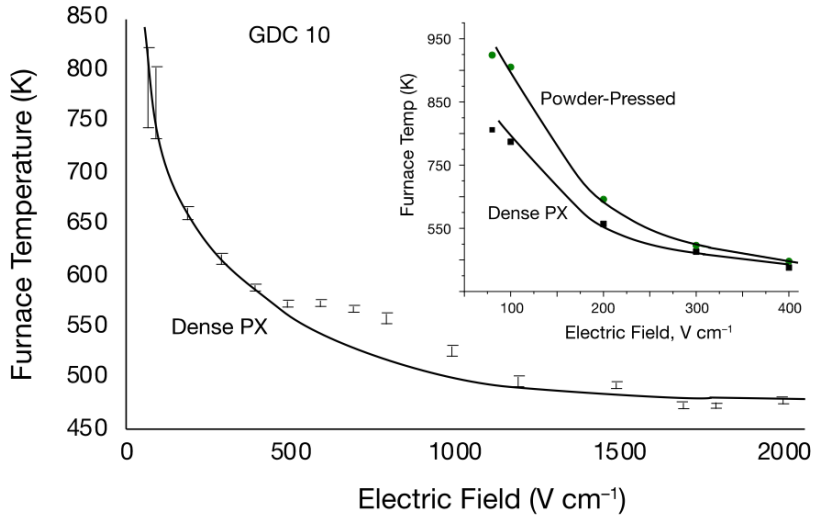
Rapid-Pulse Flash Joining of High-Hardness Steels: A Proof-of-Concept Demonstration

Our lab has been exploring Flash which is a new technique used in ceramics to consolidate powders. The process is characterized by a 5 to 10 order of magnitude increase in diffusion, a significant increase in electrical conductivity and strong electroluminescence. A key feature of Flash is its ability to be triggered at very low temperatures, usually a material's Debye temperature which tends to be significantly lower than its melting temperature as shown below (Misra 2019).



Most welding processes require line of sight to the weld area and require melting. Here we report a totally new welding modality where we use solid-state flash-joining to bond high-hardness AR500 martensitic steel armor plate coupons (3 × 3 × 5 mm) and high-speed tool-steel (Ø 1.5 mm × 10 mm) in air at room temperature without melting at temperatures almost 700 degrees C below the materials melting temperature. A digitally shaped current pulse train consisting of a 0.1 s high-density ignition burst followed by two energy-modulated pulses at 60 % and 30 % amplitude creates a transient flash event (<0.5 s) at the buried interface where the two samples are touching, driving the interface into a controlled state of Flash and enabling nearly instantaneous defect-mediated diffusion while keeping peak temperature below the alloy's solidus. The process is non-line-of-sight, tolerant of surface misalignment, and should be readily extendable to dissimilar materials or ceramics! There is no process to weld ceramics today.

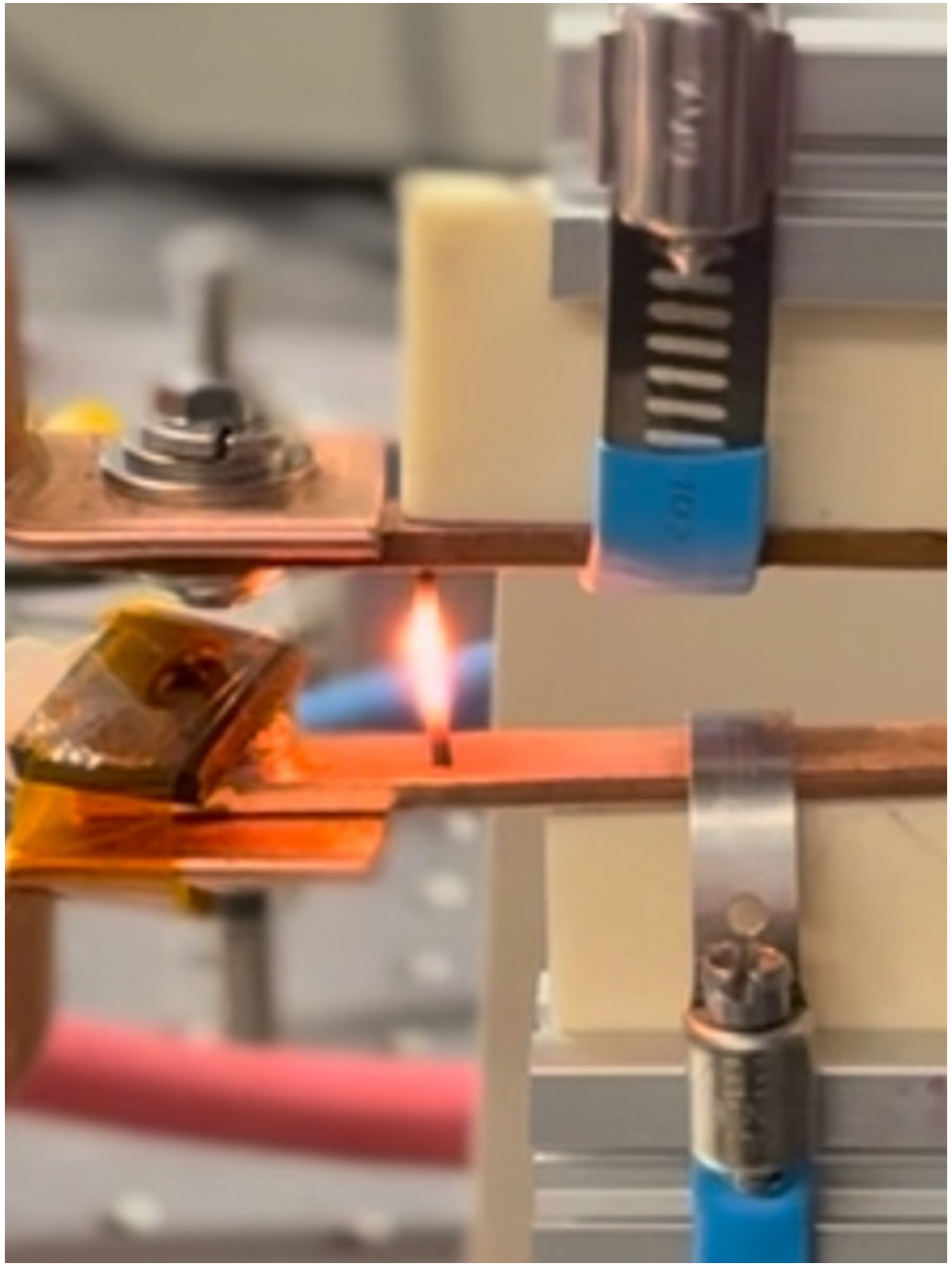
Governing equations for Joule power, thermal diffusion, and Frenkel-pair generation are presented, outlining design windows that suppress melting. Results position rapid-pulse flash joining as an energy-efficient alternative to spot welding or brazing for ultra-hard or dissimilar materials. Welding ultra-hard steels (AR500) and HSS is challenging because melting causes temper softening, residual stress, cracking.

Experimental Methods:
Materials

- AR500 martensitic plate sectioned into 3 × 3 × 5 mm coupons; ends ground to 600-grit.
- M2 high-speed steel pins, Ø 1.5 mm, length 10 mm; ends polished to 1 μm.

Electrical set-up

- Programmable supply: 120 A or 300A 10V DC power supplies were used and combined with a PicoScope to generates the control waveform.
- Pulse strategy: A basic waveform of 0.6 seconds was generated with 0.10 s linear ramp to 100 A (~60 A mm^{-2} for AR500; 50 A mm^{-2} for HSS) followed by a 0.20 s hold at 60 % amplitude (72 A) and a 0.30 s hold at 30 % amplitude (36 A). We used the Picoscope to vary the time of the pulses between 0.3 seconds and 3 seconds to test parameters for various configurations.
- Kelvin probes measured voltage and resistance and fed it back to the PicoScope.
- Axial clamp pressure was estimated at 4 MPa. The samples were attached to a linear rail to maintain alignment during welding.
- In-operando: current, Kelvin voltage, type K thermocouple



Theory and Governing Equations

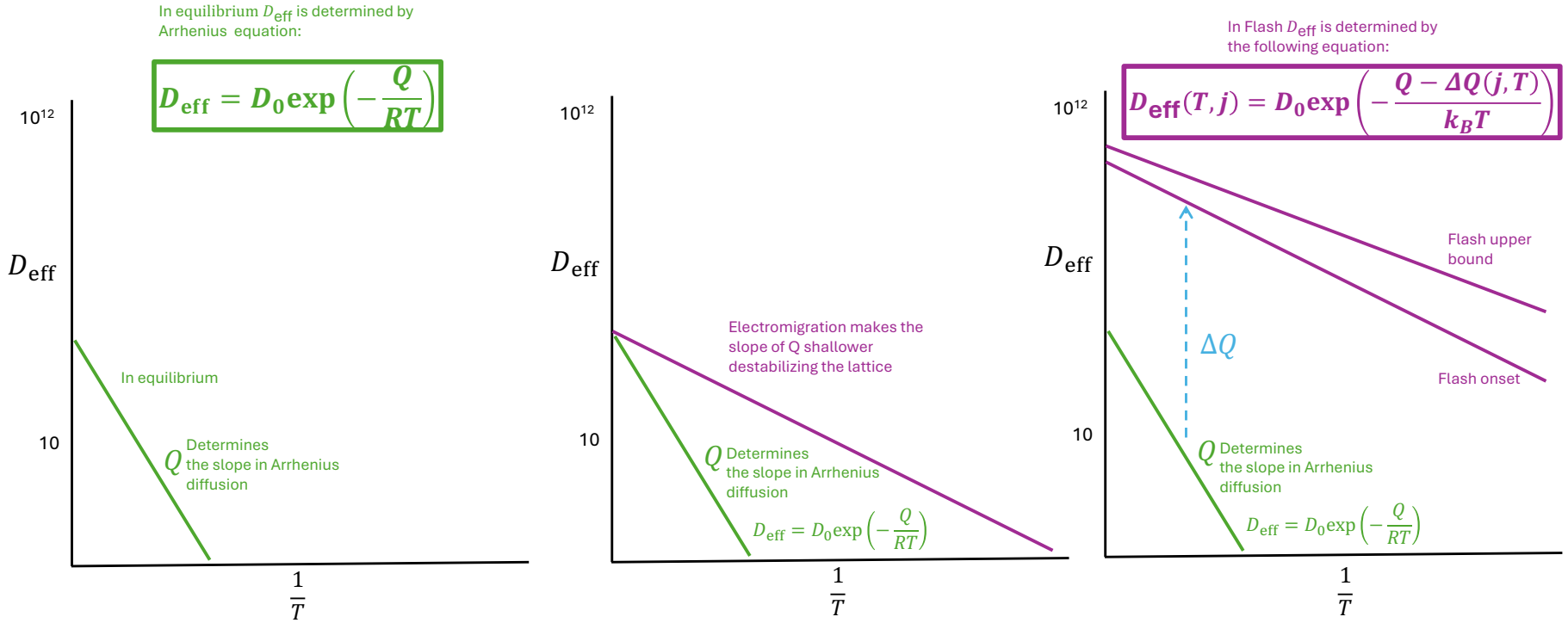
We developed a model to estimate the Joules required and were able to quickly calibrate it to our system.

Parameter	Value	Units	Description				
Contact area A	0.0642	cm^2	Bond interface area				
Hot layer thickness t	0.005	cm	Depth of heated skin per plate				
Density ρ	7.85	g/cm^3	AR500 density				
Specific heat c_p	0.49	$J\,g^{-1}\,°C^{-1}$	@ 300 °C				
Target ΔT at bonding surface	1000	°C	Rise to flash temp				
Interface resistance R_int	0.0002	Ω	Electrical across bond				
Peak current I_peak	250	A	Hold current				
Hold time t_hold	10	s	Duration at peak				
Current ramp time fraction	50%	% of t_hold	Fraction of total energy in ramp				
Efficiency η	0.50%	–	Fraction captured in bond layer				
Sensitivity analysis							
Efficiency η	0.50%	0.20%	0.30%	0.75%	1%	0.60%	0.80%
Heated mass m (g)	0.0050397	0.0050397	0.0050397	0.0050397	0.0050397	0.0050397	0.0050397
Ideal energy to ΔT (J)	2.47	2.47	2.47	2.47	2.47	2.47	2.47
Electrical energy (hold)	125	125	125	125	125	125	125
Total electrical energy (J)	**250**	**250**	**250**	**250**	**250**	**250**	**250**
Captured energy (J) at interface	1.25	0.5	0.75	1.875	2.5	1.5	2
Predicted ΔT (°C) at interface	506	202	304	759	1012	607	810

The chart below explains how we gain extreme super diffusion that enables this new kind of welding:

How does a material transition to a state of Flash?

Above the Debye temperature and a threshold (AC or DC) electric field sufficiently high to put a metal or ceramic in a state of Flash, heat is initially generated via joule heating and as the temperature rises the exponential effect of electromigration kicks in, reducing the activation energy for atomic diffusion and enhancing mobility. Where, D_{eff} is effective diffusivity (m^2/s), D_0 is the equilibrium pre-exponential factor, Q is equilibrium activation energy (J), $\Delta Q(j,T)$ is the field induced reduction from electromigration and phonons $(Q_{em} + Q_{ph})$ (J), k_B: Boltzmann constant (1.381×10^{-23} J/K), T is absolute temperature (K), and j is current density (A/m^2).



1. **Joule heating in constricted contact**

$$P(t) = I(t)^2\, R_{\mathrm{int}}(T)$$

2. **Peak interface temperature (1-D), adiabatic temperature rise**

$$\Delta T_{max} = \frac{\eta \int_0^{\tau} I^2 R_{int}\, dt}{m_{zone}\, Cp}$$

where η≈1% captured fraction. with Cp ≈ 600 J kg^{-1} K^{-1} for steel at 800–1000 °C.

3. **Defect generation energy**

$$E_{def} = N_F E_F = \int (P_{in} - P_{rad} - P_{cond})dt$$

4. **Flash/no-melt criterion**

$$\Delta T_{max} < T_{solidus} - T_0$$

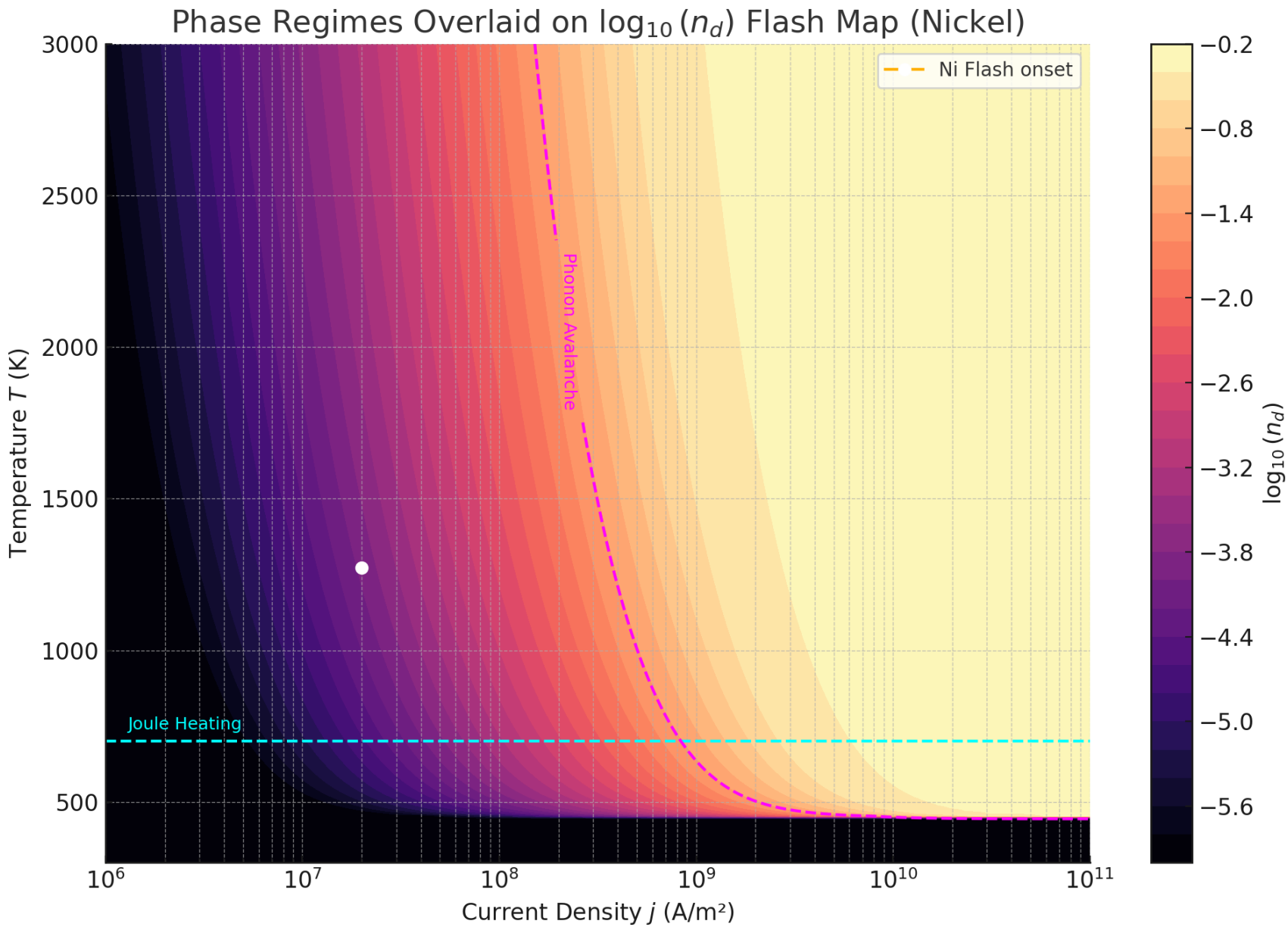
Calculated ΔTmax = 1040 °C (AR500 solidus ≈1450 °C) providing a significant safe margin. What is happening in Flash and how to put any metal or ceramic in Flash can be derived with the following set of governing equations which we developed over the past few months:

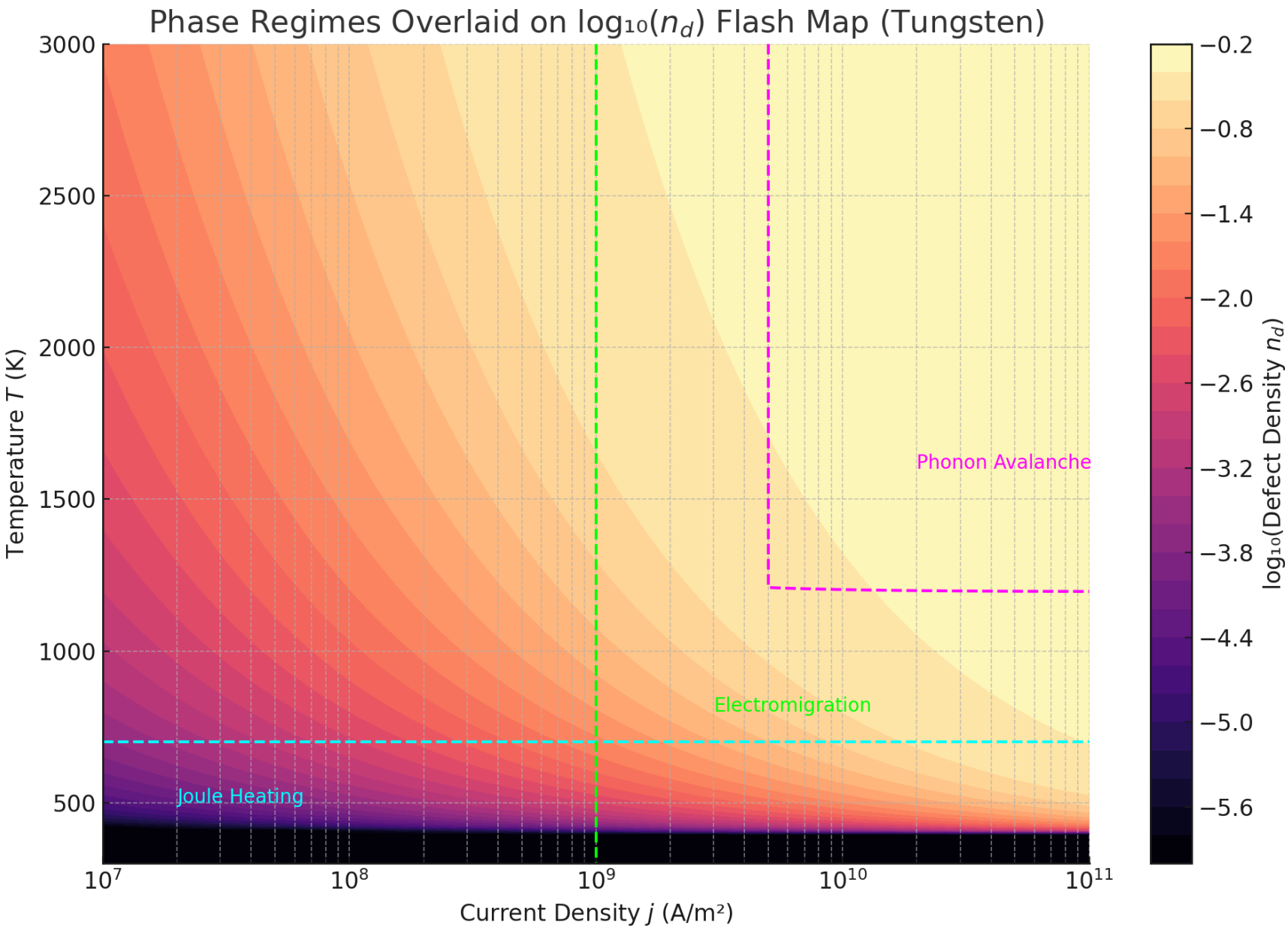
Cat.	Tag	Equation	Purpose	Units
Baseline transport				
A	S1	$D(T) = D_0 \exp[-Q/(k_B T)]$	Arrhenius lattice diffusion	$m^2\ s^{-1}$
A	S2	$\Theta_D = \frac{\hbar v_s}{k_B}(6\pi^2 n)^{1/3}$	Debye temperature	K
Non-linear phonons / defects				
B	S3	$N_{\mathrm{ph}}(T) = \int_0^{\omega_D} \frac{g(\omega)}{e^{\hbar\omega/k_B T} - 1}\, d\omega$	Phonon population	—
B	S4	$\tau_{\mathrm{gen}}^{-1} = \gamma N_{\mathrm{ph}}^2$	Defect-generation rate	s^{-1}

Cat.	Tag	Equation	Purpose	Units
B	Main	$\Delta Q_{\mathrm{ph}} = \eta u^2,\ u^2 \propto T/\Theta_D - 1$	Phonon barrier drop	eV
B	S5	$\dot{H}_{\mathrm{defect}} = n_d H_F/\tau_{\mathrm{gen}}$	Calorimetric sink	W m^{-3}
Field / electromigration				
C	Main	$J_{\mathrm{em}} = \frac{Z^* e\rho j D_0}{k_{\mathrm{B}}T}\exp[-(Q - \beta\rho j)/(k_{\mathrm{B}}T)]$	Atom flux	m^{-2} s^{-1}
C	S17	$\beta = \beta_0/\rho_{\mathrm{RT}}$	β–resistivity rule	eV Ω^{-1} m^{-1} (A m^{-2})$^{-1}$
C	S6	$p_{\mathrm{em}} = \frac{B\,(Z^* e\rho j)^2}{E_A}$	Back-stress	Pa
C	S20	$J_{\mathrm{em}}(j_{\mathrm{th}}, T) = J_{\mathrm{cr}}$	Critical flux	m^{-2} s^{-1}
C	S21	$j_{th} = \frac{J_{cr} k_B T \exp\left(\frac{Q - \Delta Q(j_{th}, T)}{k_B T}\right)}{\lvert Z^*\rvert e\rho D_0 C}$	Closed-form threshold current	A m^{-2}
Diffusion & resistivity collapse				
D	S14	$D_{\mathrm{eff}} = D_0\exp\left[-\left(Q - \Delta Q_{\mathrm{ph}} - \beta\rho j\right)/(k_{\mathrm{B}}T)\right]$	Bulk D_{eff}	m^2 s^{-1}
D	S15	$D_{\mathrm{eff}} = D_{\mathrm{lat}} + \delta D_{\mathrm{gb}}\, a/d$	+GB pipe diffusion	m^2 s^{-1}
D	S19	$\rho_{\mathrm{eff}} = \frac{\rho_{\mathrm{eq}}}{1 + \gamma J_{em}}$	Resistivity collapse	Ω m
Plasma & carriers				
E	S16	$n_e(t) = \beta J_{em} t/L$	Carrier build-up	m^{-3}
E	S18	$\omega_p = \sqrt{n_e e^2/(\varepsilon_0 m_e)}$	Plasma frequency	rad s^{-1}
E	Main	$p_e = n_e k_{\mathrm{B}} T_e$	Plasma pressure	Pa
Power balance / envelope				

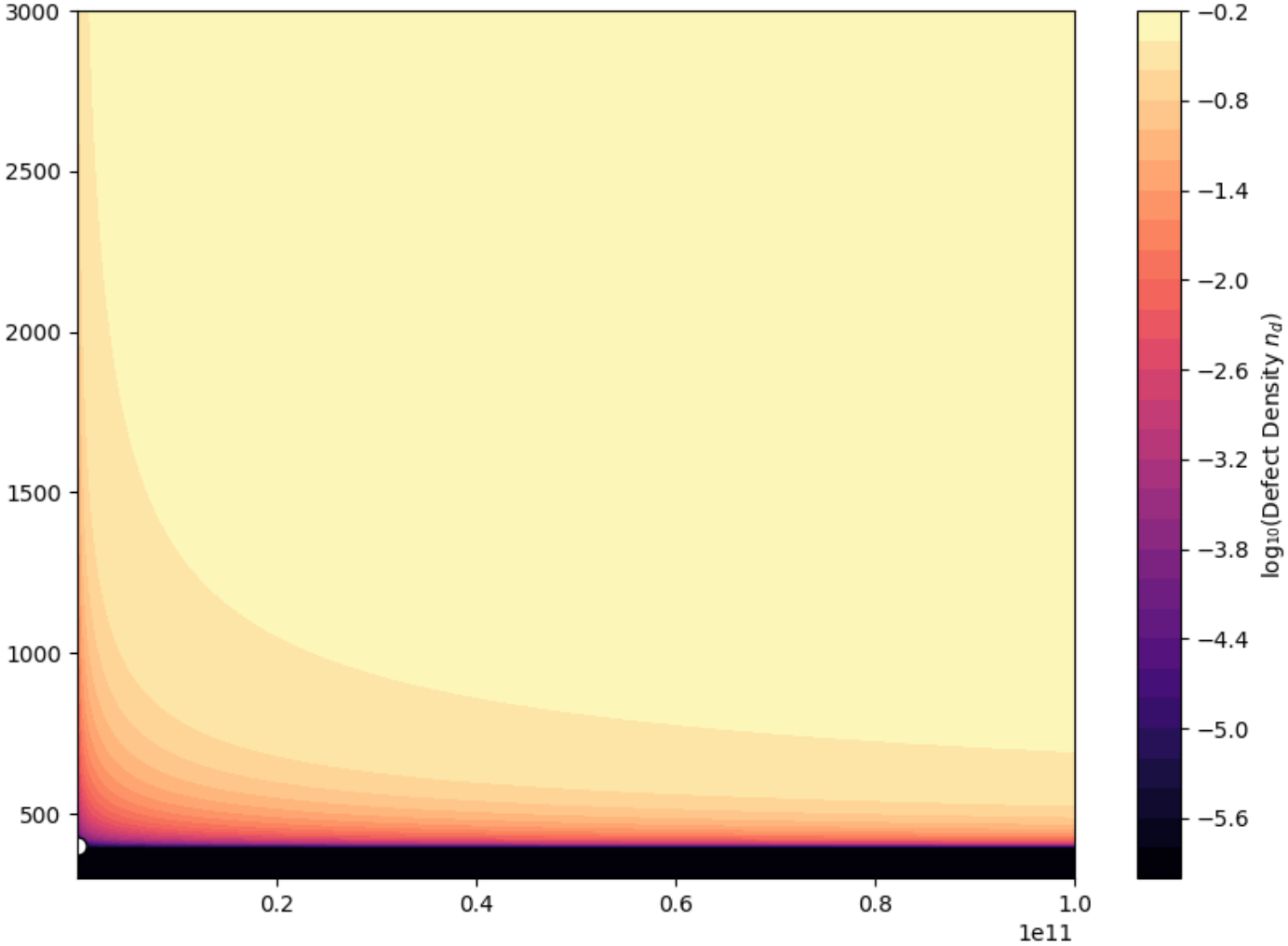
Cat.	Tag	Equation	Purpose	Units
F	Main	$P = Ej = \rho j^2$	Input power density	W m^{-3}
F	S13	$P_{\mathrm{melt}} = \sigma_{\mathrm{SB}}(T_m^4 - T^4)$	Thermal-runaway roof	W m^{-3}
F	Fit	$P_{\mathrm{th}}(T^*) = A(T^* - 1)^{\alpha}$	Saddle fit	W m^{-3}
Calorimetry & capacity				
G	S22	$\Delta H_{\mathrm{deficit}} = C_d C_{\mathrm{atom}} E_d + \beta(J) J_{em} t E_{eh}/L$	Energy deficit	J m^{-3}
G	S23	$C_d(J) = \frac{C_{\max}}{1 + e^{-\kappa(J - J_c)}}$	Capacity sigmoid	—
Mixed conduction / ratios				
H	S7	$\sigma_{\mathrm{tot}} = \sigma_e + \sigma_{\mathrm{ion}}$	Ceramics total σ	S m^{-1}
H	S12	$L/L_0 = 1 + \lambda n_d$	Lorenz correction	—
Microwave / AC drive				
I	S10	$j_d = \varepsilon \varepsilon_0 \omega E$	Displacement current	A m^{-2}
I	S11	$j_{\mathrm{th}}(E_{\mathrm{AC}}) = j_{\mathrm{th}}(0)\left[1 - \Delta Q_{\mathrm{ph}}(E_{\mathrm{AC}})/0.10\ \mathrm{eV}\right]$	GHz shift	A m^{-2}
Diagram axes & thresholds				
J	Axes	$T^* = T/\Theta_D,\ P,\ n_d$	Universal coordinates	
J		$n_d^* = 0.05$	Flash entry threshold	

(All constants—k_{B}, e, ε_0, $\hbar$—carry their conventional SI units.)

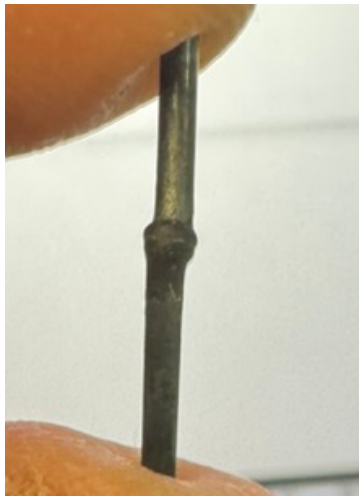

Phase Regimes Overlaid on $\log_{10}(n_d)$ Flash Map (Nickel)
Ni Flash onset
Phonon Avalanche
Joule Heating
Temperature T (K)
Current Density j (A/m²)
$\log_{10}(n_d)$
3000
2500
2000
1500
1000
500
10^6
10^7
10^8
10^9
10^{10}
10^{11}
−0.2
−0.8
−1.4
−2.0
−2.6
−3.2
−3.8
−4.4
−5.0
−5.6


Phase Regimes Overlaid on log₁₀(n_d) Flash Map (Tungsten)
Temperature T (K)
3000
2500
2000
1500
1000
500
10^7
10^8
10^9
10^{10}
10^{11}
Current Density j (A/m²)
Joule Heating
Electromigration
Phonon Avalanche
log₁₀(Defect Density n_d)
−0.2
−0.8
−1.4
−2.0
−2.6
−3.2
−3.8
−4.4
−5.0
−5.6

We used our governing equations to model the process maps above showing Nickel and Tungsten entry into a Flash stable state and the animation below shows how steep the ramp to Flash can be.


3000
2500
2000
1500
1000
500
0.2
0.4
0.6
0.8
1.0
1e11
−0.2
−0.8
−1.4
−2.0
−2.6
−3.2
−3.8
−4.4
−5.0
−5.6
log₁₀(Defect Density n_d)

Discussion



The samples produced show excellent bonding and mechanical properties. One of the more interesting features of this process is the ability to weld non line of sight materials which is not a feature available to most welding modalities like laser, e-beam, TIG, MIG, etc. This differs from resistance welding in that you do not melt the part, and you operate in a completely different voltage and power regime.

Process	Thermal field	HAZ width	Filler / flux	Line-of-sight?
Resistance spot-weld	Local melt nugget (1800 °C)	1–2 mm	None	Yes
Laser weld/e-beam	Fusion + keyhole	<0.5 mm	None	Yes
Brazing	850–1100 °C dwell >30 s	Bulk heating	Ag/Cu filler	Yes
Rapid-pulse flash (this work)	700-1000 °C, 0.3 s, solid-state	<0.3 mm	None	**No**

- **Physics difference**: bonding via defect-mediated diffusion; Frenkel pair concentration estimated ~0.1 mol % from calorimetry.

- **Control lever**: duty-cycled pulse prevents runaway; reducing to 60 % and 30 % amplitudes keeps dTdt < critical melt slope.
- **Scalability**: Can scale to join large plates or tiled in larger spots; super-cap bank for 2 kA industrial tool would be practical.
- **Materials**: Would enable dissimilar material welding including ceramics as long as the welding happens above the Debye temp of both materials.

We have experimentally validated a novel millisecond-flash, non-line-of-sight joining method for ultra-hard steels using only shaped current pulses. The absence of melting eliminates softening and opens a pathway to join refractories, ceramics and metal hybrids.

	GMAW (MIG/MAG)	TIG	SMAW (Stick)	Resistance	Laser	Friction Stir	E-Beam Thin	E-Beam Thick	OPA Civan Thick	This work
CAPEX	>$5k	>$5k	$3k	$50k	>$200k	>$150k	$1,000k	$1,000k	>$5,000k	<$5k
Max penetration depth	6-10mm (line of sight)	3-5mm (line of sight)	6-12mm (line of sight)	2-3mm (line of sight on one side)	2-10mm (line of sight)	5-20mm (line of sight)	5mm (line of sight)	25mm (line of sight)	70cm (line of sight)	3D non line of sight
Consumable	$3/kg	$5/kg	$5/kg	$2/h	-	-	$5/h	$5/h	-	-
Gas	$2.7/h	$1.44/h	-	-	$0.5/h	-	-	-	-	-
Power	$0.5/h	$1/h	$1/h	$2/h	$2/h	$0.5/h	$1/h	$1/h	$3.5/h	-
Depreciation	$0.5/h	$0.5/h	$0.3/h	$5/h	$20/h	$15+$1/h	$100/h	$100/h	$400/h	$0.5/h
Heat affected zone	Large	Large	Large	Minimal	Small	Small	Minimal	Minimal	Minimal	Minimal (tailorable)
Productivity 70% OEE	21m/h	12m/h	6.3m/h	80m/h (wheel)	84m/h	42m/h	63m/h	6m/h	126m/h	540 m/h
Cost per meter*	$0.60/m	$1.24/m	$1.43/m	$0.1	$0.27/m	>$0.39/m	>$1.68/m	$25.24/m	>$3.21/m	$0.00231/m 0.01 Wh/w
Skill required	Basic	High dexterity	Basic	Basic	Extensive	Extensive	Extensive	Extensive	PhD	Basic

At 46 J per flash bond, even a 3 600-weld-per-hour line consumes only 46 Wh (0.046 kWh), so at \$0.05 kWh^{-1} the power cost is ≈ \$0.002 per hour making it effectively negligible.

Acknowledgements

I want to thank David Bono and Quentin Bolse who helped me reduce this to practice! Full paper on this new technique is process.


Supplementary:

When do you have stable Flash? A step-by-step derivation from first principles of the total atomic/defect flux

$$\boxed{J_{\text{eff}} = J_{\text{em}} + J_{\text{phonon}} + J_{\text{recomb}}}$$

Notation in line with the supplemental governing equations (set S1–S21) above.

Starting point: continuity for point-defect density

Let

$n_d(\mathrm{r}, t)$ = atomic-fraction of Frenkel pairs (vacancy + interstitial)

$\mathrm{J}(\mathrm{r}, t)$ = net defect flux (pairs $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$)

$$\frac{\partial n_d}{\partial t} = -\nabla \cdot \mathbf{J} + \dot{G}_{\text{bulk}} - \dot{R}_{\text{bulk}}$$

where $\dot{G}$ and $\dot{R}$ are bulk generation and recombination rates (pairs $\mathrm{m}^{-3}\ \mathrm{s}^{-1}$).

We rewrite the right-hand side entirely as fluxes along a representative length ℓ (one jump distance, $\sim a$):

$$\mathbf{J}_{\text{eff}} = \underbrace{\mathbf{J}_{\text{drift}}}_{J_{\text{em}}} + \underbrace{\dot{G}_{\text{avalanche}}\,\ell/}_{J_{\text{phonon}}} + \underbrace{-\dot{R}_{\text{rec}}\,\ell/}_{J_{\text{recomb}}}.$$

Everything that follows is the microscopic origin of those three terms.

1 Electron-wind and electromigration flux J_{em}

1.1 Force on an atom

An atom that experiences an electron wind current j feels

$$F_{\text{em}} = Z^* e\,\rho\,j. \qquad \text{(E1)}$$

Z^* = effective charge number (≈10 for W)

e = elementary charge

ρ = resistivity (Ω m)

1.2 Mobility–diffusivity link

Einstein: $D = \mu\,k_B T$.
Atomic mobility $\mu = D/(k_B T)$.

1.3 Linear-drift flux

$$J_{\text{em}}^{(0)} = \frac{n_{\text{sites}} D F_{\text{em}}}{k_B T} = \frac{Z^* e \rho j D}{k_B T}, \qquad \text{(E2)}$$

where n_{sites} is absorbed into D (we speak of *per-site* flux).

1.4 Non-linear ("β") barrier lowering (S17)

A high current also reduces the activation barrier:

$$Q_{\text{eff}} = Q - \beta \rho j, \qquad D(T, j) = D_0 \exp\left[-\frac{Q_{\text{eff}}}{k_B T}\right]$$

Insert $D(T, j)$ into (E2):

$$J_{\text{em}} = \frac{Z^* e \rho j D_0}{k_B T} \exp\left[-\frac{Q - \beta \rho j}{k_B T}\right] \qquad \text{(E3)}$$

This is exactly Eq. S5.

2 Phonon-driven avalanche flux J_{phonon}

Literature experiments show that once $T \gtrsim \Theta_D$ and current is high, optical/electrical data indicates non-linear defect generation.

Following S4–S6:

2.1 Phonon population above Debye cut-off

$$u(T) = \frac{T}{\Theta_D}, \qquad N_{\text{ph}} \sim u^3.$$

2.2 Barrier-lowering by phonons (S4)

$$\Delta Q_{\text{ph}}(T) = \eta\,(u^2 - 1)\,H(u - 1),$$

where H is the Heaviside step function and $\eta \sim 0.3$eV.

2.3 Generation rate (defect pairs $\mathrm{m}^{-3}\ \mathrm{s}^{-1}$)

$$\dot{G}_{\mathrm{avalanche}} = \nu\, N_{\mathrm{ph}} \exp\left[-\frac{E_F - \Delta Q_{\mathrm{ph}}}{k_{\mathrm{B}} T}\right], \qquad \text{(P1)}$$

- $\nu \sim 10^{12}\ \mathrm{s}^{-1}$ is an attempt frequency.
- E_F is the Frenkel pair formation energy.

Multiply by ℓ to convert to a flux:

$$J_{\mathrm{phonon}} = \ell\, \dot{G}_{\mathrm{avalanche}} \ \propto j^n (u^2 - 1)\, H\, (U - 1) \exp\left[-\frac{E_F - \Delta Q_{\mathrm{ph}}}{k_{\mathrm{B}} T}\right] \qquad \text{(P2)}$$

where n(≈2) captures the observed super-quadratic field-coupling (photon intensity $\propto j^2$).

3 Recombination flux J_{recomb}

If a Frenkel pair lives on average τ_{rec}:

$$\dot{R}_{\mathrm{rec}} = \frac{n_d}{\tau_{\mathrm{rec}}} \quad \Rightarrow \quad J_{\mathrm{recomb}} = -\ell\, \frac{n_d}{\tau_{\mathrm{rec}}}. \qquad \text{(R1)}$$

Typical tungsten values:
$\tau_{\mathrm{rec}} \sim 10^{-4}$ to 10^{-5} at 1000–1300 K.

4 Effective flux and defect-density evolution

Putting (E3), (P2), (R1) into the continuity equation yields the Flash master rate equation.

$$\frac{\partial n_d}{\partial t} = \underbrace{\frac{Z^* e \rho j D_0}{k_{\mathrm{B}} T\, \ell} \exp\left[-\frac{Q - \beta \rho j}{k_{\mathrm{B}} T}\right]}_{J_{\mathrm{em}}/\ell} + \underbrace{\frac{\nu\, \ell\, N_{\mathrm{ph}} \exp\left[-\frac{E_F - \Delta Q_{\mathrm{ph}}}{k_{\mathrm{B}} T}\right]}{J_{\mathrm{phonon}}/\ell}} - \underbrace{\frac{n_d}{\tau_{\mathrm{rec}}}}_{J_{\mathrm{recomb}}/\ell} \qquad (\bigstar)$$

At steady state ($\partial n_d / \partial t = 0$) this equation defines the Flash phase line in the j–T space phase diagram.

In summary:

- Equations E3, P2, R1 are the microscopic derivations.
- Stable Flash is when
  $J_{\text{em}} + J_{\text{phonon}} = J_{\text{recomb}}$.
  That reproduces the abrupt jump in n_d
- All coefficients can be extracted from experiments (resistivity, calorimetry, light emission) or DFT
- Flash ignition in a fully dense solid happens when the two positive source terms on the right-hand side (electron-wind drift + phonon avalanche) outrun the recombination sink.

Symbol	Meaning
n_d	Frenkel-pair (vacancy + interstitial) fraction
$Z^* e \rho j$	Electron-wind force per atom
$D_0 e^{-(Q-\beta\rho j)/k_B T}$	Current- and temperature-dependent diffusivity (barrier Q lowered by $\beta\rho j$)
ℓ	One jump length (≈ lattice spacing)
ν	Attempt frequency ($\sim 10^{12}$ s^{-1})
$N_{\text{ph}}(T)$	Nonequilibrium phonon population $\propto (T/\Theta_D)^3$
$\Delta Q_{\text{ph}}(T)$	Phonon-induced barrier drop (zero below Θ_D)
E_F	Frenkel pair formation energy (≈ 3.9 eV for W)
τ_{rec}	Frenkel-pair lifetime (10^{-5}–10^{-4} s near 1000 °C)