7TH ANNUAL SF_6 GAS MANAGEMENT SEMINAR 2022

TESLA

Tough & Ecological Supercritical Line Breaker for AC

TESLA – Or How We Avoid Using SF_6 in Our Circuit Breaker

Lukas Graber, Ph.D.

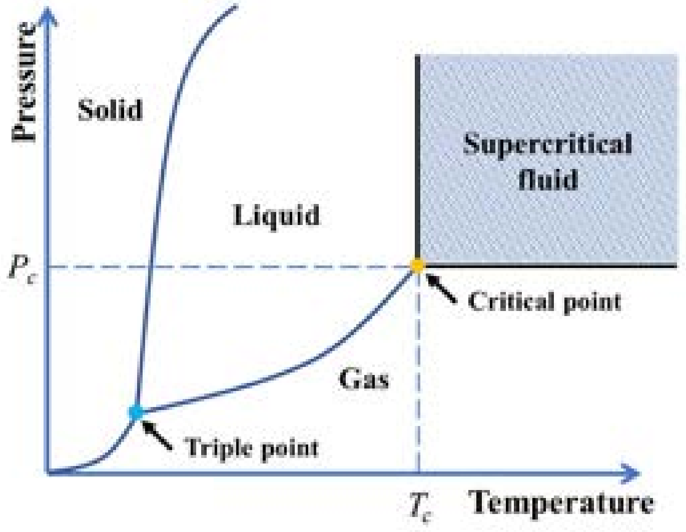
Associate Professor, Georgia Tech

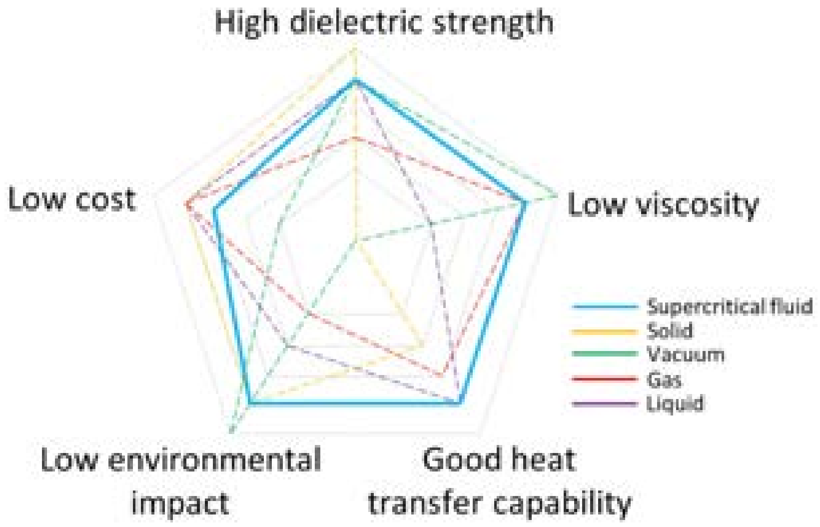
Content

- The limits of vacuum, gas, and liquid media
- Supercritical fluid mixtures
- Challenges with SCF breaker design
- Target specifications of TESLA, conceptual design, and timeline
- Bonus: EDISON, our DC circuit breaker

Limits of Vacuum, Gas, and Liquid Media

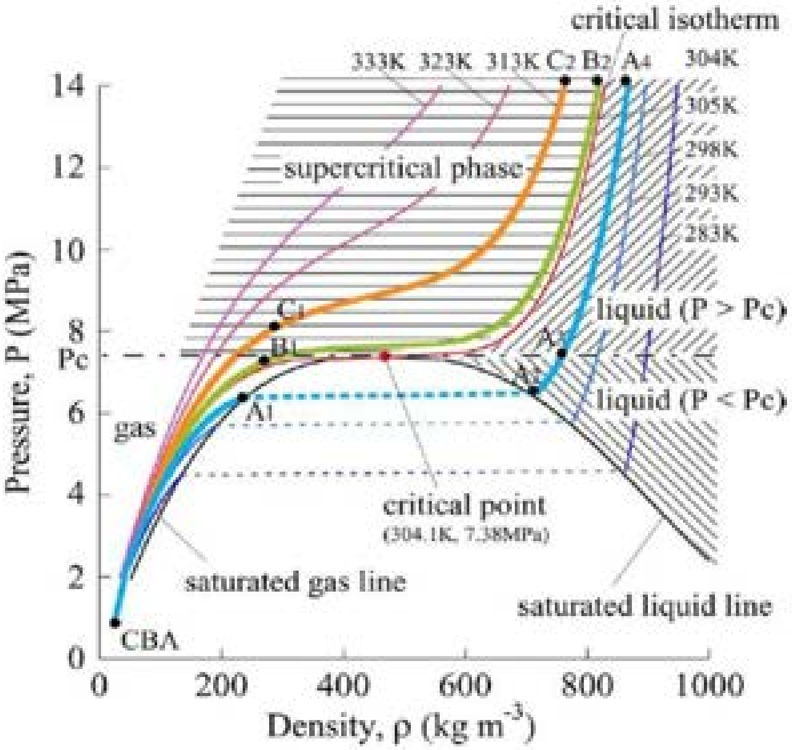
- Choice of media:
  - Vacuum
    - Bad heat transfer, limits power/voltage/current ratings
  - Gas
    - Limited dielectric strength
    - Dissociation & decomposition
  - Liquid
    - High viscosity, incompressible
    - Dissociation & decomposition
  - Solid
    - Does not support motion
    - Non self-healing/restoring

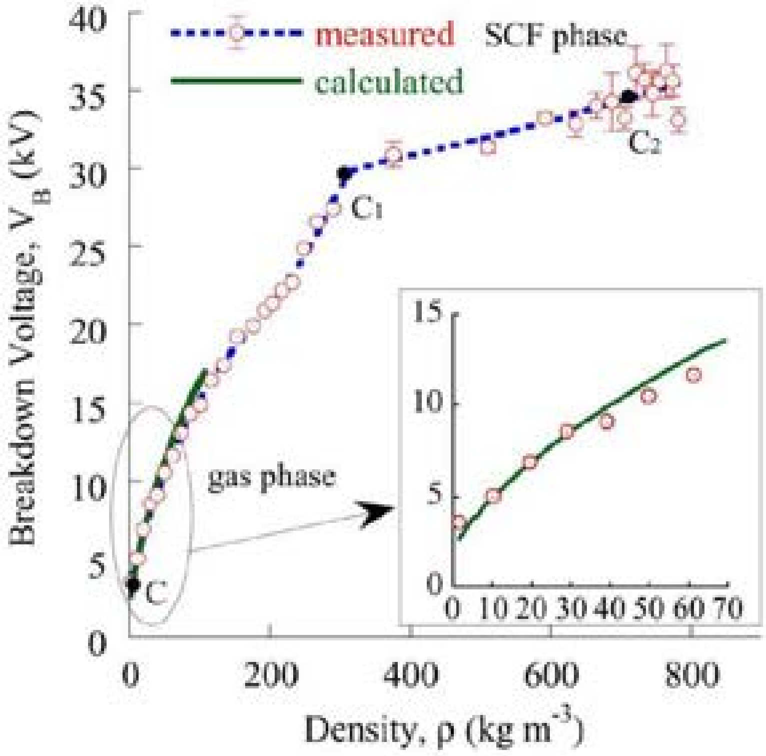


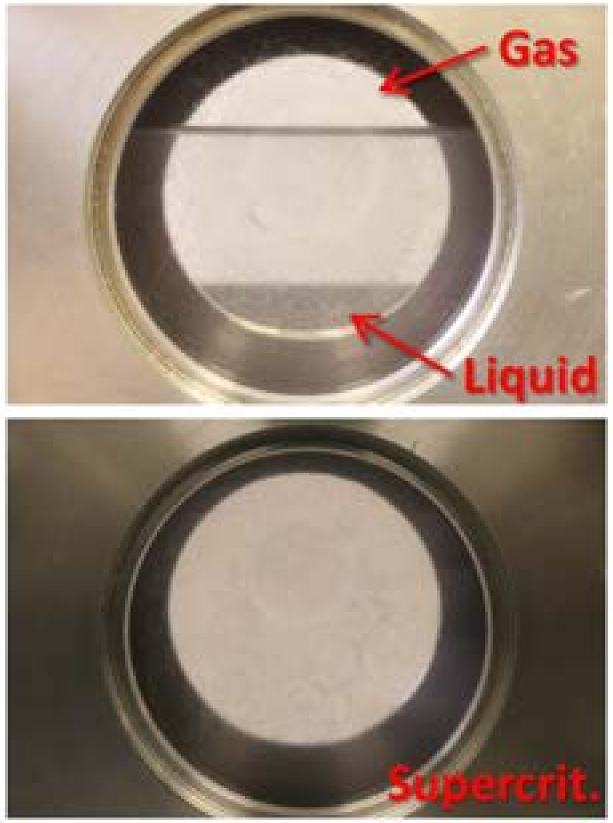


A. Cruz et al., EDISON flyer (2022)

Supercritical Fluids





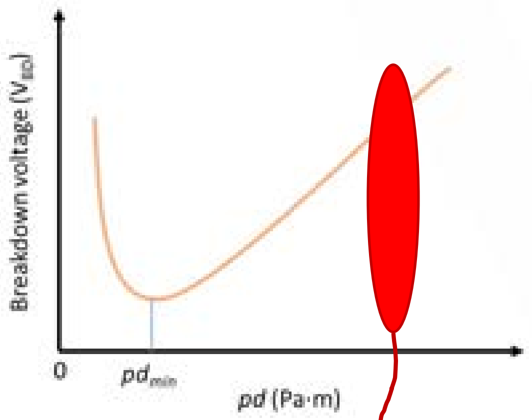


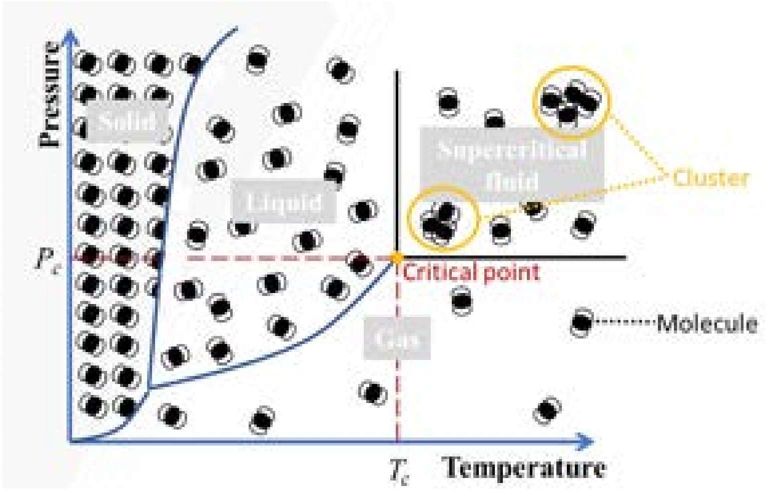
T. Kiyan *et al.*, "Negative DC pre-breakdown phenomena and breakdown-voltage characteristics of pressurized carbon dioxide up to supercritical conditions," *IEEE transactions on plasma science*, vol. 35, no. 3, pp. 656-662, 2007.

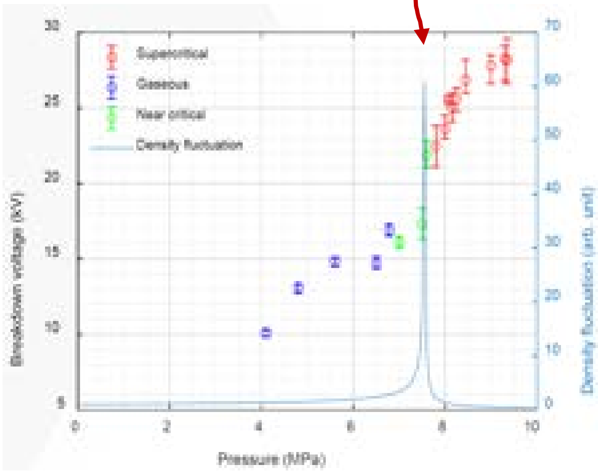
J. Wei *et al.* (c. 2019)

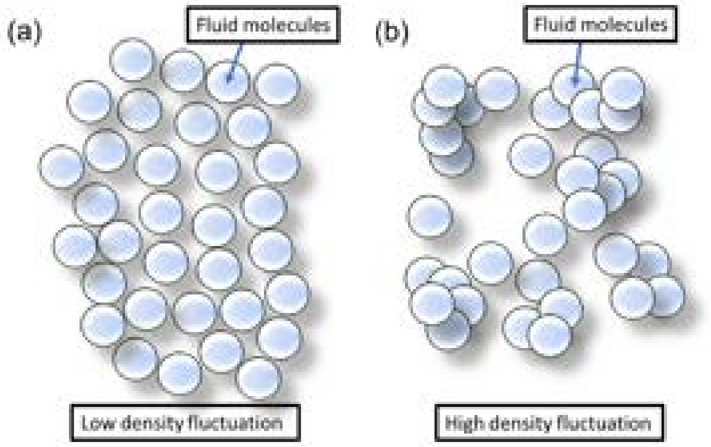
Dielectric Anomaly with Supercritical Fluids

- Dielectric strength increases with density
  - Paschen's law (uniform field)
  - Reason: Drop in mean free path leads to drop in probability of inelastic collisions (ionization, excitation, attachment)
- Density fluctuation reaches maximum at critical point due to clustering
  - Clustering leads to long mean free paths of electrons between collisions
  - Dielectric strength drops around critical point
- Further increasing temperature/pressure breaks up the clusters
  - Dielectric strength reaches new heights





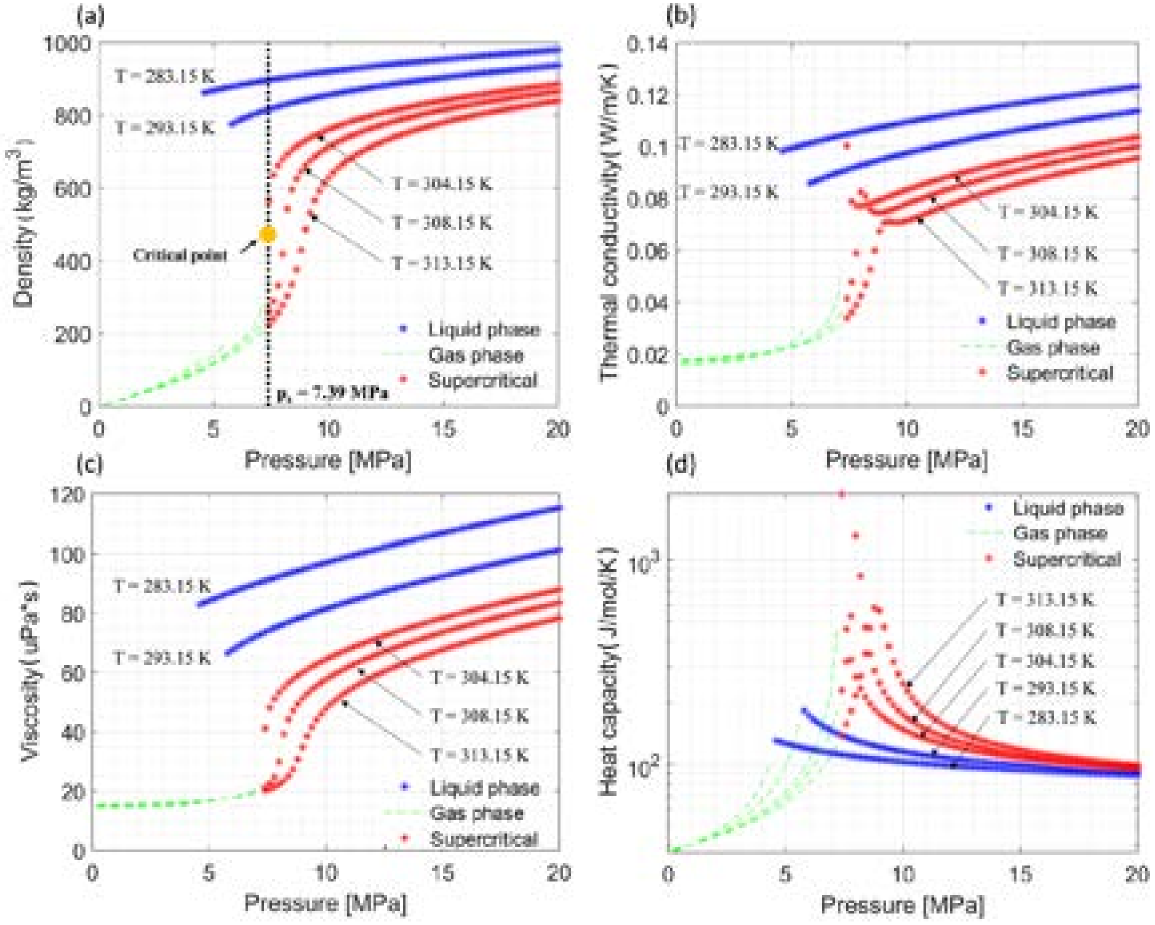




Supercritical Fluid Mixtures

- Base substance: CO_2
  - Good balance of properties
- Additives for <u>binary</u> mixtures:
  - O_2 for better arc performance, reduction of carbon deposits, longer life of fluid
  - H_2 for higher thermal conductivity
  - C_2H_6 for lower critical temperature
  - CF_3I for higher dielectric strength (we measured 350 kV/mm in uniform field)

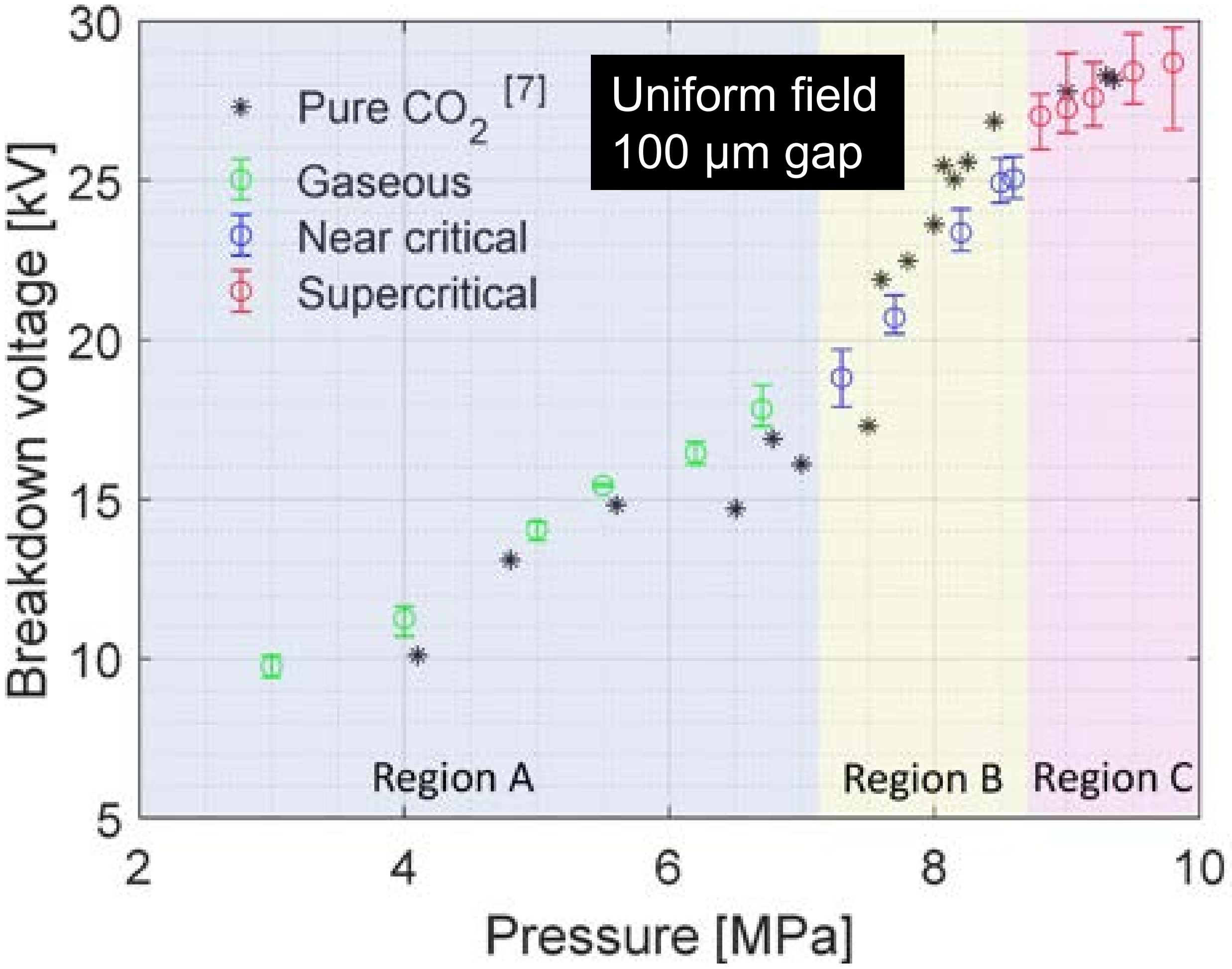
Pure CO_2 (base substance):



J. Wei , A. Cruz, F. Haque, C. Park, L. Graber, “Investigation of the dielectric strength of supercritical carbon dioxide–trifluoroiodomethane fluid mixtures,” *Phys. of Fluids*, 32, 103309 (2020)

Dielectric Strength of CO_2-CF_3I (sc)

- Intrinsic dielectric strength
  - Uniform field
  - Small gap
  - 100% self-restoring
- This particular mixture is not meant for arc quenching
  - Most suitable for non-arcing high power density applications, incl. high energy physics
- 25-30 kV in 100 µm gap uniform field
  - 250-300 kV/mm, higher than many solids and liquids

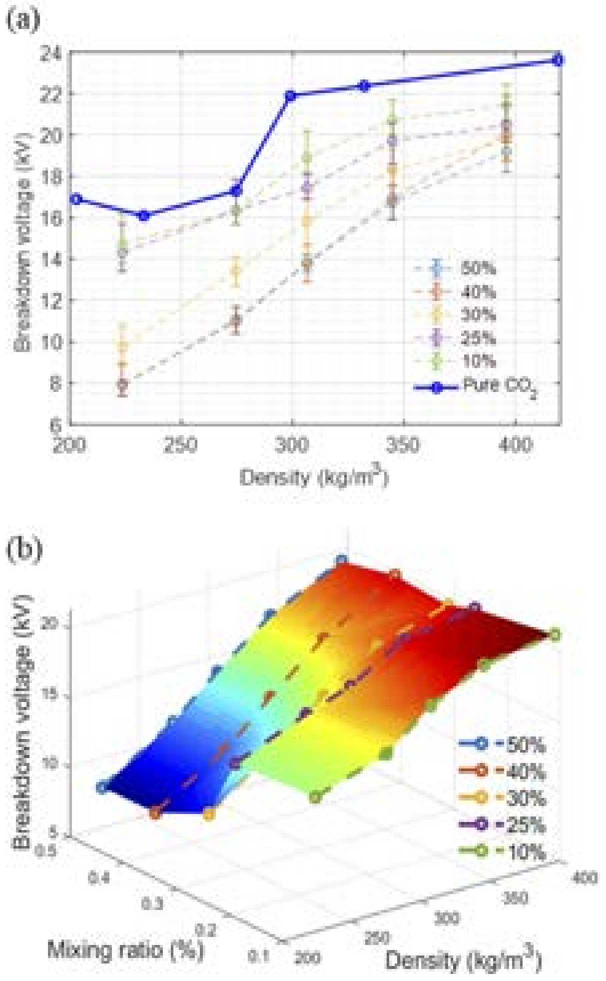


J. Wei et al., *IEEE Conference on Electrical Insulation and Dielectric Phenomena*, 2020

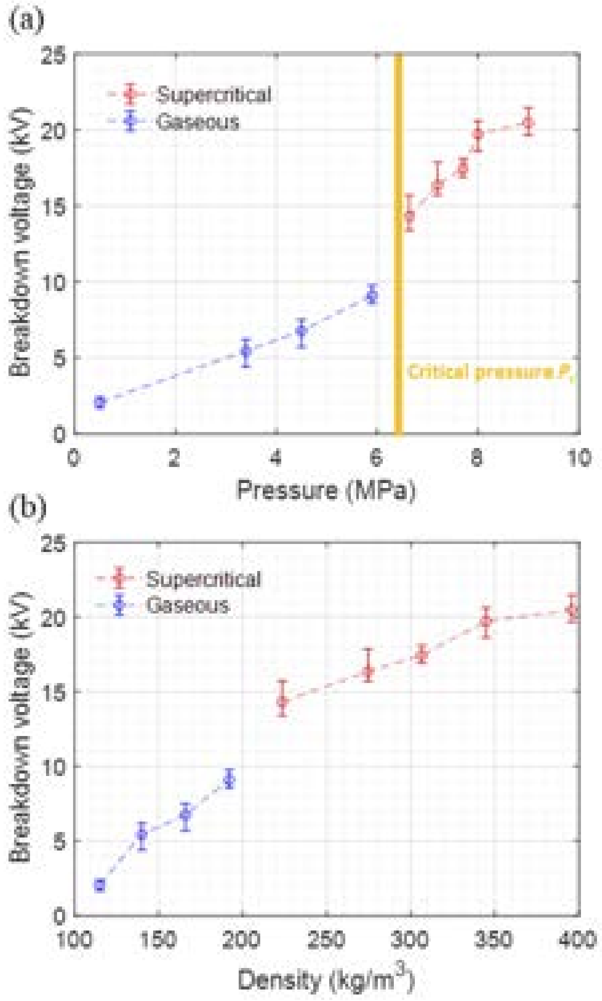
Dielectric Strength of CO_2-C_2H_6 (sc)

- Same experimental conditions
- Azeotropic mixture of 75% CO_2 + 25% C_2H_6 (by mass) has the lowest critical temperature (~RT)
  - Less heating effort
- Intrinsic strength lower than pure CO_2
- Unwanted polymerization can occur (deterioration)

0-50% C_2H_6 (by mass):

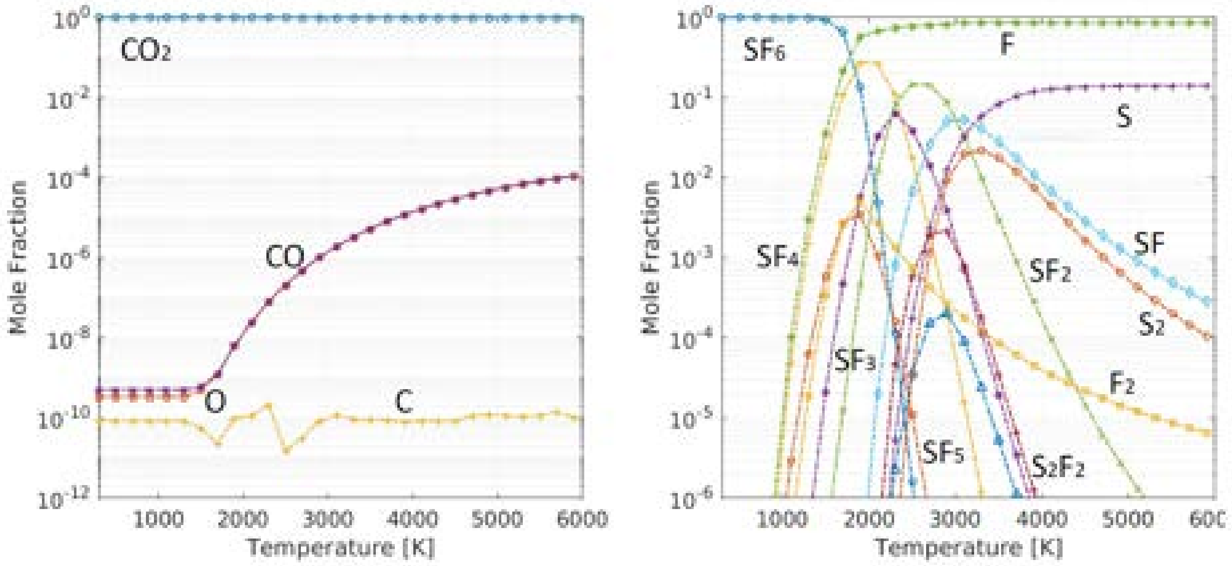


75% CO_2 + 25% C_2H_6 (by mass):



J. Wei et al., *Phys. Fluids* 32, 053305 (2020)

Dissociation in the Arc

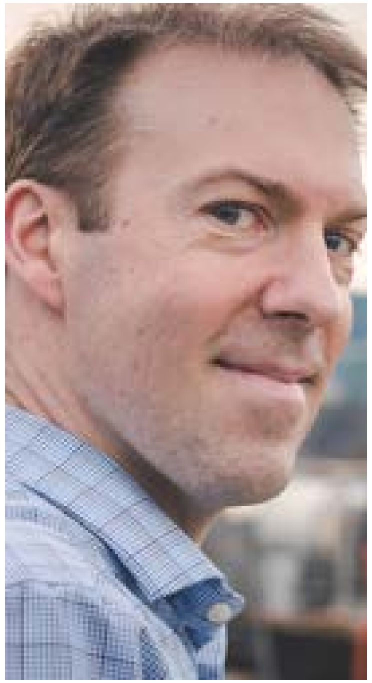


L. Graber, C. Park *et al.*, TESLA proposal (2021)

- Complex molecules (here: SF_6) tend to dissociate into many different species that do not recombine to the original substance
  - Result: Reduced life expectancy of the medium, potentially more deposits and wear on other parts of the breaker
- Pure CO_2 can result in carbon deposits since some of the released oxygen reacts with metal vapor. Additional O_2 can minimize this effect.

TESLA[1] Team

[1]Tough & Ecological Supercritical Line Breaker for AC



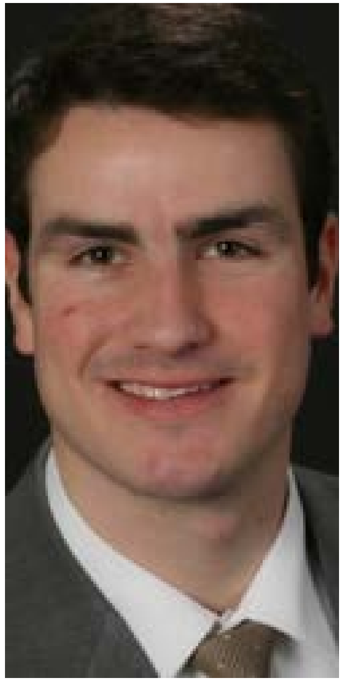
Lukas Graber
Principal investigator

Santiago Grijalva
Grid applications and value proposition

Jonathan Goldman
Tech-to-market, start-up company

Lauren Garten
MOV studies

Chanyeop Park
Design considerations, decomposition products, and synthetic testing



Juergen Rauleder
Fluid dynamic, design, CFD

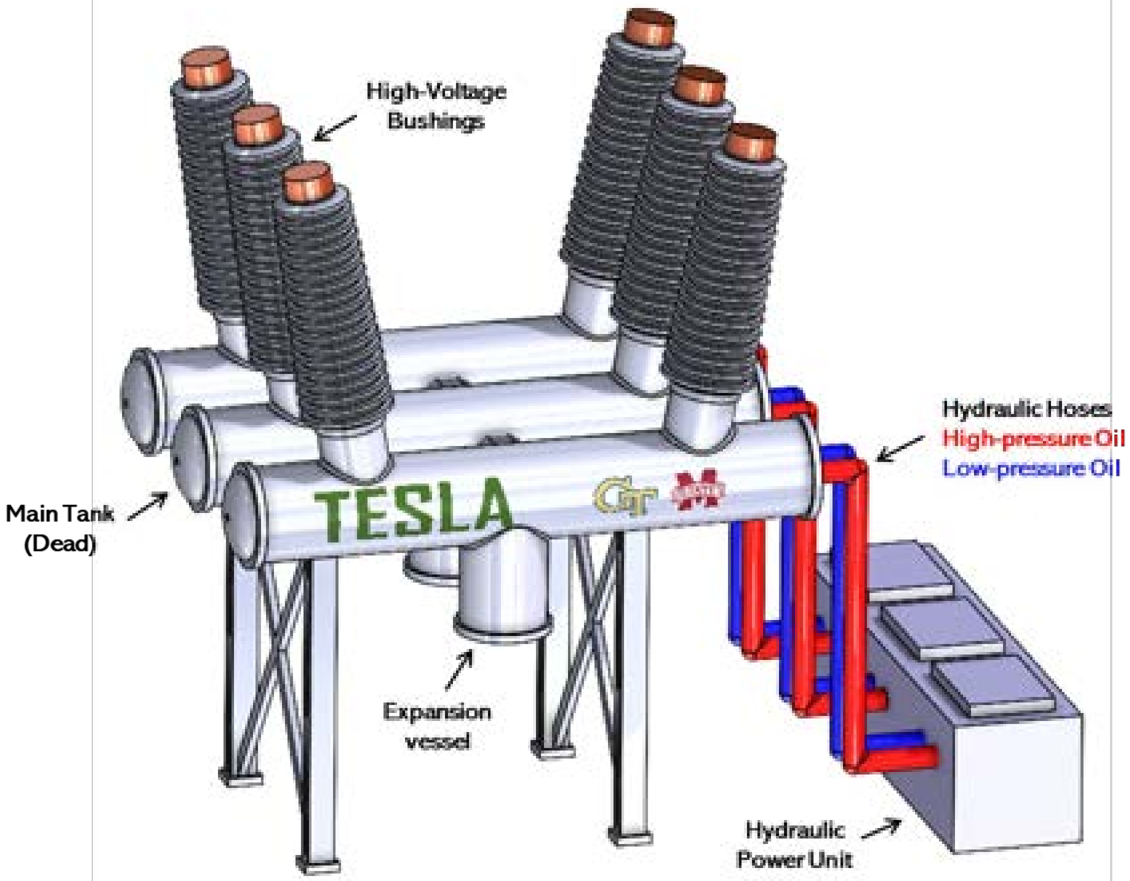
Zhiyang Jin
Project management, electrical-thermal-mechanical design

Collaboration: Georgia Institute of Technology + University of Wisconsin UW Milwaukee

Sponsor: arpa·e

TESLA Project Objective

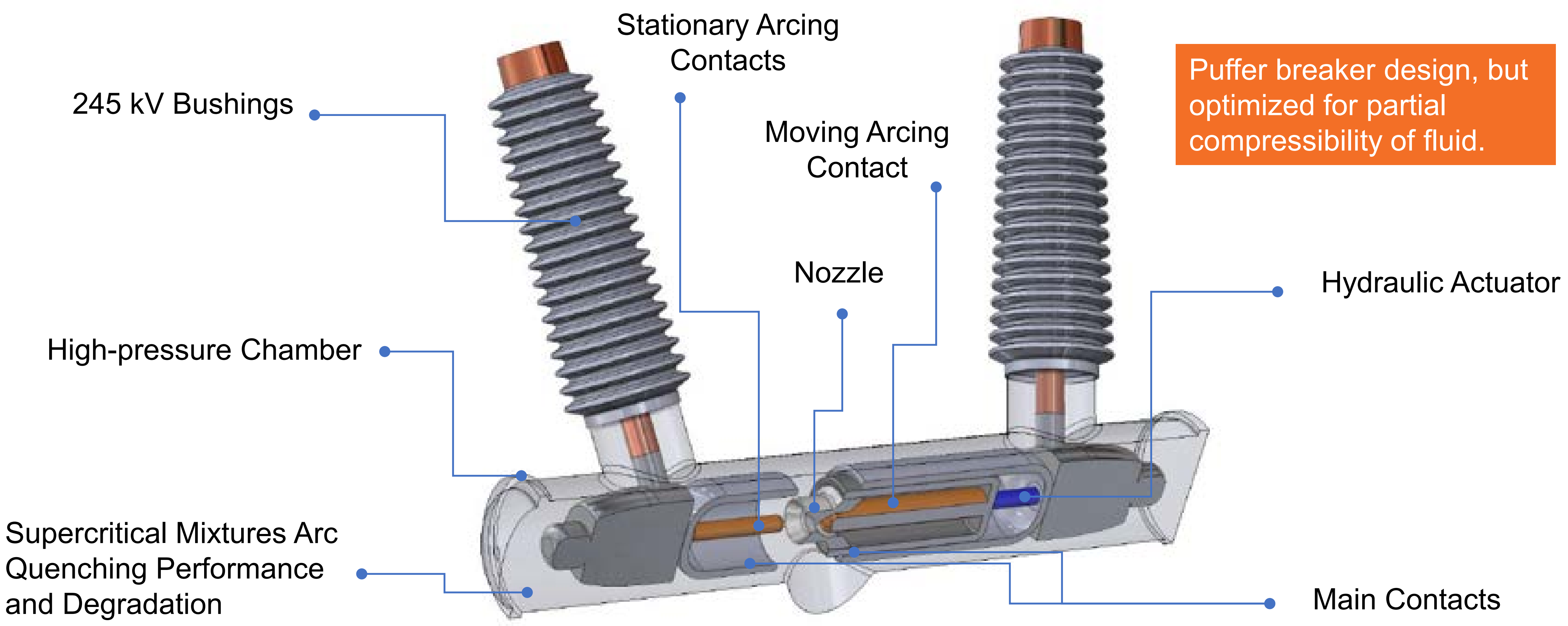
- Development of SF_6-free 245 kV, 4 kA (63 kA) dead tank three-phase circuit breaker[1]
  - Smaller footprint: > 30% volume reduction
  - Less maintenance effort and longer service time
  - Reduced carbon footprint
- Unique technologies
  - New switching medium: Supercritical CO_2-based mixtures
  - Supercritical CO_2 has higher dielectric strength and longer life expectancy than SF_6
  - More efficient arc quenching mechanism
  - Flexibility due to detached hydraulic power unit
  - Guaranteed leak-free design (all-metal sealing)



L. Graber, C. Park et al., TESLA proposal (2021)

[1]A reduced-scale version might develop in a version that is suitable for distribution systems.

TESLA: Tough and Ecological Supercritical Line Breaker for AC



Schematic drawing of single-phase TESLA (partially cross-section view)

Puffer breaker design, but optimized for partial compressibility of fluid.

Challenges

- High pressure fluid (8-12 MPa steady-state)
  - Safety aspects
  - Pressure rise during arcing phase (likely higher than SF_6)
- Fluid with low viscosity/high diffusivity
  - Seal around flanges, fittings, actuators etc.
- Compressible limit of fluid
  - Design of nozzle and piston to limit solidification
  - Absorption of shockwaves (“hammer arrestor”)
  - CFD code for partially-compressible, low viscosity, highly turbulent flow (plus ionization, electrohydrodynamics EHD, magnetohydrodynamics MHD)
- Build substation-grade apparatus with students on campus

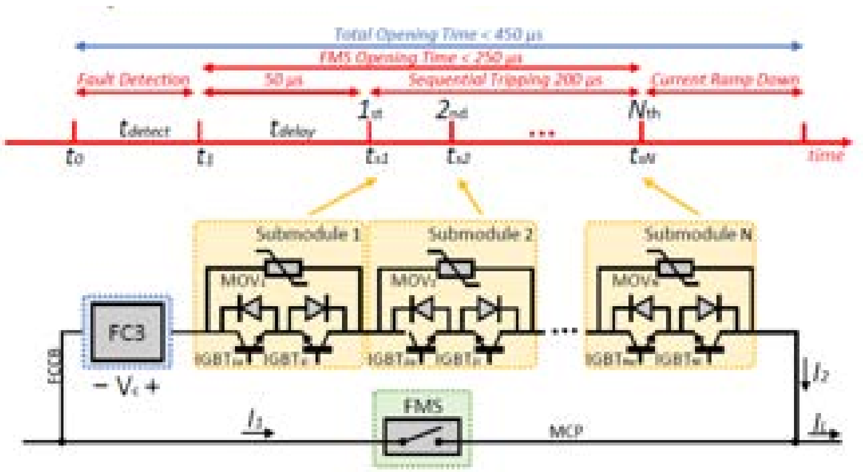
TESLA Project Timeline

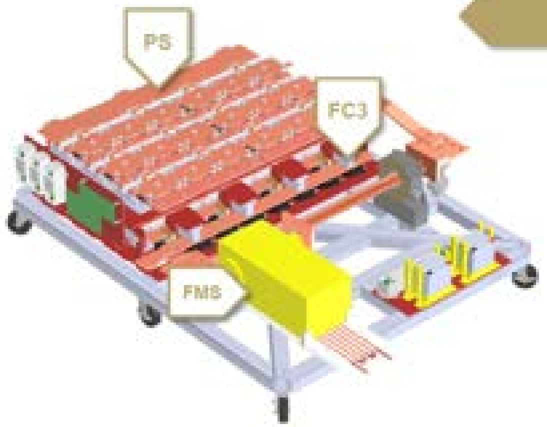
- Funded by ARPA-E through their SF6-FREE program
  - June 2022 – May 2025
- Design, build, and test/demonstration of reduced-scale version at UWM (by 2024)
  - LC synthetic test circuit to initiate current waveform and superimpose TRV
  - BIL high voltage testing
  - Heat run at RMS current (in short circuit)
- Design, build, and test of full-scale version at KEMA-PA (by 2025)
  - Same as above, plus:
  - Power testing at full 63 kA symmetrical RMS fault current
- Includes tech-to-market strategy
  - Currently in early phase of customer discovery interviews.
  - We are looking forward to discuss our commercialization efforts with utilities, switchgear manufacturers, and suppliers.

Bonus: EDISON (Efficient DC Interrupter with Surge Protection)

Specifications	Units	Value
Rated Voltage (DC)	kV	12
Peak Interruption Voltage	kV	24
Rated Continuous Current	kA	2
Peak Fault Current	kA	8
Minimum Source Inductance	µH	300
Maximum Energy Absorbed	kJ	30
Fault Clearing Time	µs	450
Trip Slew Rate	A/µs	40
	kA	3
FMS Volume	L	270
Power Density	MW/m³	60
Efficiency	-	99.97%
Power Density	MW/m³	60
Arc Energy in an incident*	cal/cm²	0.01
	J/cm²	0.04

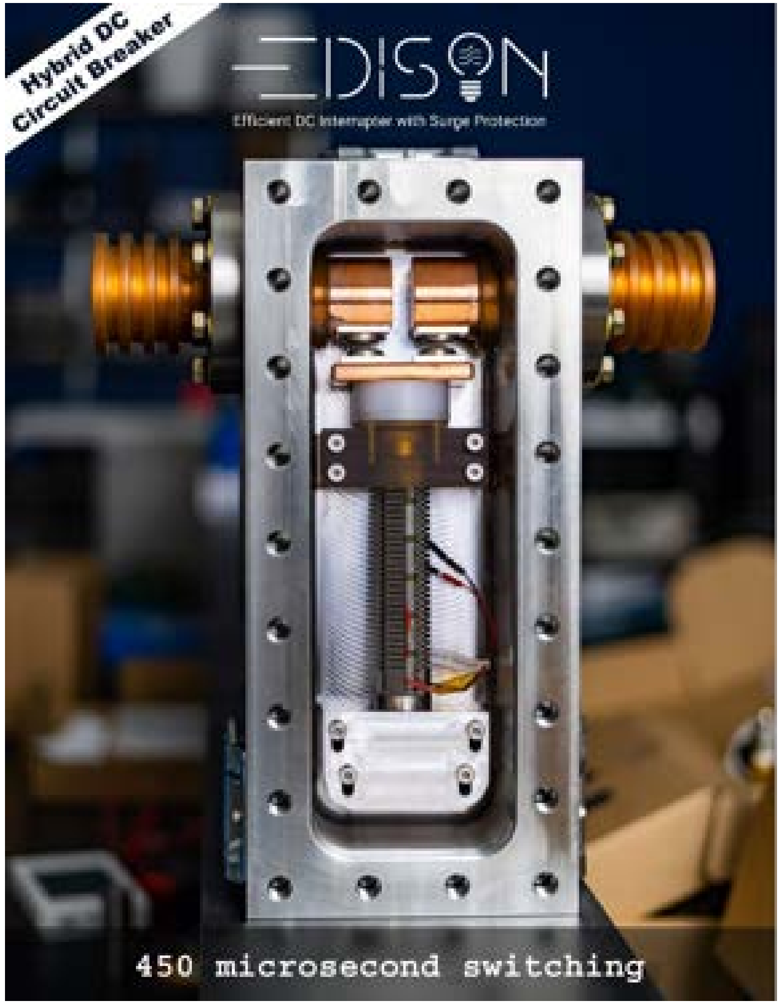
* Calculation is based on an 8-kA fault current in 500 µs





Blade

- OPEN Failure Mode
- Scalable & Modular
- Volume 0.4 m³
- Potential Application: Data Centers, All-Electric Ships, etc.



A. Cruz et al., EDISON flyer (2022)

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Thank you

- Special thanks to my collaborators, students, staff in the mechanical machine shop.
- Sponsors:
  - ARPA-E: TESLA and EDISON projects
  - NSF: Fundamental research on supercritical fluid mixtures