NANOFLUIDS FOR ENHANCED ECONOMICS AND SAFETY OF NUCLEAR REACTORS

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University Park Hotel at MIT, Cambridge, MA
November 29, 2007

Outline

- Intro to nanofluids
- Nanofluid heat transfer (state of the art)
- Promising nuclear applications
- Research gaps
- Conclusions

Nanofluids

- *Nanofluids are engineered colloids* = *base fluid (water or any other liquid)* + *nanoparticles*
- *Nanoparticle materials: oxides (Al_2O_3, ZrO_2, SiO_2, Fe_3O_4), stable metals (Au, Cu), carbon (diamond, PyC, fullerene), polymers (teflon), etc.*
- *Particle size is small (1-100 nm)*

High surface to volume ratio → *Higher energy and mass transfer rates*

Low mass → *High colloidal stability (no sedimentation)*

Low inertia → *Little erosion*

State of the art

Nanofluid heat transfer enhancement

1) Thermal conductivity enhancement

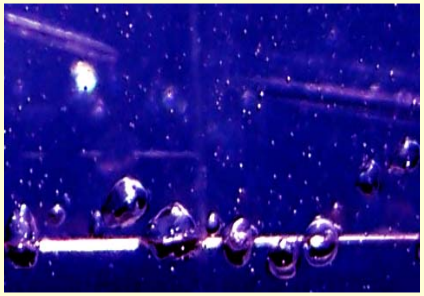
2) Convective heat transfer enhancement (up to +40%)

3) Critical Heat Flux enhancement

Ref*/Group	Nanofluid(s)	Heater type	Max CHF enhancement
1/U-Texas	Al_2O_3 in water, 0.001-0.025 g/L	Cu plate	200%
2/Lockheed	SiO_2 (15-50 nm) in water, 0.5 v%	NiCr wire	60%
3/UC-Santa Barbara	Al_2O_3 (38 nm) in water, 0.037 g/L	Ti layer on glass substrate	67%
4/ Pohang Univ.	TiO_2 (27-85 nm) in water, 0.01-3 v%	Cu plate	50%
5/U-Texas	Al_2O_3 (70-260 nm) and ZnO in water Al_2O_3 in ethylene glycol	Cu plate	200%
6/KAIST	Al_2O_3 (10-100 nm) in water, 0.5-4 v%	Stainless steel	50%
7/Pohang Univ.	TiO_2 (85 nm) in water, 10^{-5}-10^{-1} v%	NiCr wire	200%
8/U-Florida	SiO_2, CeO_2, Al_2O_3 (10-20 nm) in water, 0.5 v%	NiCr wire	170%
9/U-Missouri	Au (4 nm) in water	Cu plate	175%
10/MIT	SiO_2 (20-40 nm), ZrO_2 (110-250 nm), Al_2O_3 (110-210 nm) in water, 0.001-0.1 v%	Stainless steel wire	80%

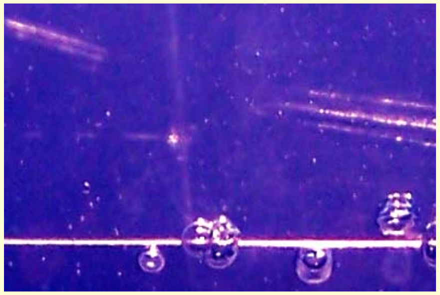
1) and 2) are highly controversial + not really useful in nuclear. 3) can be beneficial in nuclear systems.

Nanofluid Critical Heat Flux

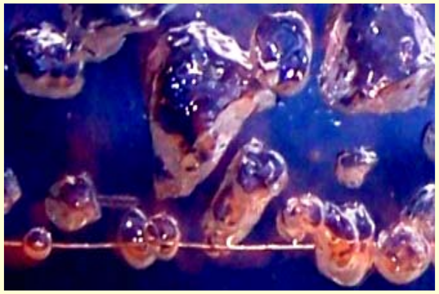


DI water (0.5 MW/m ^{2})

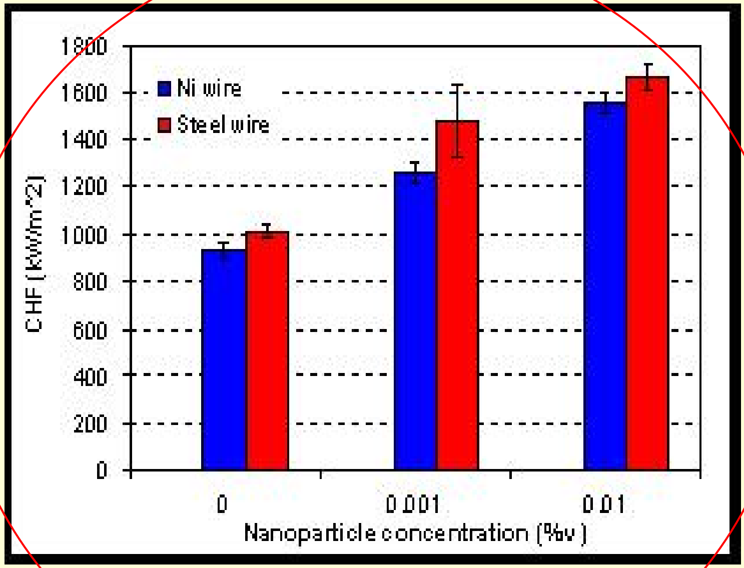
DI water (1 MW/m^2)



Nanofluid (0.5 MW/m^2)



Nanofluid (1 MW/m^2)



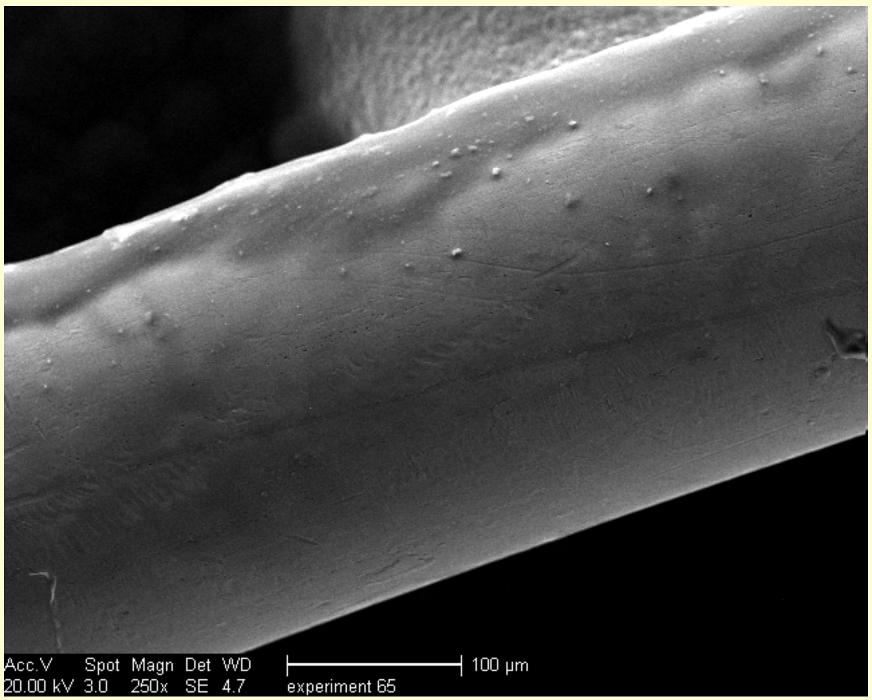
Water-based nanofluid with ZrO_2 particles

•Very significant pool boiling CHF enhancement observed at low nanoparticle concentrations with various nanoparticle materials (ZrO_2, Al_2O_3, SiO_2, diamond)

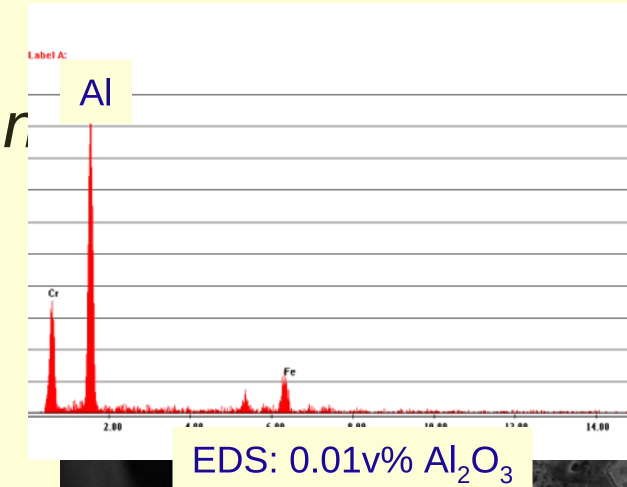
•CHF enhancement confirmed for the first time also in *flow boiling* (MIT paper, J. Heat Transfer, Apr 2008, in press)

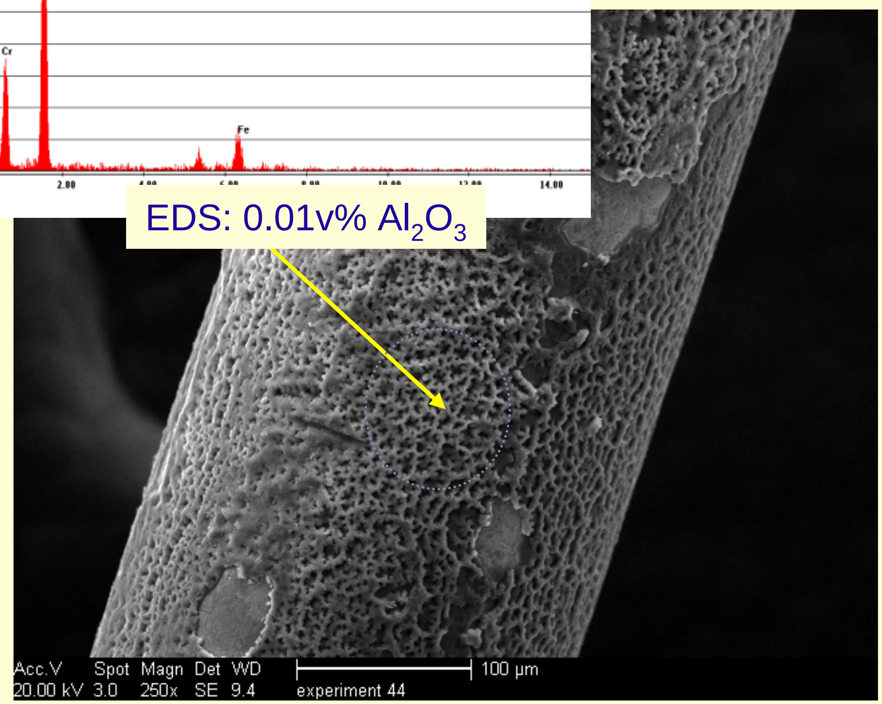
Why Does CHF Increase?

•Thermophysical properties do n… …centration



SEM Picture of SS316 Wire
After Boiling of DI Water

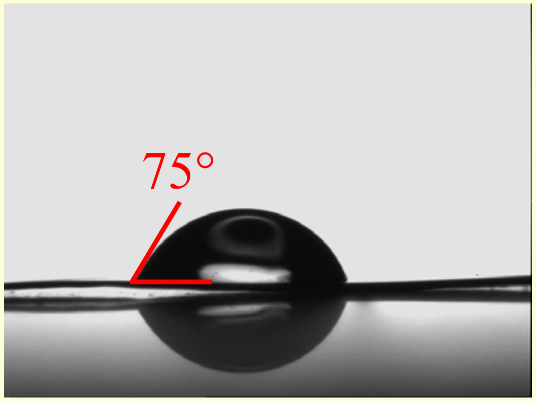




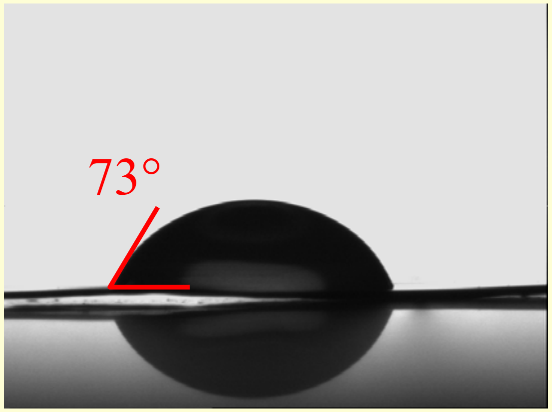
SEM Picture of SS316 Wire
After Boiling of 0.01v% Al_2O_3 Nanofluid

•Nanoparticles deposit on surface upon nanofluid boiling

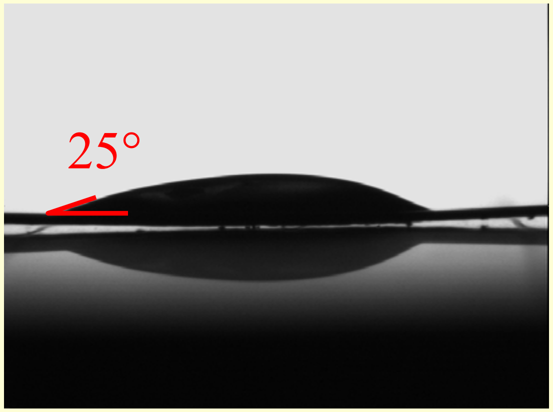
Why Does CHF Increase?



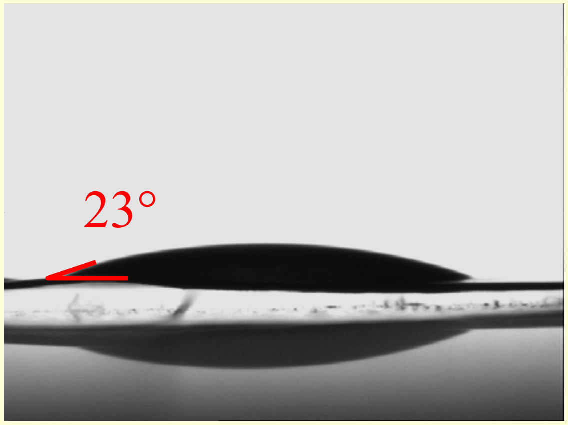
Pure water on surface boiled in pure water



Nanofluid on surface boiled in clean water



Pure water on surface boiled in nanofluid



Nanofluid on surface boiled in nanofluid

Surface wettability increases dramatically ⇒ CHF enhancement

Nuclear Applications of Nanofluids

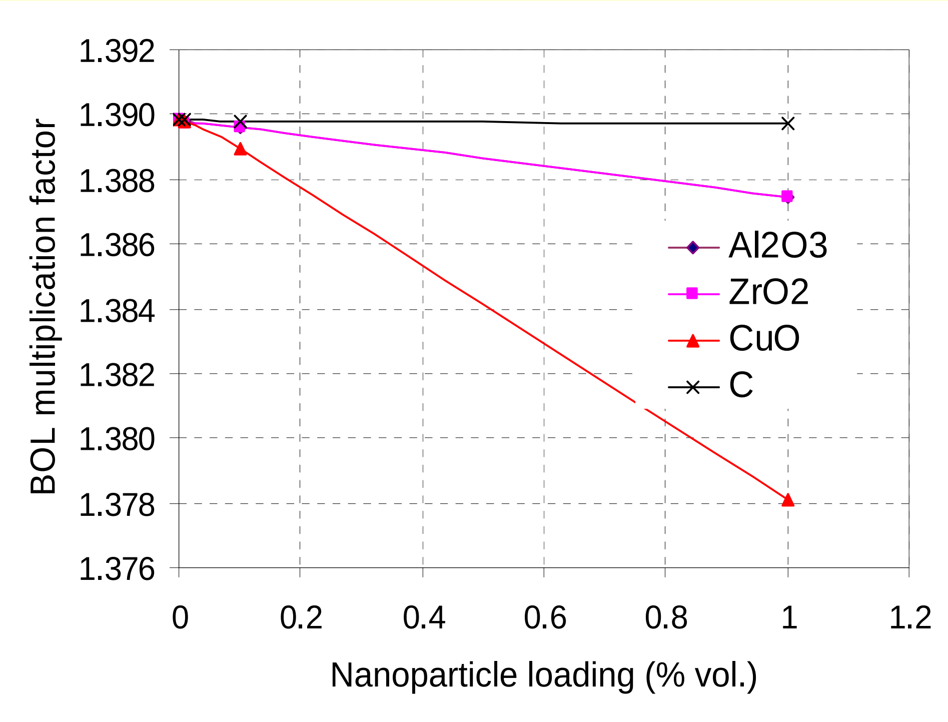
1) *PWR main coolant*

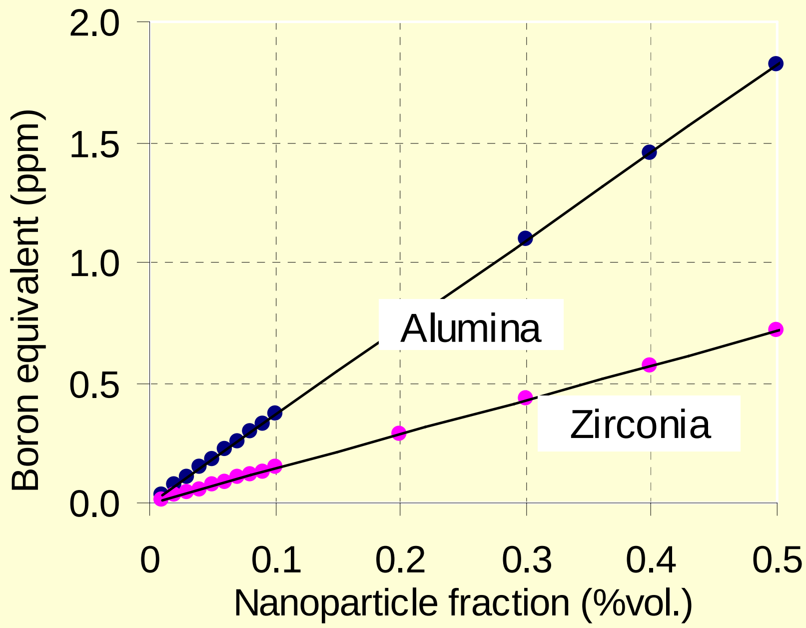
2) *Safety systems for LWRs*

3) *Management of severe accidents (in-vessel retention)*

PWR Main Coolant - Neutronics

Simulations of 17×17 PWR FA with CASMO





Negligible penalty on reactivity

Negligible change in void reactivity coefficient

PWR Main Coolant - Activation

Nanoparticle Material	Dominant radionuclide, Decay	Half-life	Activity (per unit coolant volume)
Carbon	C-14, β^- (no γ)	5,700 yrs	0.001 $\mu Ci/cm^3$
Silica	Si-31, β^- (γ: 1.3 MeV)	2.6 hrs	0.04 $\mu Ci/cm^3$
Alumina	Al-28, β^- (γ: 1.8 MeV)	2 min	10 $\mu Ci/cm^3$
Zirconia	Zr-95, β^- (γ: 0.7 MeV)	64 days	0.2 $\mu Ci/cm^3$
Gold	Au-198, β^- (γ: 0.4 MeV)	2.7 days	3,000 $\mu Ci/cm^3$
Platinum	Pt-197, β^- (γ: 0.2 MeV)	18 hrs	6 $\mu Ci/cm^3$
Iridium	Ir-194, β^- (γ: 0.3 MeV)	19 hrs	2,500 $\mu Ci/cm^3$

- *All specific activities calculated for 0.001 vol% nanoparticle loading, 5×10^{13} n/cm^2s thermal neutron flux.*
- *Cross sections from BNL website.*
- *Assumed residence time in core 0.65 s, outside core 16.5 s.*
- *The target for coolant activity during refueling at Seabrook Station is <0.1 μCi/cm3.*

PWR Main Coolant – Thermal-hydraulics

Target is to increase core power density:

- ☑ +20% in existing PWRs
- ❑ +40% in future PWRs

For uprates in existing PWRs the constraints are:

- Same FA design (17×17) and core size
- No replacement of RPV, SGs, main piping
- Same core outlet temperature

Two limits considered:

1. No fuel melting at 112% overpower
2. MDNBR>1.3 at 112% overpower

MDNBR is the most limiting.

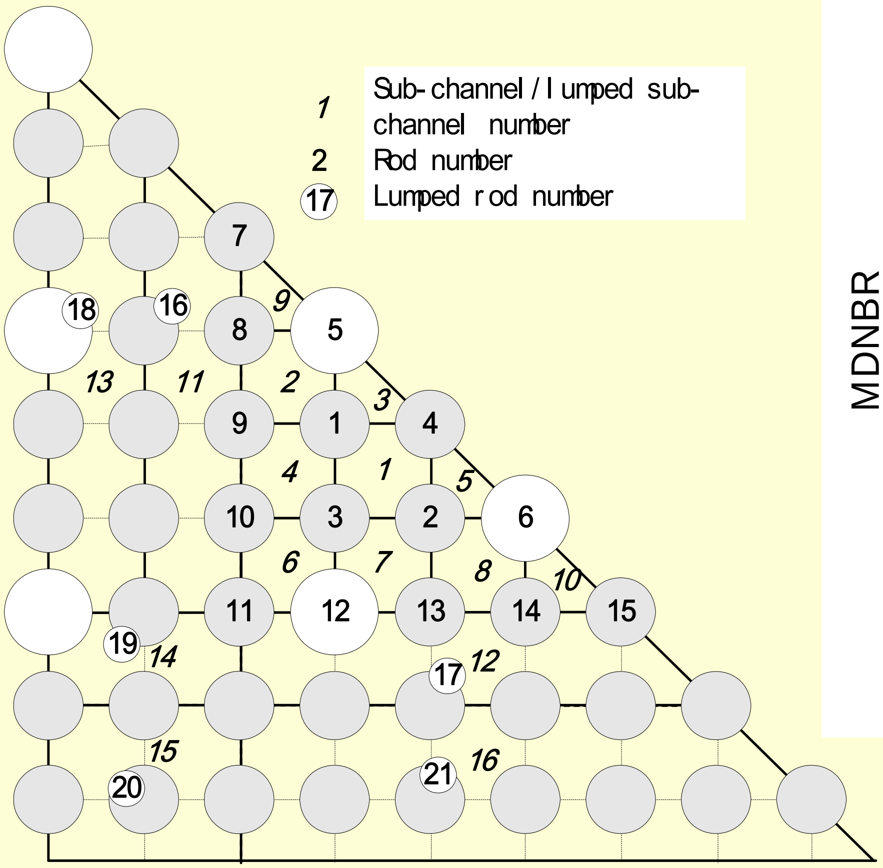
PWR Main Coolant – Thermal-hydraulics (2)

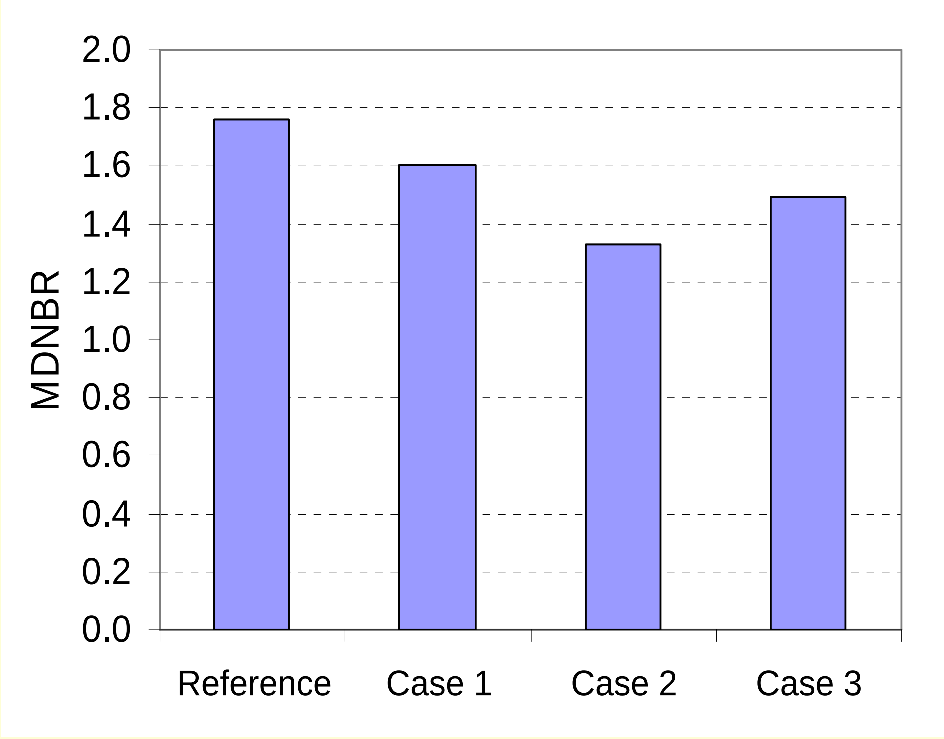
Case #	$\dot{Q}$ (MW_{th})	$\dot{M}$ (kg/s)	T_{in} (^oC)	T_{out} (^oC)	ΔT (^oC)
Reference	3,411	17,700	292.3	324	31.7
1	4,093 (+20%)	21,240 (+20%)	292.3	324	31.7
2	4,093 (+20%)	17,700	286.0	324	38.0 (+20%)
3	4,093 (+20%)	19,470 (+10%)	289.1	324	34.9 (+10%)

- *"Reference" is a 4-loop Westinghouse PWR plant*
- *Main pump replacement probably needed in Cases 1 and 3*
- *Turbine-generator replacement probably needed in all 3 Cases*
- *Thermal efficiency somewhat lower than "Reference" (<1%) because of lower steam pressure in the SGs in all 3 Cases*

PWR Main Coolant – Thermal-hydraulics (3)

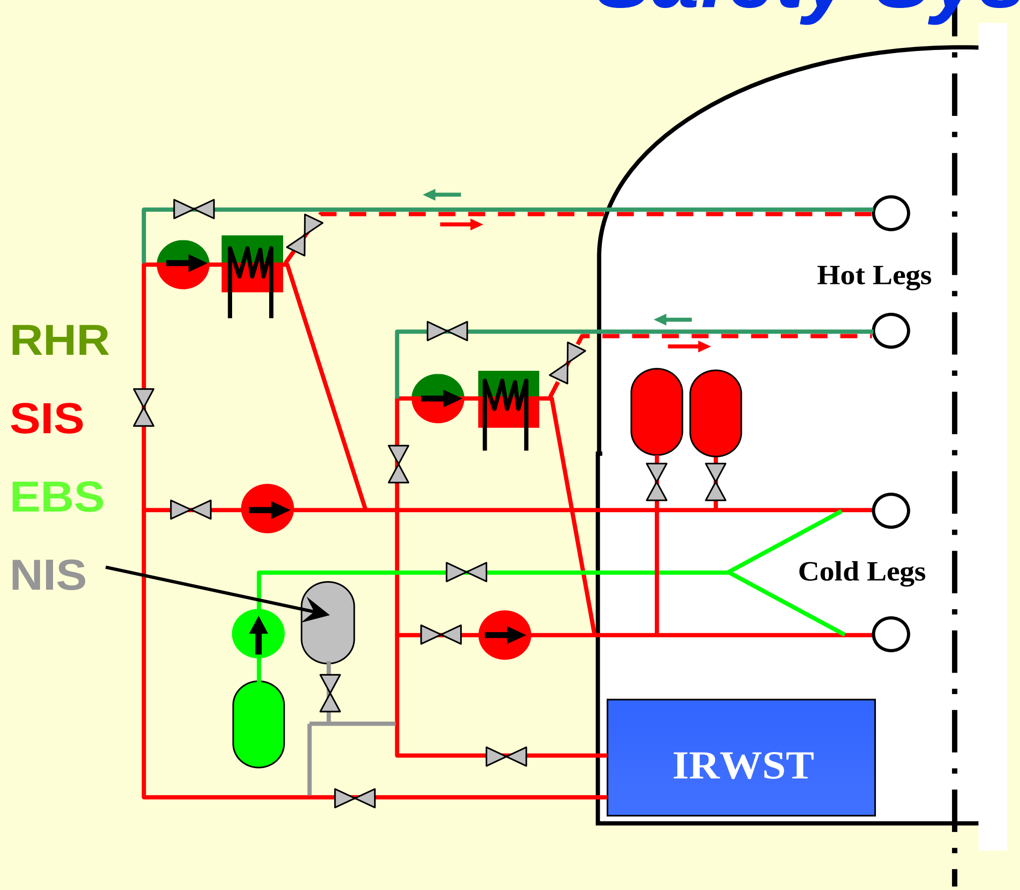
Subchannel analysis with VIPRE (F_h=1.65, F_Q=2.5, +12% overpower, -5% flow, +2.2°C inlet T, -200 kPa P, W-3 corr.)





Depending on uprate approach, up to +30% CHF gain may be needed from the nanofluid, to achieve +20% uprate

Safety Systems

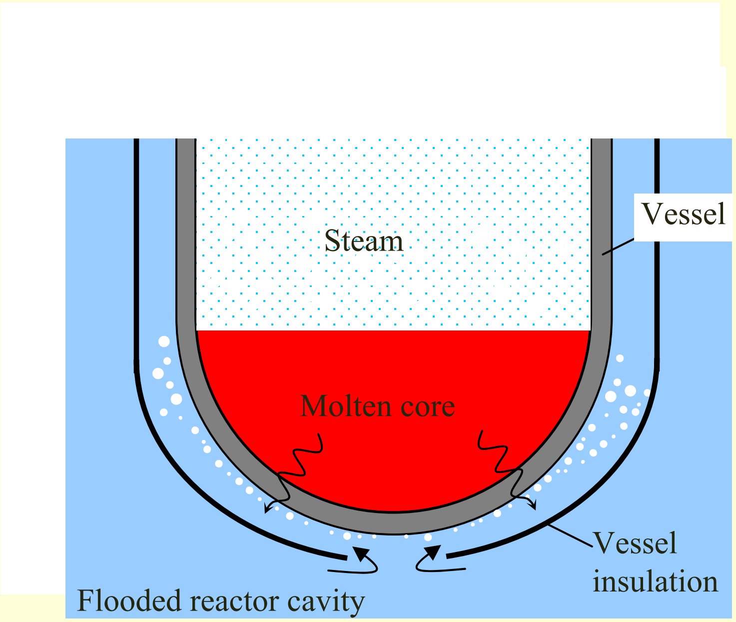


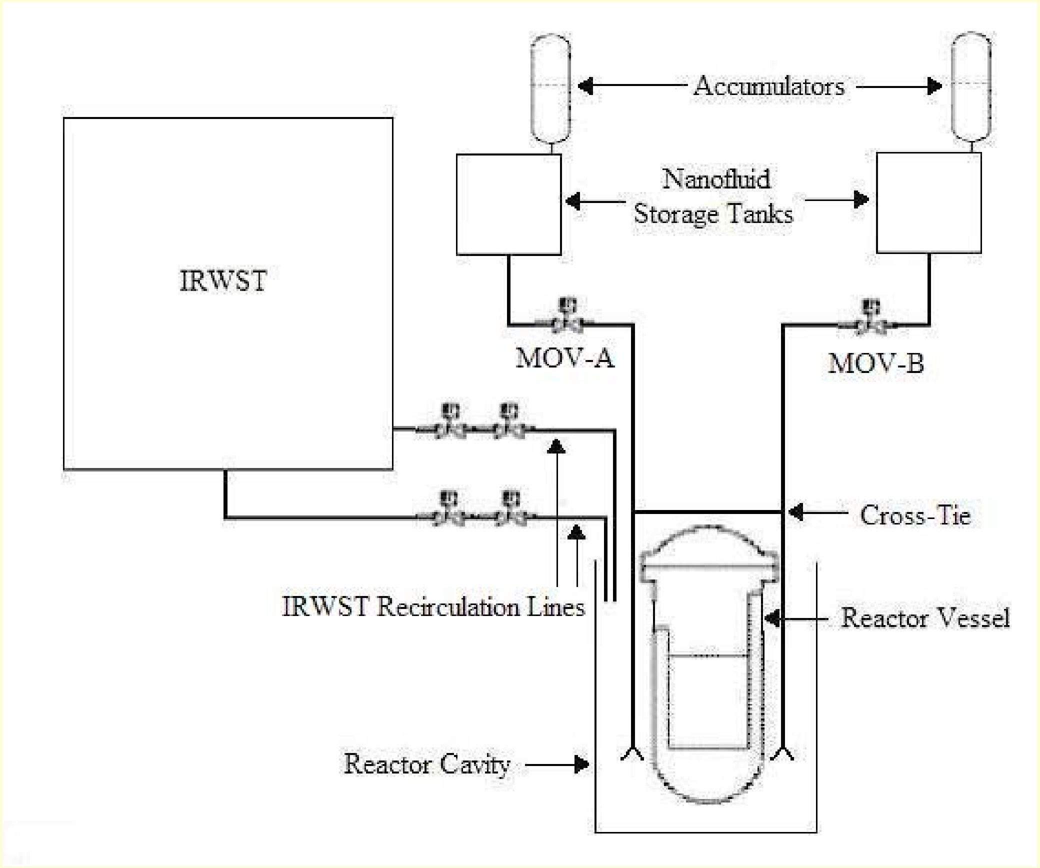
Design of EPR ECCS with low-pressure nanofluid tank

- CHF increase alone not sufficient here
- **Post-CHF heat transfer is key**. Nanoparticles can accelerate core quenching because:

1) increase wettability and 2) increase axial thermal conduction

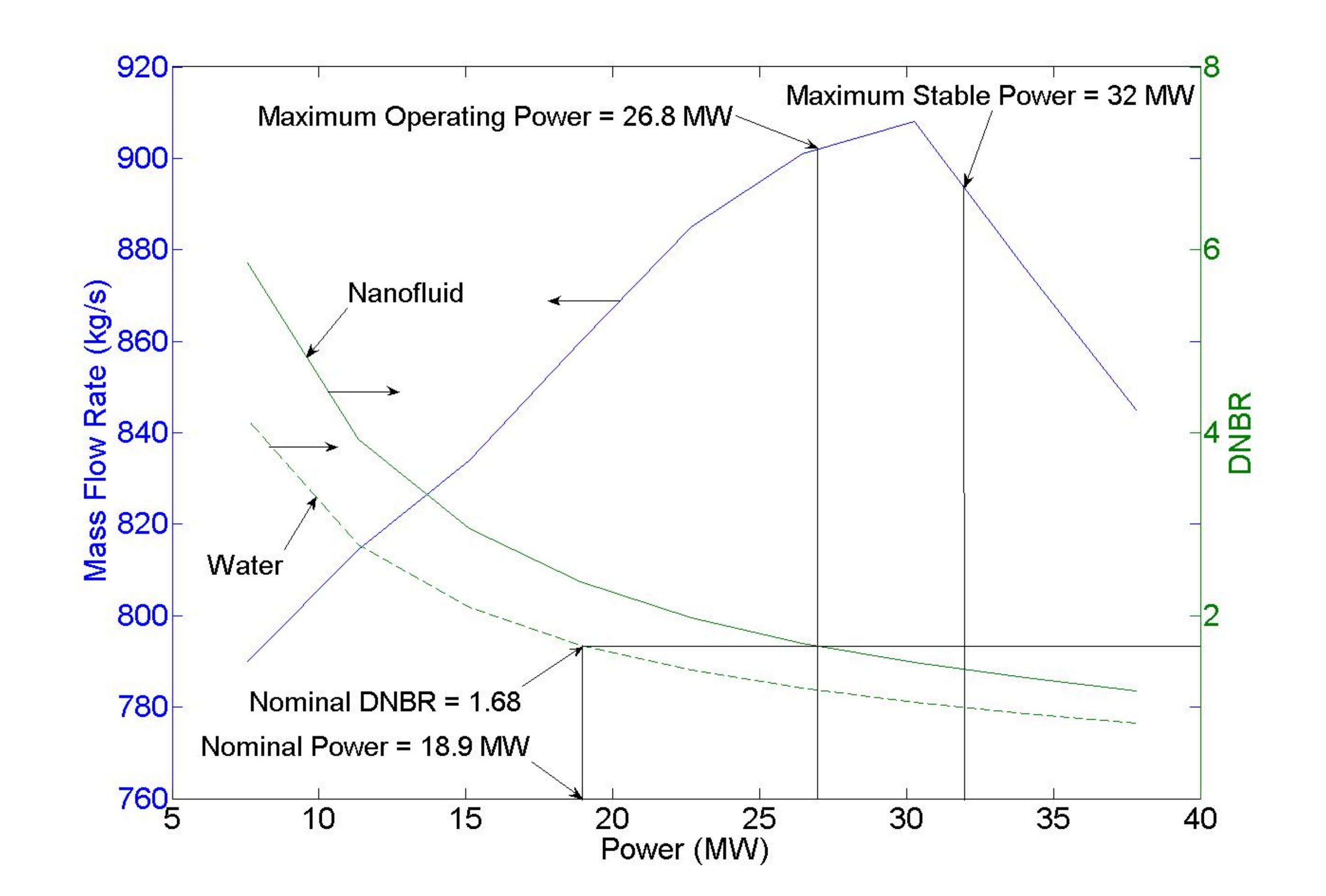
Severe Accidents (In-Vessel Retention)





Concentrated nanofluid is injected in already flooded reactor cavity, thus creating a dilute nanofluid (verified with CFD)

Severe Accidents (In-Vessel Retention) (2)



Use of a nanofluid results in a stable +40% heat removal enhancement with the same margin to DNB (CHF)

Severe Accidents (In-Vessel Retention) (3)

Mean particle diameter in alumina nanofluid, as measured with DLS

Time (hrs)	20%wt	0.01%v	0.001%v
0	37.8 nm	n/a	n/a
1	n/a	42.6 nm	52.3 nm
6	n/a	32.6 nm	33.4 nm
24	n/a	46.7 nm	46.7 nm

- Nanofluid stays stable for at least 24 hours after dilution
- Stability of nanofluids also successfully tested in γ-radiation
- Nanofluid stable in LiOH and boric acid, but not in STP

Interest in nuclear applications of nanofluids

Industry:

1. AREVA (PWR primary system + ECCS)
2. Westinghouse (severe accidents)
3. EPRI (heat transfer enhancement)

Others:

1. NRC (severe accidents)
2. DOE (heat transfer enhancement)

Research gaps

1) Demonstration of heat transfer performance at prototypical reactor conditions

- High-pressure CHF test in bundle geometry for PWR application
- Low-pressure quench test in bundle geometry for safety systems (ECCS) application
- Low-pressure CHF test in hemispherical gap for in-vessel retention application

Research gaps (2)

2) Demonstration of compatibility/stability of nanofluids with prototypical reactor chemistry/radiation environments

- Potential issues for PWR application: erosion, corrosion, clogging, neutron-induced instability
- Potential issues for ECCS and severe accident application: design of nanofluid delivery systems, gamma-induced instability, compatibility with boric acid, LiOH and STP

Conclusions

- Nanofluids offer potential for significant enhancement of the pool and flow boiling critical heat flux
- Potential nuclear applications include PWR primary system, safety systems (ECCS), severe accident management (in-vessel retention)
- Major research gaps include:
  - Demo of heat transfer performance at prototypical reactor conditions
  - Demo of chemical-physical stability at prototypical reactor conditions

Backup slides

Nanofluid Thermal Conductivity

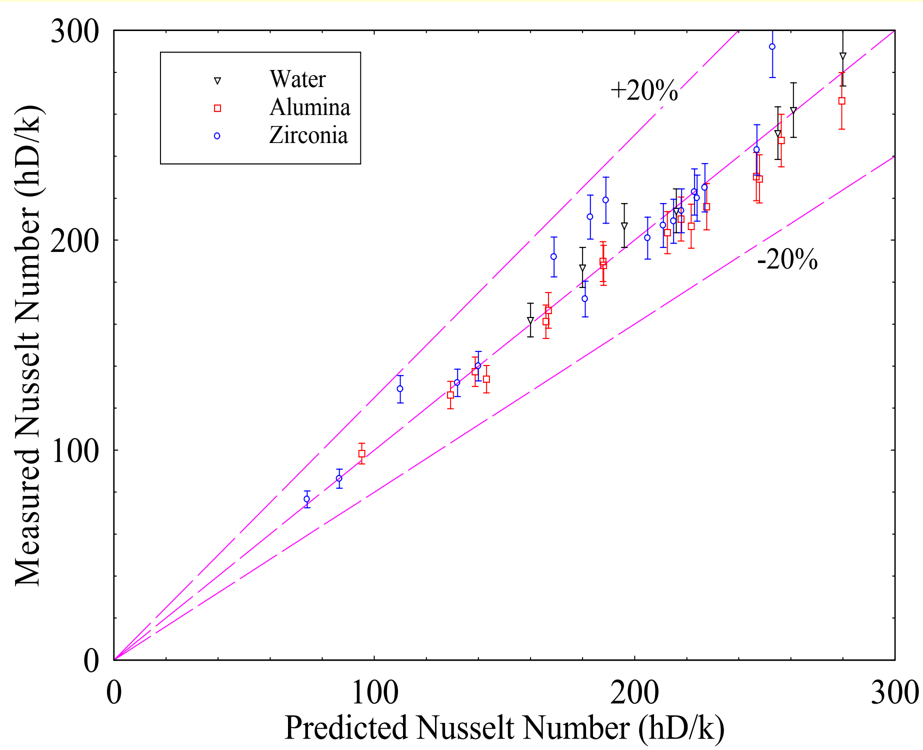
Measured thermal conductivity of >20 nanofluids with transient hot wire technique (±2% experimental uncertainty)

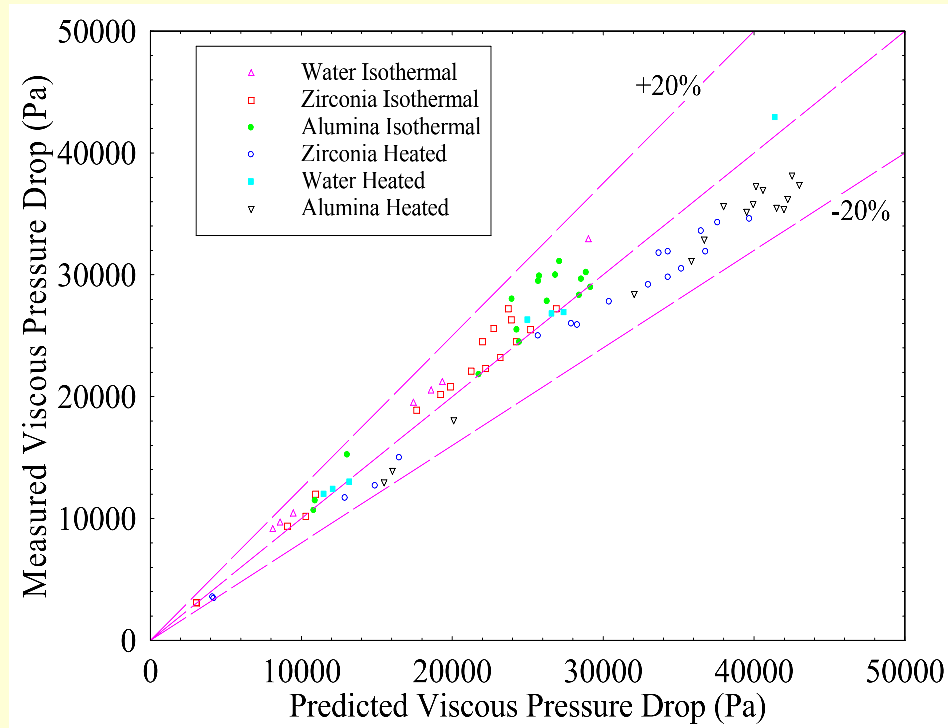
Particle	Liquid	Maker	Preparation	Loading (wt)	Loading (vol)	pH	Conductivity
	EG						0.25
Ag	EG	MIT	No Surfactants/No pH	0.029	-	-	0.25
Al2O3	EG	MIT	No Surfactants/No pH	-	~3	8.5	0.28
Au	EG	Meliorum	Surfactants	-	1	-	0.25
CuO	EG	MIT	No Surfactants/No pH	-	~1	4.15	0.27
SiO2	EG	MIT	No Surfactants/No pH	-	1.6-3.3	-	0.28
ZrO2	EG	MIT	No Surfactants/No pH	-	4	-	0.28
	H2O						0.59
Al2O3	H2O	SA	pH	10	-	4.3	0.63
Al2O3	H2O	RPI	Surfactants	-	2 (0.5)	8.15 (7.05)	0.64 (0.62)
Al2O3	H2O	Nyacol	pH	20	-	4	0.68
Al2O3	H2O	Meliorum	pH	10	-	3.9	0.62
Au	H2O	Meliorum	Surfactants	-	5	-	0.58
Cu	H2O	MIT	No Surfactants/No pH	-	-	6.5	0.5
CuO	H2O	MIT	No Surfactants/No pH	-	<5	7.12	0.59
Diamond	H2O	UF	No Surfactants/No pH	-	-	6.67	0.62
Diamond	H2O	MIT	No Surfactants/No pH	-	-	6	0.6
Fe3O4	H2O	MIT	Polymer Surfactant	-	1	8.54	0.56
Pt	H2O	Meliorum	?	0.0486	-	-	0.57
SiO2	H2O	Applied Nano	pH	10	-	10.17	0.63
SiO2	H2O	Polimi	?	34	18.6	7.13	0.63
SiO2	H2O	MIT	No Surfactants/No pH	-	-	-	0.57
Teflon	H2O	Polimi	No Surfactants/No pH	10.2	5	3.35	0.58
ZnO2	H2O	MIT	No Surfactants/No pH	-	0.4	7.15	0.59
ZrO2	H2O	SA	pH	10	-	2.7	0.62
ZrO2	H2O	MIT	No Surfactants/No pH	17	4	5.27	0.62
ZrO2	H2O	Applied Nano	pH	10	-	4.17	0.59
ZrO2	H2O	Nyacol	pH	20	-	4.17	0.59

No abnormal thermal conductivity enhancement observed

Nanofluid Convective Heat Transfer

Measured heat transfer coefficient and pressure drop in flow loop





•Nanofluids seem to follow traditional heat transfer behavior (provided measured nanofluid properties are used)

•No abnormal enhancement detected so far