SAND2020-12983C

ANS Virtual Winter Meeting

Nuclear is good for you.

Impact of Ionizing Irradiation on Surface Wettability: Fundamentals and Application in Engineering Superhydrophobic Surfaces

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Massachusetts Institute of Technology

Sandia National Laboratories

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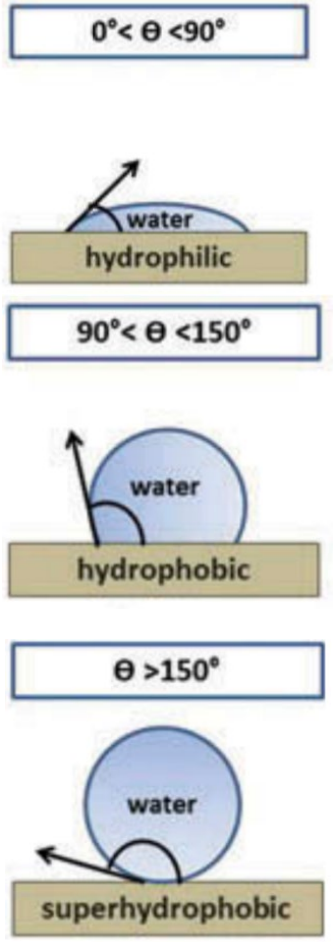
Surface Wettability: What is it and Why it is important

- Surface wettability impacts surface-to-coolant interfacial energy and mass transport
- For a water-cooled nuclear power plant:
  - heat transfer, particularly under two-phase flow (boiling, condensation, quench temperature)
  - Corrosion and fouling (e.g. CRUD)
- Surface wettability is typically correlated to static contact angle measurements as a first-order approximation
- Oxidation of typical nuclear material candidates (Zircaloy, Steels, etc.) results in better surface wettability (or hydrophilicity).



DOI: 10.1080/15583058.2017.1290850

What About The Impact of Ionizing Radiation?

[HTML] Radiation induced surface activation on Leidenfrost and quenching phenomena

T Takamasa, T Hazuku, K Okamoto, K Mishima… - … thermal and fluid …, 2005 - Elsevier

Improving the limit of boiling heat transfer or critical heat flux requires that the cooling liquid can contact the heating surface, or a high wettability, highly hydrophilic heating surface, even if a vapor bubble layer is generated on the surface. In our previous study, contact …

☆ 99 Cited by 47 Related articles All 9 versions Web of Science: 32

Surface wettability caused by **radiation induced surface activation**

T Takamasa, T Hazuku, K Mishima… - Thermal science and …, 2004 - inis.iaea.org

[en] Improving the limit of boiling heat transfer or critical heat flux requires that the cooling liquid can contact the heating surface, or a high-wettability, highly hydrophilic heating surface, even if a vapor bubble layer is generated on the surface. From this basis, we …

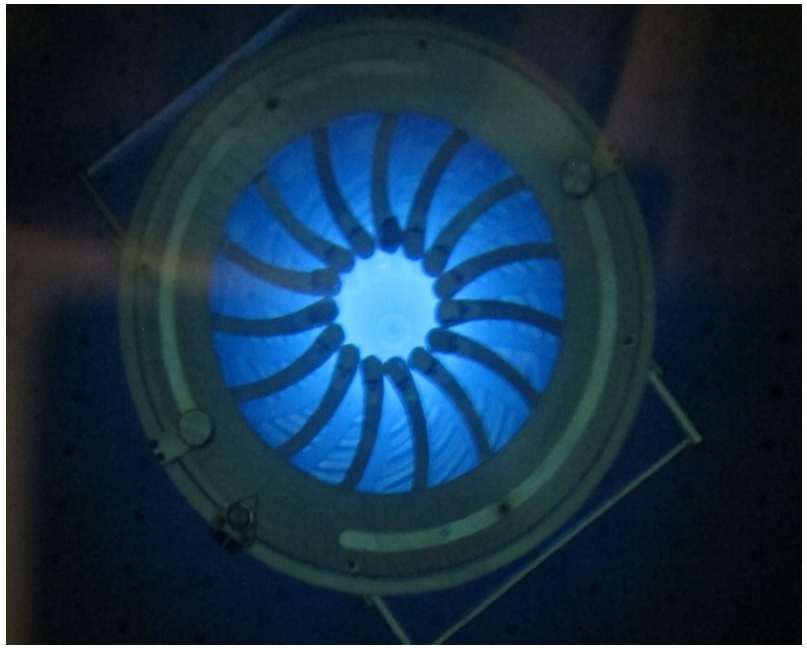
☆ 99 Cited by 14 Related articles All 4 versions

[HTML] Critical heat flux enhancement in downward-facing pool boiling with **radiation induced surface activation** effect

H Gong, AR Khan, N Erkan, L Wang… - International Journal of …, 2017 - Elsevier

Ex-vessel cooling is an important concept for ensuring safety in a nuclear power plant. Many researchers have focused on critical heat flux (CHF) enhancement using reactor pressure vessels. Previous studies mainly focused on other types of enhancement methods, and few …

☆ 99 Cited by 15 Related articles All 4 versions Web of Science: 15



Cobalt-60 source:
Sandia Gamma Irradiation Facility (GIF)
NSUF Facility

https://www.sandia.gov/research/facilities/gamma_irradiation_facility.html

Postulated Mechanism Behind Radiation Induced Activation (RISA) (1)

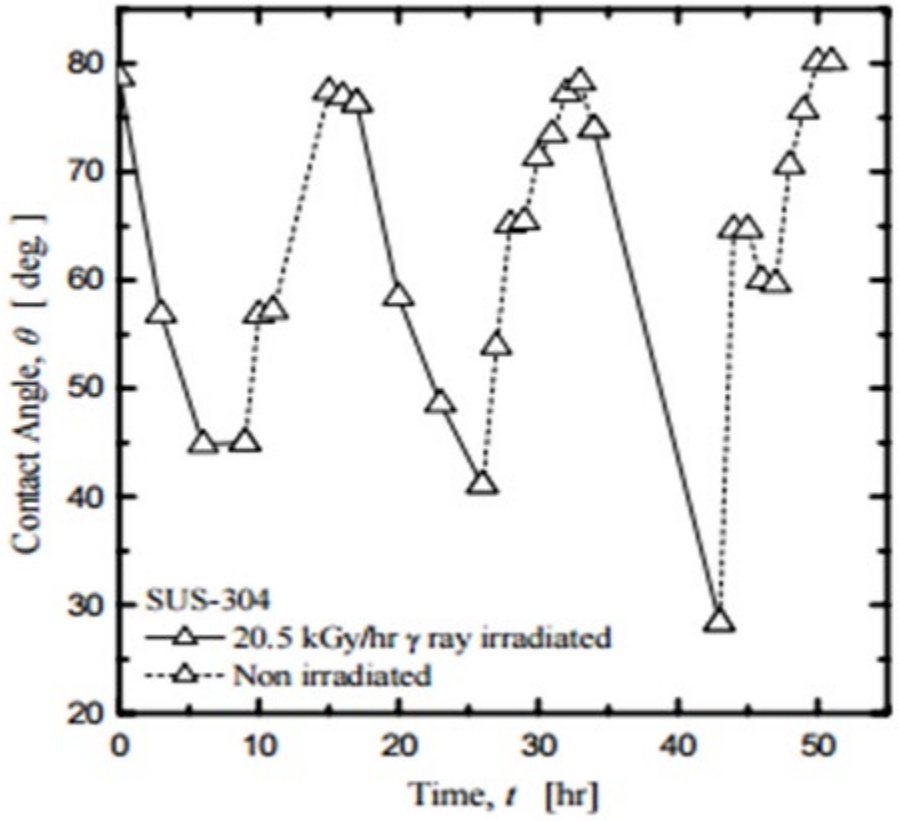


Image From: Imai Y., et al., ICONE10-22747 (2002)

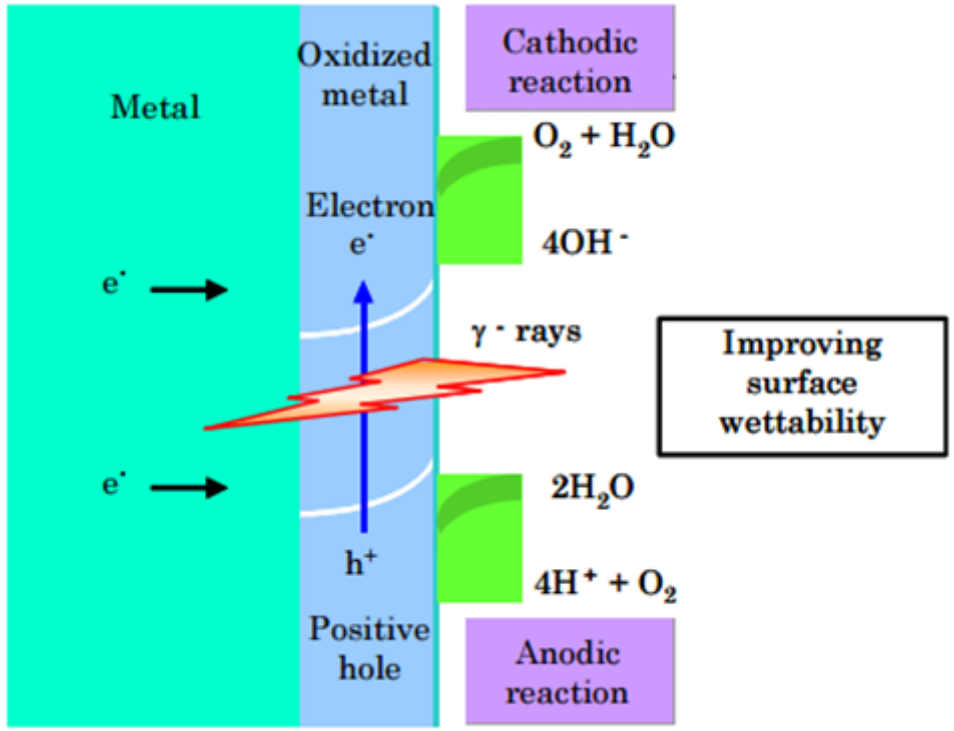
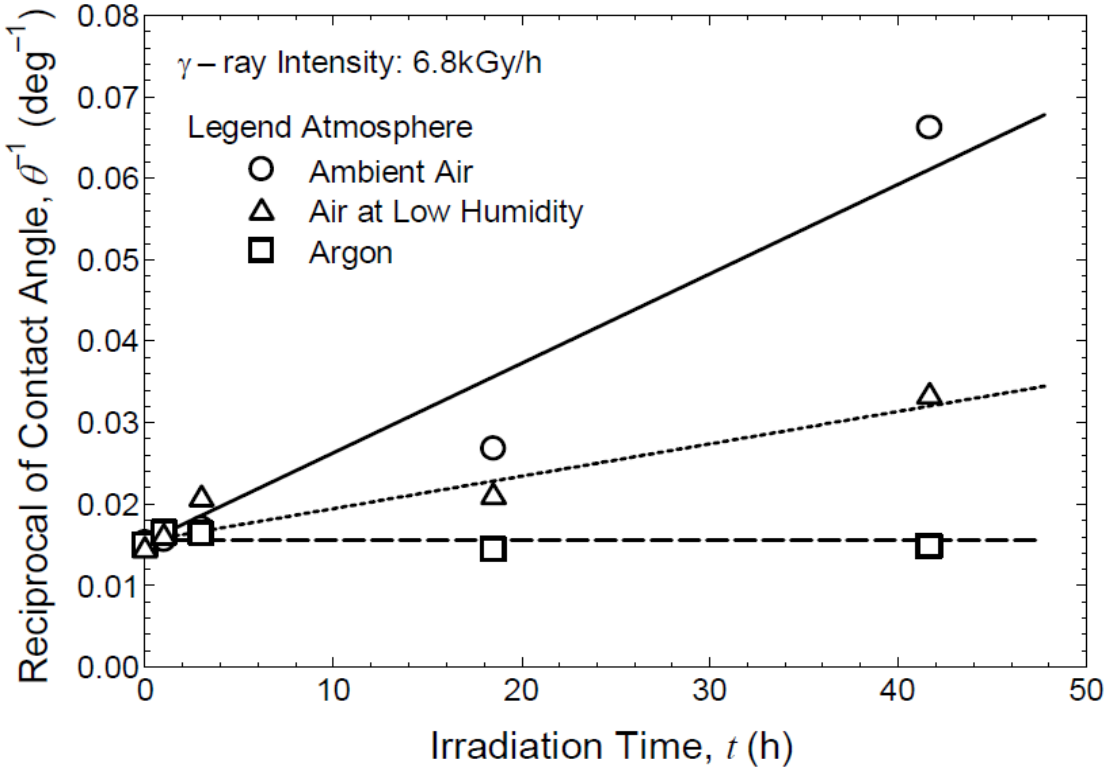
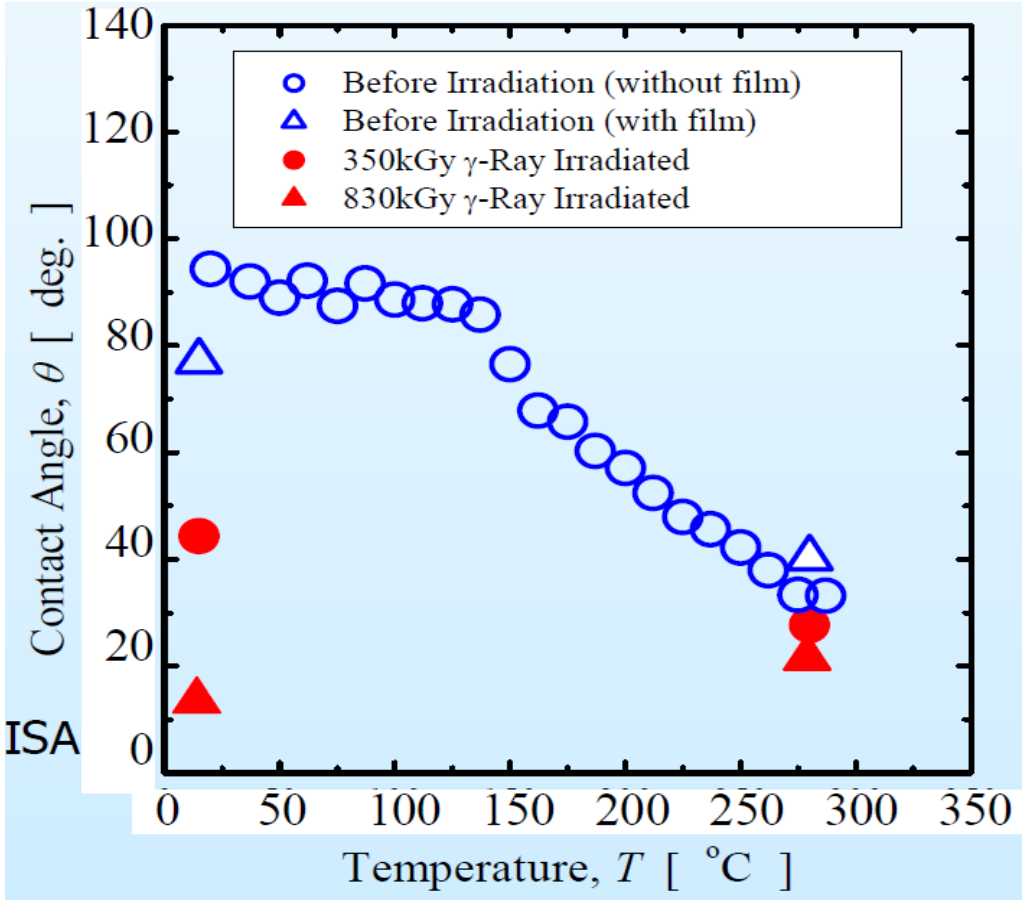


Image From: Takamasa T., et al., J. of NST, 41 (2004)

Postulated Mechanism Behind Radiation Induced Activation (RISA) (2)



Y. Honjo, F. Masahiro, T. Takamasa, K. Okamoto, *Journal of Power and Energy Systems*, **3**, pp. 216-227, 2009.



http://www2.kaiyodai.ac.jp/~takamasa/RISA%20Studies/RISA01.pdf

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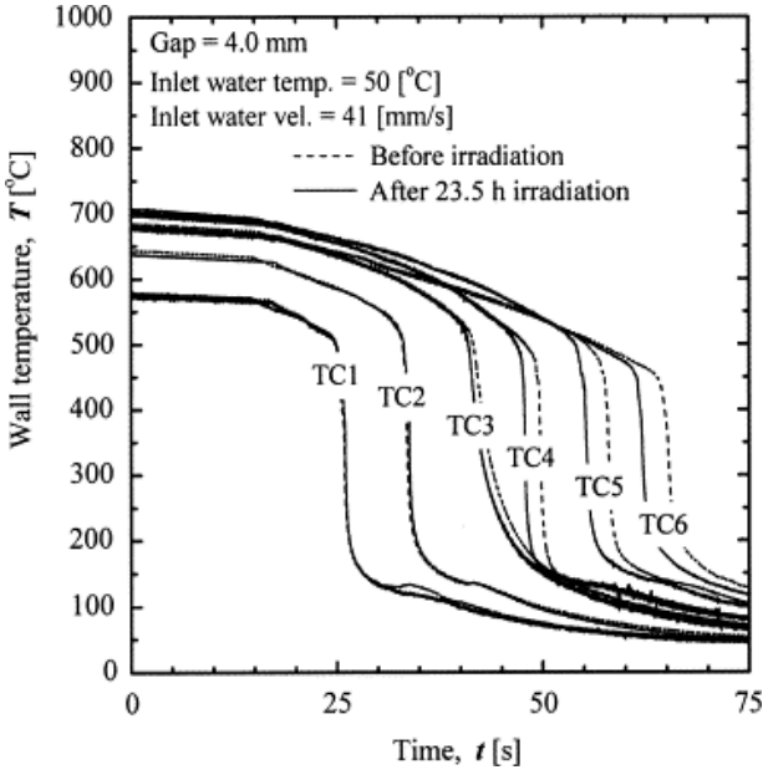
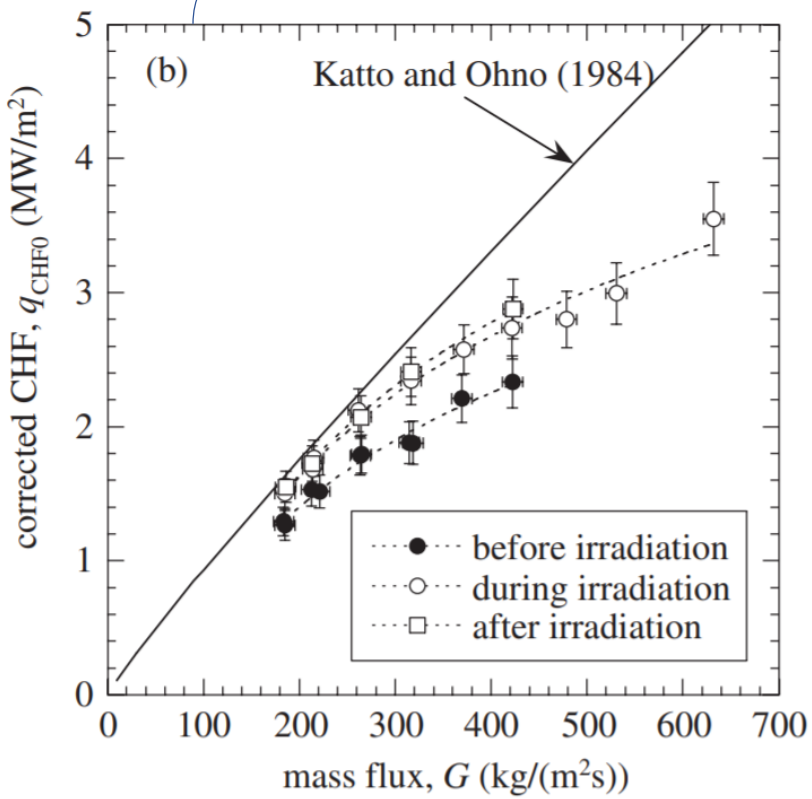
Implication of RISA for Nuclear Fuel

Out-of-Pile

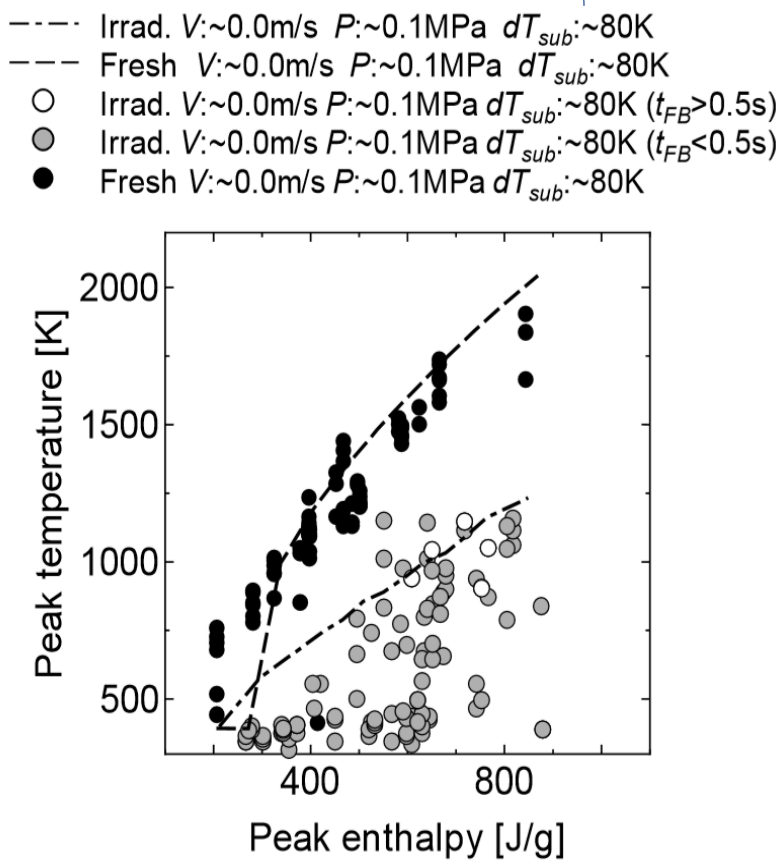


https://doi.org/10.1016/j.expthermflusci.2004.05.014

In-Pile



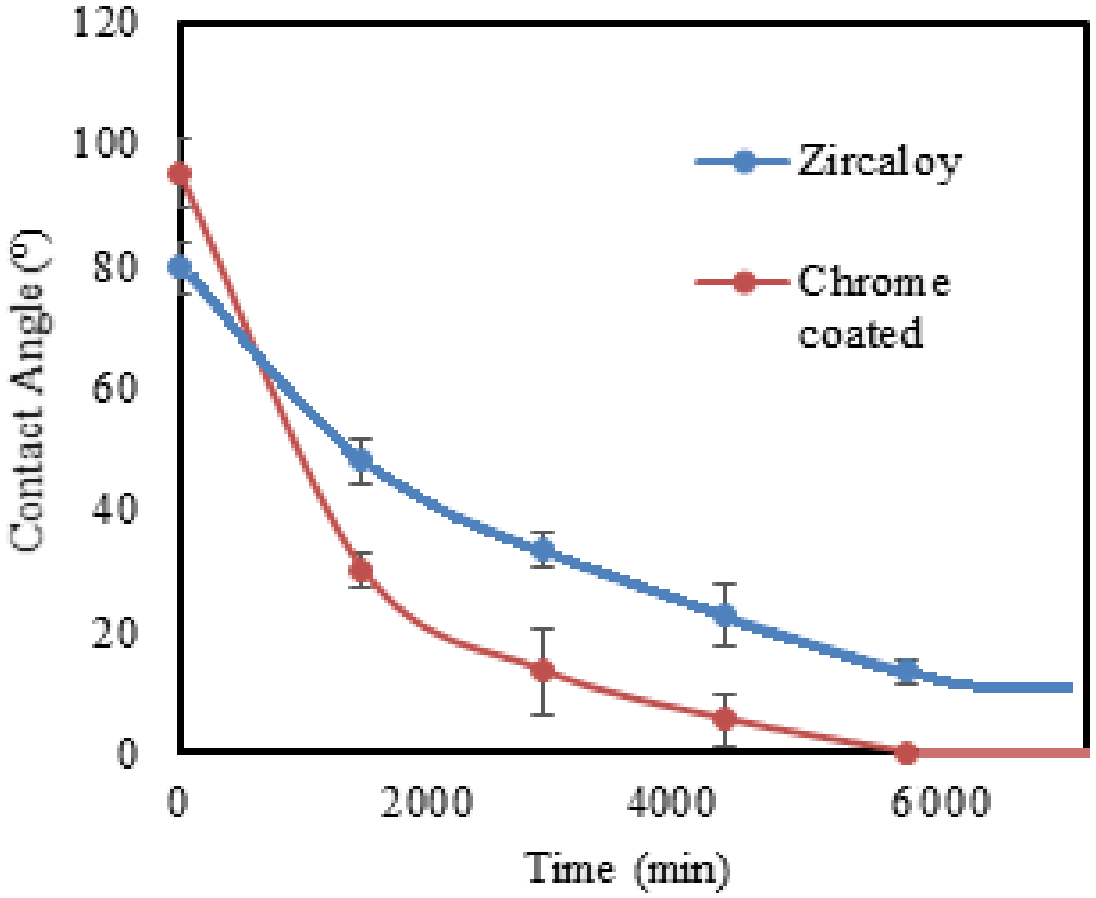
DOI: 10.1080/18811248.2007.9711272

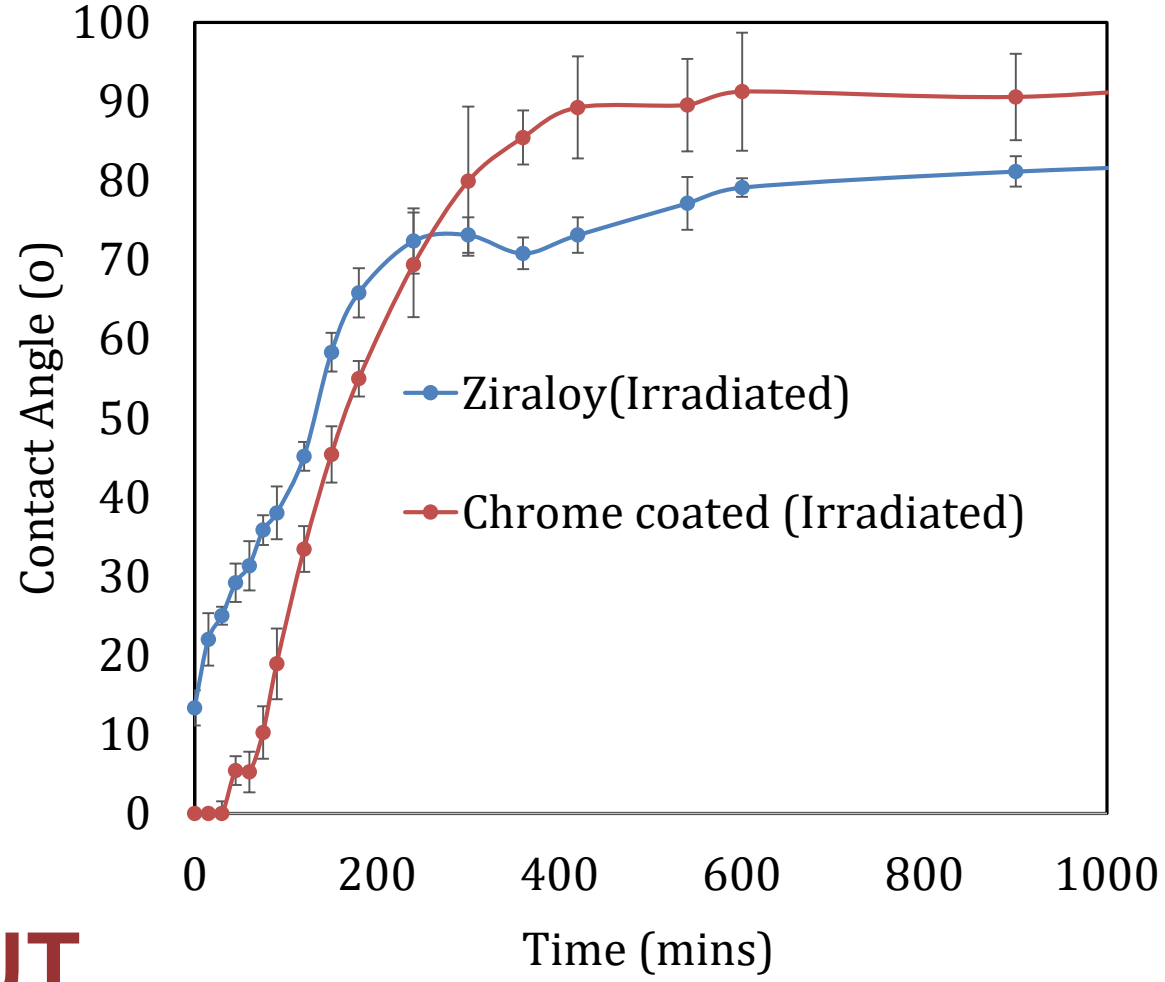


IAEA-TECDOC-CD-1775, 2015

MIT Study: Similar Trends with Metallic Surface

Seshadri A., Philips B., Shirvan K., JHT, 127 2018





BUT…

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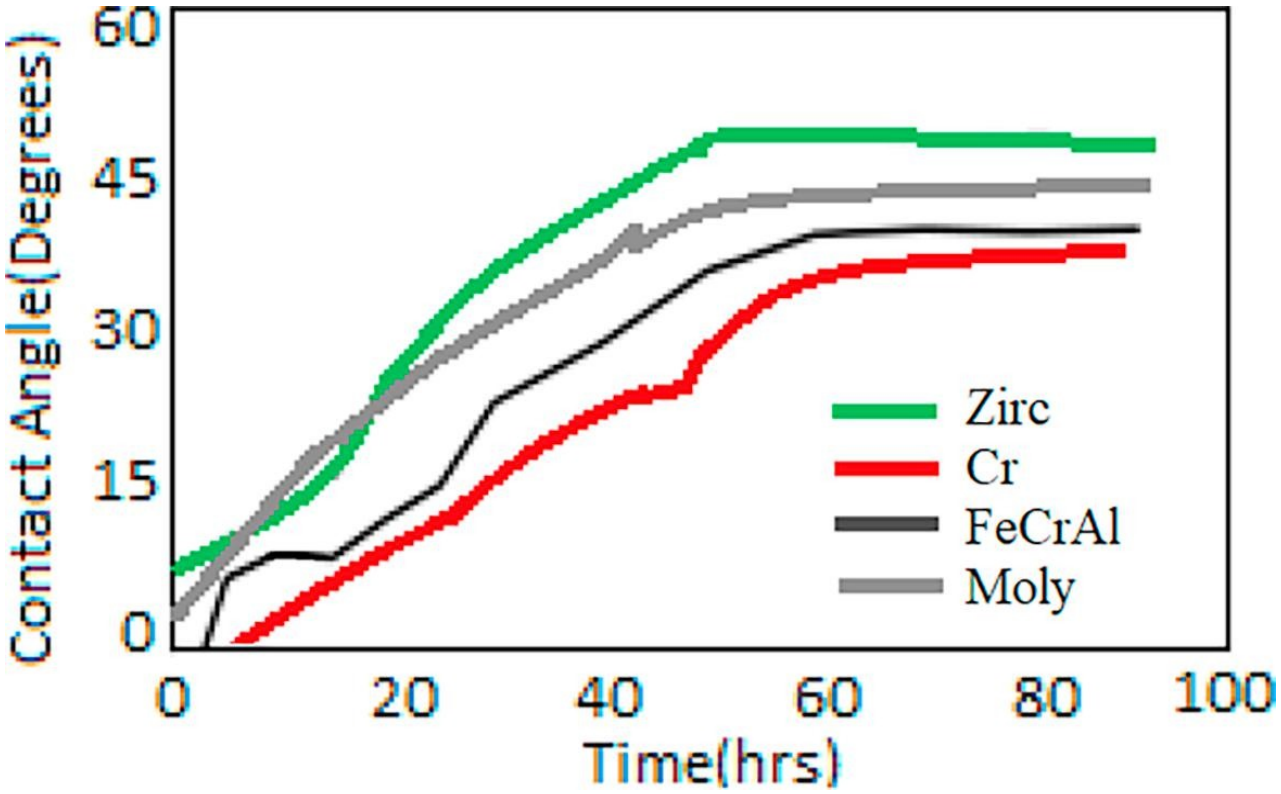
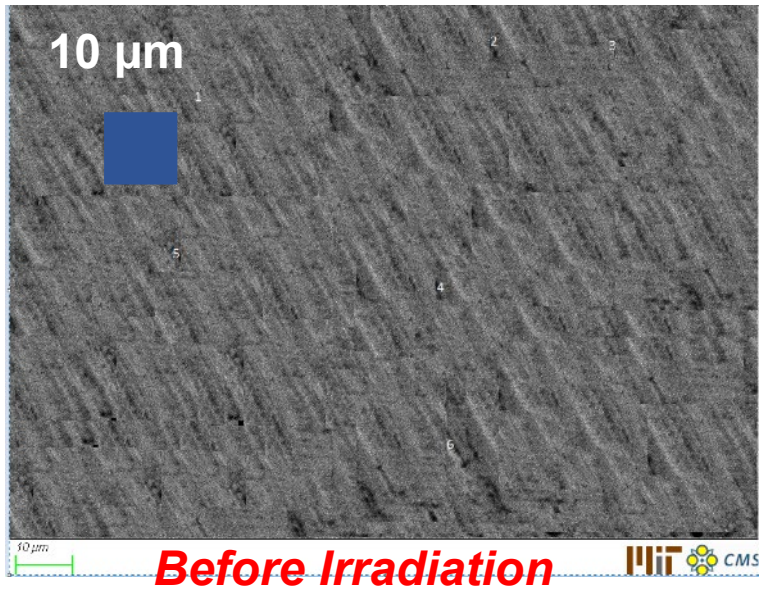
The Hydrophobic Recovery Can Be Driven by Environment Contamination

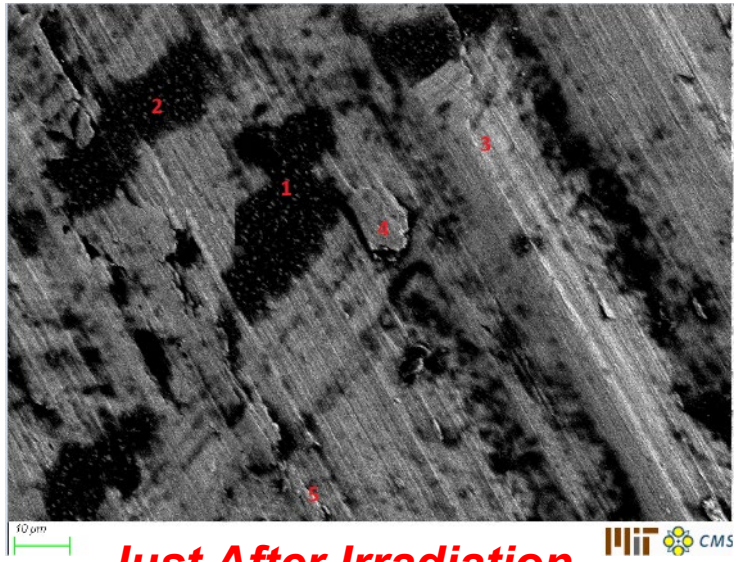


Seshadri and Shirvan, NED, 338, Nov, 2018

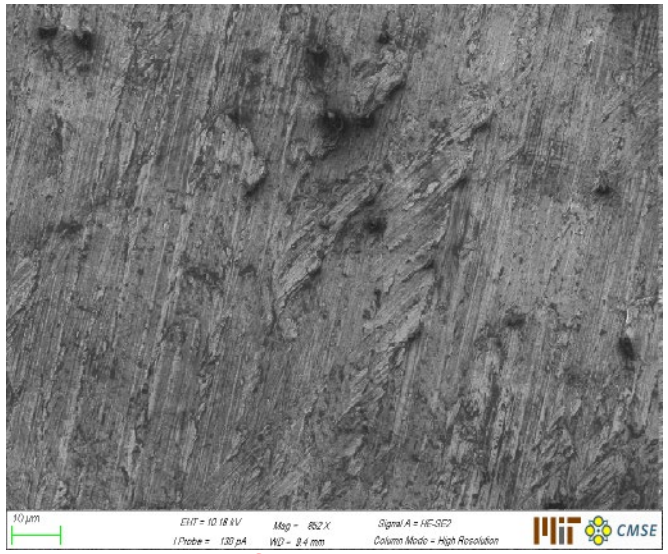
- Post-steam oxidation, various material undergo hydrophobic recovery.
- Contaminants and Organics in air slowly deposit on the surface
  - Well known effect in surface chemistry community



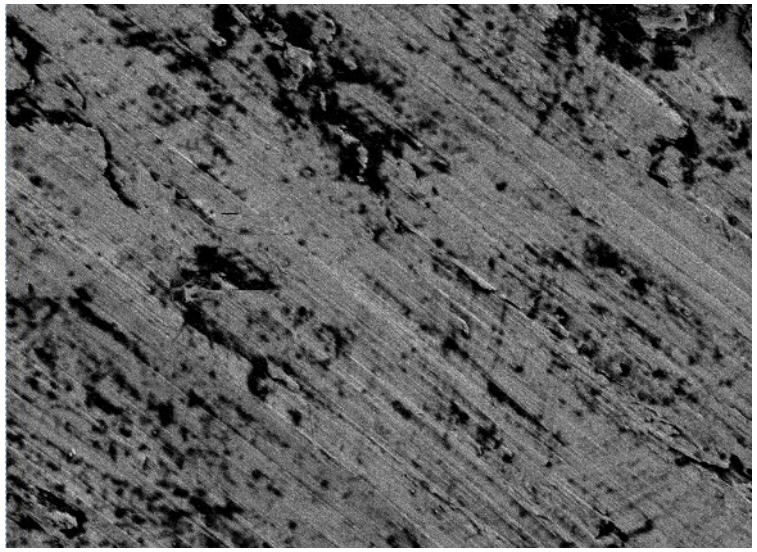
Before Irradiation



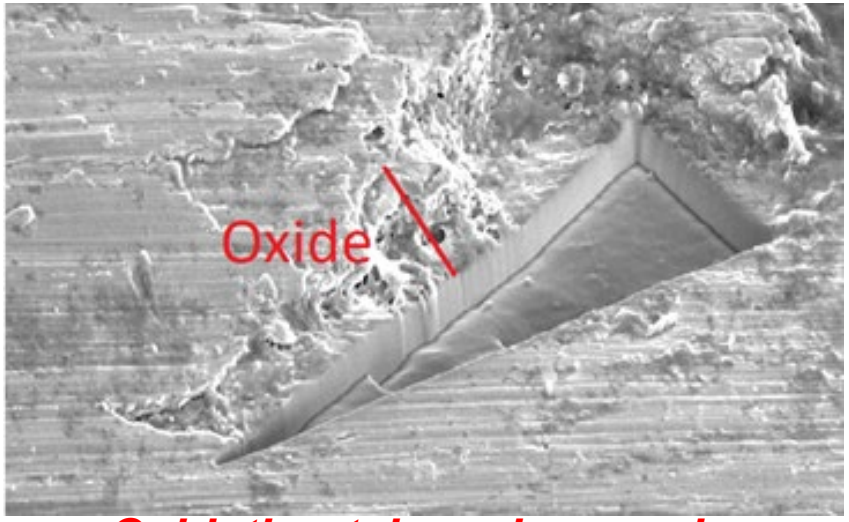
Just After Irradiation



24 hr After Irradiation



Just After Heating to > 300°C



Oxidation takes place under gamma radiation

RISA Effect is Permanent for >~ 300 °C

Implies cladding nano-surface engineering is not feasible without considering role of ionizing radiation

Massachusetts Institute of Technology

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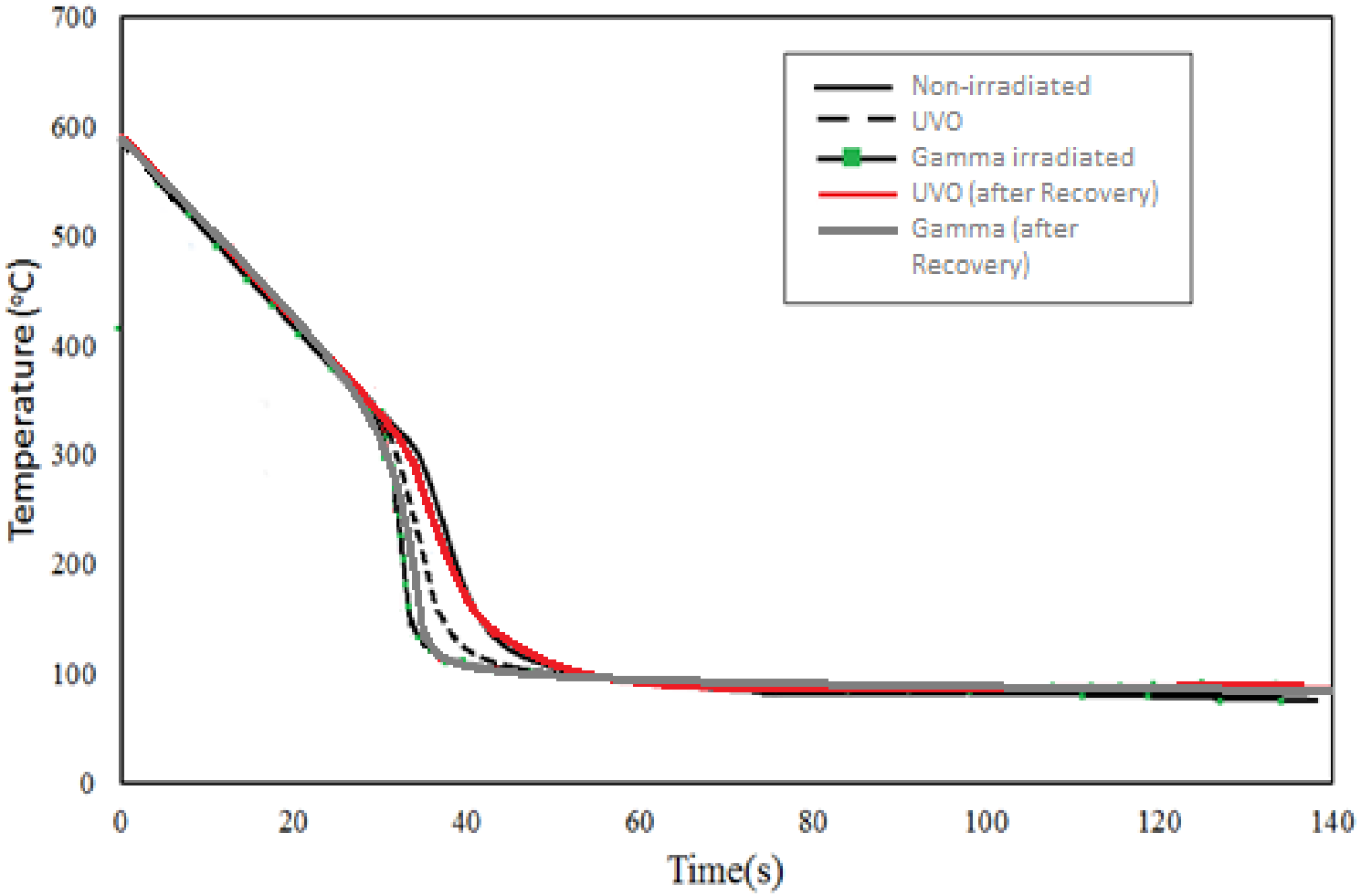
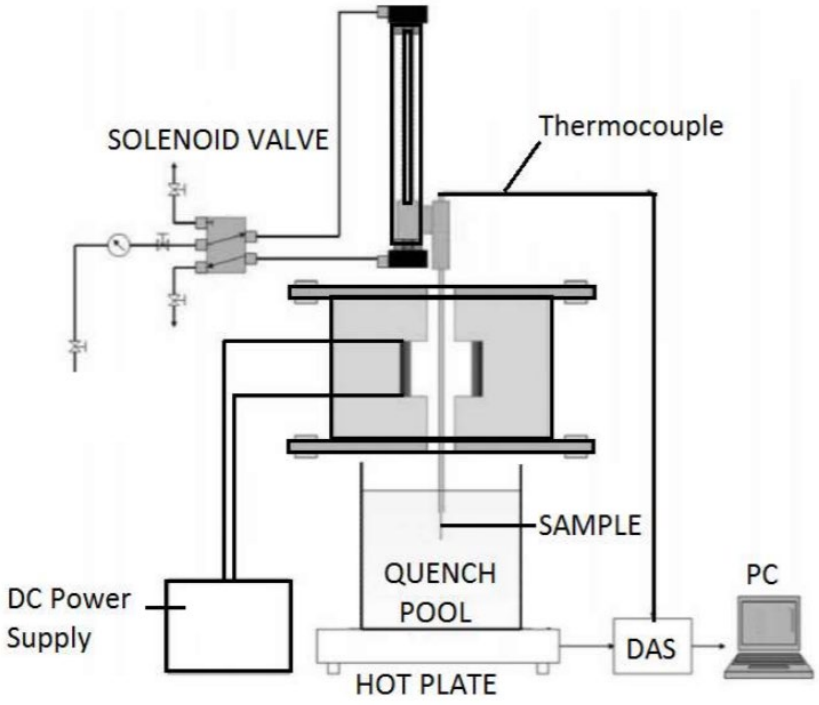
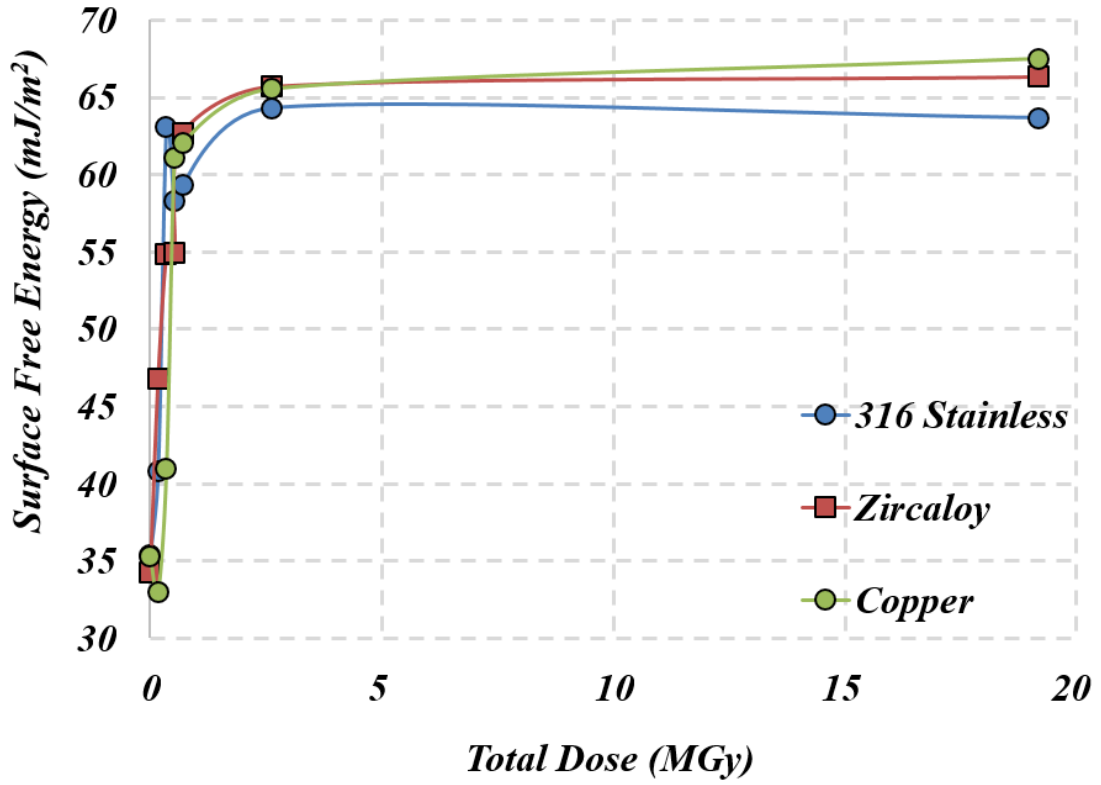
RISA Effect is Permanent for Quench

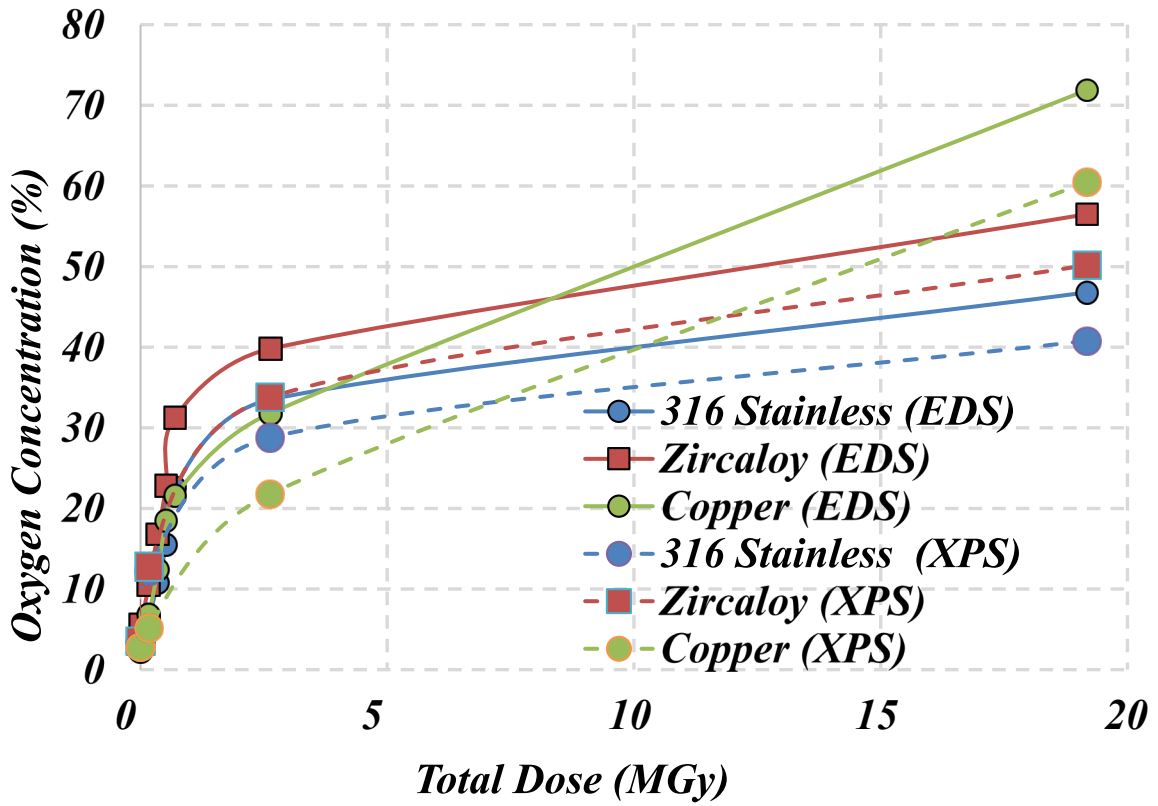




RISA Impacts Wide Range of Materials

Seshadri, Forrest, Shirvan, Applied Surface Science, Vol, 514, June 2020





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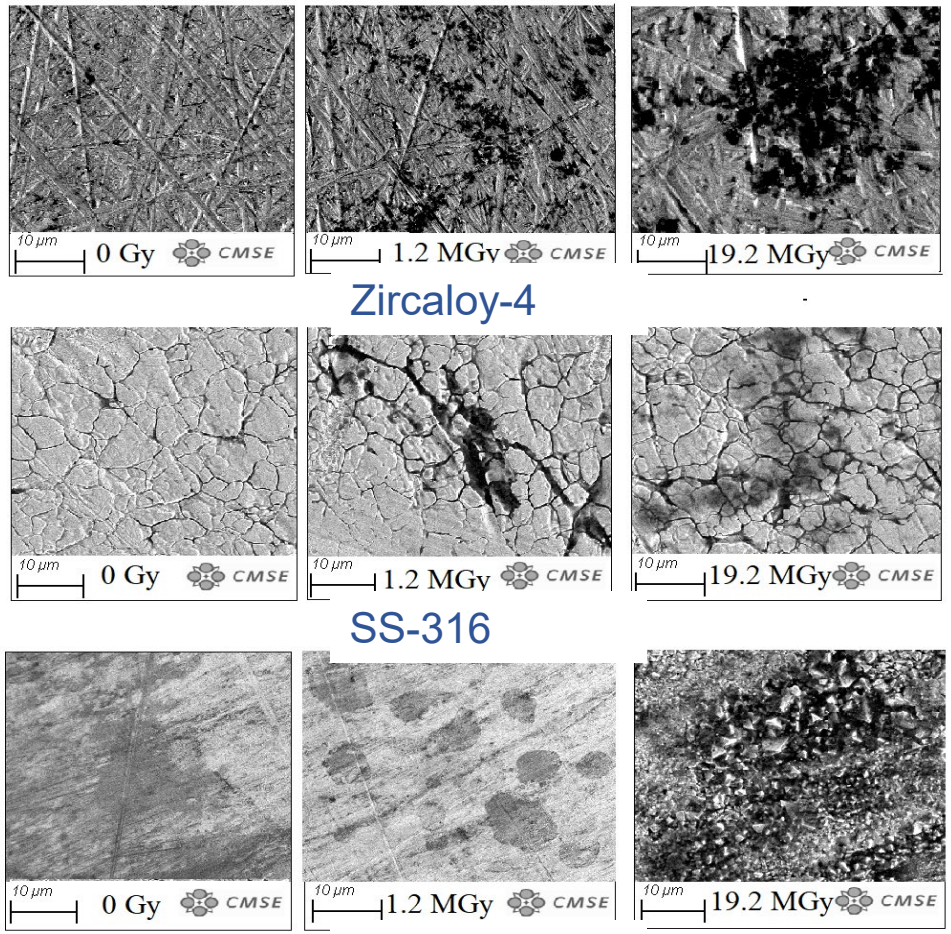
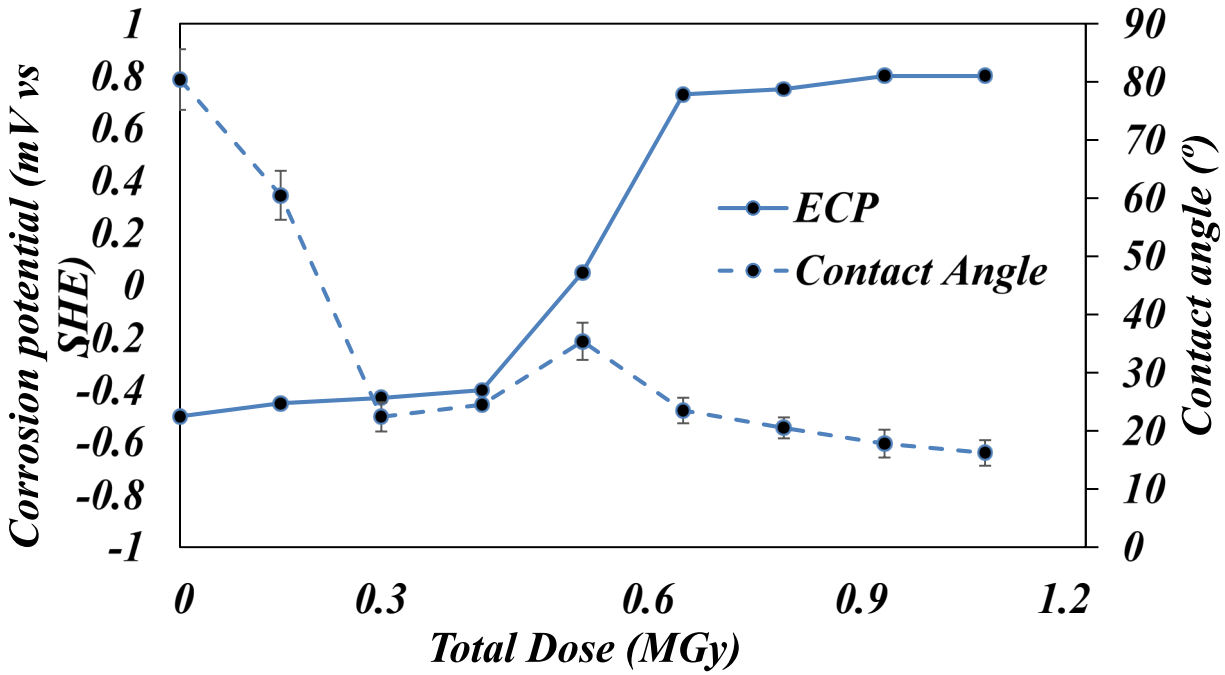
Relationship of Surface Wettability to Corrosion





SS-316 (Potentially capturing Iron II to Iron III oxide transition)

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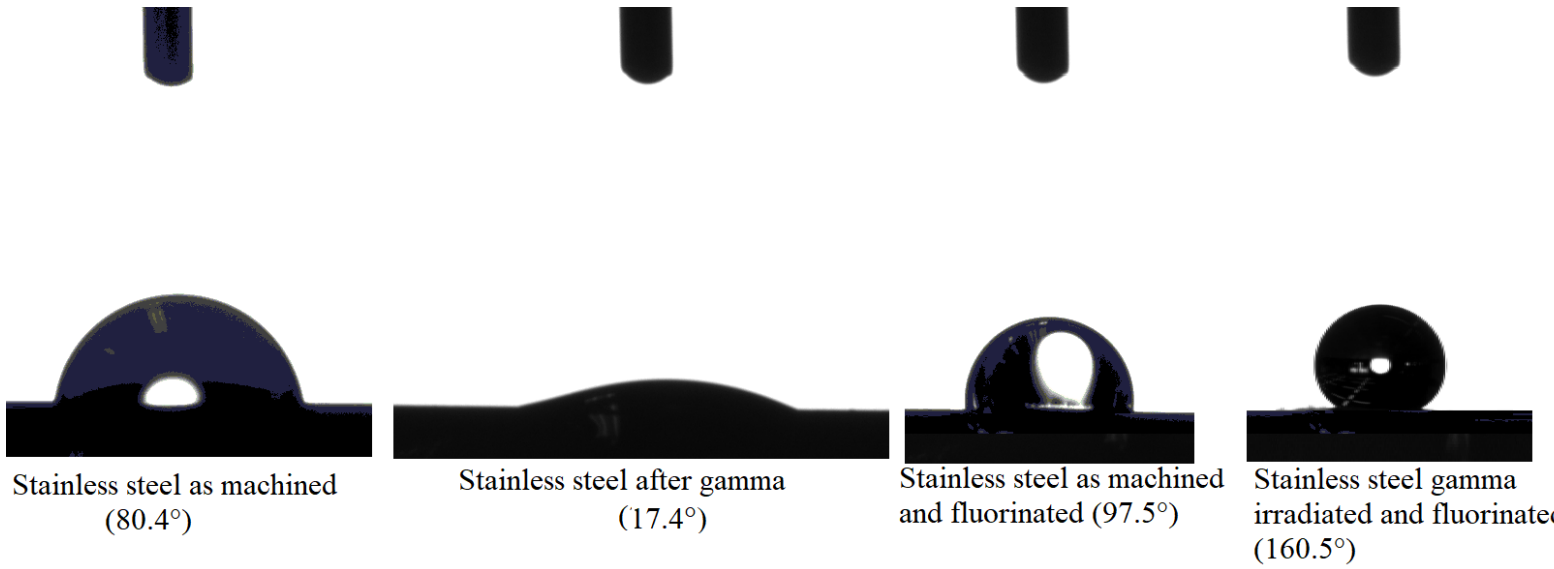
With New Understanding, Is Surface Modification and Texturing Possible?

- Gamma-rays are cheap and scalable
- Effective with metals and ceramics
- Fluorination of the surface after gamma radiation results in durable, superhydrophobic surfaces

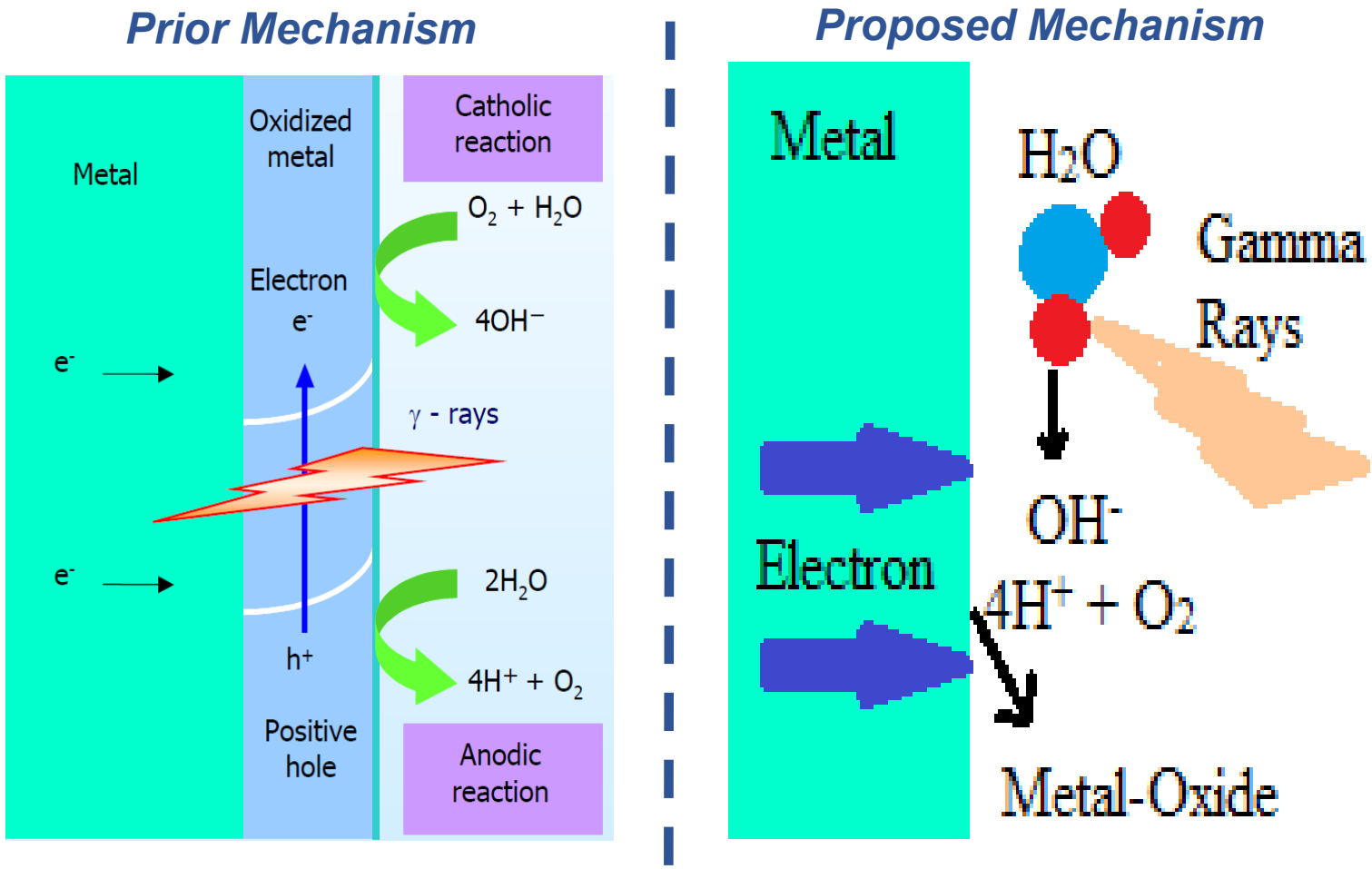
Contact angle measurement for stainless steel for various conditions/treatments



Shirvan K., Seshadri A., Philips B.,
Superhydrophobic Surfaces, U.S. Patent No. 16/842,110, 7 Apr. 2020.
Filed June 18, 2019

Summary

- RISA has shown to increase surface wettability with first discovery in early 2000s
  - Mechanism was thought to be formation of hydroxyl groups on metal-oxide surface and the effect was deemed temporary
  - Careful investigation led to discovery that oxidation is the deriving mechanism and the effect was observed to be permanent.



Path Forward and Acknowledgements

- Explore surface texturing with gamma-rays
- Separate effect understanding of ionizing radiation role in corrosion of advanced nuclear materials (e.g. SiC Composites)
  - Important for surface engineering, new materials and understanding of in-situ corrosion under fission and ion beams

Maryla Wasiolek and Don Hanson (Sandia) for support at GIF.
U.S. Department of Energy, Office of Nuclear Energy under DOE Idaho Operations Office Contract DE-AC07- 051D14517 as part of a Nuclear Science User Facilities experiment.

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