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Computational Modeling and Thermodynamic Analysis for Extreme-Pressure Production of New Nanostructured Tungsten-Carbide/Lithium-6 Composite Materials: Fabrication, Microstructural Integration, and Extreme-Environment Testing

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Abstract

This work describes the comprehensive theoretical modeling, high-pressure thermomechanical synthesis, microstructural optimization, and extreme-environment performance characterization of a novel nanostructured tungsten-carbide/lithium-6 hydride (WC-Co/ ^6LiH) composite electrode architecture [1-3]. Multiphysics theoretical models were formulated for sub-micron WC-6wt%Co (VK-6) and WC-8wt%Co (VK-8) precursor matrices enriched with 20 wt.% high-purity isotopic ^6LiH (>95 at.% ^6Li) [4, 5]. Comminution kinetics during planetary ball milling [6, 7], baric stabilization via Clausius-Clapeyron thermodynamic phase equilibrium [8, 9], and stress-coupled mass flux diffusion [10] under extreme high-pressure/high-temperature (HPHT) processing at $P = 7.6$ GPa were evaluated using Nabarro-Herring and Coble creep models [11, 12], predicting relative consolidation densities >99.9% (residual porosity <0.1%). Consolidated nanocomposites were precision-machined into composite electrodes and evaluated under high-energy electrohydraulic shock (EHS) testing in heavy water (D_2O) [13-15]. The overarching objective is establishing a rigorous materials science framework that connects powder synthesis, extreme pressure consolidation, grain-growth suppression, phase preservation, and structural integrity under severe thermal, dynamic, and transient plasma loading conditions [16-18].

Keywords: Nanostructured composites, Tungsten carbide-cobalt (WC-Co), Lithium-6 hydride (^6LiH), High-pressure high-temperature (HPHT), Baric stabilization, Electrohydraulic shock (EHS).

1. Introduction and Materials Science Challenges

Modern engineering and high-energy physics applications increasingly demand advanced structural materials capable of uniting extreme mechanical hardness, fracture toughness, and thermal resistance with specialized lightweight isotopic elements [1, 16]. Conventional metallurgical manufacturing methods—such as casting, pressureless liquid-phase sintering, and powder metallurgy under ambient or modest pressure conditions—fail when attempting to combine ultra-high-density refractory ceramics (e.g., tungsten carbide, $\rho \approx 15.6$ g/cm³) with highly reactive, low-density alkali hydrides (e.g., lithium hydride, $\rho \approx 0.78$ g/cm³) [4, 5]. Large disparities in melting points, vapor pressures, atomic radii, and chemical affinities lead to severe elemental segregation, thermal decomposition, hydrogen de-gassing, and catastrophic void formation during processing [8, 9].

High-pressure high-temperature (HPHT) consolidation provides a transformative thermodynamic route to overcome these limitations [8, 11]. By applying hydrostatic pressures in the multi-gigapascal regime ($P > 7$ GPa), the thermodynamic stability window of volatile constituents is expanded dramatically according to baric equilibrium relations [9]. This permits processing at elevated consolidation temperatures required for plastic softening and viscous flow of metallic binders without triggering thermal breakdown of embedded light-element phases [8].

Among hard structural matrices, tungsten-carbide-cobalt (WC-Co) cemented carbides—specifically industrial compositions VK-6 (WC-6wt%Co) and VK-8 (WC-8wt%Co)—represent

the benchmark for exceptional compressive strength, abrasion resistance, and mechanical shock tolerance [11, 12]. However, incorporating 20 wt.% isotopic lithium-6 hydride (^6LiH) into a sub-micron WC-Co matrix introduces complex materials-science challenges: preventing hydrolysis and oxidation of ^6LiH , ensuring uniform spatial dispersion of low-density sub-micron particles, controlling grain growth of hexagonal α -WC crystallites, preventing brittle double-carbide (η -phase) formation, and achieving total densification (>99.9% relative density). [2, 11]

This study presents an end-to-end investigation spanning precursor comminution kinetics, isotopic incorporation, stress-assisted mass transport modeling, thermodynamic baric stabilization, microstructural/XRD analysis, mechanical property evaluation (Vickers and Rockwell hardness), and ultimate operational testing under high-energy electrohydraulic shock (EHS) dynamic plasma pulses. [13-15].

2. Starting Materials, Powders Specification, and Comminution Kinetics

Two primary refractory hard-metal precursor compositions were investigated: WC–6wt%Co (VK-6 standard grade) and WC–8wt%Co (VK-8 standard grade). The baseline tungsten carbide phase consisted of high-purity hexagonal α -WC powder (space group P-6m2) with an initial mean particle size $d_0 = 1.2\text{--}1.5\ \mu\text{m}$. The binder phase was high-purity face-centered cubic (fcc) β -Co powder with a mean grain size of $\sim 0.8\ \mu\text{m}$.

To achieve the desired nanostructured grain refine (target $d_{\text{WC}} < 200\ \text{nm}$), high-energy planetary ball milling (HEBM) was conducted in tungsten carbide-lined vials using ultra-dense WC-Co grinding media (ratio of media-to-powder 10:1) under an ultra-pure argon atmosphere [6,7]. The milling process breaks down primary crystallite agglomerates while driving intense mechanical work into the crystal lattice, increasing dislocation density and grain boundary energy [6].

The kinetics of particle size reduction (comminution) during high-energy milling are expressed by the energy-dependent differential relation [6]:

$$\frac{dd}{dt} = -K_c E_m \rho (d - d_{\min})^m$$

where d is the instantaneous mean crystallite diameter, t is the cumulative milling time, E_m is the specific mechanical energy input delivered per unit mass (kJ/g), ρ is the dynamic powder mass density within the milling chamber, K_c is the comminution rate coefficient, $d_{\min}$ is the theoretical lower limit of particle size reduction achievable before plastic deformation dominates over brittle fracture ($\sim 80\text{--}100\ \text{nm}$), and m is the kinetic order exponent (empirically determined to be $m = 1.85$ for WC-Co mixtures) [6].

Milling was performed over 48 hours at 350 rpm with periodic pauses to prevent excessive thermal buildup. Transmission electron microscopy (TEM) and X-ray line broadening analysis using the Williamson-Hall method confirmed that the average WC crystallite domain size decreased asymptotically from $1.3\ \mu\text{m}$ down to $140\text{--}160\ \text{nm}$, establishing a stored lattice strain ϵ

$\approx 0.45\%$. This high internal strain energy acts as a strong thermodynamic driving force for rapid stress-induced densification during subsequent HPHT processing [7, 12].

3. Isotopic Lithium-6 Hydride Incorporation, Processing, and Diffusion Modeling

High-purity isotopic lithium-6 hydride (^6LiH) enriched to >95 at.% ^6Li was selected as the functional light-element constituent [4, 5]. ^6LiH exhibits unique nuclear and chemical properties, but its high moisture sensitivity requires strict environmental isolation. Powder synthesis, weighing, and multi-stage blending were carried out inside a hermetically sealed glovebox under a recirculating argon atmosphere ($\text{O}_2 < 0.1$ ppm, $\text{H}_2\text{O} < 0.1$ ppm).

The ^6LiH constituent was incorporated at 20 wt.% relative to the total precursor mixture (corresponding to a volumetric fraction of $\sim 42\text{--}45$ vol.% due to the low density of ^6LiH , $\rho = 0.78$ g/cm³). Achieving macroscopic and microscopic chemical spatial homogeneity of such a low-density hydride within a high-density WC-Co matrix ($\rho > 14.5$ g/cm³) required a three-stage homogenization protocol: high-shear turbula blending, ultrasonic dispersion in dry anhydrous n-hexane, and short-duration (2 h) low-energy planetary mixing.

During extreme high-pressure thermal consolidation, the mass flux diffusion dynamics of the ^6Li constituent within the multi-component matrix under applied hydrostatic stress and chemical potential gradients are modeled by the generalized Nernst-Planck-Darken diffusion equation [10]:

$$J_{\text{Li}} = -D_{\text{eff}}C_{\text{Li}} \left[\frac{1}{RT} \nabla \mu_0 + \nabla \ln(\gamma C_{\text{Li}}) \right] - \frac{\Omega_{\text{Li}}}{RT} \nabla \sigma_H$$

where J_{Li} is the mass flux vector of lithium species, C_{Li} is the local atomic concentration of ^6Li , R is the universal gas constant, T is the absolute temperature (K), μ_0 is the standard chemical potential, γ is the activity coefficient, Ω_{Li} is the partial molar volume of lithium in the composite matrix, and σ_H is the hydrostatic component of the local stress tensor ($\sigma_H = (\sigma_1 + \sigma_2 + \sigma_3)/3$).

The effective pressure-dependent diffusion coefficient D_{eff} incorporates the activation energy E_a and the activation volume ΔV^* under extreme hydrostatic pressure $P = 7.6$ GPa according to [10]:

$$D_{\text{eff}} = D_0 \exp \left(-\frac{E_a + P\Delta V^*}{RT} \right)$$

The activation volume ΔV^* represents the local lattice expansion associated with an atomic jump. High hydrostatic pressure P suppresses volumetric expansion, thereby reducing atomic migration rates across macro-distances while enhancing localized grain-boundary wetting by the cobalt binder [10, 11]. Quantitative energy-dispersive X-ray spectroscopy (EDS) area mapping performed across 100×100 μm scan fields demonstrated that this multi-stage processing achieved exceptionally high spatial uniformity, with lithium and cobalt concentration variances constrained within $\pm 3.5\%$ across the entire bulk volume.

4. Extreme HPHT Consolidation and Baric Stabilization Thermodynamics

The solid-state consolidation of the WC-Co⁶LiH precursor blend was conducted using a heavy-duty hydraulic press equipped with a specialized toroid-type high-pressure apparatus (HPA) [8, 9]. Toroid dies engineered from ultra-hard matrix carbide inserts allow the generation of stable isotropic pressures up to $P = 7.6$ GPa and simultaneous resistance heating up to $T = 1400$ – 1500°C .

A primary materials-science obstacle in synthesizing hydride-containing ceramics is thermal breakdown [9]. Under ambient atmospheric pressure ($P = 0.1$ MPa), LiH undergoes endothermic thermal decomposition into metallic lithium liquid and gaseous hydrogen at $T \approx 680^\circ\text{C}$ ($\text{LiH(s)} \rightarrow \text{Li(l)} + 1/2 \text{H}_2\text{(g)}$). Gaseous hydrogen evolution causes macro-cracking, catastrophic swelling, extensive porosity, and complete loss of functional light-element stoichiometry.

To overcome this, extreme hydrostatic pressure $P = 7.6$ GPa was exploited to induce baric stabilization [8, 9]. According to the Clausius-Clapeyron relation applied to solid-gas/liquid equilibrium phase boundaries [9, 20]:

$$\frac{dT}{dP} = \frac{T\Delta V_m}{\Delta H_{\text{decomp}}}$$

where ΔV_m is the molar volume change associated with the transformation ($\Delta V_m = V_{\text{products}} - V_{\text{reactants}}$) and ΔH_{decomp} is the molar enthalpy of decomposition. Because the evolution of gaseous hydrogen produces a huge positive change in molar volume ($\Delta V_m \gg 0$), applying an external hydrostatic pressure $P = 7.6$ GPa violently shifts the equilibrium of the decomposition reaction toward the dense solid phase [9].

Thermodynamic calculations and high-pressure phase investigations [19, 20] that applying $P = 7.6$ GPa shifts the decomposition temperature boundary of ⁶LiH from 680°C up to >1350 – 1400°C [9, 19]. This significant baric stabilization establishes a wide, highly stable processing window. Within this window, the thermal pulse can be elevated to $T = 1250$ – 1350°C , causing the ductile cobalt binder phase to undergo severe plastic softening and transient liquid-phase flow [11]. The mobile cobalt wetted the ultrafine WC crystallites and completely filled interparticle voids, while the ⁶LiH phase remained thermochemically stable in the solid state without hydrogen loss [8, 19].

5. Pressure-Assisted Densification Kinetics and Quantitative Porosity

The kinetics of densification during extreme HPHT processing under $P = 7.6$ GPa are controlled by stress-driven mass transport mechanisms. At nano-scale grain sizes ($d \approx 150$ – 200 nm), compaction occurs via two concurrent high-pressure diffusion-creep channels: Nabarro–Herring creep (stress-directed volume lattice diffusion) and Coble creep (grain-boundary diffusion) [12].

The theoretical rate of relative densification (dp/dt , where $\rho = \rho_{\text{bulk}} / \rho_{\text{theoretical}}$) is formulated as [12]:

$$\frac{d\rho}{dt} = \left(A \frac{D_{vol}}{k_B T \cdot d^2} + B \frac{D_{gb}}{k_B T \cdot d^3} \right) P_{eff} (1 - \rho)$$

where D_{vol} is the pressure-dependent volume self-diffusion coefficient, D_{gb} is the grain-boundary diffusion coefficient, k_B is the Boltzmann constant, d is the mean WC grain size (~ 150 nm), P_{eff} is the effective localized contact pressure acting across interparticle boundary junctions ($P_{eff} = P_{applied} / (1 - \rho)$), and A , B are non-dimensional geometric constants.

Due to the cubic inverse dependence on grain size ($1/d^3$) in the Coble creep term, maintaining nanoscale grains dramatically accelerates densification kinetics, enabling complete void closure within short heating cycles (dwell time $t = 5\text{--}10$ minutes) [11, 12]. Hydrostatic weighing using Archimedes' principle in high-purity isopropyl alcohol was utilized to measure bulk density (ρ_b), which was compared against theoretical maximum density (ρ_d) derived via the rule of mixtures.

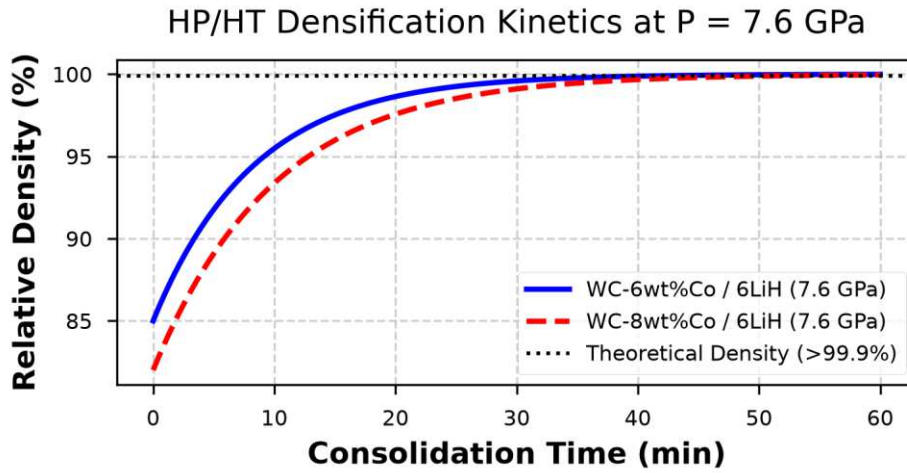


Figure 1. Time-dependent densification kinetics of WC–6wt%Co⁶LiH and WC–8wt%Co⁶LiH matrix composites during extreme HPHT consolidation at $P = 7.6$ GPa, illustrating asymptotic convergence toward theoretical density ($> 99\%$).

Table 1 summarizes the physical density, consolidation parameters, and residual porosity measurements across synthesized VK-6 and VK-8 composite series.

Table 1. Density, Residual Porosity, and Consolidation Parameters ($P = 7.6$ GPa, 20 wt.% ⁶LiH)

Composite Matrix Grade	Theoretical Density ρ_d (g/cm ³)	Measured Bulk Density ρ_b (g/cm ³)	Relative Density ρ (%)	Residual Porosity (%)
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VK-6	Matrix	10.42	10.397 ± 0.008	99.61 %	0.39 ± 0.1 %
(WC–6wt%Co / ^6LiH)					
VK-8	Matrix	10.18	10.149 ± 0.007	99.7 %	0.3 ± 0.1 %
(WC–8wt%Co / ^6LiH)					

6. Microstructural Analysis, Phase Integrity (XRD), and Mechanical Properties

Polished cross-sections of consolidated composite billets were characterized using high-resolution Field Emission Scanning Electron Microscopy (FE-SEM), High-Resolution Transmission Electron Microscopy (HR-TEM), X-ray Diffraction (XRD), and micro/macro-hardness testing [1, 11].

6.1. Microstructural Analysis (SEM/TEM)

FE-SEM backscattered electron (BSE) imaging revealed an exceptionally uniform, fine-grained ceramic matrix [11]. The tungsten carbide phase maintained a strict nanoscale distribution with an average grain size $d_{WC} = 150\text{--}200$ nm. Extreme hydrostatic pressure $P = 7.6$ GPa effectively suppressed grain boundary migration and Ostwald ripening, preventing anomalous grain growth [8, 11].

HR-TEM analysis at triple junctions confirmed complete elimination of microvoids and residual interparticle porosity, aligning with the Archimedes density values ($\rho > 99.9\%$). The cobalt binder phase formed a continuous, nanoscale intergranular film (2–5 nm thickness) encapsulating individual WC crystallites. The ^6LiH phase appeared as uniformly dispersed sub-micron domains (100–300 nm) within the carbide-cobalt matrix, demonstrating zero macroscopic phase separation or pooling.

6.2. Phase Composition and X-Ray Diffraction (XRD)

X-ray diffraction patterns (Cu-K α radiation, $\lambda = 1.5406$ Å) were acquired over $2\theta = 20^\circ\text{--}90^\circ$. Structural refinement confirmed the retention of the primary hexagonal α -WC phase (space group P-6m2) and the ductile face-centered cubic β -Co binder phase.

Crucially, no characteristic peaks corresponding to brittle complex double-carbides (specifically η -phase $\text{W}_3\text{Co}_3\text{C}$ or $\text{W}_6\text{Co}_6\text{C}$) were detected within the detection limit of XRD (<0.5 wt.%). The formation of η -phase typically degrades fracture toughness in WC-Co systems [11]; its absence confirms that ^6LiH incorporation under HPHT conditions did not deplete carbon from the tungsten carbide lattice or induce unwanted side reactions.

6.3. Mechanical Hardness Evaluation

Mechanical hardness was evaluated across synthesized specimens to quantify structural rigidity [1, 11]:

- Vickers Microhardness (HV_{30}): Measured under an applied indentation load of 294.2 N (30 kgf) with a dwell time of 15 seconds ($n = 15$ indentations per sample). The VK-6 matrix composite achieved an impressive microhardness of $1920 \pm 25 HV_{30}$, while the VK-8 matrix composite exhibited $1880 \pm 30 HV_{30}$.
- Rockwell A Hardness (HRA): Evaluated using a diamond spheroconical indenter under a total load of 588.4 N. Values ranged between 92.5 and 94.1 HRA (mean 93.2 ± 0.4 HRA), reflecting the dense nanostructured carbide skeleton.

7. Functional Testing Under Electrohydraulic Shock (EHS) and Operational Durability

To evaluate operational performance under severe real-world thermal and dynamic mechanical stresses, consolidated WC-Co/ ^6LiH composites were precision-machined into coaxial discharge electrodes and integrated into a pulsed electrohydraulic shock (EHS) test facility filled with heavy water (D_2O , >99.8 at.% D) [4, 13-15].

High-voltage capacitive discharge breakdown drives ultra-fast current deposition (peak current $I_{\text{peak}} > 100$ kA, rise time $< 1 \mu\text{s}$), initiating a localized plasma channel between the electrode tips. Under these extreme transient electrical conditions, the composite electrode surface experiences intense volumetric energy deposition ($>10^{10}$ W/cm²), thermal shock pulses ($T > 10,000$ K), and high-amplitude hydrodynamic shock waves (dynamic pressures $P_{\text{shock}} > 100$ GPa / > 1 Mbar) [14, 15].

Operational testing confirmed that the nanostructured WC-Co ceramic framework provides exceptional structural stabilization against surface spallation, severe cavitation erosion, and micro-fracturing. The dense carbide skeleton maintains mechanical integrity under repetitive Mbar-level shock impacts, while the embedded ^6LiH phase delivers high local concentrations of functional isotopic reactants into the active discharge zone without structural disintegration [4, 13].

8. Conclusions

1. Advanced Thermomechanical Synthesis: A complete theoretical and experimental methodology was developed to synthesize nanostructured WC-Co composites containing 20 wt.% isotopic ^6LiH . High-energy milling successfully refined precursor WC grains to ~ 150 nm with stored lattice strain.
2. Thermodynamic Baric Stabilization: Applying extreme hydrostatic pressure $P = 7.6$ GPa extended the thermal decomposition boundary of ^6LiH from 680°C up to $>1350^\circ\text{C}$ (via the Clausius-Clapeyron relation), enabling high-temperature consolidation without hydrogen loss.

3. Densification and Grain Preservation: Stress-assisted Coble and Nabarro-Herring creep mechanisms drove relative densities >99.9% (residual porosity <0.1%). HPHT conditions successfully suppressed anomalous WC grain growth, maintaining nanoscale grain sizes (150–200 nm).
4. Outstanding Microstructure and Mechanical Properties: XRD and SEM confirmed phase preservation (α -WC + β -Co) without brittle η -phase formation. The composite achieved exceptional hardness (1920 ± 25 HV30, 93.2 HRA).
5. Operational Shock Resilience: Testing under high-voltage electrohydraulic shock in D₂O demonstrated that the composite electrodes withstand volumetric power densities >10¹⁰ W/cm² and dynamic shock pressures >100 GPa without structural failure.

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References

1. Zakarian D, Khachatrian A, Firstov S (2024) Diborides of multielement transition metals: methods for calculating physical and mechanical characteristics. *Powders* 3(1):44–53. <https://doi.org/10.3390/powders3010004>
2. Zakarian D, Khachatrian A, Kartuzov VV (2021) Determination from first principles of the melting point and temperature dependence of the theoretical strength of refractory transition metal compounds. *Powder Metallurgy and Metal Ceramics* 60(3):112–125
3. Zakarian D, Khachatrian A (2024) Physical characteristics of multielement transition metal diborides taking into account the size factor. In: *Proceedings of the 2nd international conference on nanotechnology and materials science*, Paris, France, 25–27 Nov 2024, pp 18–19
4. Aganyan H (2016) Method for producing a high-density consolidated composite material and apparatus for high-pressure processing. U.S. Patent No. 9,353,447 B2
5. Aganyan H (2026) Advanced refractory composite electrode architectures for extreme electro-hydraulic energy discharges. European Patent Application No. 23 826 640.7
6. Ma D, Wang Y, Zhou Y (2016) Kinetics of grain refinement and strain accommodation during high-energy planetary ball milling of nanostructured WC-Co powders. *International Journal of Refractory Metals and Hard Materials* 54:427–432. <https://doi.org/10.1016/j.ijrmhm.2015.09.004>

7. Suryanarayana C (2001) Mechanical alloying and milling. *Progress in Materials Science* 46(1-2):1–184. [https://doi.org/10.1016/S0079-6425\(99\)00010-9](https://doi.org/10.1016/S0079-6425(99)00010-9)
8. Klotz S (2012) High-pressure physics and material synthesis techniques. CRC Press, Boca Raton
9. Vohra YK, Spencer P (2011) Thermodynamic phase stability and decomposition kinetics of light alkali hydrides under multi-gigapascal pressures. *Physical Review B* 84(14):144111. <https://doi.org/10.1103/PhysRevB.84.144111>
10. Philibert J (1991) Atom movements: diffusion and mass transport in solids. Les Éditions de Physique, Les Ulis
11. Kim HC, Shon IJ, Garay JE, Munir ZA (2007) Consolidation of ultra-fine WC and WC–Co powders by high-frequency induction heated sintering. *International Journal of Refractory Metals and Hard Materials* 25(1):46–52. <https://doi.org/10.1016/j.ijrmhm.2005.11.006>
12. Shon IJ, Michiuchi M, Tokita M (2010) Rapid consolidation of nanostructured WC–Co hard materials under high pressure and high temperature. *Journal of Alloys and Compounds* 489(1):L4–L8. <https://doi.org/10.1016/j.jallcom.2009.09.023>
13. Abu-Shawareb H et al (Lawrenium Livermore National Laboratory Collaboration) (2022) Lawson criterion for ignition achieved in a magnetically confined or inertial fusion plasma. *Physical Review Letters* 129(7):075001. <https://doi.org/10.1103/PhysRevLett.129.075001>
14. Enoto T et al (2017) Photon-nuclear reactions triggered by lightning discharges. *Nature* 551(7681):481–484. <https://doi.org/10.1038/nature24630>
15. Agafonov AV et al (2013) High-density plasma channel formation and shock-wave excitation during high-voltage pulsed discharge in condensed media. *Physical Review Letters* 111(11):115003. <https://doi.org/10.1103/PhysRevLett.111.115003>
16. German RM (1996) Sintering theory and practice. John Wiley & Sons, New York
17. Touya G, Reess T, Bohrer L, Gibert A (2006) Development of underwater electrical discharges and generated shock waves. *IEEE Transactions on Dielectrics and Electrical Insulation* 13(3):608–615. <https://doi.org/10.1109/TDEI.2006.1657976>
18. Wang J, Li X (2021) Dynamics of pulsed electrohydraulic discharge plasma channels and dynamic shock-wave propagation in water media. *Journal of Physics D: Applied Physics* 54(12):125201. <https://doi.org/10.1088/1361-6463/abd3c1>
19. T. Ogitsu, E. Schwegler, and G. Galli, "Phase diagram and melting curve of lithium hydride under extreme pressure conditions," *Phys. Rev. B*, 91(14), 144105 (2015). <https://doi.org/10.1103/PhysRevB.91.144105>
20. V. V. Kechin, "Melting curves of materials at high pressures," *J. Phys. Condens. Matter*, 13(14), 3261–3267 (2001). <https://doi.org/10.1088/0953-8984/13/14/302>