3D MODELLING OF THERMAL LOADS DURING UNMITIGATED VERTICAL DISPLACEMENT EVENTS IN ITER AND JET

ID: 2762

F.J. Artola[1], R.A. Pitts[1], I.S. Carvalho[1], G. Simic[1], A. Loarte[1], S.N. Gerasimov[2], M. Kong[3], A. Redl[4], the EUROfusion Tokamak Exploitation Team* and JET contributors**

Email: javier.artola@iter.org

[1]ITER Organization, Route de Vinon sur Verdon, 13067 St Paul Lez Durance Cedex, France
[2]UKAEA, Culham Campus Abingdon, Oxon, OX14 3DB, United Kingdom
[3]EPFL, Swiss Plasma Center, CH-1015 Lausanne, Switzerland
[4]Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching b. M., Germany

* See author list in E. Joffrin et al. to be published in NF Special Issue: Overview and Summary Papers from the 29th FEC
** See author list in "Overview of T and D-T results in JET with ITER-like wall" by C.F. Maggi et al. to be published in Nuclear Fusion Special Issue.

Introduction and motivation

- **Why:** Unmitigated Thermal & Current Quenches (TQ & CQ) can melt Plasma Facing Components in ITER [1] even for the new W armored First Wall (FW) [2,3]
- **Gap**: Axisymmetric codes miss toroidal asymmetries expected in unmitigated disruptions when $q_{95} < 2$
- **Novelty:** First 3D plasma + 3D wall prediction of TQ & CQ heat loads
- **Aim of this work:**
  - ➢ Model validation on JET upward-going Vertical Displacement Events (VDE) for the Be wall
  - ➢ Study melting and heat localization for a 15 MA ITER L-mode plasma for the W FW

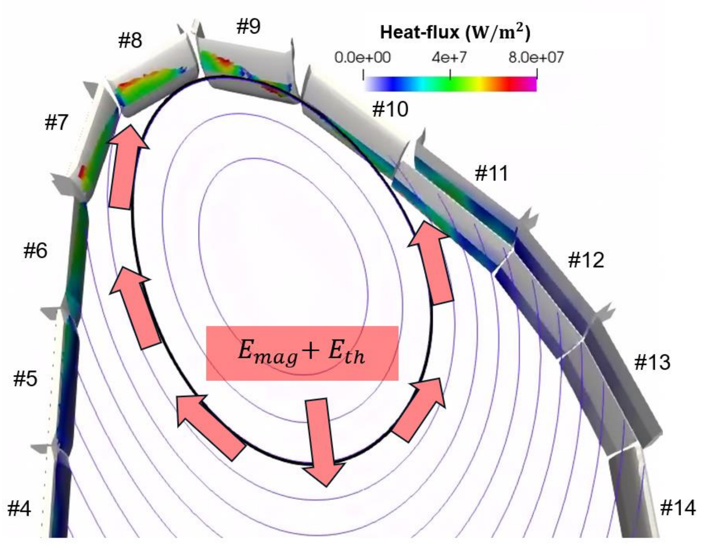


Fig 1. Example of an ITER CQ simulation with JOREK together with the FWP indexing and the perpendicular heat fluxes on the FW. The equilibrium is taken at t=0.391s with $q_{95} = 1.7$.

The JOREK MHD simulations

MHD setup

- **Model:** Reduced-MHD with JOREK + STARWALL (thin-wall EM coupling) [4]. Variables: (ψ, Φ, j, w, T) with $T_i = T_e = T/2$; constant n_e and $v_\parallel = 0$
- **Not included:** Impurity radiation, PWI, JET iron core effects, poloidal wall resistance.
- **Energy balance:** Initial thermal energy and ohmic heating dissipated by par. conduction + ⊥ convection
- **Resolution:** Toroidal harmonics 0…3 + diffusive-time re-scaling for ITER [4].

Plasma boundary conditions → wall heat flux

- No flow ($\boldsymbol{v} \cdot \boldsymbol{n} = \boldsymbol{0}$), $T_e = 1$ eV
- $q \approx q_\parallel = -\kappa_{Spitz}(\overline{T})\nabla_\parallel T_e;\ \ \overline{T} = \max(T_e, 30\ eV)$
- Oversimplified, but conduction-limited SOL [5] during CQ → Weak sensitivity to boundary conditions

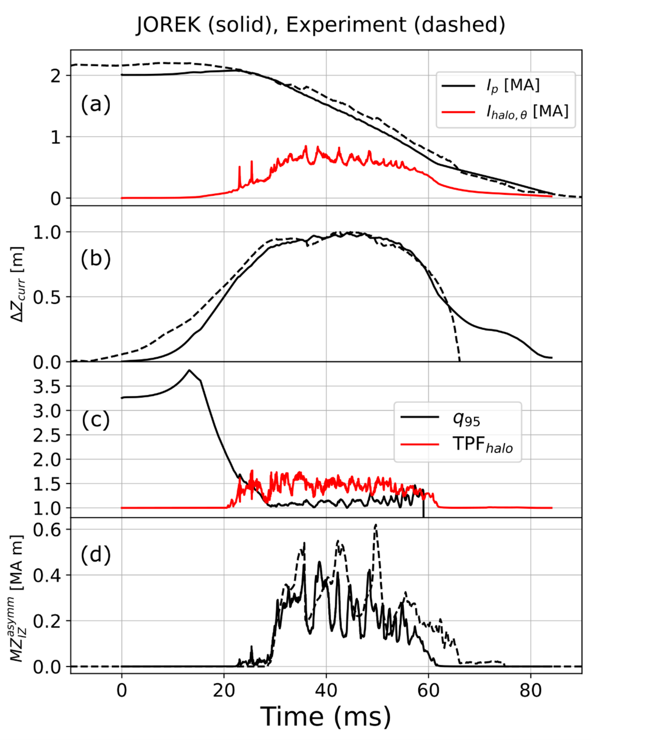


Fig 2. Comparison of JOREK values (solid) with experimental values (dashed) for shot #84832. (a) Plasma current and poloidal halo currents. (b) Vertical displacement of the current-centroid. (c) Edge safety factor and toroidal peaking factor of the poloidal halo currents. (d) n=1 asymmetry of the vertical current moment as defined in [].

Field Line Tracing (FLT) and wall temperature response

Wetted area and $q_\perp$

- FLT from wall to plasma. If no wall intersection after 5 m → element is wetted
- Successful benchmark .vs. SMITER on ITER FW Panels (FWP)
- For wetted elements, map JOREK $q_\parallel$ to 3D wall and project with wall normal → $q_\perp$

Wall temperature calculation

- Solve 1D heat diffusion equation per element
- Boundary Conditions (BC):
  - ➢ Front panel $(x = 0)$: $\partial_x T = -q_\perp(t)/k(T)$
  - ➢ Rear panel $(x = 12\text{ mm})$: $\partial_x T = 0$
- Material constants: $c_p(T), k(T), \rho = cte$ for W/Be

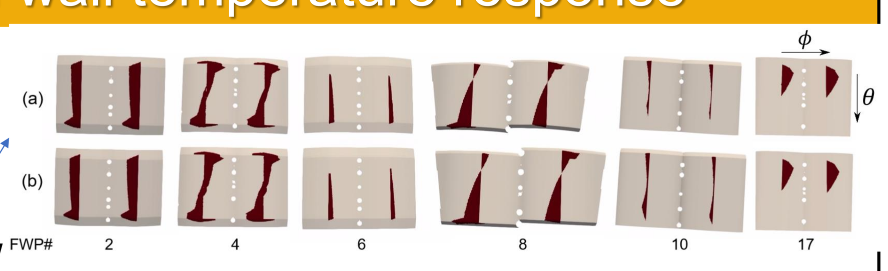


Fig 3. {Wetted area (red) calculated in SMITER (a) and JOREK (b) for 6 out of the 18 poloidally distributed FWPs for a pre-disruptive ITER X-point plasma.

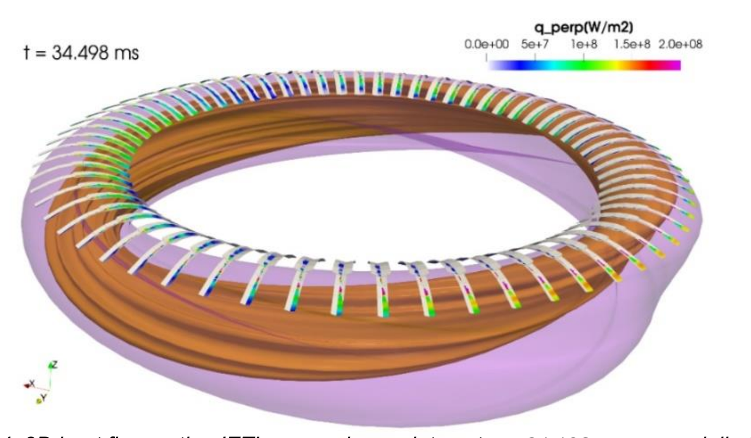


Fig 4. 3D heat flux on the JET's upper dump plates at $t = 34.498$ ms as modelled by JOREK (rainbow colormap). The orange and purple contours are electron temperature isosurfaces showing MHD activity, with respectively 75 and 50 eV.

Measurement diagnostics in JET

- **Magnetics:** current-centroid position, and toroidal asymmetries from Gerasimov's magnetic diagnostics analysis [6,7].
- **Thermocouples (TCs):** Subsurface TCs in Be Upper Dump Plates (UDP, Octant 2)
- **Halo-current shunts ("mushroom", MS)**
- **Calorimetry:** TC-based inversion [8] → total deposited energy (requires internal thermal equilibrium ⇒ cannot split pre-disruptive vs disruption).

→ Disruption energy isolation by subtraction using reference shots:

- #95110 → reference #95108 (Ne shattered-pellet mitigation). [6]
- #84832 → reference #85364 (non-disruptive, similar conditions).

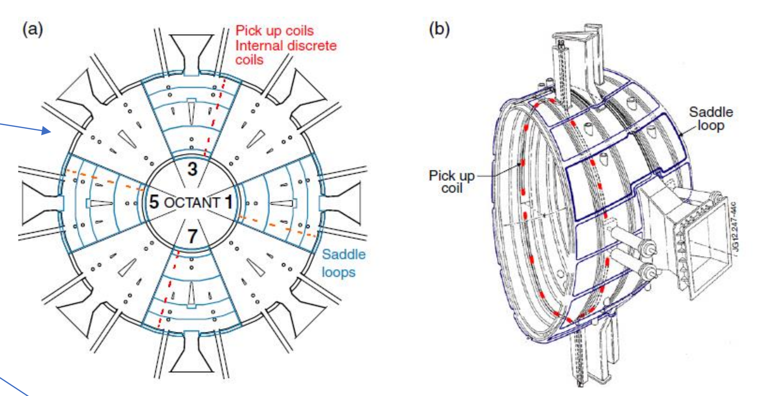
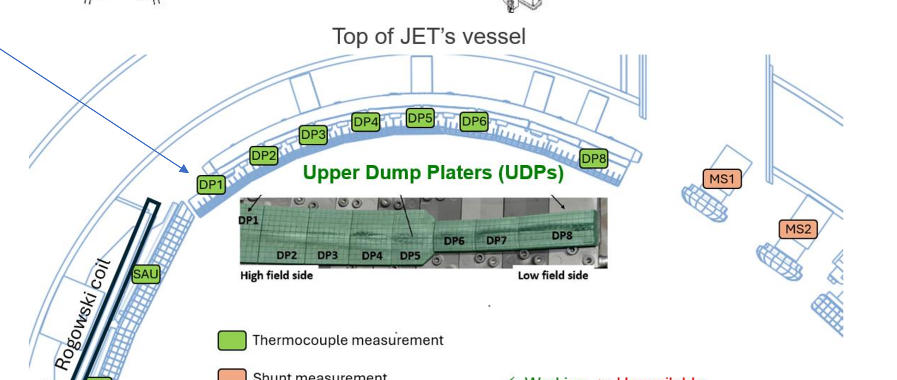


Fig 5. (a) View of JET vessel, showing the toroidal locations of the pick-up coils and saddles. (b) JET vessel octant equipped with pick-up coils and saddle loops. [7]



✓: Working, ×: Unavailable

Octant	1	2	3	4	5	6	7	8
MS1	✓	✓	✓	×	✓	✓	×	×
MS2	✓	✓	✓	✓	✓	×	×	✓
RC			✓		×		×	

Fig 6. Summary of the JET diagnostics used for thermal loads and halo currents in this study. Green boxes denote TC measurements while light-red boxes denote shunt measurements (MS1/2). The black and thick rectangular outline shows a Rogowski coil (RC) and the bottom table shows the toroidal coverage and availability for halo current measurements in each of the JET octants for the considered shots. [9[

Thermal load validation in JET

- **Simulated pulses:** #95110 (described in [4]) and #84832 (in this work)
- #84832 has × 4 the magnetic energy and × 10 the thermal energy of #95110
- **Global MHD:** good agreement for both shots (see Fig. 1)
- **Mushroom shunts →** Assess toroidal symmetry where TCs lack coverage

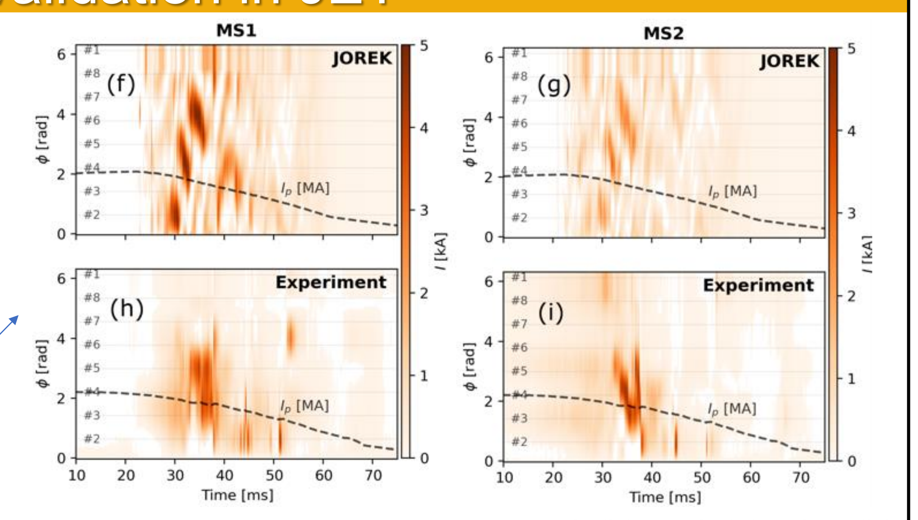


Fig 7. Toroidal current distribution measured by the mushroom shunts MS1 (f,h) and MS1 (g,i) in JOREK (f,g) and in the experiment (h,i). The indices (show the octant on which the measurement is taken.

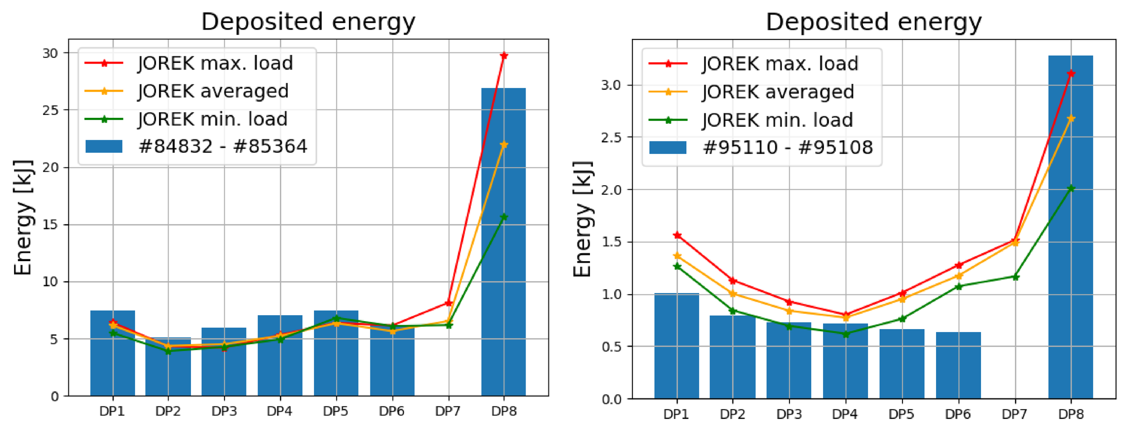


Fig 8. Energy deposited on the UDPs in experiment (blue bars) and calculated in the JOREK (lines). JOREK results have been scaled down by a factor $(1 - f_{rad})$ to account for missing radiation losses. Exp. error expected to be < 20 % [9].

Deposited energy on UDPs

- Exp. values bracketed by sim. min/avg/max toroidal sectors
- **Toroidal asymmetry ~20%**, strongest at **UDP 8** (TQ-dominated).

Max. surface temperature on UDPs

- #95110: no Be melting (consistent with exp.)
- #84832: Be melting in UDPs 7-8. (consistent with exp.). Longest melt duration ~6 ms
- Melting only occurs when both TQ and CQ phases act together

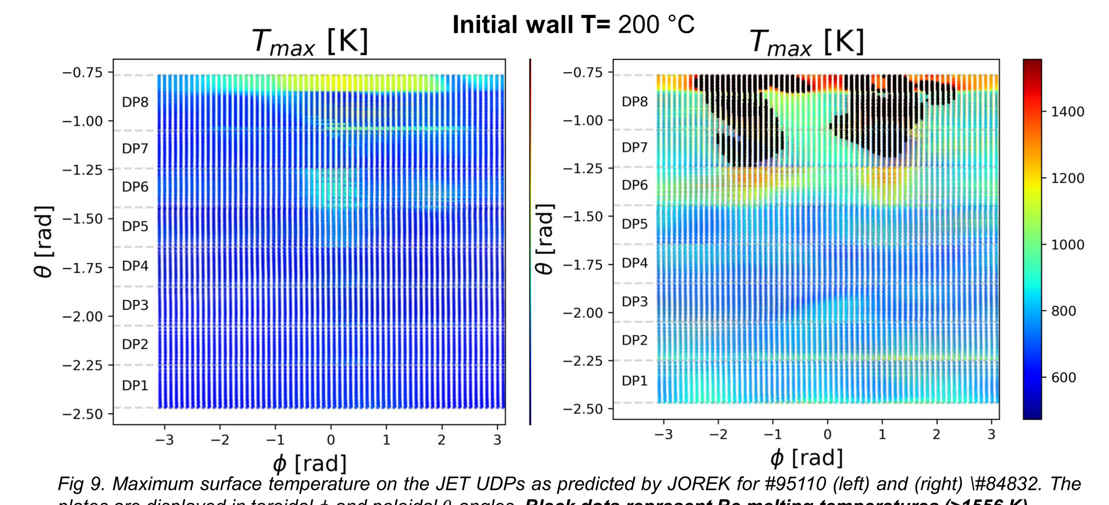


Fig 9. Maximum surface temperature on the JET UDPs as predicted by JOREK for #95110 (left) and (right) \#84832. The plates are displayed in toroidal ϕ and poloidal θ angles. **Black dots represent Be melting temperatures (>1556 K).**

Prediction for a 15 MA unmitigated VDE

- **Scenario:** 15MA upward VDE [4], L-mode with modest $W_{\text{thermal}} = 30\text{ MJ}$ for TQ, but worst case for CQ
- **Where/when melting occurs:**
  - TQ (~6 ms): first melting on FWP #11, short melt duration (~2 ms)
  - CQ (~240ms): Strongest melting on FWP #10 on upper port wings (near perp. Incidence), long melt durations ~20 ms
- **Energy deposition toroidal asymmetry:** peaking of ~3 for TQ and ~2 for CQ

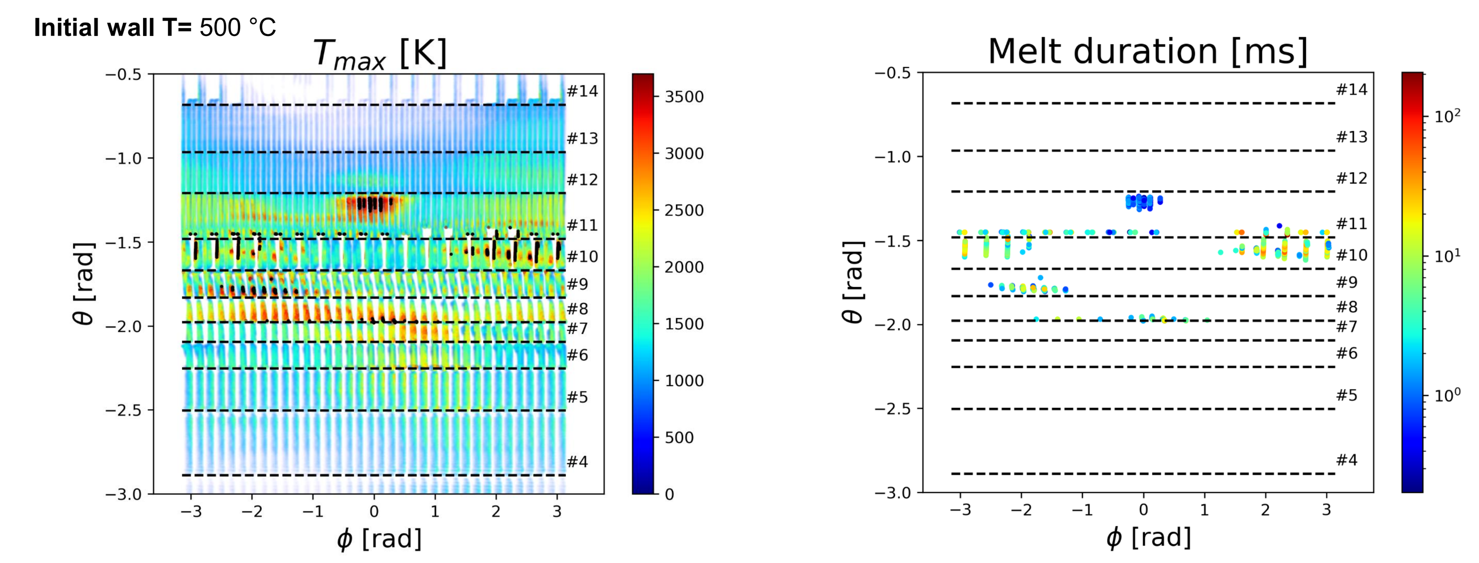


Fig 10. Maximum surface temperature (left) and melt duration (right) on the ITER FW during a 15MA unmitigated upward VDE. The FW surface is represented in toroidal ϕ and poloidal θ coordinates, with the poloidal index of the FW panels (#). Black dots mark elements where the surface temperature exceeds the W melting point (>3695K).

Conclusions and future work

- **Validation (JET):** Global trends and energy deposition reproduced; CQ conduction-limited → weak sensitivity to simplified BCs. Melting requires TQ+CQ (TQ pre-heats, CQ sustains).
- **ITER (15 MA upward VDE, CQ 240 ms):**
  - **Main W FWPs**: only marginal, short melts.
  - **Strong melt near upper ports**: tens of ms melts due to near-normal incidence.
  - Toroidal asymmetries raise peaks (×2 CQ, ×3 TQ), while MHD and motion broadens deposition. Energy poloidal spread λ_E is tens of cm.
    → Contrast: 2D TOKES shows CQ melting at 10 MA [3] for W FW due to fixed EQ.,& λ_E =3.5 cm
- **Next steps:**
  Include radiation & impurity physics, improved sheath/density BCs. Couple to melt-evolution solvers (e.g., MEMENTO) for melt motion/droplet/lifetime impacts; TOKES TQ studies guided by these results, including possible self-mitigation via W evaporation/radiation.

References

[1] COBURN, J. et al, Nucl. Fusion 62 (2022) 016001..
[2] PITTS, R.A. et al, Nucl. Fusion 42 (2025) 101854.
[3] PITTS, R.A., TOKES simulations of first wall and divertor damage during unmitigated disruptions on ITER, IAEA-CN-316-2152, presented at the 29th Fusion Energy Conference, UK, 2023.
[4] ARTOLA, F.J. et al, Plasma Physics and Controlled Fusion 66 (2024) 055015.
[5] STANGEBY, P.C., The Plasma Boundary of Magnetic Fusion Devices, Taylor \& Francis Group, Great Britain (2000)
[6] GERASIMOV, S.N. et al, Phys. Scr. 99 (2024) 075615
[7] GERASIMOV, S.N. et al, Nucl. Fusion 54 (2014) 073009
[8] MATTHEWS, G.F. et al, Journal of Nuclear Materials 12 (2017) 227-233.
[9] JEPU, I. et al, Nucl. Fusion 59 (2019) 086009.
[10] PASCHALIDIS, K. et al, Journal of Nuclear Materials 206 (2024) 114603.

www.iter.org

30th IAEA Fusion Energy Conference (October 2025)

china eu india japan korea russia usa