Advanced Gen-3 Concentrating Solar Power (CSP) Technologies and Analysis

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Rensselaer

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Outline

- Why we need Concentrating Solar Power (CSP)?
- Three different receiver pathways for Gen3 CSP: all have significant technical, economic, or reliability risk.
- Our project in exploring Salt Chemistry and Materials Selection/Compatibility
- Additional solar efforts from colleagues

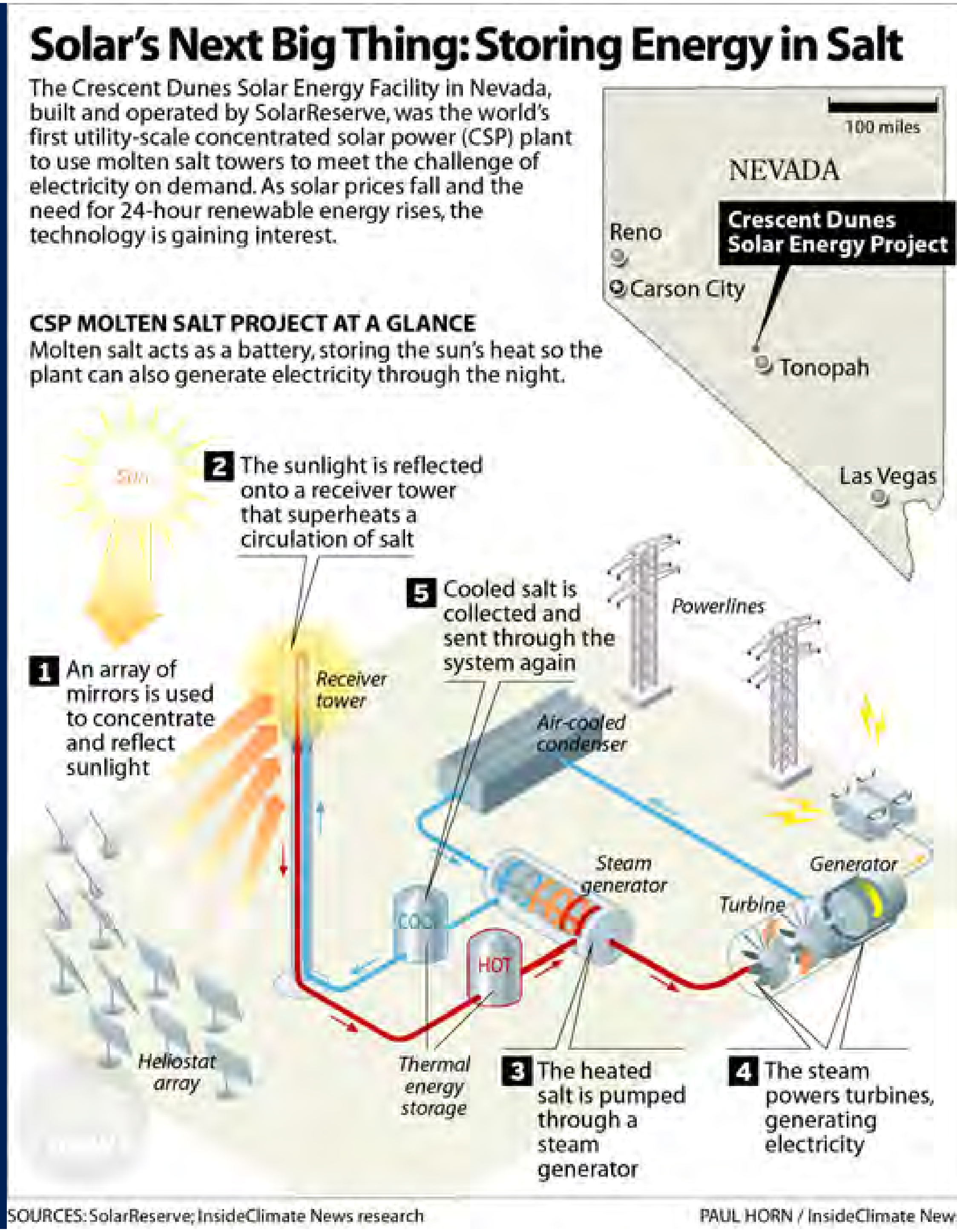
We'll need CSP's Thermal Energy Storage (TES) next because it is dispatchable

Two forms of solar generation:
Photovoltaic (PV) and Concentrating solar power (CSP)

PV: simple, low cost, but not dispatchable (you can't turn it on when you want it). It is changing the grid from a "base load grid" to a lumpy grid with gaps.

CSP: dispatchable, can be turned on or off on demand, supplying its own thermally stored solar energy to dispatch power any time on demand.

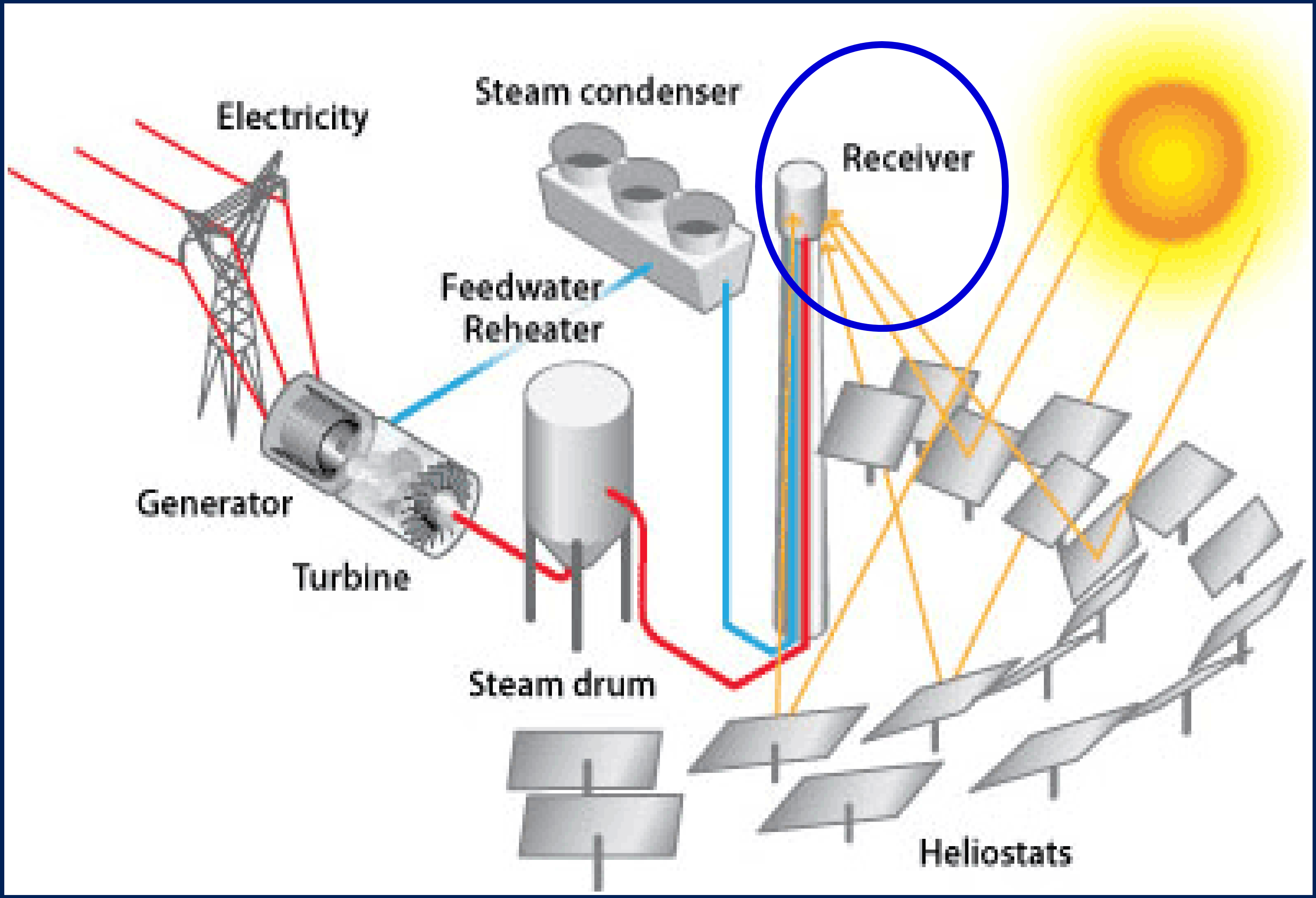
CSP is well-suited for covering the recurring gaps, especially the evening peak period after the sun sets, in PV generation.


Solar's Next Big Thing: Storing Energy in Salt
The Crescent Dunes Solar Energy Facility in Nevada, built and operated by SolarReserve, was the world's first utility-scale concentrated solar power (CSP) plant to use molten salt towers to meet the challenge of electricity on demand. As solar prices fall and the need for 24-hour renewable energy rises, the technology is gaining interest.
100 miles
NEVADA
Reno
Carson City
Crescent Dunes Solar Energy Project
Tonopah
Las Vegas
CSP MOLTEN SALT PROJECT AT A GLANCE
Molten salt acts as a battery, storing the sun's heat so the plant can also generate electricity through the night.
Sun
1 An array of mirrors is used to concentrate and reflect sunlight
2 The sunlight is reflected onto a receiver tower that superheats a circulation of salt
Receiver tower
5 Cooled salt is collected and sent through the system again
Powerlines
Air-cooled condenser
Steam generator
Generator
Turbine
COOL
HOT
Heliostat array
Thermal energy storage
3 The heated salt is pumped through a steam generator
4 The steam powers turbines, generating electricity
SOURCES: SolarReserve; InsideClimate News research
PAUL HORN / InsideClimate News

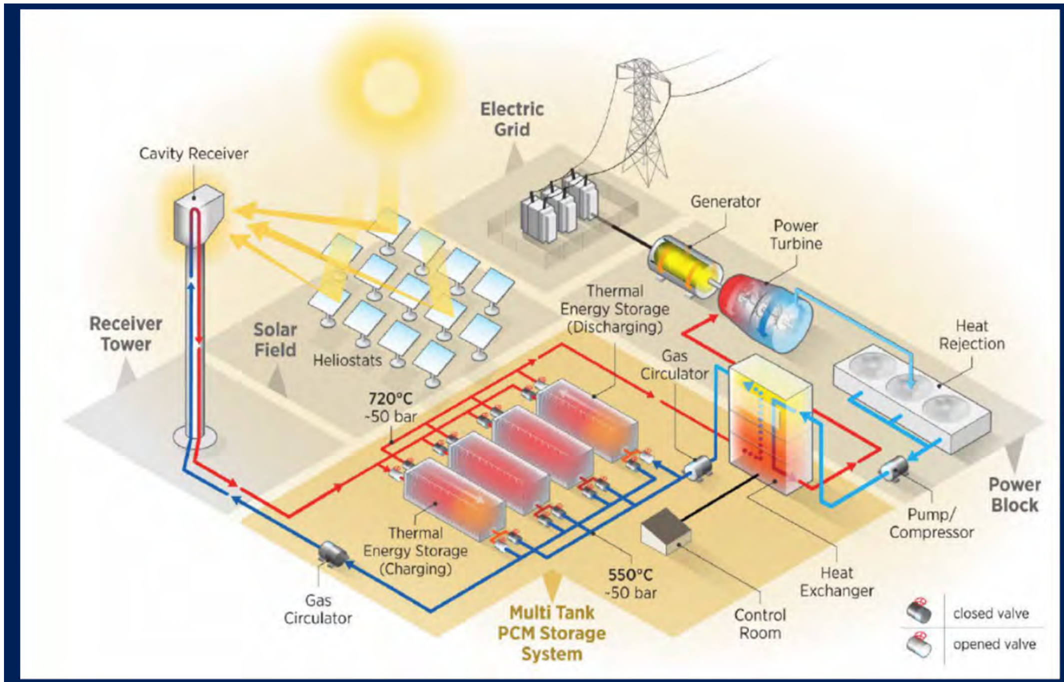
110-MW^e Crescent Dunes Solar Energy Project in Tonopah, Nevada. (source: SolarReserve). This molten-salt power tower is designed for 10 hours of thermal storage and an annual capacity factor of 52%.

Project	Country	MWe	Storage Capacity (hours)	Power Purchase Agreement Price (PPA) (¢/kWh)	Status	Completion Date
Crescent Dunes	U.S.	110	10	13.7	Operation	Q4 2015
Noor III	Morocco	150	7.5	16.3	Construction	Q4 2017
Redstone	South Africa	100	12	12.5 (PPA to be signed)	Development	Q3 2018
DEWA CSP Project Phase I	United Arab Emirates	200	12	8.0 (targeted)	Planning	Q2 2021
Copiapo	Chile	240	14	6.3 (bid)	Planning	TBA

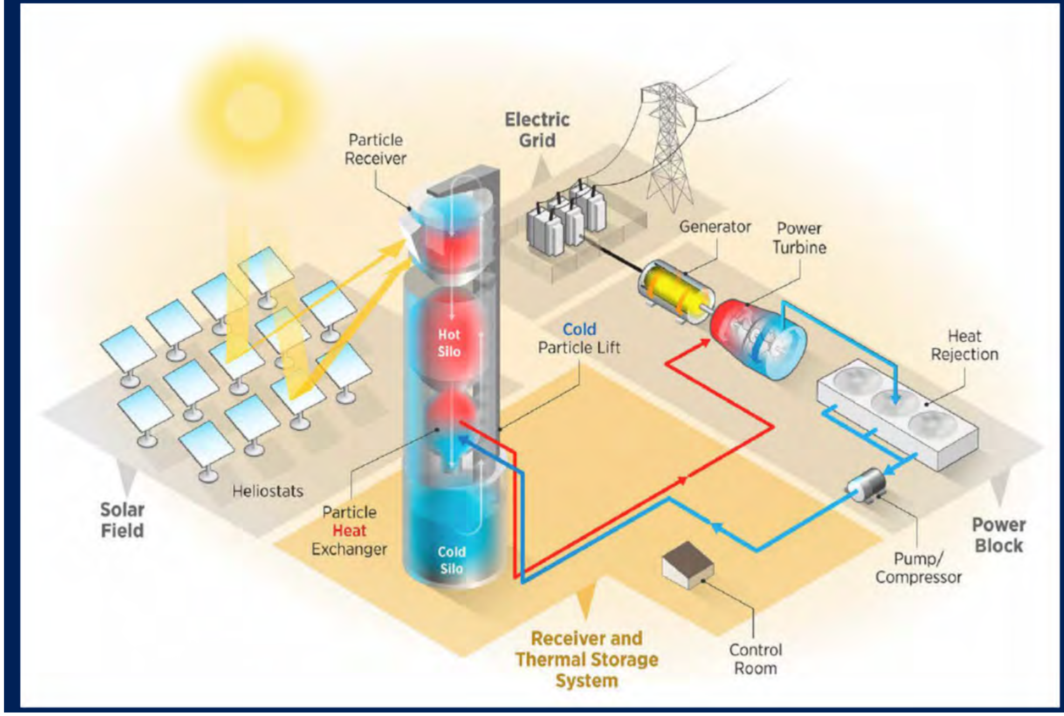
Gen3 CSP: Lower the cost of a CSP system by nearly 40% toward DOE's 2030 cost goals of $0.05 per kWh for baseload configurations.



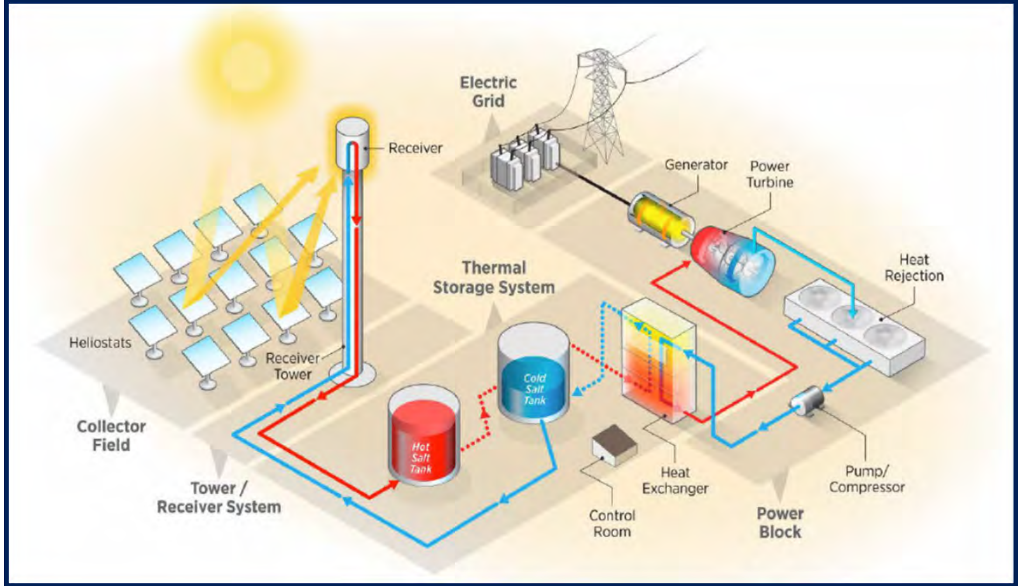
Three different receiver pathways in Gen3 CSP.



Gas-phase receiver pathway:
Gas-phase receiver system with a modular phase-change material (PCM) thermal storage system. Led by **Shaun Sullivan, Brayton Energy**.



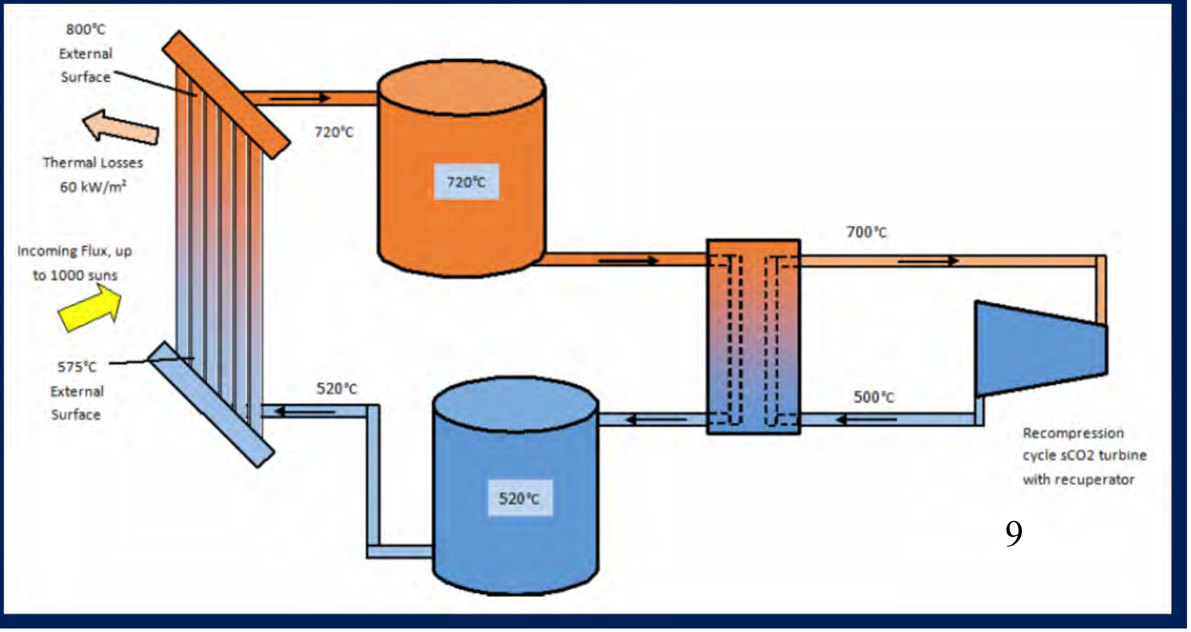
Particle receiver pathway:
Falling-particle receiver system with integrated storage and heat exchange for a power cycle. Led by **Cliff Ho, Sandia National Laboratories (SNL)**.



Molten-salt receiver pathway: Molten-salt power tower with direct storage of salt. Led by **Craig Turchi, National Renewable Energy Laboratory (NREL).**

Current and advanced salt designs are conceptually similar but future designs envision higher salt temperatures with a sCO^2-Brayton power cycle.

High temperature molten salt loop schematic with potential surface and fluid temperatures.

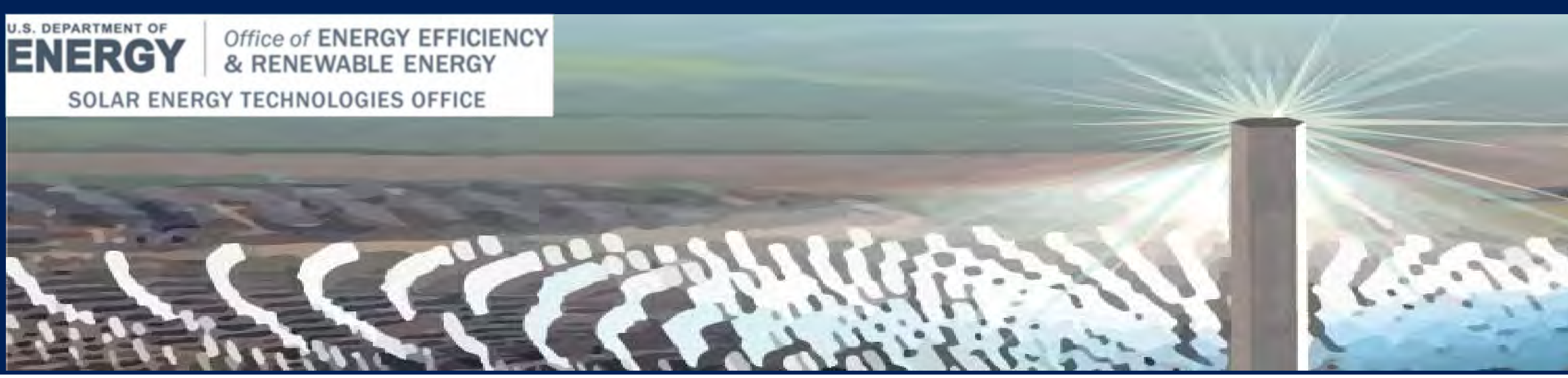


Various pathways show promise for cost-effective, reliable performance. The technical gaps and risks are overlaid on the pathways. No pathway through all sub-systems exists without at least one significant technical, economic, or reliability risk, **as indicated in red**.

COLLECTOR FIELD	RECEIVER	THERMAL TRANSPORT	THERMAL STORAGE	HEAT TRANSFER MEDIA	HEAT EXCHANGE	POWER CYCLE
SOLID MEDIA	• **Thermal Efficiency:** • Particle Loss • Flow Velocity Control and Monitoring	• Reliability • Mechanical and Thermal Efficiency • Scalability • Insulation	• Charging and Discharging Particle loss, Efficiency, Scalability	• Particle Attrition • Optimized Performance Character	• Low Cycle Fatigue • Particle Mass Flow Control • Ramp Rates & Transients	
MOLTEN SALT	• Thermal Conductivity • Thermal Stability • Tube Strength and Durability	• **Pipe Material Compatibility** • Freeze Recovery • Pumps Valves Seals • Leak Detect	• **Corrosion Behavior** • **Chemistry Monitoring and control** • Tank Cost	• Characterize Material Properties • Cost / Supply Chain	• **Material Compatibility w/ salt & CO_2** • Freeze Protection • Thermal Ramp Rates	
GAS	• High Pressure Fatigue • Absorptivity Control and Thermal Loss Management	• Recirculator Cost & Operating Power • Large Pipes High Cost	• **Storage Concept not Determined**	• Low Thermal Conductivity • Low Heat Capacity	• Requires High Area • Multiple Heat Exchangers • Cascading Temperature	

The Harsh Environment of Molten Salts

- Temperature: room to 800°C
- Salts: The ternary salt provided by Israel Chemicals Ltd (ICL), then purified by NREL.
  - mol.%: 44.7 $MgCl_2$ – 25.8 KCl – 29.4 NaCl
  - wt.%: 53.9 $MgCl_2$ – 24.3 KCl – 21.8 NaCl
- Major issues: corrosion (safety) and price!



Our Team: Roles and Technical Gaps/Challenges

Investigators	Institution	Role
Li (Emily) Liu	Rensselaer Polytechnic Institute	Lead the project; develop and implement the *in-situ* Neutron Reflectometry (NR) and VISION spectroscopies.
Robert Hull	Rensselaer Polytechnic Institute	Develop and implement the *in-situ* Transmission Electron Microscope (TEM) and X-ray Photoelectron Spectroscopy (XPS) methodologies.
Jinsuo Zhang	Virginia Tech	Develop and implement the electrochemistry studies; lead salt property modeling efforts.

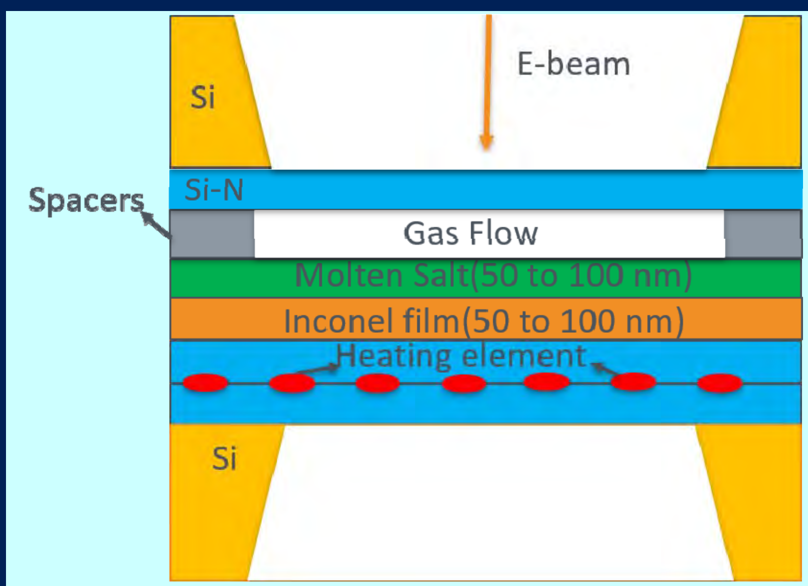
Technical Gaps and Challenges

Salt Chemistry: Develop, validate, and publish thermophysical, thermodynamic, and transport properties for the candidate salt compositions across the range of planned operating temperature using reagent-grade salts. Determine impurity effect on properties from industrial-grade salts.

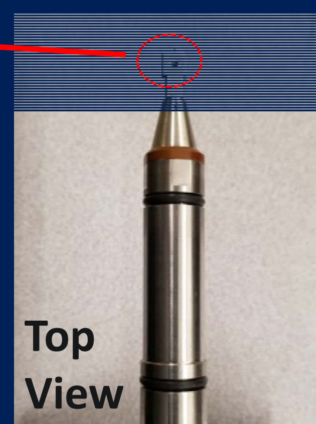
Materials Selection/Compatibility: Develop the correlations between corrosion kinetics and salt structure/dynamics which will lead to potential recommendations of selections of containment material and salts.

Hull: New In-situ TEM capabilities and studies: Experimental Design

In-situ TEM imaging and diffraction of Inconel corrosion at controlled changes in temperature and partial pressures of varying gases (oxygen, water vapor).

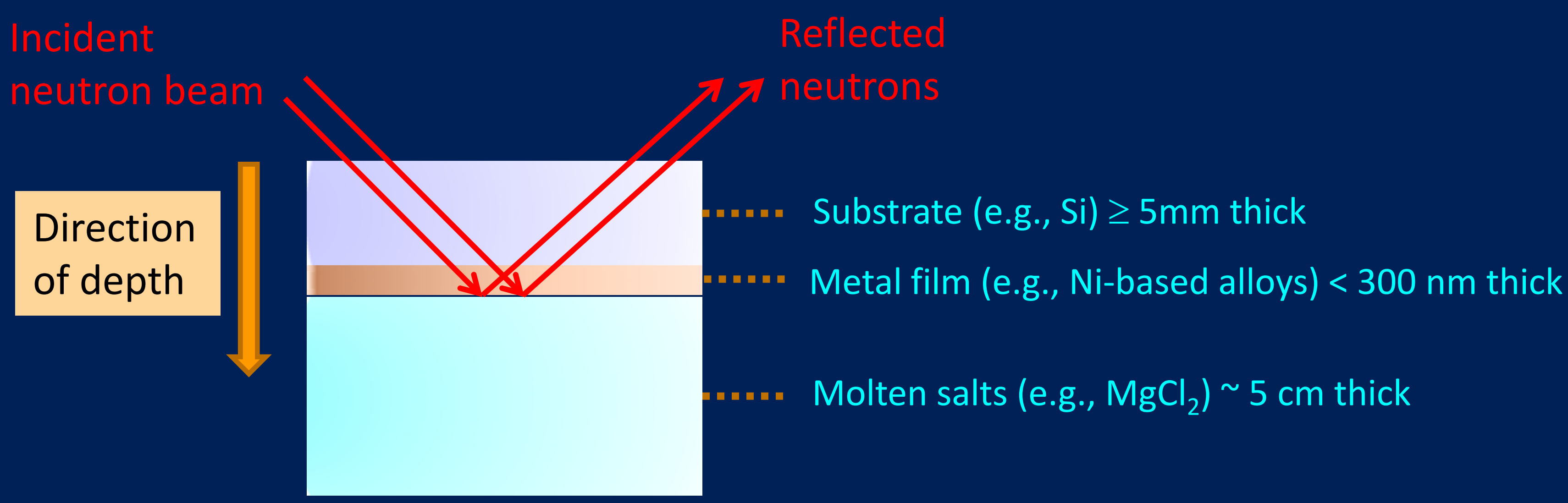


Schematic of in-situ TEM sample



Gas Holder manufactured by Hummingbird Scientific.

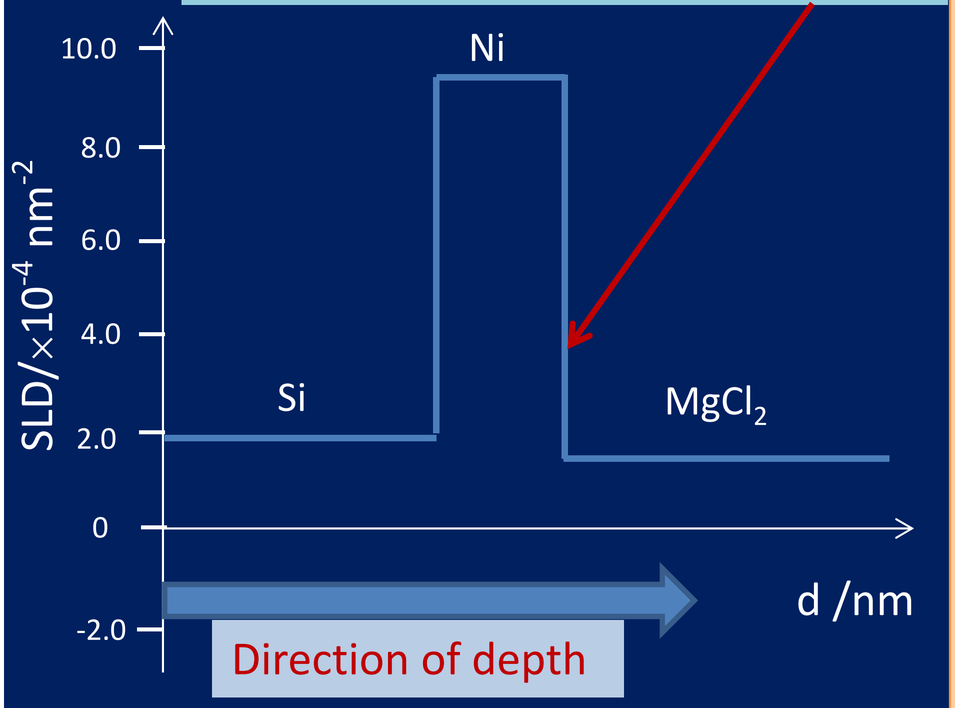
Liu: 1 - Neutron Reflectometry in-situ study of metal/interface/salts



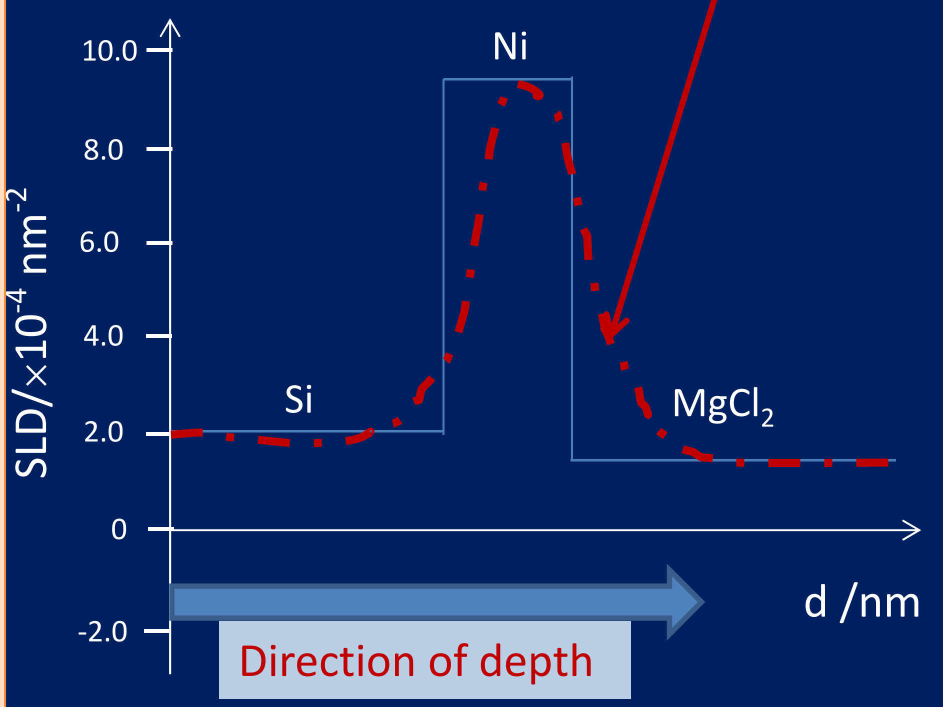
Measure: Reflectivity and dynamic structure factor of neutrons from metal, salts, and interface

For example, from Scattering Length Density (SLD)

Theoretical Scattering Length Density (SLD) without corrosion

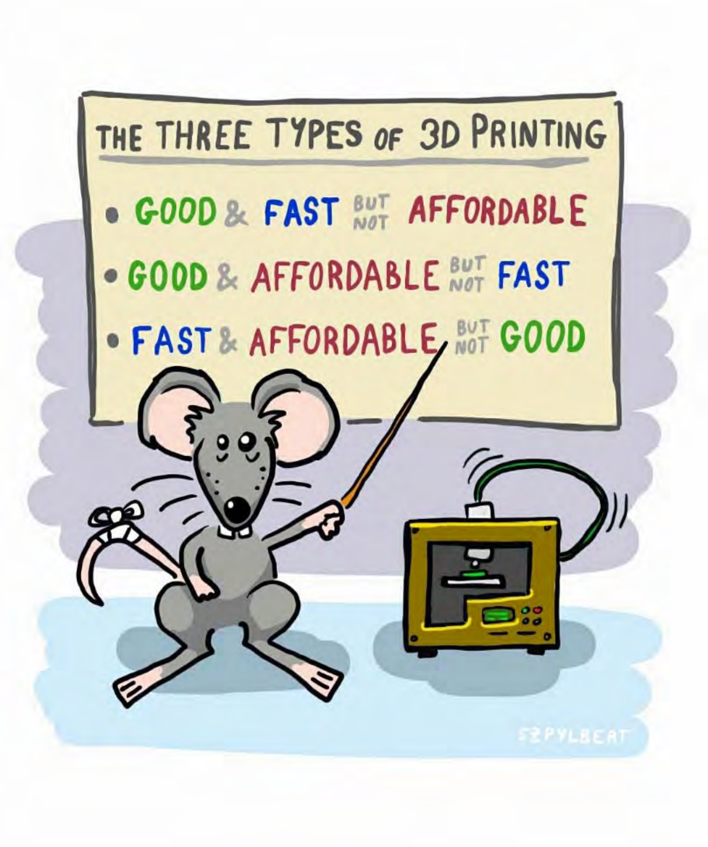


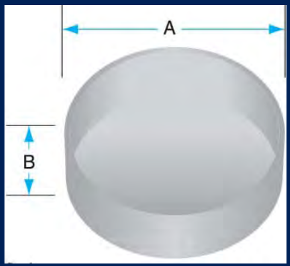
SLD when atomic level interaction or density change occurs

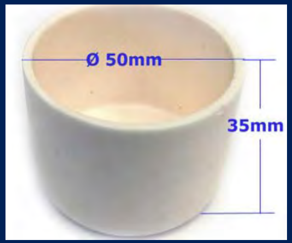


In-situ and real time change: density, roughness, composition, structure, etc.

In progress: manufacturing and initial testing







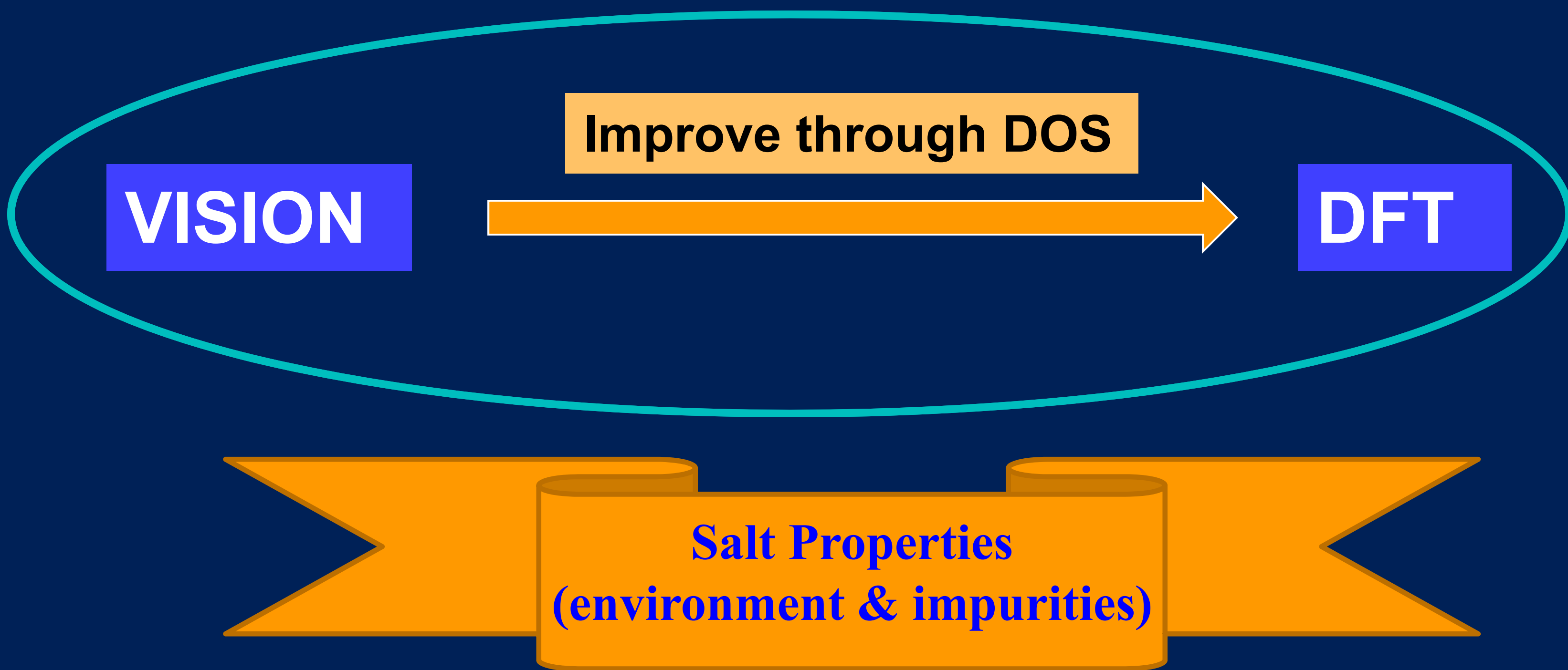
(a) sapphire

(b) quartz

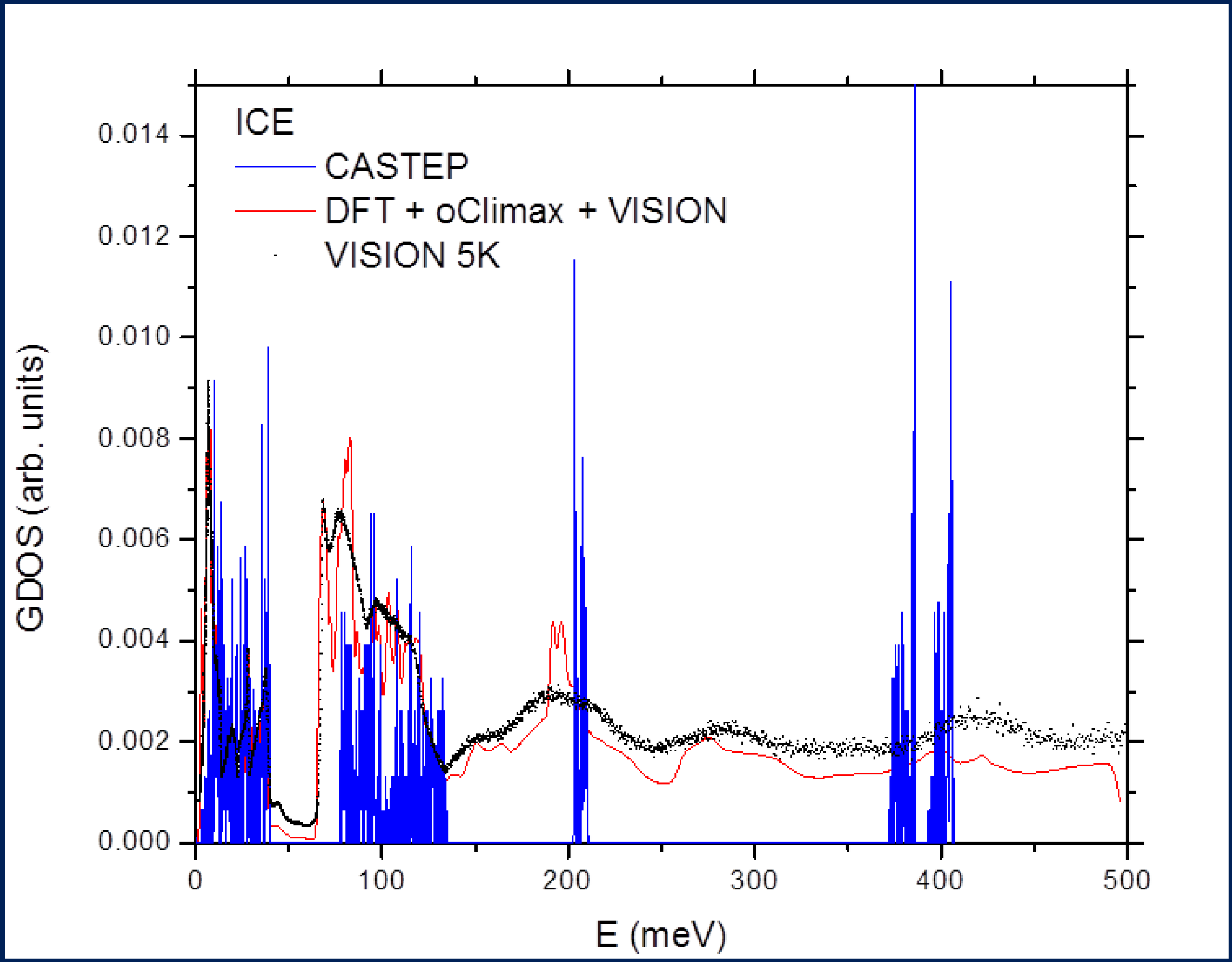
(c) alumina

2 - Salt Chemistry by Vibrational Spectroscopy – VISION

We can match density of states (DOS) measured from VISION experiments, taken at Spallation Neutron Source (SNS) of Oak Ridge National Laboratory ORNL), and calculated from density functional theory (DFT).



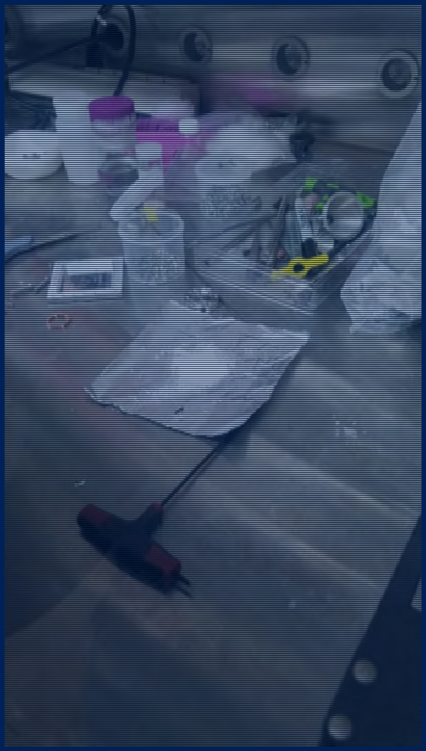
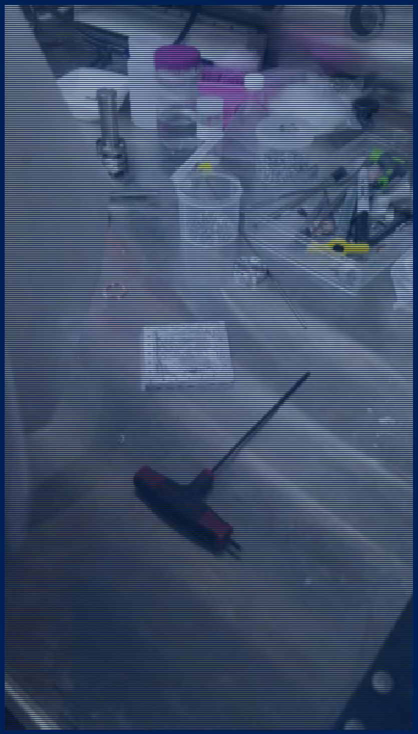
Improvement of DOS: VISION to DFT

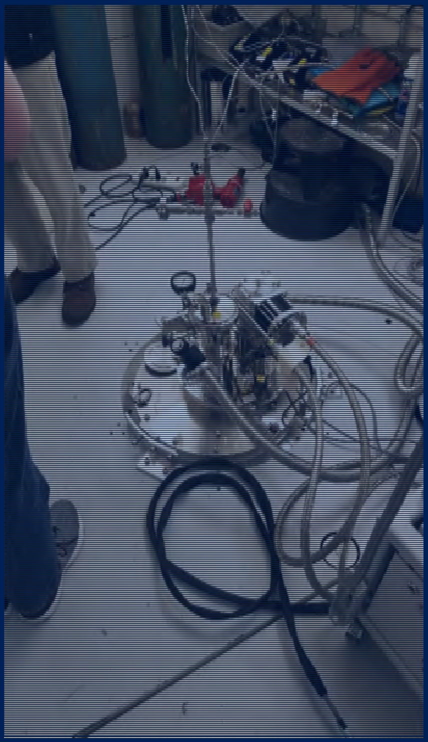


K. Ramić, et al., ***Annals of Nuclear Energy***, **120, pp. 778-787 (2018).**

K. Ramic, thesis title: "From Experiments to DFT Simulations: Comprehensive Overview of Thermal Scattering for Neutron Moderator Materials."

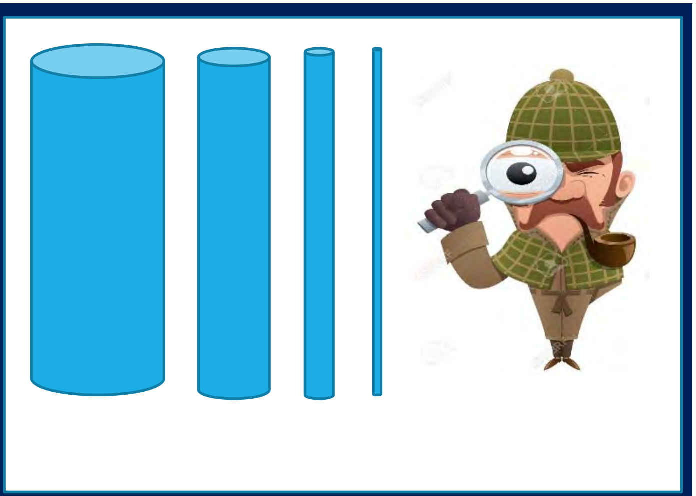
First VISION Experiment



Two different salts & temperatures:

- NREL (purified salts from ICL): 5, 150, 298, 340, 373, 420, and 473 K
- Virginia Tech (purified salts from websites such as VWR and Sigma-Aldrich): 5, 150, 298, 373, and 473 K

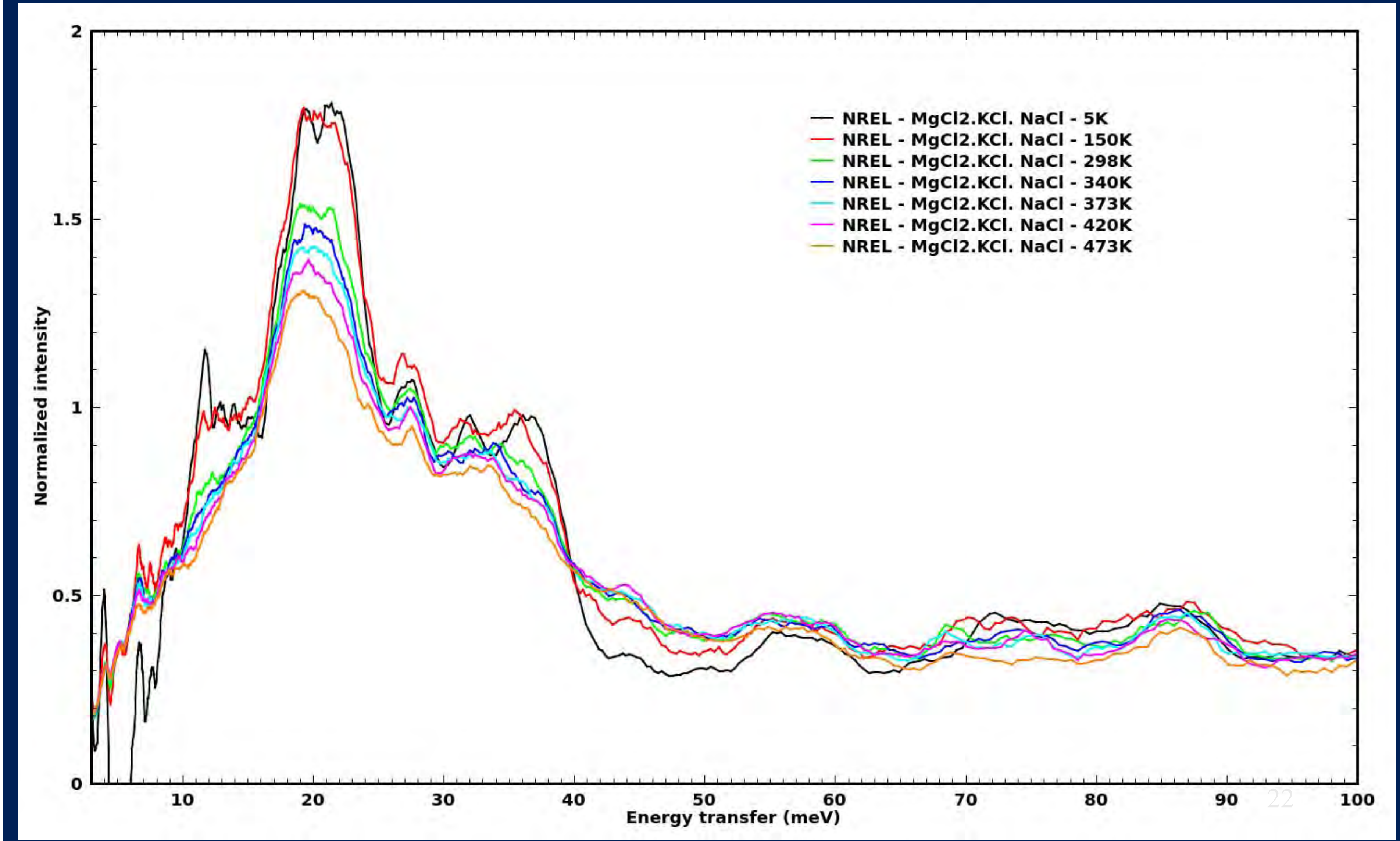


VISION measures

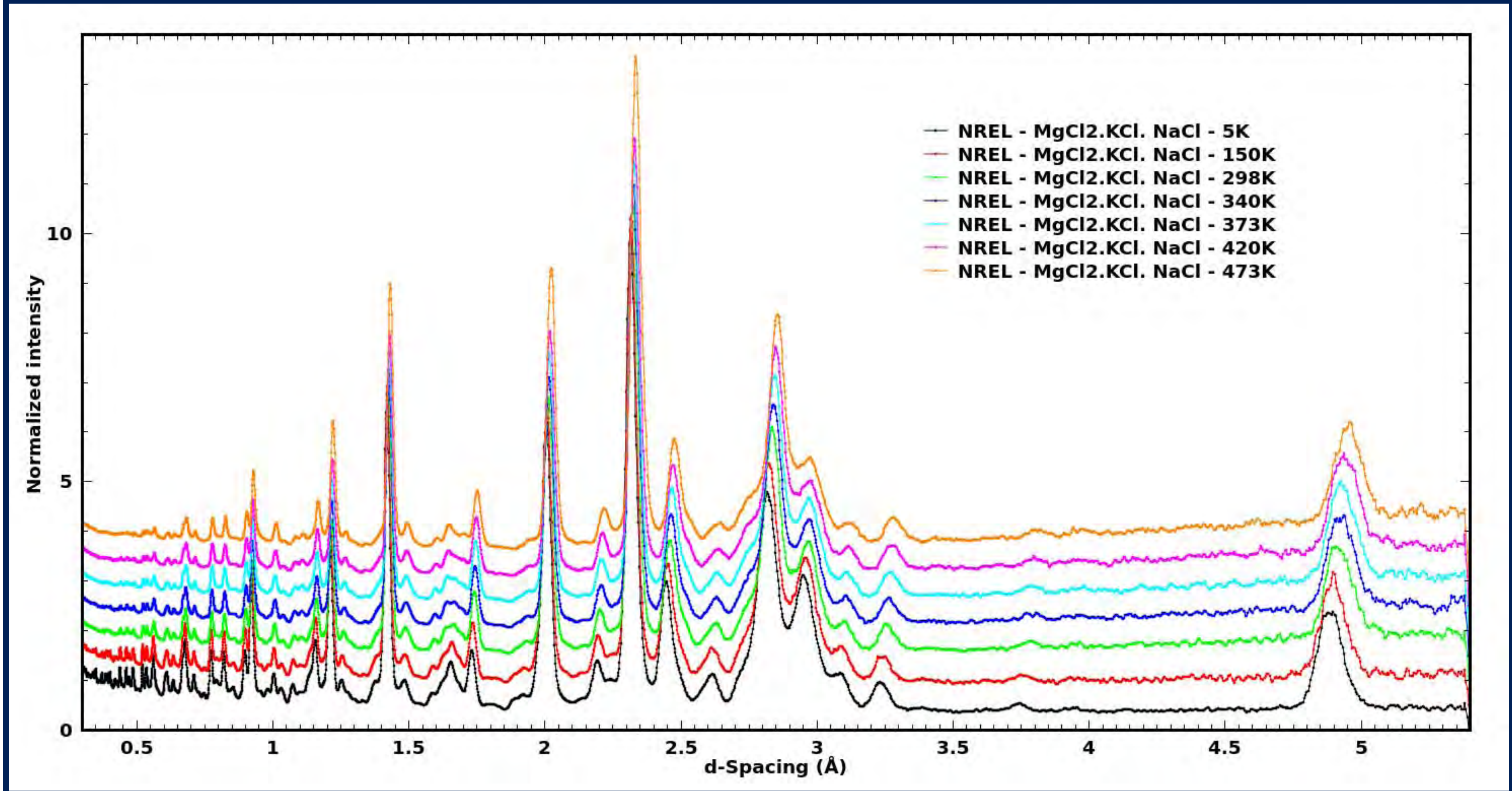
Dynamic Structure Factor $S(Q, \omega)$ and Diffraction

In analysis: $g(\omega)$ is an integral of $S(Q, \omega)$

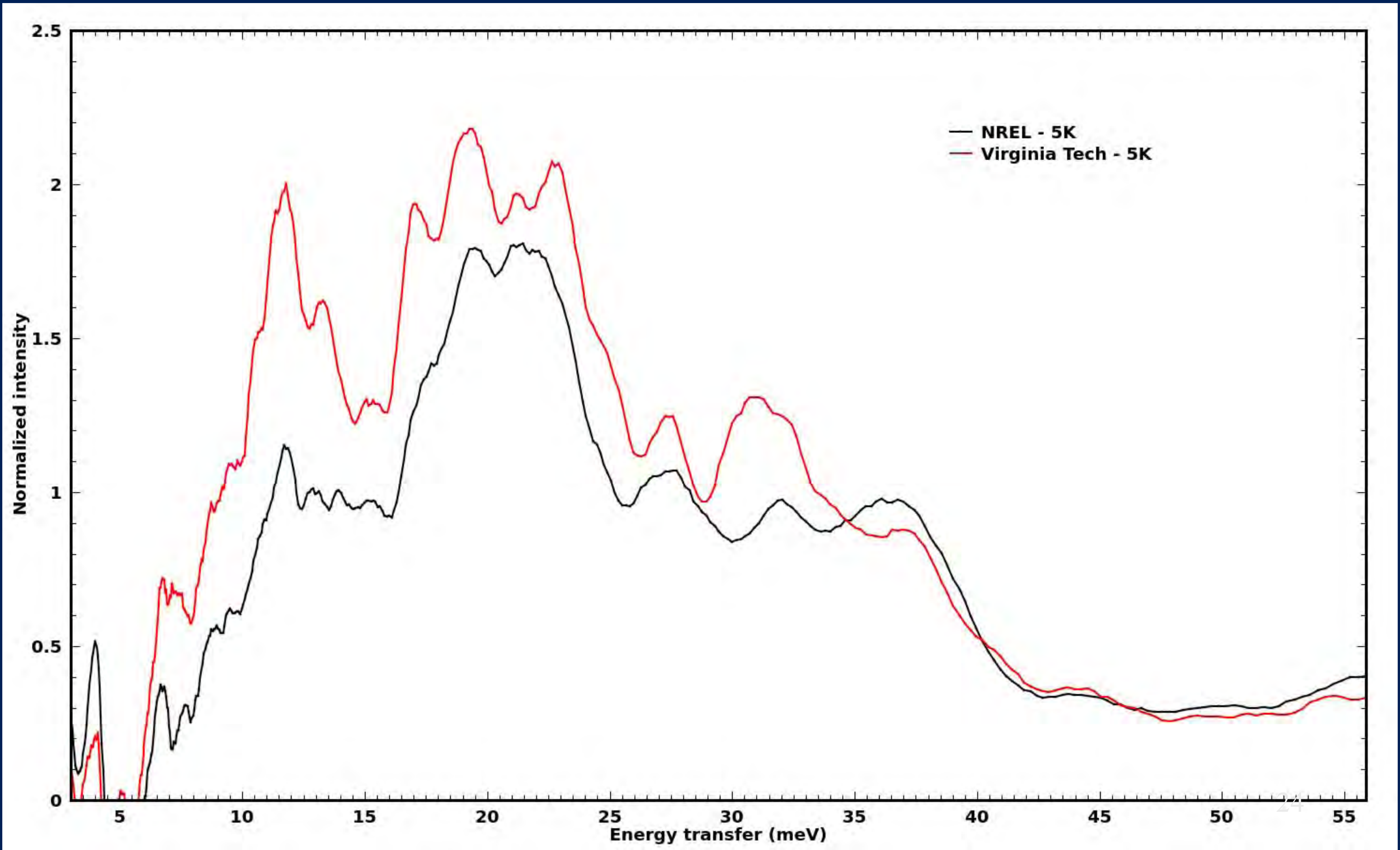
The NREL salt: S(Q, ω) for dynamics



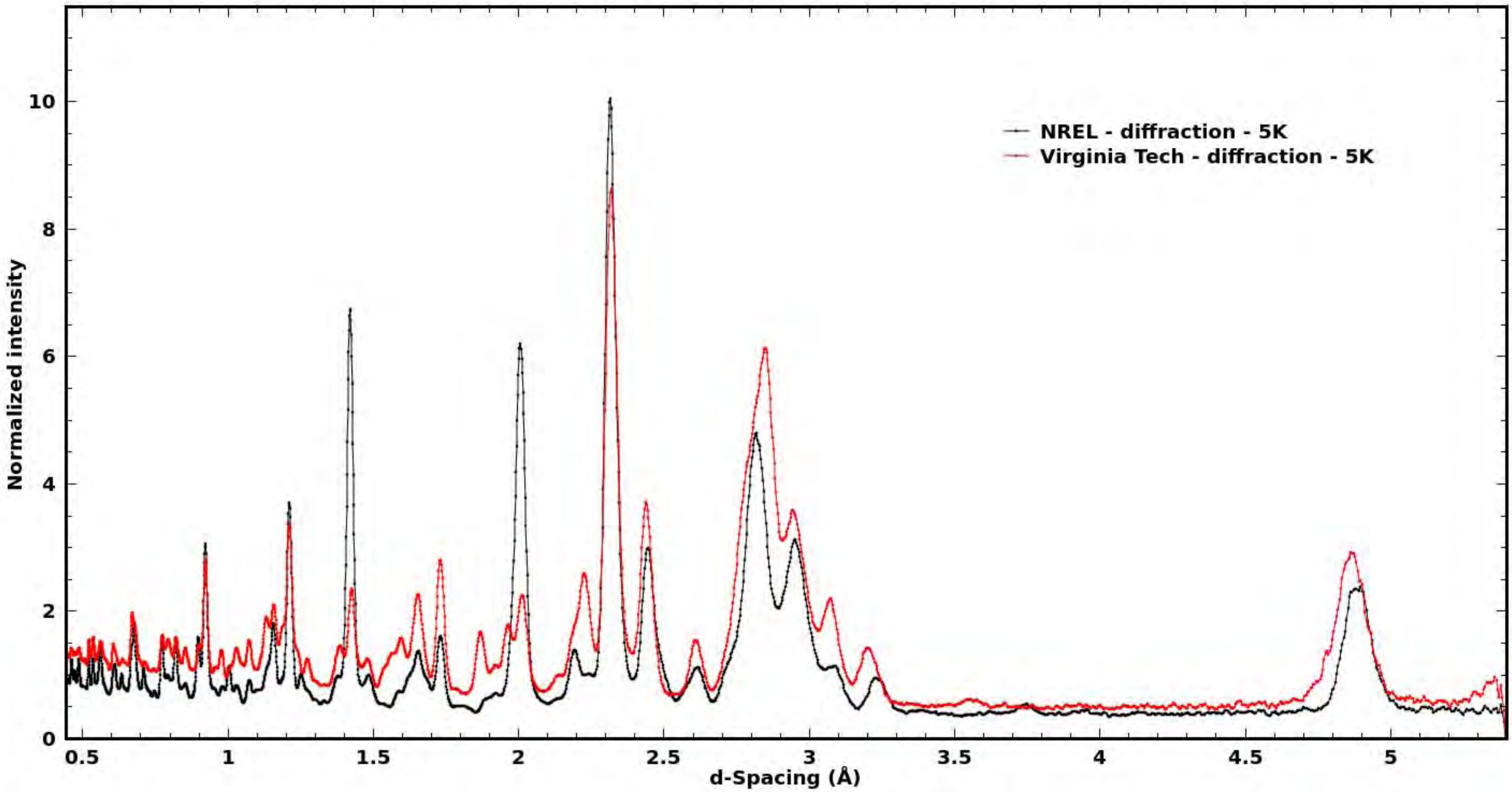
Simultaneous Neutron Diffraction: structure



S(Q,ω) comparison between two salts at 5K

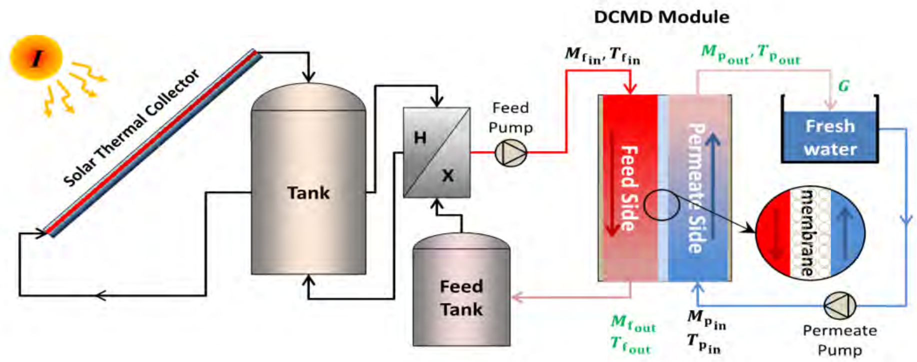


Diffraction comparison between two salts at 5K



Smart Solar Powered Desalination Systems for a Sustainable Future

by: Mamadou Lamine Diagne



Solar collector temperature dynamics

Solar Collector

$$T_t(x,t) = -\frac{q(t)}{A} T_x(x,t) + \frac{\eta G\, I(t)}{A\rho C}$$

Coupled parabolic/hyperbolic PDE

Normalized Membrane desalination

$$f_t(x,t) = -\alpha_f f_{xx}(x,t) + \lambda_f f(x,t)$$

$$p_t(x,t) = -\alpha_p p_{xx}(x,t) + \lambda_p p(x,t)$$

$$f_x(0,t) += -\frac{\gamma_f}{\gamma_p} p_x(0,t)$$

Temperature evolution in the feed and the permeate regions.

Objectives

- Develop a cascaded PDE control-oriented models for the combined process (complete the model with mass flow rate dynamics and a more detailed membrane pressure dynamics)
- Investigate the optimal operating conditions for the combined solar thermal membrane distillation system
- Efficient optimization strategies, optimal control approaches and monitoring methods
- Account for model uncertainties and time-delay arising from the non-colocation of actuators and sensors

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Collaborators

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SUMMARY

1) CSP is an important and exciting renewable solar energy field.

2) Moving forward: innovative in-situ capabilities and best models will need to be developed to address challenges in CSP.

Questions & Answers