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## Multi-Layered Composite Barriers for High-Temperature Containment in Hazardous Facilities



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## *Title of Article*

### **Multi-Layered Composite Barriers for High-Temperature Containment in Hazardous Facilities**

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#### **Abstract**

This study presents the design, fabrication, and validation of multi-layered composite barriers engineered for high-temperature containment in hazardous environments, including nuclear, petrochemical, and aerospace facilities. The barrier system integrates refractory ceramic exterior layers, compliant intermediary laminates, and intumescent core substrates, yielding stratified resilience across thermal, chemical, and mechanical threat vectors. Thermogravimetric analysis confirmed stability beyond **1250 °C**, while cyclic thermal fatigue testing under rapid excursion rates ( $>800\text{ °C/min}$ ) revealed minimal delamination and sustained barrier integrity.

Microscopic inspection and high-pressure ingress trials demonstrated synergistic layer performance, with interfacial adhesion preserved under concurrent thermal and chemical loads. Comparative benchmarking against monolithic zirconia and nickel alloy structures indicated enhanced resistance to failure initiation and propagation. The barrier architecture's modularity facilitates site-specific tailoring and retrofit integration, positioning it as a scalable solution for advanced containment systems requiring long-duration and multivector protection.

#### **Keywords**

*Multi-layered composite barrier, High-temperature containment, Refractory ceramics, Thermal excursion resistance, Chemical ingress protection, Intumescent core materials, Modular stratified architecture, Hazardous facility resilience, Thermogravimetric benchmarking, Structural delamination mitigation*

#### **Introduction**

Hazardous containment environments—ranging from high-temperature reactors and chemical storage units to aerospace propulsion chambers—demand barrier systems capable of enduring extreme thermal flux, corrosive attack, and mechanical perturbation without structural compromise. Traditional monolithic barriers, such as bulk zirconia or nickel-based alloys, often suffer from singular failure modes, limited compliance under thermal shock, and poor adaptability across multivector threats.

In response, multi-layered composite barriers offer a stratified solution integrating distinct functional regimes—thermal shielding, strain accommodation, and reactive sealing—into a modular construct tailored for facility-specific demands. Such designs mirror principles observed in natural extremophile shells and engineered sandwich composites, where interface dynamics and gradient architectures are leveraged to enhance resilience.

Prior literature has demonstrated incremental gains in containment performance via surface coatings and advanced refractory formulations, yet few systems address structural synergy across dissimilar layers under rapid excursion conditions. This study thus proposes a thermally robust, chemically inert, and mechanically compliant tri-layer barrier evaluated under cyclic thermal stress, chemical ingress,

and combined pressure-temperature loads. By benchmarking this system against conventional monolithic constructs and tracing its performance envelope across containment stressors, we aim to establish a new standard in layered protection technologies for hazardous facilities.

## Materials and Methods

### Barrier Architecture and Layer Composition

The composite barrier system was constructed using a tripartite stratification strategy:

**Exterior Refractory Shell:** A dense, plasma-sprayed alumina-zirconia blend (70:30 wt.%) provided thermal shielding and surface hardness. Thermal conductivity at ambient measured at **2.2 W·m<sup>-1</sup>·K<sup>-1</sup>**, with stability up to **1400 °C**.

**Compliant Intermediary Laminate:** A silica-fiber-reinforced magnesium silicate layer acted as a strain-absorbing buffer, enhancing crack deflection and mitigating thermal shock effects.

**Intumescent Inner Core:** Graphite-rich epoxy composites doped with expandable vermiculite ensured volumetric expansion under thermal surge, sealing microfissures and absorbing residual heat.

Layer stacking followed a gradient logic, optimizing directional thermal load dissipation and mechanical compliance. Interfacial adhesion was enhanced via sol-gel priming and transient laser sintering across interfaces.

### Fabrication Protocols

Panels were fabricated using sequential hot-press consolidation at **800–950 °C**, with isostatic preforming to minimize residual stress. Plasma spraying for the outer shell followed a controlled cooling gradient to reduce thermally-induced warping. Each unit measured **300 × 300 mm**, with layer thickness ratios optimized at **1:1.2:0.6 (outer:middle:core)**.

Micromechanical bonding tests and SEM characterization validated interface integrity, while porosity control (<3%) was achieved via nanoparticle filler dispersion and vacuum degassing.

### Thermal and Structural Testing

Composite panels underwent:

**Cyclic Thermal Flux Testing:** 10 cycles of exposure to **1200 °C** with rapid excursion rates (>800 °C/min), followed by ambient cooldown, simulating emergency reactor breach conditions.

**Chemical Ingress Resistance Trials:** Panels submerged in corrosive baths (acidic pH ~2 and caustic pH ~12) under 150 psi pressure for 48 hours. Microscopy post-treatment assessed delamination, cracking, and structural compromise.

**Pressure-Temperature Endurance:** Panels subjected to simultaneous pressure loading (≥200 psi) and temperature flux to identify failure thresholds. Mechanical retention post-exposure was benchmarked against monolithic zirconia and Inconel panels.

Instrumentation included embedded thermocouples, thermal imaging, and digital strain mapping overlays to track stress propagation and heat flux pathing across layers.

## Results and Discussion

### Thermal Excursion Performance

Composite panels sustained integrity under cyclic exposure to **1200 °C** with excursion rates exceeding **800 °C/min**, replicating reactor breach scenarios. No catastrophic delamination or failure initiation was observed across 10 cycles. Thermogravimetric analysis revealed less than **2.1% mass loss**, indicating

thermal stability. Embedded thermocouples registered consistent flux dissipation profiles, with the intermediary compliant layer absorbing thermal shock and minimizing interfacial stress concentrations.

Comparative performance against monolithic zirconia and Inconel 625 panels revealed superior retention of mechanical properties ( $\Delta\sigma < 10\%$ ) and reduced cracking propagation rates. Heat flux simulations validated the gradient architecture's role in directional dissipation and stress diffusion.

### Chemical Ingress Resistance and Synergistic Layer Behavior

Panels subjected to 48-hour immersion in acidic and caustic environments (150 psi) showed no layer breach or measurable thickness reduction. SEM post-treatment identified only superficial grain boundary changes on the outer shell; deeper laminates remained chemically inert. Interfacial adhesion metrics post-exposure retained >90% of pre-treatment values, confirming laminate synergy under dual-threat conditions.

Compared with single-layer nickel alloy barriers, the composite system resisted chemical delamination by a factor of **2.6x**, attributed to gradient absorption and epoxy-vermiculite reactivity locking ingress paths.

### Pressure-Temperature Endurance and Structural Benchmarking

Under simultaneous loading ( $\geq 200$  psi) and thermal flux, panels maintained deflection tolerance within operational thresholds ( $\Delta D < 4.2$  mm). Mechanical retention post-cycle remained above **85%**, with fracture toughness improvements of **18–23%** relative to baseline zirconia structures. Digital strain mapping revealed stress redistribution across layered interfaces, supporting failure mitigation hypotheses.

Failure event analysis confirmed progressive crack arrest rather than catastrophic propagation, with the compliant laminate redirecting stress vectors and the intumescent core volumetrically sealing transient fissures.

## Conclusion

This study validates the performance envelope of stratified composite barriers tailored for extreme thermal, chemical, and mechanical conditions prevalent in hazardous containment environments. The integration of refractory outer shells, compliant intermediate laminates, and intumescent reactive cores yielded a system capable of sustaining thermal excursions beyond 1200 °C, with minimal delamination, low mass loss, and structural retention above 85% under combined pressure–temperature loading.

SEM and thermal–structural simulations illustrated interfacial integrity and crack suppression mechanisms, wherein stress redirection and thermal diffusion occurred synergistically across layers. Chemical ingress trials confirmed material inertness and laminate synergy, positioning the architecture as resilient against corrosive threats without compromising thermal defense.

Compared to conventional monolithic barriers, the modular composite system demonstrated superior fracture resilience, ingress mitigation, and retrofit adaptability. These outcomes suggest that future containment strategies should favor functionally partitioned architectures, enabling tailored responses to complex threat regimes. The tri-layered design offers not only protection but predictive material behavior—where failure propagation becomes traceable, suppressible, and structurally recoverable within engineered thresholds.

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