD analysis confirmed full carburization of the three metals with no residual elemental metal. SEM micrographs of the RVC foam structure before and after infiltration with NbC-ZrC-TaC are shown in Figures 2 and 3, respectively. The uniformity of the coating around each

foam ligament looks very good. In this case, the material is nominally 5 vol% coating and 3 vol% RVC foam core (92 vol% open porosity).

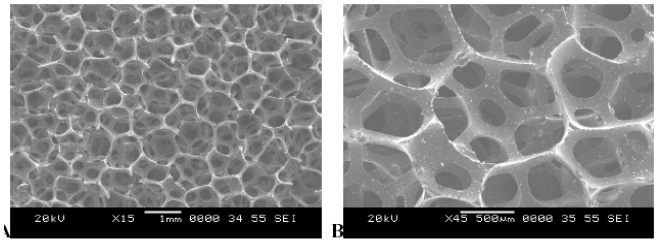


Figure 2. SEM micrographs of 65-ppi RVC foam before infiltration with NbC-ZrC-TaC

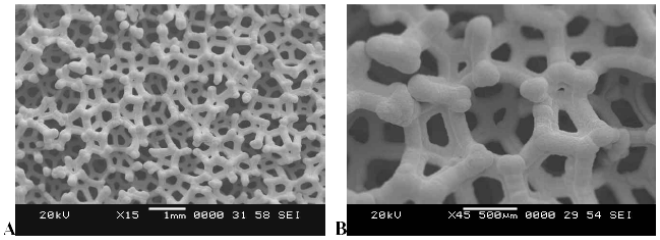


Figure 3. SEM micrographs of 65-ppi RVC foam after infiltration with NbC-ZrC-TaC

However, although tricarbide compositions in the range of the target were established, the composition was inconsistent between infiltration runs during Phase I development because of variability in the pellet feed material. However, the goal of demonstrating the feasibility of simultaneous deposition of the three carbides and infiltrating a foam structure was accomplished. The ability to apply the three carbides in the form of individual layers was also performed in Phase I, although the work is now focusing on deposition of a solid solution.

As part of the phase-II work a solid solution of the carbides is being infiltrated, followed by a ZrC encapsulation which protects the U content of the tricarbide from reaction with hot hydrogen. The outer ZrC layer needs to remain crack-free, as shown in Figure 4, throughout thermal cycling and neutron irradiation. Unlike traditional structures, the open-cell foam does not suffer from stress concentration in locally thick wall areas and has repeatedly demonstrated high thermal shock resistance in chemical rocket applications.

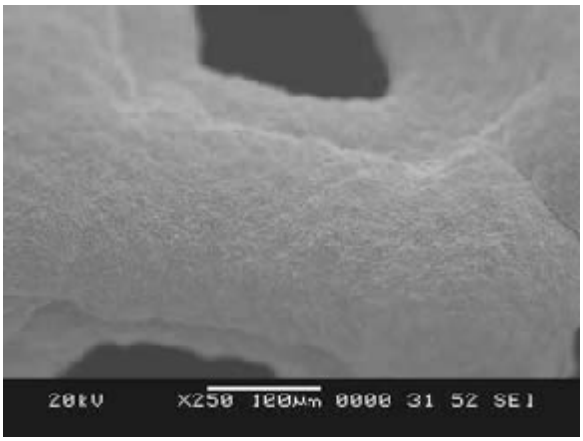


Figure 4: SEM micrograph of crack-free ZrC outer layer on layered TaC-NbC-ZrC foam.

An SEM micrograph of an individual foam ligament cross-section is shown in Figure 5 for the layered approach. The dark core of the RVC foam skeleton can be seen, as can the layers of zirconium carbide, niobium carbide and tantalum carbide.

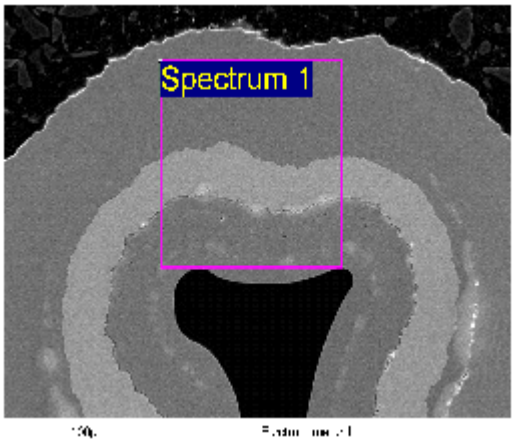


Figure 5: Polished cross-section of individual tricarbide foam ligament

The vapor phase alloying approach now being developed involves mixing multiple metal chloride vapor streams. A scanning electron micrograph (SEM) of tricarbide foam produced during initial development is shown in Figure 6. An individual coated foam ligament is shown in Figure 7. EDS revealed that the coating is fully dense, and all three of the carbide materials deposited, although their relative concentrations require further improvement. Samples of the tricarbide foam will soon be sent to the University of Florida for hot hydrogen exposure testing.

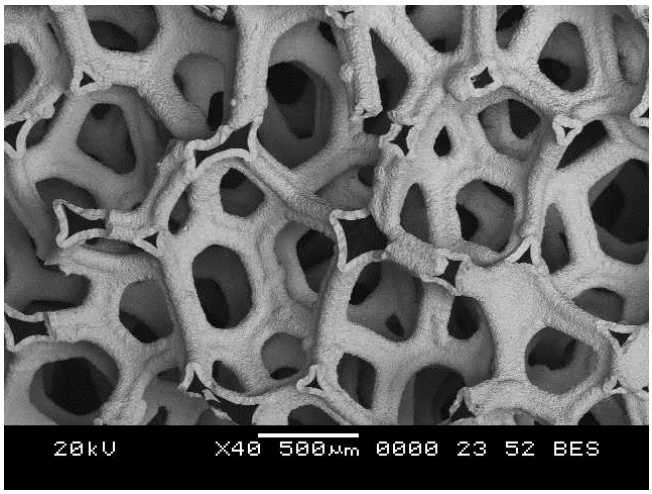


Figure 6: SEM micrograph of 65-ppi tricarbide foam

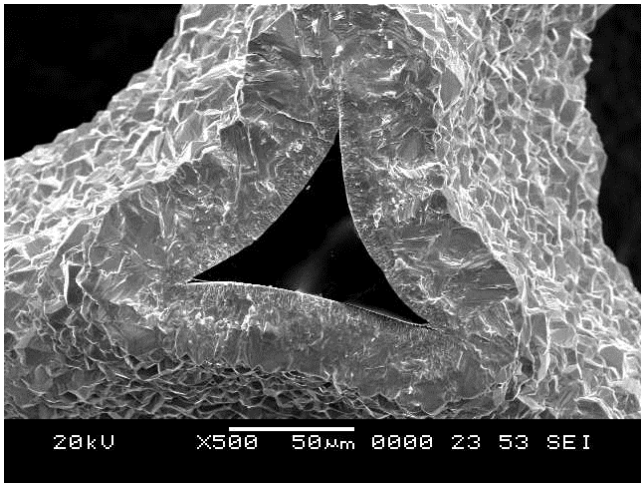


Figure 7: SEM micrograph of tricarbide coating on individual carbon foam ligament

III. CFD ANALYSIS OF POROUS MEDIA

Detailed CFD analysis of the foam structure is required on the micro-scale to determine the best porosity, linear pore density and the size of the ligaments for reduced pressure drop and optimal strength and heat transfer. In parallel, detailed neutronics and general reactor scoping studies, described in section IV and in a companion paper, were needed to evaluate enrichment requirements and the quantity of UC needed in the ligaments. Thus, the composition ratio of the UZrNbC matrix was determined by the nuclear requirements and re-evaluated in the CFD models for its effect on heat transfer.

III.A. Periodic Foam Model

A complete micro-model of various porosity foam structures was developed. A micro-model is needed to optimize the ligament size, thermal conductivity and porosity of the engineered material. A lumped porous media model would not be useful for this purpose. In addition, the micro-model provides detailed information on the flow distribution and mixing throughout the foam and the influence of stagnation zones on the temperature distribution in the ligaments. The CFD-2000 code distributed by Adaptive Research was modified to automatically generate the thousands of blockages that comprise the foam ligament structure. A small periodic model is shown in Figure 8. This is a significant achievement in the application of MP CFD to porous media. .For the first time, these detailed CFD models were used to solve the conjugate heat transfer problem between the foam ligaments and the gas propellant given volumetric heat generation in each ligament

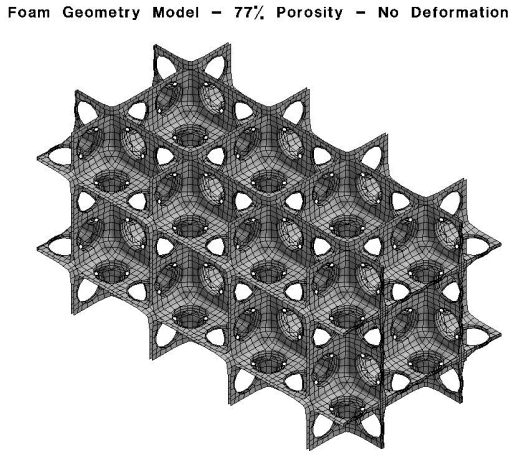


Figure 8. Periodic foam CFD model.

III.B. Randomized Window Permeabilities

In an effort to improve the fidelity of the micro-models the window permeabilities could be adjusted easily in a random fashion from fully open to completely closed. This reproduced the cross-flows and mixing observed in the real foams; however, it was possible given a limited number of windows and orientations, that the variable windows may skew the flow distribution in small models.

III.C. Deformed Foam Model

To further improve the fidelity of the micro-models without relying on variable windows, the CFD code was used to deform the mesh on a periodic model. The resultant structure more closely represents the actual foam as shown in Figure 9. Windows have variable sizes and orientations as do the ligaments to some extent. This

created the necessary amount of cross-flows and mixing to capture most of the physics of the actual foam on the micro scale.

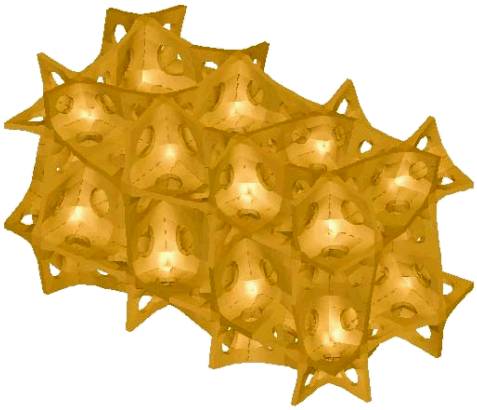


Figure 9. Slightly deformed foam CFD model

Figure 10 below presents the streamlines and ligament temperature distribution for a 1.0 s simulation for a 5 kW/cm^3 power density with 10 m/s H_2 flow velocity at the inlet of a 77% porous tricarbide foam. The deformed model approaches the geometry of the actual foam reasonably well. Obviously, the 1.0 s point is not quite at steady state and longer simulations are required. All window porosities were taken as completely open in these simulations. Note the high degree of mixing and cross flows through the model. Also note, that the pressure drops are still quite low (~290 Pa), even though this model represents only 1/3 the radial thickness of a proposed fuel element. The exit radial hydrogen velocity is almost 6 m/s. Even with a factor of three scale-up, the calculation shows that high power density fuels can be maintained well below the melting point at reasonable flow velocities and power densities necessary to produce the high thrust required for nuclear thermal propulsion.

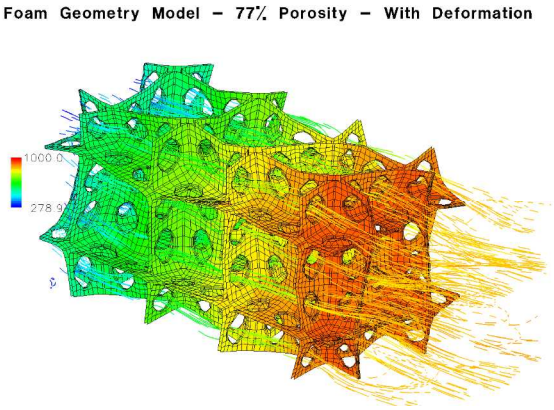


Figure 10. Hydrogen streamlines and matrix temperature distribution in kelvin for 10 m/s H_2 at the inlet and a 5 kW/cm^3 power density.

III.D. Massively Parallel CFD Analysis

In order to have enough cells and windows to be statistically relevant it was obvious that massively parallel computations were required. The CFD-2000 navier-stokes solver known as STORM was modified for MPI applications and installed on Sandia's 256-node ICC cluster known as Liberty.[12] Parallel access to many processors allows the CFD modeling to investigate flow distributions through full-radius fuel annuli. From this, we are in the process of developing design correlations for pressure drop and temperature distributions in full-size fuel element prototypes. These correlations must be benchmarked against tests on full-sized fuel element prototypes. But, at this stage, new, more accurate lumped porous media modules can be developed for system studies and thermal-aerolic CFD analyses of the entire core.

III.E. Helium Flow Testing

Three of six prototype foam modules were supplied by Ultramet and tested at Sandia's Plasma Materials Test Facility under the phase-I project. All were 65-ppi foam cylinders of nominal dimensions 3.8 cm ID x 5 cm OD x 6.4 cm long (1.5" ID × 2.0" OD × 2.5" long), with carbide densities of 15, 17, 22, 26, 34, and 42% by volume. For our first attempt at producing test articles with a composition that closely matched the target of 41%ZrC:41%NbC:18%TaC, the three materials were infiltrated into the foam in layers (each microns thick) to the desired percentage. TaC was infiltrated first (the surrogate for UC), followed by NbC then ZrC. One of the test components is shown in Figure 11. A molybdenum attachment flange was bonded to one end using a commercially available aluminum oxide adhesive, and a molybdenum cap was attached to the opposite end.

Flow testing was performed on the 85%, 78% and 58% porosity modules. Helium mass flows from 0 to 35 g/s were used at an absolute background pressure of 4 MPa to characterize the pressure drop across the 6 mm thick foam in radial flow. The helium entered from the open-flanged end of the specimen and flowed radially outward.

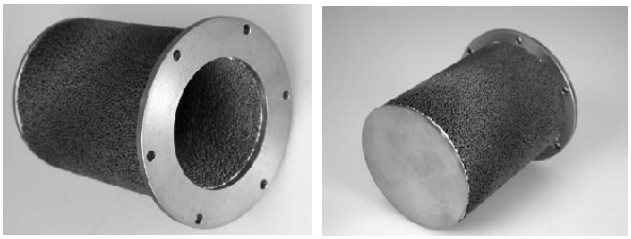


Figure 11: Phase-I tricarbide foam test articles

Figure 12 summarizes the pressure drop data for the three 6-mm-thick modules. Note that both the 85% and 78% porosity foams have an extremely low pressure drop, less than 350 Pa (<0.05 psia), at the highest mass flows (28 g/s) obtainable on the helium flow loop. As expected, the

high density foam had the largest pressure drop of 24 kPa (<3.5 psia) at 27 g/s of mass flow. The 85% and 78% porosity foams could be used in either radial flow for a NEP application or axial flow for an NTP application; or a combination of the two geometries is possible for a hybrid, bi-modal application.

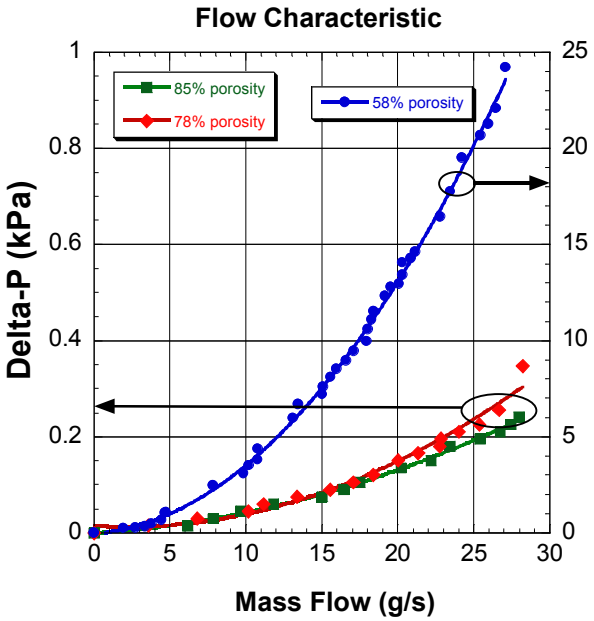


Figure 12: Pressure drop vs mass flow rate during radial flow at 4 MPa.

Thermal test data were obtained on the two modules of most interest, 85% and 78% porosity. The modules were ohmically heated to between 200 and 300 °C with no helium flow. After a steady state temperature was achieved across the module, a constant helium flow rate of 0.9 g/s was quickly started and the foam thermocouple responses were tracked during the cooldown. Since the mass of the foam was known as well as the specific heat of the tricarbide, 0.329 J/gC, it was easy to determine the power loss during cooldown. Approximately 524 W was removed from the 85% module and 585 W from the 78% module during the first few seconds of the cooldown. Here, the conductive losses to the support structure are small, and radiation losses are negligible. The slope of each cooldown curve, as shown in Figure 13, provides an estimate of the effective convective heat transfer coefficient, h. Values of 489 W/m^{2}K and 627 W/m^{2}K were obtained for the 85% and 78% porous modules. The area to volume ratio for 65 ppi foam is approximately 5100 m^2/m^3 for the 85% porosity foam and 7100 m^2/m^3 for the 78% porosity foam. The average effective h is a factor of 28.5 and 39.6 above that of a smooth tube of similar dimensions or an equivalent channel in a pin-type core geometry.

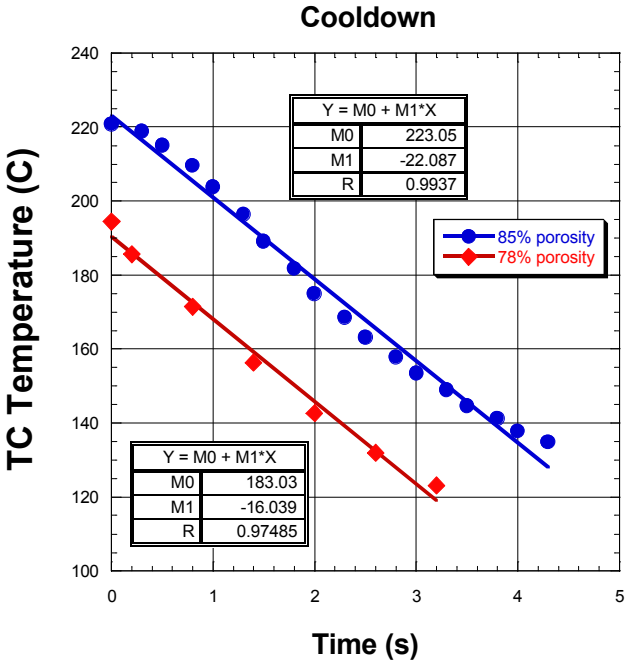


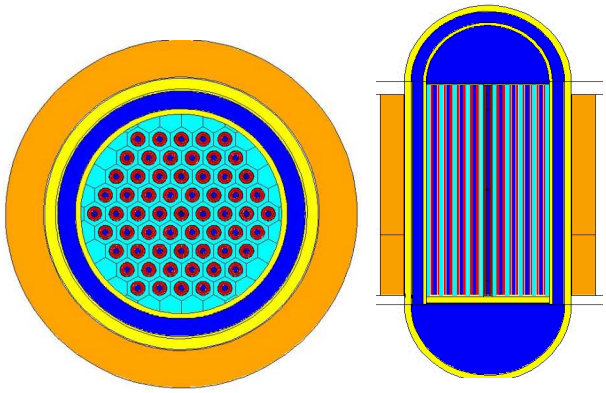
Figure 13. Outlet thermocouple temperature versus time during initial cooldown with 0.9 g/s helium flow at 4 MPa.

The thermal tests revealed that the 78% porosity foam performed better than the 85% foam. This is mostly attributable to the higher surface to volume ratio. Yet, the penalty in additional pressure drop is minuscule. The higher density foam also has an advantage in allowing for the use of more fissile material at lower enrichments than the 85% porous foam. The CFD modeling performed under task 1 revealed that an 87% porous foam would have only slightly better heat transfer than a 77% case using a ligament thermal conductivity of 25 W/mK. However, for the k=23 W/mK ligaments in these tricarbide prototypes, the higher thermal mass and surface area of the 77% porosity foam had a slightly greater effect in the experiment than the models predicted. It was clear, however, that the performance between the 77% and 85% porous foam was very similar and both would be a good candidate from a thermal perspective. For space applications, cores of compact size and high power density are preferred to minimize mass, and this pushes the design to higher density foams than thermal efficiency alone would dictate.

IV. REACTOR DESIGN CONCEPT

A conceptual reactor design was analyzed with MCNP at Sandia to verify that a compact space propulsion reactor

is feasible even when constructed of high porosity (70%) foam fuels. It was found that a heterogeneous reactor core design consisting of YH_2 moderated 60% porous tricarbide foam with 10% UC enriched to 93.5% U-235 was possible with a critical diameter of 35 cm using 7 cm of Be reflector. This core consists of 61 fuel annuli 8-mm-thick and 56 cm in height with a pitch of approximately 4 cm. The MCNP model is shown in Figure 14. The current element uses radial hydrogen inflow with the YH_2 on the outside. Criticality can be achieved and reactivity control ensured with this design, yet it provides sufficient safety shutdown margin in the event of water emersion. A 500 MW_t NTP core is possible.[13]



r-θ r-z

Figure 14. MCNP model of reactor concept. (red – tricarbide fuel, cyan – YH_2 moderator, blue – H_2 coolant, yellow – Hastelloy-X, orange – Be reflector)

A 2-million-element FEM-based CFD simulation was performed of a single fuel element. The results from the analysis indicated that it was possible to maintain the yttrium hydride temperatures below 1400K while producing 500 MW of power in the core by flowing hydrogen between the moderator and the porous fuel at 13 MPa and 10% of the sonic velocity for hydrogen (~183 m/s).

A larger CFD model of the entire NTP core consisting of 5.7 million elements was also completed.. The steady state velocity distributions are shown in Figure 15 The model includes the downcomer and an uncooled CFC nozzle. Preliminary thermal results indicate that the inlet flow should first be used to cool the nozzle before entering the downcomer. The temperature distributions in the remainder of the core are reasonable, but more work needs to be done to improve the flow distribution before a satisfactory thermal analysis can be obtained.

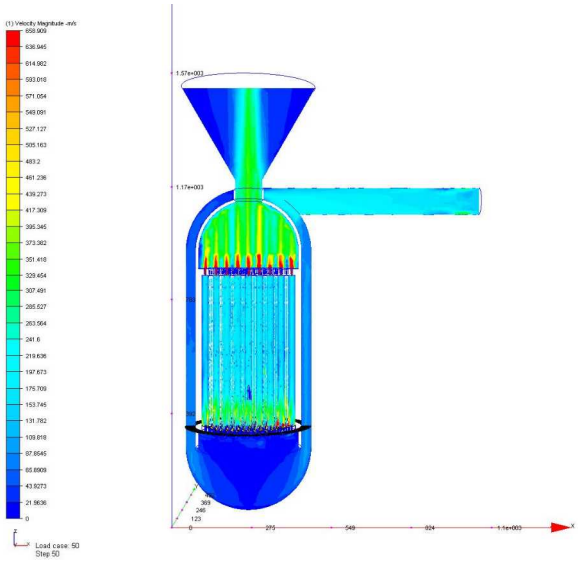


Figure 15. Velocity distributions inside the NTP core were obtained from CFD model.

V. RECENT DEVELOPMENT

A new CVI reactor for the deposition of the tricarbide containing UC is now operational at the University of Florida. Initial checkout runs of the INSPI hot-hydrogen test facility used to establish tricarbide survivability have also been performed using surrogate tricarbide (TaZrNbC) foam fabricated by Ultramet as a baseline.

V.A. Deposition of UC,NbC,ZrC foams

The CVI technology developed at Ultramet was recently transitioned to INSPI at the University of Florida. INSPI has the state license to work with depleted uranium in the development of the new tricarbide foam fuel. The inclusion of Ultramet's CVI technology permits the fabrication of UC containing foams at INSPI while taking full advantage of INSPI's extensive background in the development of tricarbide fuels for their square lattice honeycomb concept.[10] The infiltration conditions as well as CVI reactor components were part of this transition. NbC has been successfully infiltrated into high porous TaC foam substrates and experiments for deposition of the UZrNbC tricarbide will soon begin. Figure 16 shows the CVD reactor in operation.

Figure 16. CVD reactor in operation during initial deposition of NbC into TaC foam.

V.B. Hot Hydrogen Testing

Following fabrication of $(U_{0.1},Zr_{0.675},Nb_{0.225})C$ foam fuel elements, specimens will be subjected to hot hydrogen exposure at INSPI in order to evaluate the retention of uranium in the foam. Demonstrating the robustness of the tri-carbide foam fuel to withstand the expected conditions of a hot hydrogen environment is a significant milestone for the program. At the expected ultrahigh temperatures above 2800 K encountered in a nuclear thermal propulsion system, uranium mass losses will result as a consequence of interaction with the hot hydrogen and vaporization from the fuel element surface. Integrity of the fuel elements must be maintained as well as retaining sufficient uranium to prevent significant reactivity losses.

To demonstrate the robustness of the tricarbide foam fuel, samples will be exposed to a hot hydrogen environment at temperatures between 2500 K and 3000 K. To achieve these very high temperatures, a 25 kW, 450 kHz induction heater will be used to heat a tungsten susceptor/heater containing the tri-carbide fuel samples. Initial checkout runs of the hot-hydrogen test facility have been performed using surrogate tricarbide (TaZrNbC) foam fabricated by Ultramet as a baseline and no foam degradation (mass or visual change) was found, as expected. This ability to flow hot hydrogen at a rate of 2 g/min. was successfully demonstrated at INSPI in previous work.[9,14] INSPI will utilize an extensive array of uranium-capable materials characterization equipment to document the material response.

VI. CONCLUSIONS

This article has presented a brief overview on our progress to develop a foam fuel matrix for space propulsion. We have shown that the materials processing technology is at hand. The potential exists to produce both layered and a solid eutectic mixture of tricarbide in foam form. A tricarbide foam is mechanically robust and can operate at high temperature with very low pressure drop. We have also performed preliminary design calculations that indicate a foam fuel matrix could be used in a compact, high power density core with great efficiency. We have presented our advances in MP CFD modeling of the foam structure on the micro-scale and discovered optimal foam properties concerning porosity, ligament size and ligament thermal conductivity.

Uranium bearing tricarbide foam fabrication and hot-hydrogen testing are being performed to demonstrate resistance to degradation and potential loss of reactivity. Follow-on efforts are expected to include fuel assembly fabrication and in-pile neutron irradiation to address burnup and lifetime issues.

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NOMENCLATURE

CFD	Computational Fluid Dynamics
CVD	Chemical Vapor Deposition
CVI	Chemical Vapor Infiltration
EDS (EDX)	Energy Dispersive X-ray Spectroscopy
ICC	Institutional Computing Cluster
INSPI	Innovative Nuclear Space Power and Propulsion Institute
MCNP	Monte Carlo N-Particle Transport Code
MP CFD	Massively Parallel CFD
MPI	Message Passing Interface
NTP	Nuclear Thermal Propulsion
NEP	Nuclear Electric Propulsion
PBR	Pebble Bed Reactor
RVC	Reticulated Vitreous Carbon
SEI	Space Exploration Initiative
SEM	Scanning Electron Microscopy
SNTP	Space Nuclear Thermal Propulsion
XRD	X-ray Diffraction

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