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Use of High Strength Steel for Hydrogen Containment

X. Y. Liu
University of Pennsylvania

Jun A. Kameda
University of Pennsylvania, kamedaj@seas.upenn.edu

C. J. McMahon
University of Pennsylvania

Poster presented at *The Search for a Sustainable Energy Future: Challenges for Basic Research*, A Mini-Symposium sponsored by the Energy Working Group at Penn, March 9, 2007.

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Abstract
The research involves experiments on model lab heats of an ultra-high-strength steel (high C, low Ni) and a high-toughness, high-strength steel (high Ni, low C) to determine the limits of toughness as a function of yield strength, grain-boundary purity, and hydrogen fugacity. In addition, the existence and mechanism of brittle intergranular cracking in ideally pure steels is being investigated.

Comments
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Use of High Strength Steel for Hydrogen Containment

X.Y. Liu, J. Kameda and C. J. McMahon Jr.

Department of Material Science and Engineering
University of Pennsylvania

Overview

The research involves experiments on model lab heats of an ultra-high-strength steel (high C, low Ni) and a high-toughness, high-strength steel (high Ni, low C) to determine the limits of toughness as a function of yield strength, grain-boundary purity, and hydrogen fugacity.

In addition, the existence and mechanism of brittle intergranular cracking in ideally pure steels is being investigated.

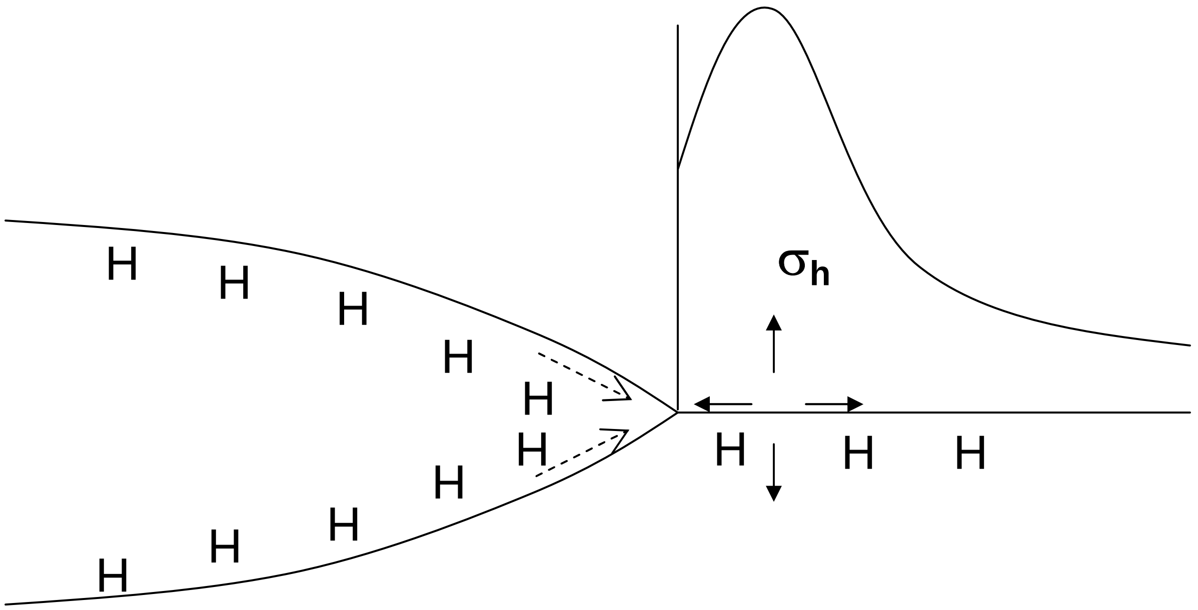
Advantage of steel for tanks and transport

- Capable of high strength (low mass)
- Economical

Challenge

- Hydrogen-induced intergranular embrittlement

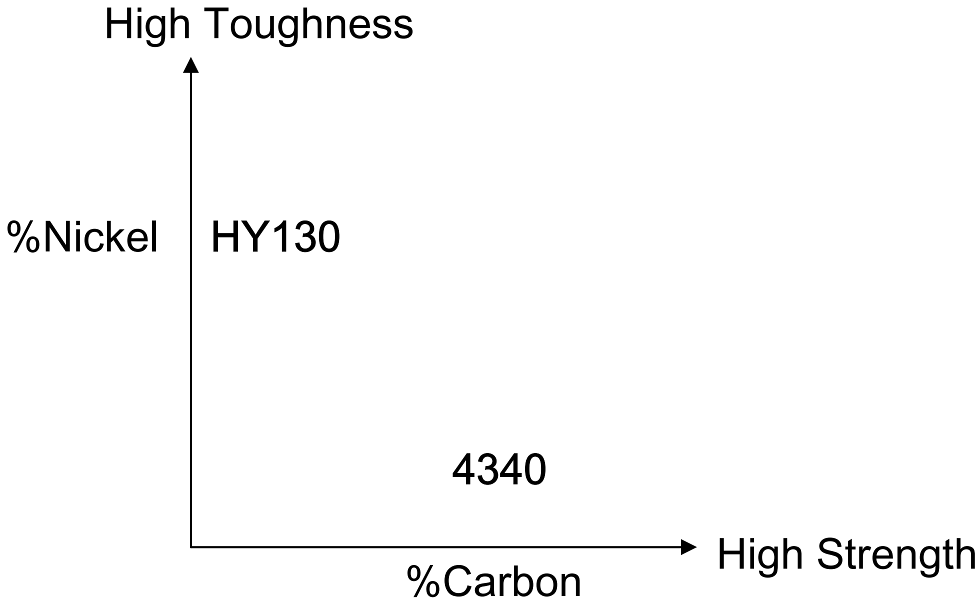
The mechanism



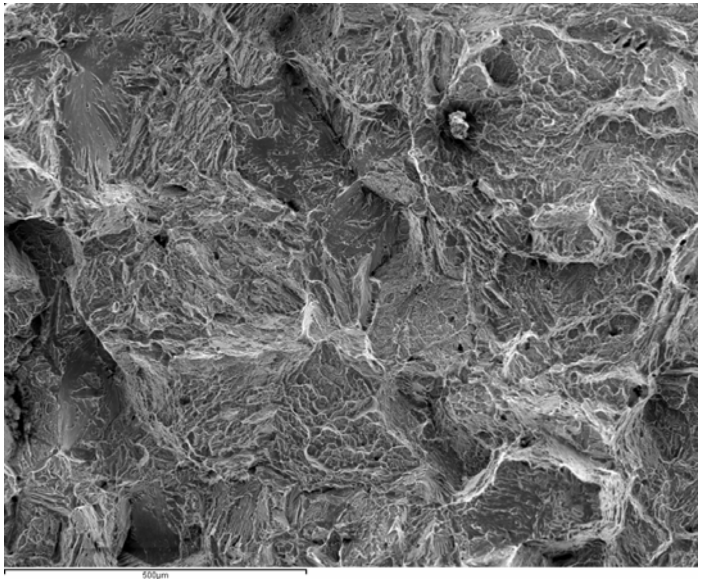
Sharp crack, Nanoscale cracking

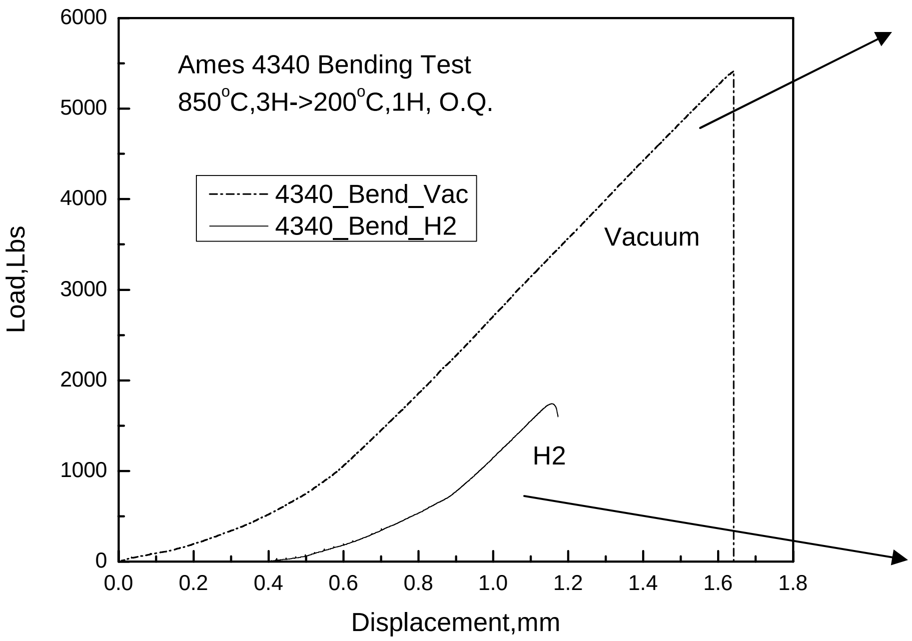
Two kinds of steels

- Inherently High-Strength (4340)
- Inherently High-Toughness (HY130)

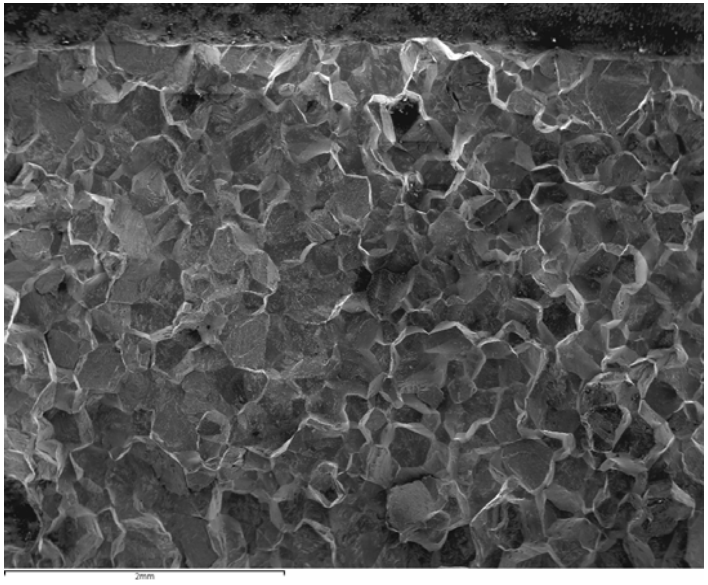


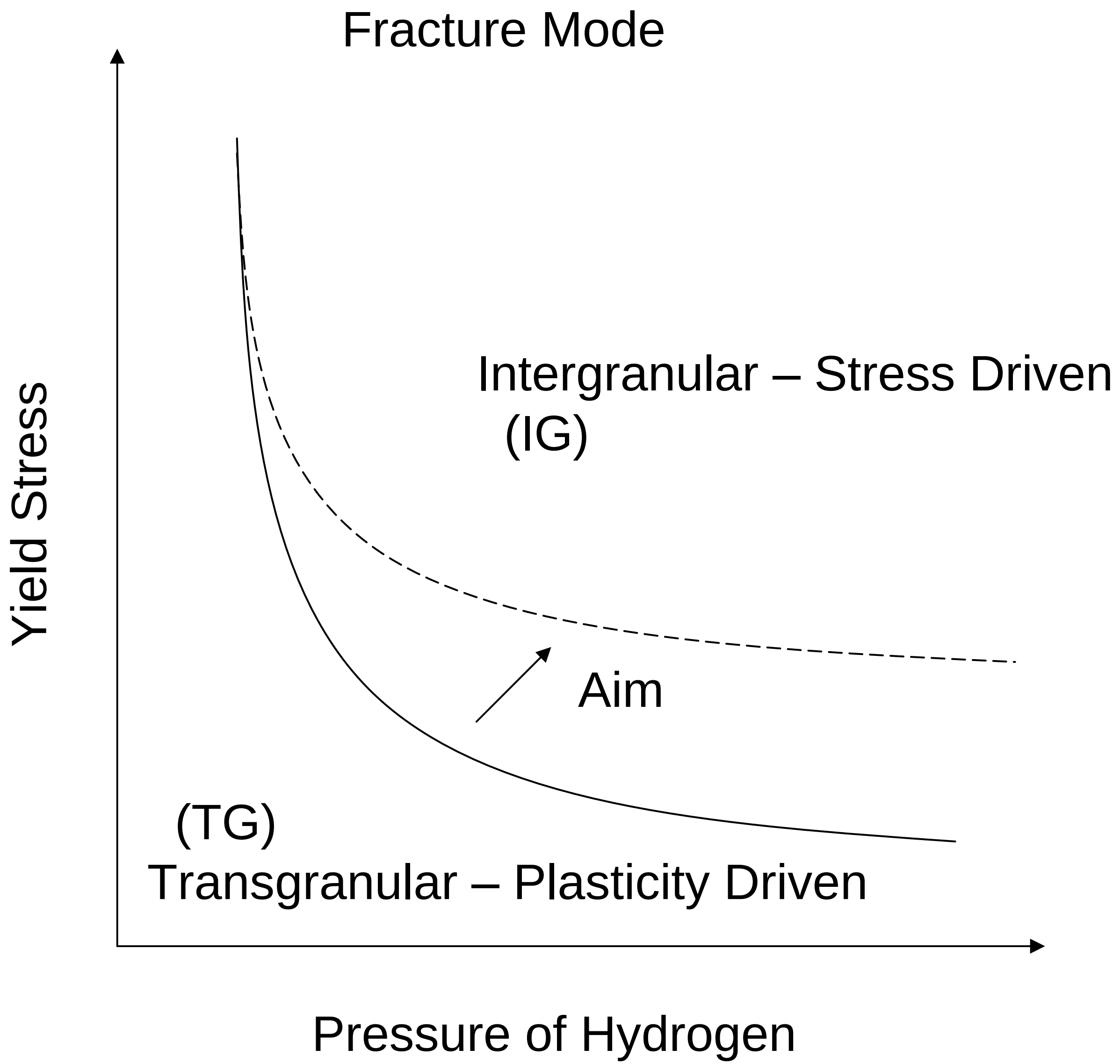
Intergranular (IG)





Transgranular (TG)





Fracture Mode
Intergranular – Stress Driven
(IG)
Aim
(TG)
Transgranular – Plasticity Driven
Yield Stress
Pressure of Hydrogen

Three Controlling Parameters

- Fugacity of hydrogen
- Yield strength of the steel
- Grain-boundary purity (and microstructure?)

- These parameters control the fracture mode of intergranular (IG) and transgranular (TG)

Hydrogen concentration(C_0) dissolved in lattice under hydrogen pressure (P)

$$C_o=0.00185\ P^{1/2}\exp(-3440/T)$$

$C_o = 10^{-8}$ at.fr under P = 1 atm.

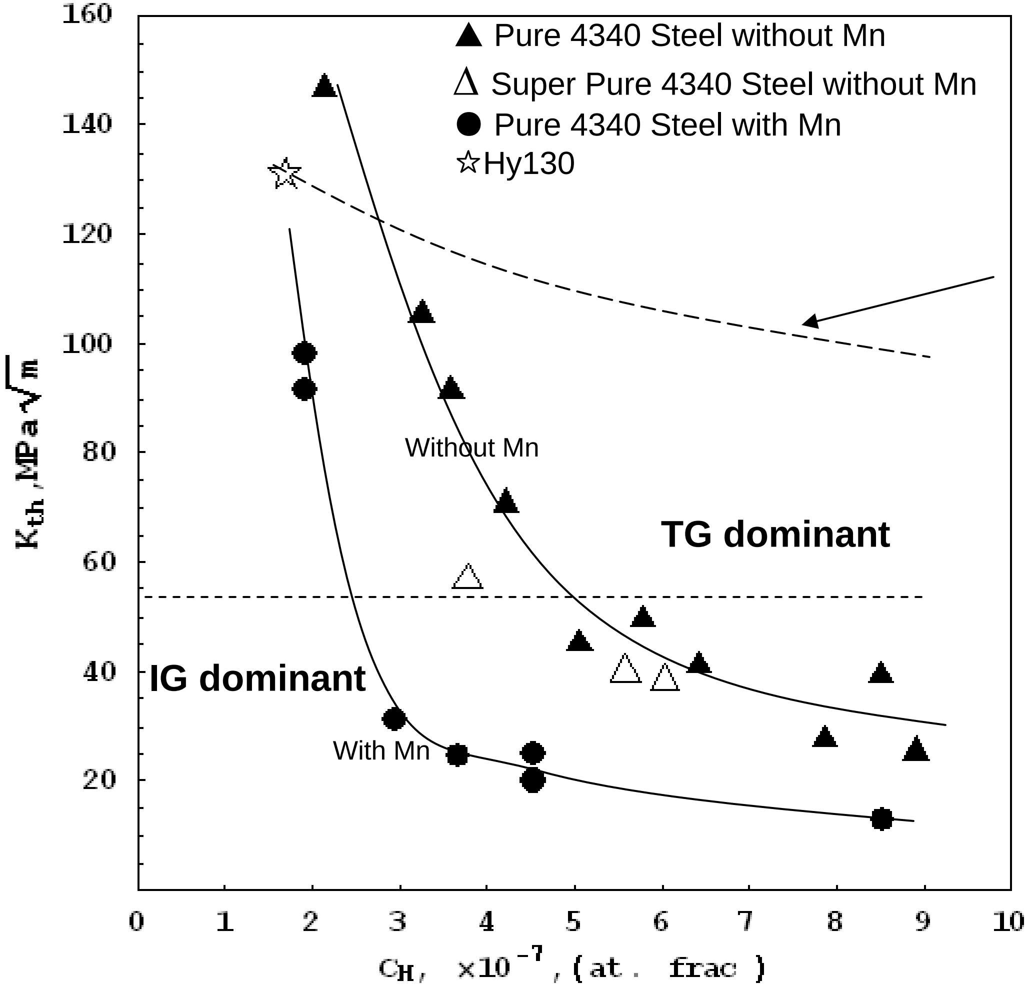
H concentration ahead of a crack tip under hydrostatic tensile stress (σ_h)

$$C_H = C_0 \exp\left(\frac{\sigma_h V_m}{R\,T}\right)$$

- **$\sigma_h=(\sigma_{11}+\sigma_{22}+\sigma_{33})/3 = 2.42\ \sigma_y$**
- **molar volume of hydrogen in iron: $V_m=2.1\times10^{-6}\ m^3/mole$**

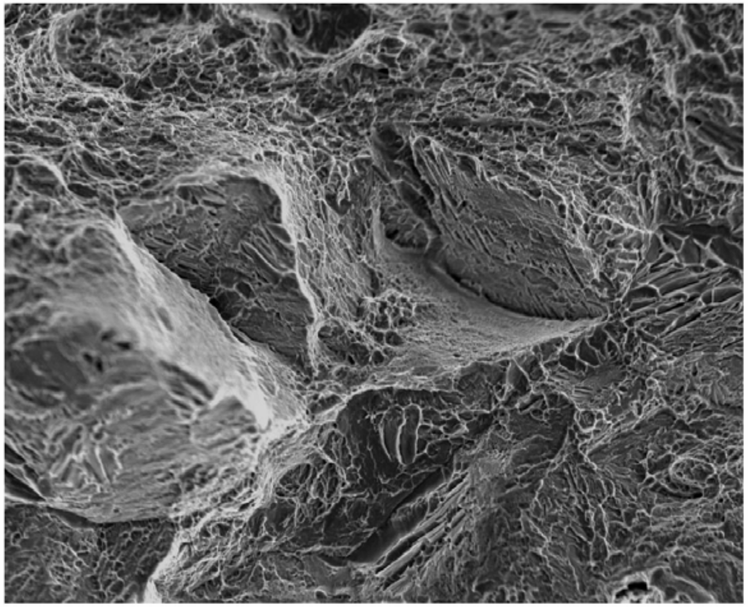
$C_H= 10^{-6}$ at.fr under σ_y=1750 MPa P_{H2}=1 atm

Effect of Purity of High Strength Steel



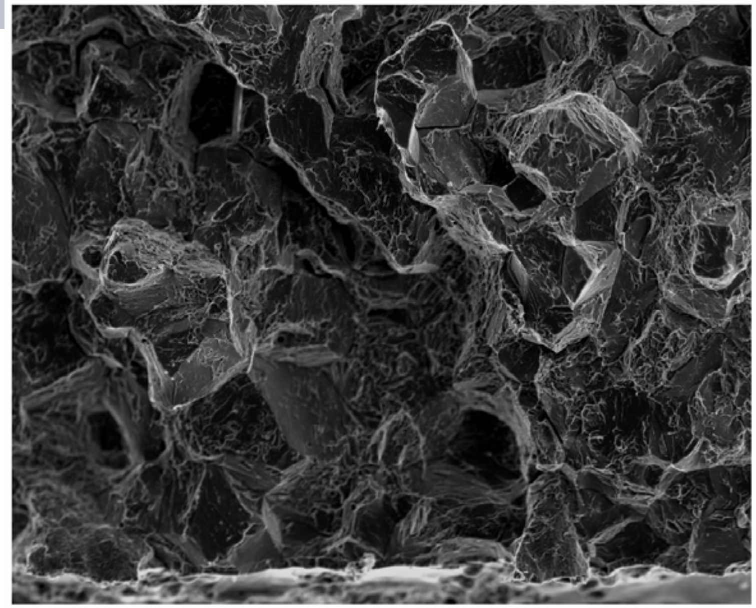
Is this possible?

$$C_H = 0.00185\,(P_{H_2})^{\frac{1}{2}}\ \mathrm{Exp}\left(-\frac{Q_s}{R\,T}\right)\mathrm{Exp}\left(\frac{2.42\,\sigma_y\,V_m}{R\,T}\right)$$



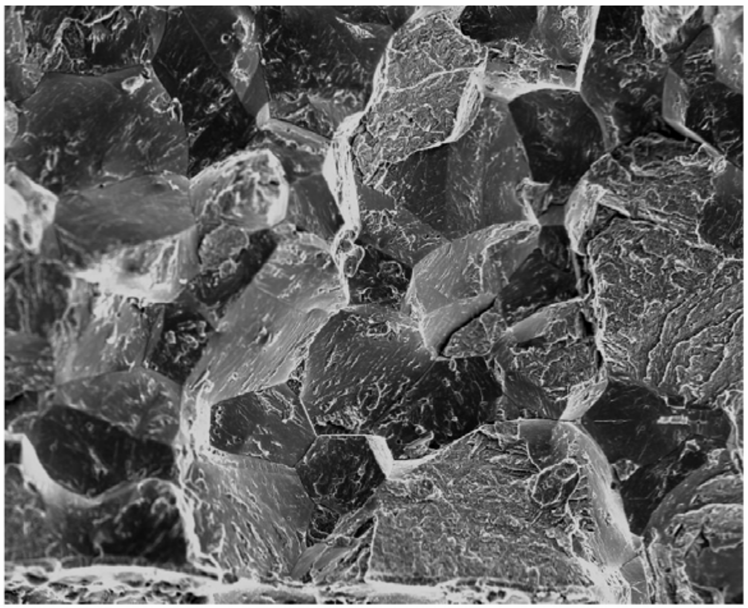
100µm

V1, Homo ->860 C,1Hour in Vacuum -> 100C,1Hour in Vacuum, Bend test in Vacuum



200µm

A1, Homo ->860 C,1Hour in Vacuum -> 100C,1Hour in Vacuum, Bend test in Air



200µm

H1, Homo ->860 C,1Hour in Vacuum -> 100C,1Hour in Vacuum, Bend test in H2

Even ideally pure grain boundaries are cracked in hydrogen at high strength levels.

Summary and Future Work

- Under low hydrogen fugacity, hydrogen induced cracking (HIC) of ultra-high strength steels grows along grain boundaries regardless of the purity.
- High-strength/high-toughness steel shows excellent resistance to HIC under low hydrogen pressure.
- To determine the limit of hydrogen fugacity that can be tolerated for high-purity/high-strength steel.
- Understanding of underlying HIC mechanism of ultra-high-purity/high-strength steel without segregated impurities and precipitates

Acknowledgement

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