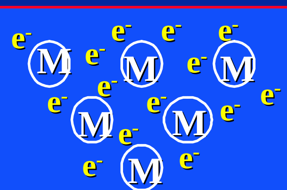
Massachusetts Institute of Technology
Harvard Medical School
Brigham and Women's Hospital
VA Boston Healthcare System

2.782J/3.961J/BEH.451J/HST524J

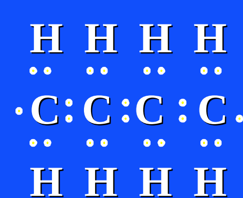
BIOMATERIALS SURVEY

M. Spector, Ph.D.

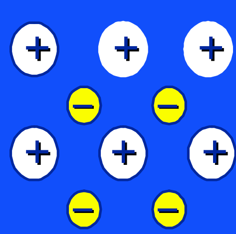
TYPES OF PRIMARY ATOMIC BONDS



Metallic
(electron "glue"
or "cloud")
-metals



Covalent
(shared- pair electrons)
-polymers
-biological macromolec.
(*e.g.*, proteins)



Ionic
(attraction
of positive
and negative ions)
-ceramics
-calcium phosphates

BIOMATERIAL APPLICATIONS

- **Nonabsorbable materials for the fabrication of permanent implants.**
- **Absorbable materials for the production of scaffolds for tissue engineering and regenerative medicine.**

COMPOSITION OF METALS (%)

Stainless Steel	Cobalt Chromium	Titanium
Fe	Co	Ti
Cr (17-20%)	Cr (27-30)	Al (5.5-6.5)
Ni (10-17)	Mo (5-7)	V (3.5-4.5)
Mo (2-4)	Ni (2.5)	Fe,C,O (0.5)
C (0.03)	Fe, C, Mn, Si (<3.1)	
Mn, P, S, Si (<2.8)		

Mechanical Prop.

ASTM#	Condition	Elastic Modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)	Endurance Limit (MPa)
Stain. steels					
F55, F56	Annealed	190	331	586	241 276
F138, F139					
	Cold forged	190	1213	1351	820
Cobalt alloys					
F75	Cast/anneal	210	448 517	655 889	207 310
	HIP*	253	841	1277	725 950
F799	Hot forged	210	896 1200	1399 1586	600 896
F90	Annealed	210	448 648		951 1220
F562	Hot forged	232	965 1000	1206	500
	Cold forged/ aged	232	1500	1795	689 793
Titanium alloy					
F67	30% Cold worked	110	485	760	300
F136	Forge anneal	116	896	965	620
	Forged/heat treated	116	1034	1103	620 689

* HIP = hot isostatically pressed; ASTM = Amer. Soc. for Test. and Matls.

ORTHOPAEDIC METALS

	ADVANTAGES	DISADVANTAGES
Stainless Steel	Strength Ease of manuf. Availability	Potential for corrosion High mod. of elasticity
Cobalt-Chromium	Strength Rel. wear resist.	High mod. of elasticity
Titanium	Strength Low modulus Corrosion resistance	Low wear resistance

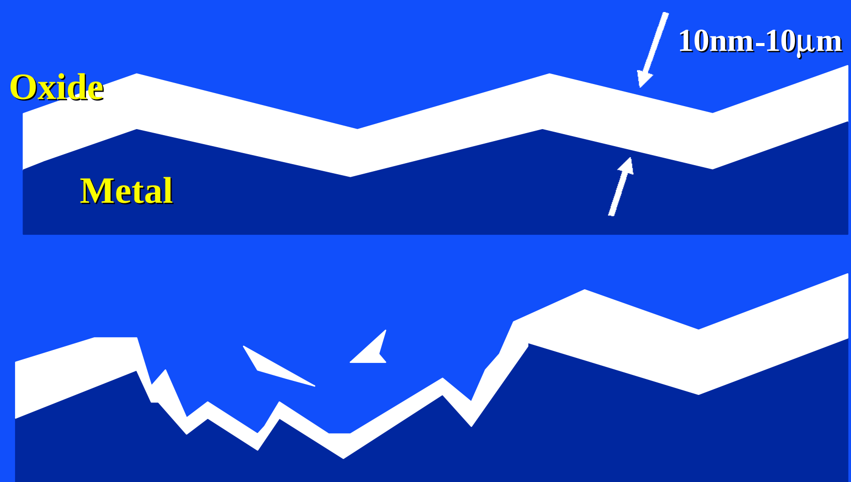
WHAT ARE CERAMICS?

- Compounds of metallic and nonmetallic (*e.g.*, oxygen) elements
- Ceramic materials:
  - Alumina (aluminum oxide)
  - Zirconia (zirconium oxide)
- Metal oxides:
  - Chromium oxide
  - Titanium oxide

ADVANTAGES OF CERAMICS

- Dense/hard (scratch resistant)
  - Related to the character of the ionic bonding
- Ability to be polished to an ultra smooth finish

THE METALLIC OXIDE (CERAMIC) SURFACE OF METALS



CHARACTERISTICS OF OXIDES THAT AFFECT THEIR PERFORMANCE

- Adherence to metal substrate
  - Related to the mismatch in bonding (oxides comprise ionic and covalent bonds in contrast to metallic bonds)
- Porosity/density
- Thickness

METALS FOR TJA:
PAST, PRESENT, AND FUTURE

1900-1940 1940-1960 1970 1980 1990 2000 2010

Stainless Steel

Cobalt-Chromium Alloy

Titanium

Oxinium

Oxinium is the first new metal alloy in orthopaedic surgery in 30 years.

WHAT IS OXINIUM?

Oxinium is a new metal alloy (zirconium-niobium) that has a ceramic surface produced by a special oxidation process.

It has also been referred to as “oxidized zirconium.”

METALS FOR TJA: PAST, PRESENT, AND FUTURE

1900-1940	1940-1960	1970	1980	1990	2000	2010

Stainless Steel

Cobalt-Chromium Alloy

Titanium

Oxinium

Selection Criteria

Inertness/Biocompatibility

Strength

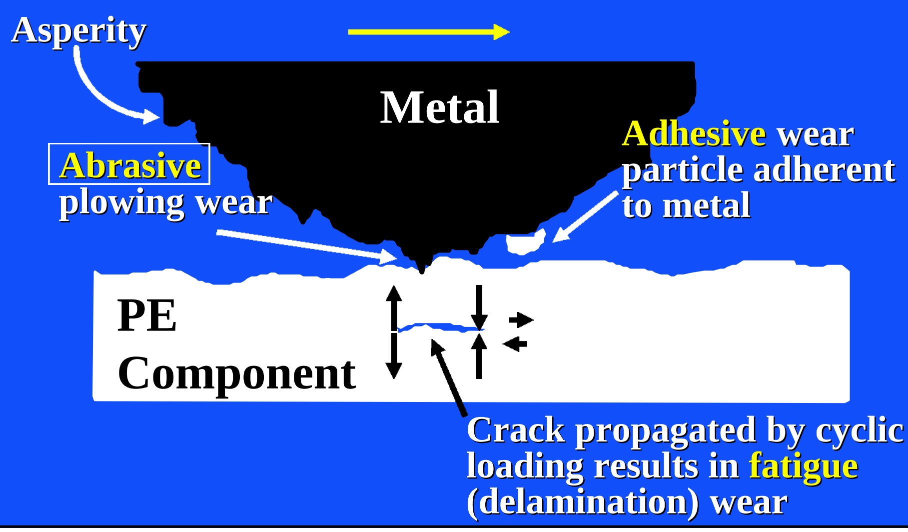
Lower Modulus

Scratch-resist.
Lubricatious
Non-Allergen.

ORTHOPAEDIC METALS

	ADVANTAGES	DISADVANTAGES
Stainless Steel	Strength Ease of manuf. Availability	Potential for corrosion High mod. of elasticity
Cobalt-Chromium	Strength Rel. wear resist.	High mod. of elasticity
Titanium	Strength Low modulus Corrosion resist.	Poor wear resistance
Oxinium	Scratch-resist. Low modulus	?

WEAR PROCESSES



EFFECT OF A SINGLE SCRATCH ON PE WEAR

- Profound effect of a single scratch; wear due to the ridge of metal bordering an scratch

Image removed due to copyright restrictions.
Diagram showing scratch profile before lapping (with ridges) and after lapping (no ridges).

10-fold increase in PE wear when the ridge bordering the scratch exceeded 2µm in height

(This type of scratch is not noticeable by eye.)

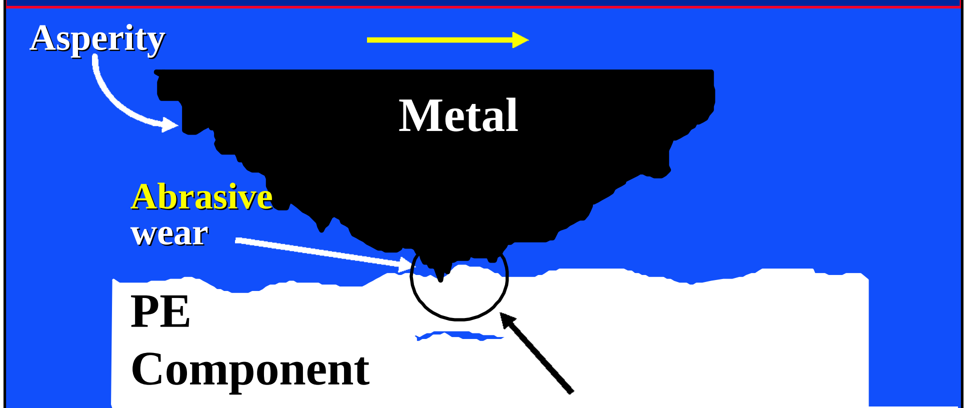
No PE wear if the metal ridge is removed

Dowson, *et al.*, Wear (1987)

Scratches on Retrieved Co-Cr Femoral Condyles
Scanning Electron Microscopy

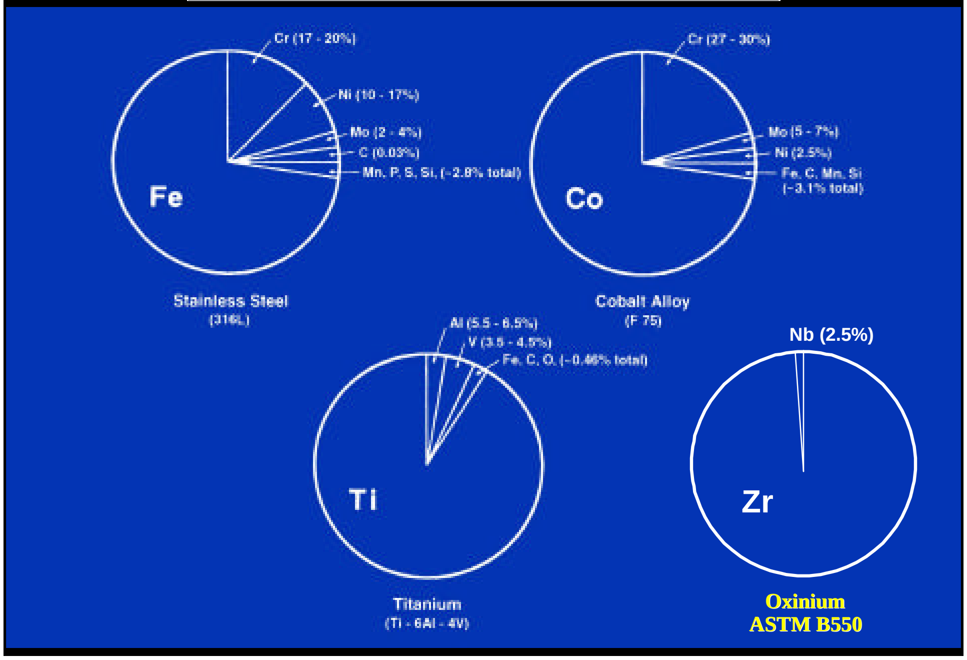
Photos removed due to copyright restrictions.

WEAR PROCESSES



Solution is a scratch-resistant metal/ceramic counterface;
X-linked PE may not be the solution

Composition of Orthopaedic Metals



COMPOSITION OF METALS (%)

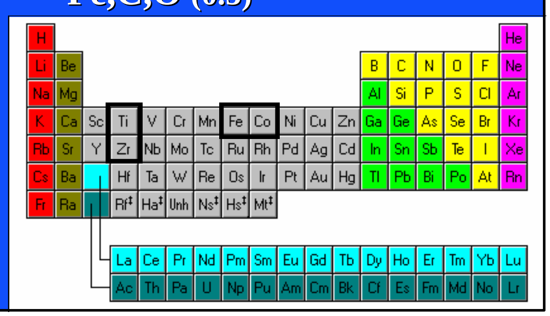
Stainless Steel
Fe
Cr(17-20%)
Ni (10-17)
Mo (2-4)
C (0.03)
Mn, P, S, Si (<2.8)

Cobalt-Chromium
Co
Cr (27-30)
Mo (5-7)
Ni (2.5)
Fe, C, Mn, Si (<3.1)

Titanium Alloy
Ti
Al (5.5-6.5)
V (3.5-4.5)
Fe,C,O (0.5)

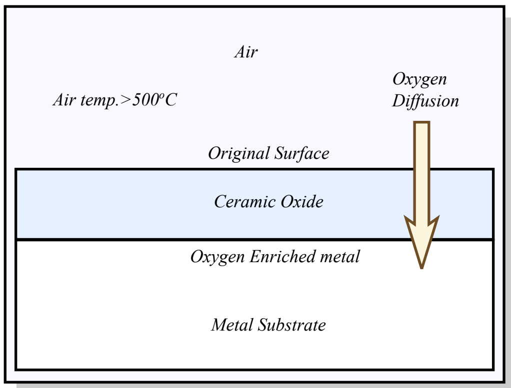
Zirconium-Niobium*
Zr
Niobium (2.5)

* Oxinium



How is the Ceramic Surface Produced on Oxinium?: Oxidation Process

- Wrought zirconium alloy device is heated in air.
- Metal <u>transforms</u> as oxide grows; <u>not a coating.</u>
- Zirconium Oxide (Zirconia ceramic) is ~5 µm thick.



Zirconium metal alloy is heated in air
Oxygen diffuses into the metal surface
Surface becomes enriched in oxygen
Surface transforms to ceramic oxide

Figure by MIT OCW.

Oxinium

Photo removed due to copyright restrictions.

- May be a more innovative a development than cross-linked PE.
- One of only 2 materials developed principally for TJA (the other is hydroxyapatite).

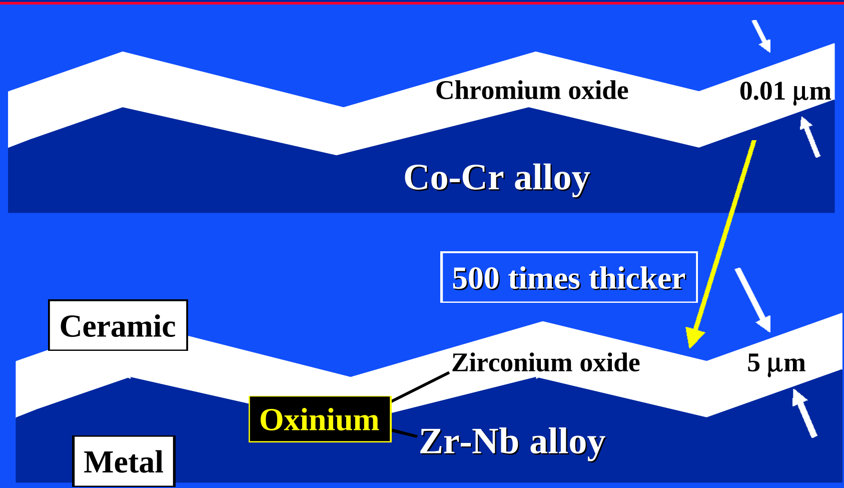
Fatigue Testing of Oxinium Femoral Components

- Fatigue strength the same as for Co-Cr devices.
- Supports 4.4 kN (1000 lbf) in 10 Mcycle fatigue test.
- Tested worst-case: thin condyle, no bone, full flexion.

Photo removed due to copyright restrictions.

*Tsai et al., SFB 2001

Co-Cr ALLOY VERSUS Zr-Nb ALLOY: THICKNESS OF THE OXIDE



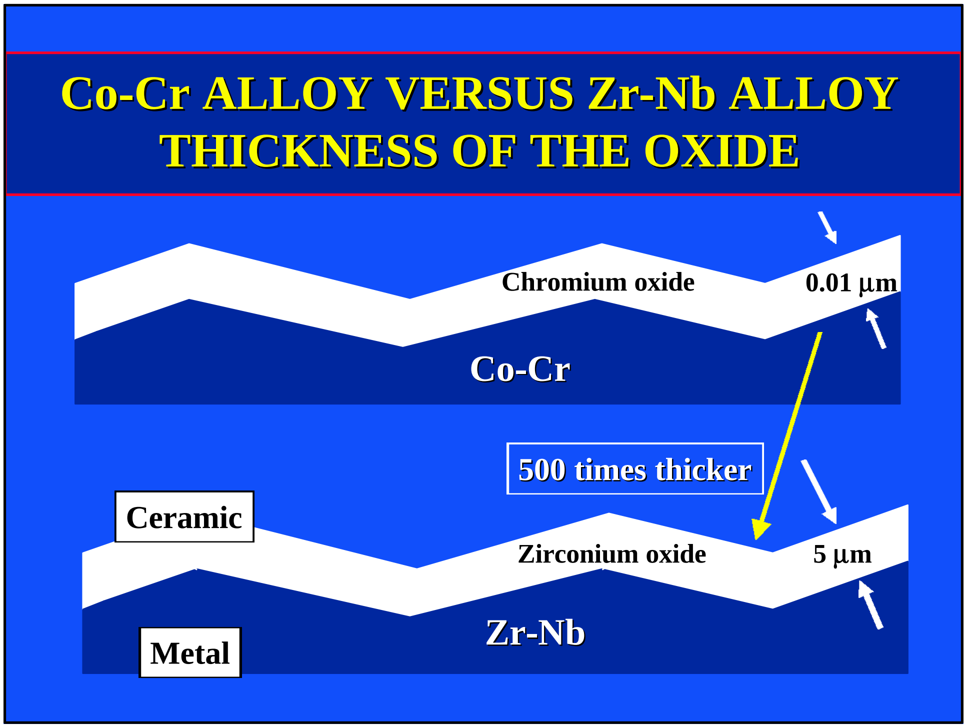
ADVANTAGES OF OXINIUM

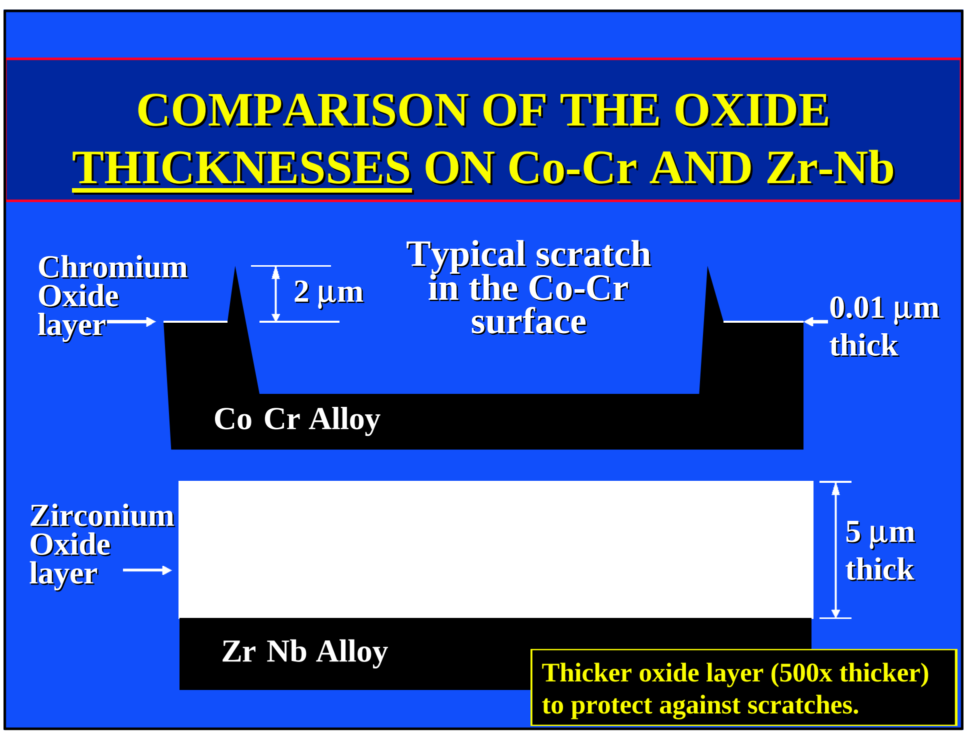
Weds the best of a ceramic with the best of a metal.

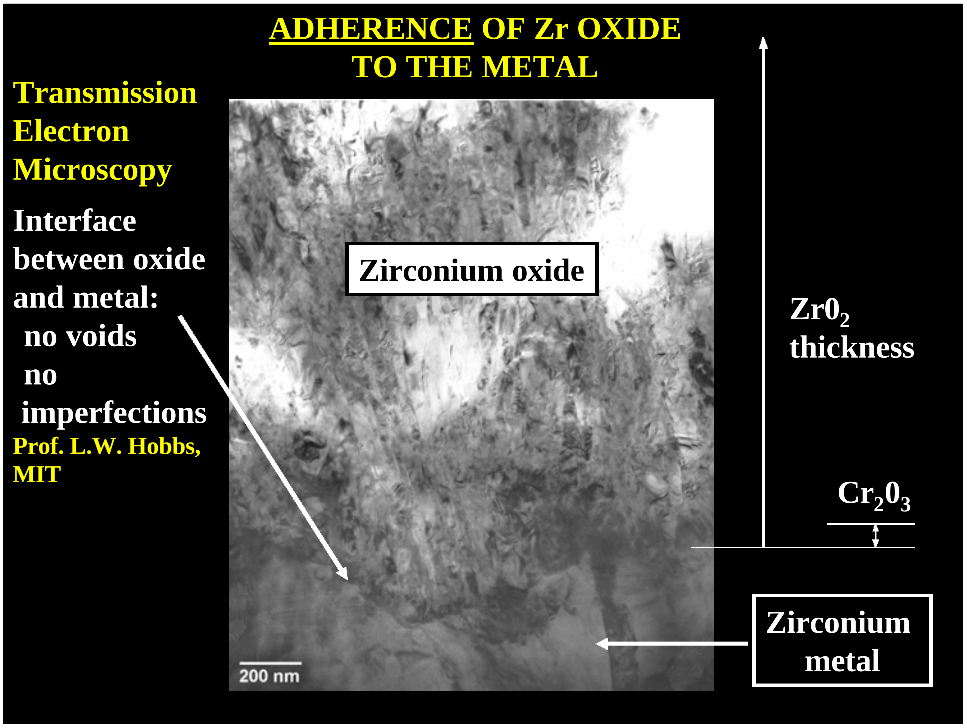
- **Scratch resistant: <u>less abrasive wear of PE</u>**
- **More lubricatious: lower friction may result in <u>less adhesive wear of PE;</u> <u>better patella articulation</u>**
- **Much lower modulus than Co-Cr alloy (similar to Ti): lower stiffness and <u>less stress shielding</u>**
- **<u>Non-allergenic</u>**

CHARACTERISTICS OF OXIDES THAT AFFECT THEIR PERFORMANCE

- **Thickness**
- **Adherence to metal substrate**
- **Porosity/density/strength of the oxide**


Co-Cr ALLOY VERSUS Zr-Nb ALLOY
THICKNESS OF THE OXIDE
Chromium oxide
0.01 µm
Co-Cr
500 times thicker
Ceramic
Zirconium oxide
5 µm
Zr-Nb
Metal


COMPARISON OF THE OXIDE
THICKNESSES ON Co-Cr AND Zr-Nb
Chromium Oxide layer
2 µm
Typical scratch in the Co-Cr surface
0.01 µm thick
Co Cr Alloy
Zirconium Oxide layer
5 µm thick
Zr Nb Alloy
Thicker oxide layer (500x thicker) to protect against scratches.



Source: Benezra, V., M. Spector, et al. "Microstructural Investigation of the Oxide Scale on Zr-2.5 Nb and its Interface with the Alloy Substrate." In Biomedical Materials -- Drug Delivery, Implants and Tissue Engineering. Mat. Res. Soc. Symp. Proc. Vol. 550, 1999, pp. 337-342.

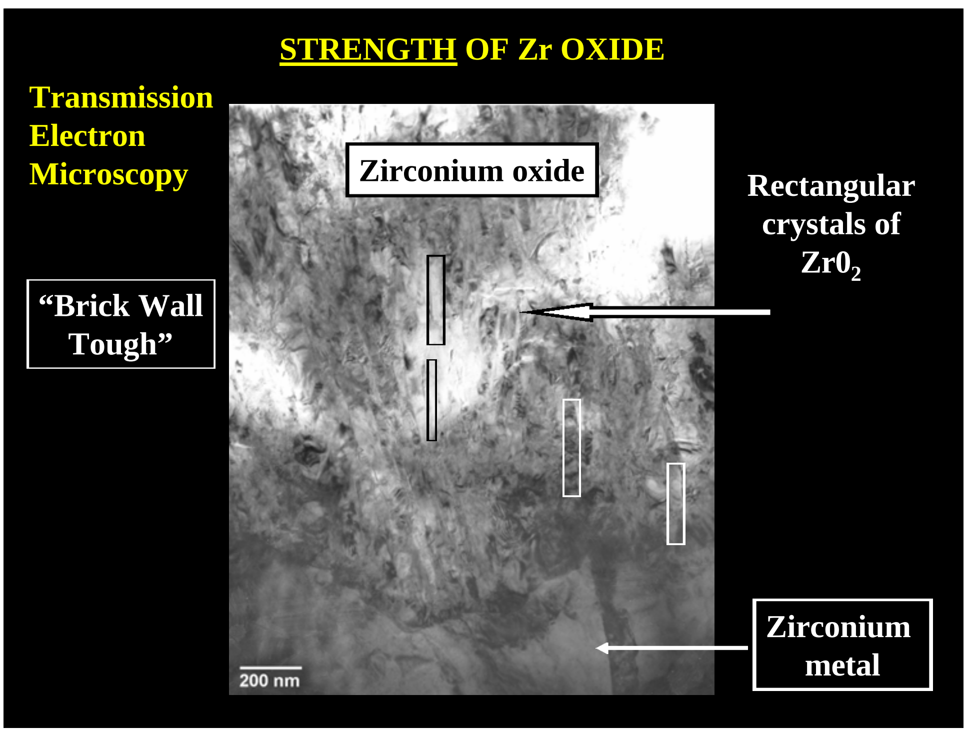


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Image removed due to copyright restrictions.
Photo of ceramic on PE hip joint.

Hip Simulator Study

I.C. Clarke and A. Gustafson
Clin. Orthop. 379:34 (2000)

Image removed due to copyright restrictions.
Graph of wear rate vs. protein content.

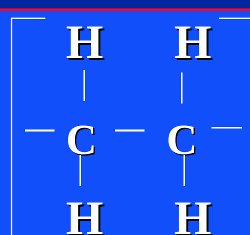
Wear of PE with OxZr versus CoCr Condyles
Knee Simulator Study

Image removed due to copyright restrictions.
Graph of mean tibial wear vs. number of cycles.

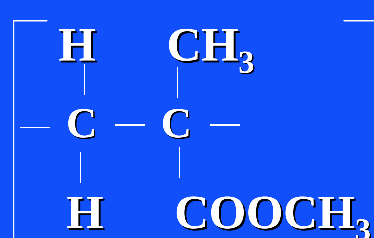
Smith & Nephew Orthopaedics

POLYMERS

Polyethylene



Polymethylmethacrylate



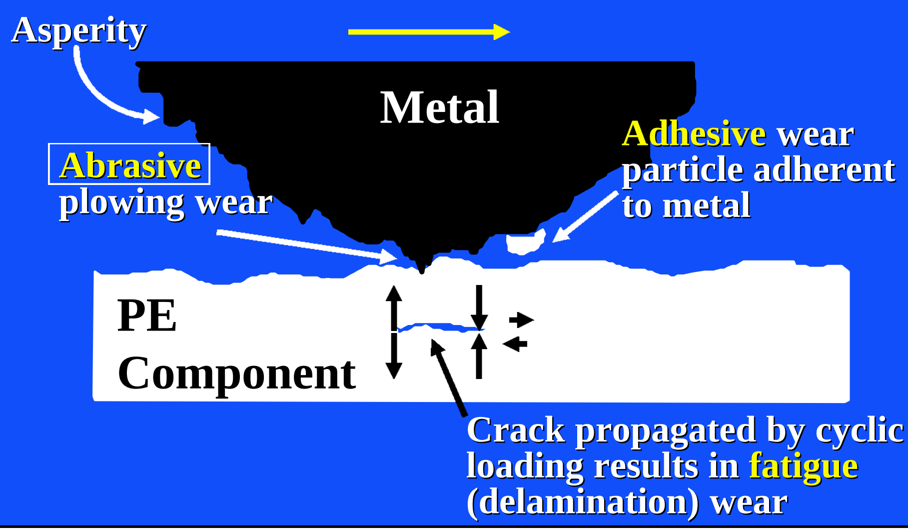
ORTHOPEDIC POLYMERS

	ADVANTAGES	DISADVANTAGES
UHMWPE	Relatively high wear resistance	Subject to oxidation
PMMA	Polymerization *in vivo*	Low fatigue strength (for load-bearing applications)

MECHANICAL PROPERTIES

	Tensile Strength (psi)	Modulus of Elasticity (10^6psi)
Stainless steel	90,000	28
Co-Cr Alloy	150,000	35
Ti (6AL-4V)	150,000	16
Bone	10–15,000	2–3
PMMA	7,000	0.2–0.5
UHMWPE	6,500	0.06–0.18

WEAR PROCESSES



POLYETHYLENE

SYNTHESIS		COMPACTION		COMP. MFG.
Hoechst	→	Westlake Poly Hi	→	Orthopedic Co.
Resin (Powder, Flake) 125 µm	→	Extruded Rod Comp. Molded Plate	→	Machined Molded
MW Catalyst		Fusion defects		Sterilization

γ-Radiation-Induced Oxidation

Photos removed due to copyright restrictions.

Fusion Defects

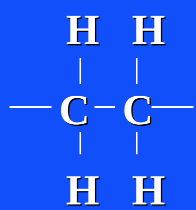
Radiation-induced x-linking

MOLECULAR STRUCTURE OF POLYETHYLENE

Micrometer Level

Fusion defects due to incomplete consolidation are cracks that can be propagated by fatigue (delamination) wear.

ULTRAHIGH MOLECULAR WEIGHT POLYETHYLENE



10-30nm

Amorphous Region
“Tie” Molecules

Diagram of PE crystallite structure removed due to copyright restrictions.

Crystallites

MOLECULAR STRUCTURE OF POLYETHYLENE

Nanometer Level

- “Tie” molecules bind PE crystallites
- Mechanical properties are related to the number of tie molecules (fracture occurs through the amorphous region comprised of tie molecules)
- Mechanical bonding between PE particles is due to entanglement of molecular chains
- Reinforcing elements (*e.g.*, fibers) added to PE are only effective if PE bonds to them

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Radiation-induced x-linking

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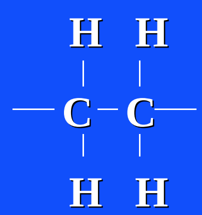

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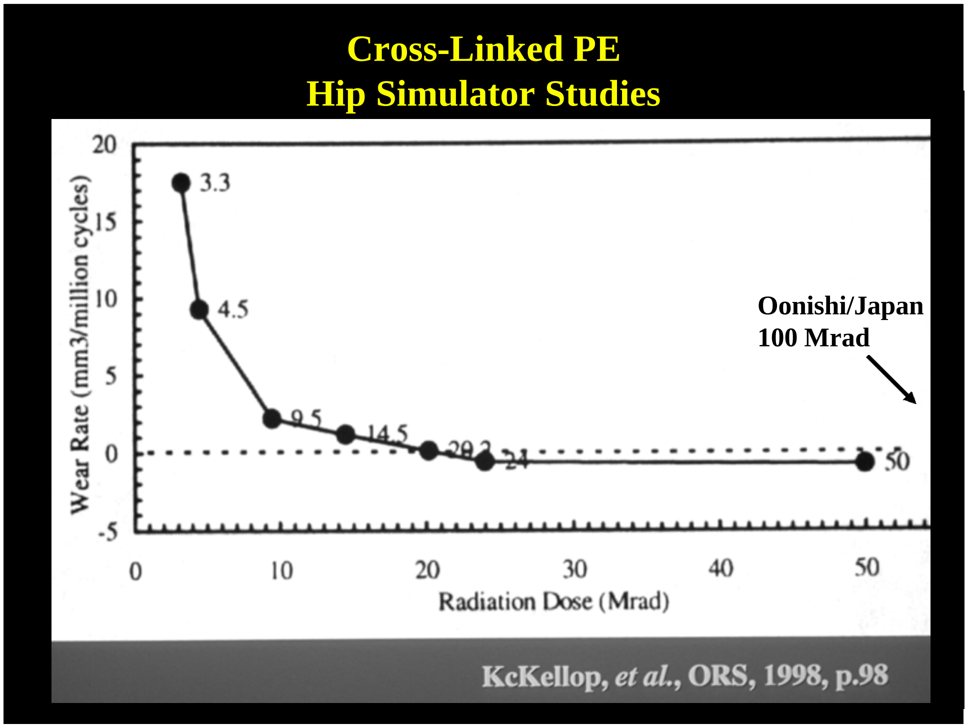


Courtesy of the Orthpaedic Research Society. Used with permission.

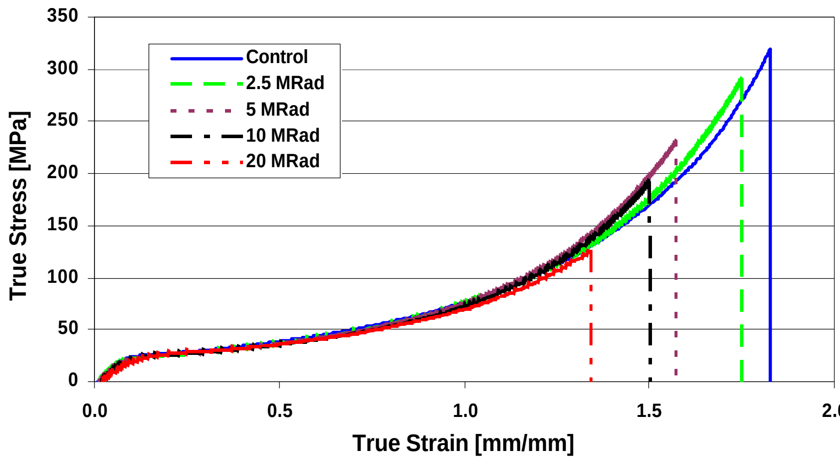
CROSS-LINKED POLYETHYLENE: TRADE-OFFS

What is Sacrificed for Lower Wear?

- Reduction in the strain to break with cross-linking; fracture at lower strain; less toughness*
- Less resistance to crack propagation

* γ-radiation cross-linked parts are tougher than e-beam cross-linked components

Representative Tensile True Strain/True Stress Plot for Control and Radiation Cross-Linked UHMWPEs



A. Bellare, *et al.*

Crack Growth Parameters for Radiation Cross-linked PE

Dose [kGy]	θ^e [rad]	θ^p [rad]	R_{ss} [mm]	J_{ss}/J_{1c}*	J_{1c} [kJm^{-2}]	T
0	0.372	1.126	22.7	55.42	2.1	31.3
25	0.404	0.759	19.4	4.25	23.8	11.3
50	0.376	0.594	16.5	1.30	76.2	2.0
100	0.328	0.439	15.2	0.56	-	-ve
200	0.217	0.276	8.2	0.22	-	-ve

*** Energy that it takes to propagate a crack.**

A. Bellare, *et al.*

CROSS-LINKED PE CUPS: POTENTIAL FOR FRACTURE

- Rim loaded cross-linked cups have a 100,000-fold decrease in their resistance to fatigue fracture, despite having only a 10-fold decrease in fracture toughness
- Cups failed after only 100 cycles

*S. Li, Soc. for Biomaterials, May 1, 1999

CROSS-LINKED PE CUPS: POTENTIAL FOR FRACTURE

- Will we be seeing more frequent fracture of cups?
- Will fracture of cups be design sensitive?
- In “solving” wear will we have introduced a new problem?

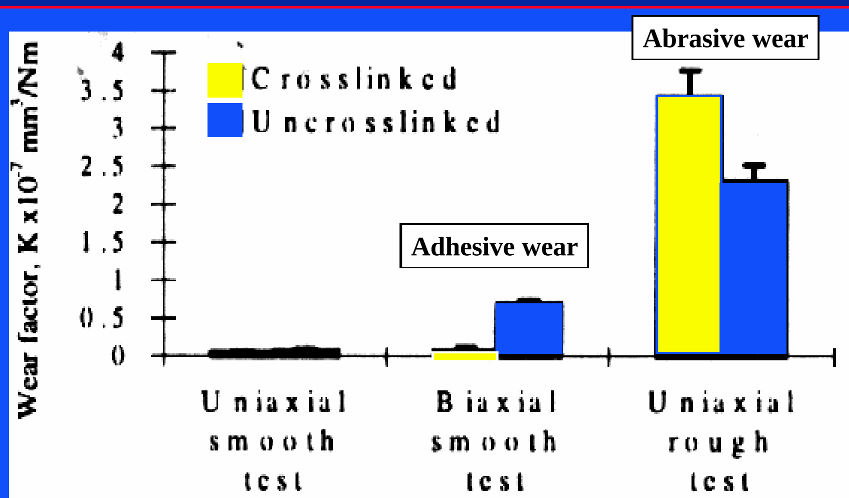
*S. Li, Soc. for Biomaterials, May 1, 1999

ROLE OF X-LINKED PE IN TKA
Electron Beam X-Linked and Melted

- **Against** (C. Rimnac and AS Greenwald)
  - Highly x-linked PEs have … inferior fracture properties”
  - “raise concerns of gross fracture in knee components”
  - “There are THR designs that utilize conventional PE with contemporary sterilization methods that have been shown to have excellent clinical long-term performance.”

AAOS Bulletin, June 2002, p. 50-51

WEAR OF CROSS-LINKED PE
H Marrs, *et al*., Trans. ORS, 1998, p. 100



EFFECTS OF A ROUGH METAL COUNTERFACE ON WEAR OF CROSS-LINKED PE
Knee Simulator

Image removed due to copyright restrictions.
Bar graph of wear rate for clean and abraded cases, CoCr/CPE vs. CoCr/XPE.

V. Good and K. Widding, S&N

In TKA, X-linked PE wears more than conv. PE (EtO) against a scratched metal counterface.

BIOMATERIAL APPLICATIONS

- **Nonabsorbable materials for the fabrication of permanent implants.**
- **Absorbable materials for the production of scaffolds for tissue engineering and regenerative medicine.**

SCAFFOLD (MATRIX) MATERIALS
Synthetic

- Polylactic acid and polyglycolic acid
- Polycarbonates
- Polydioxanones
- Polyphosphazenes
- Poly(anhydrides)
- Poly(ortho esters)
- Poly(propylene fumarate)
- Pluronic (polaxomers)
  – Poly(ethylene oxide) and poly(propylene oxide)

SCAFFOLD (MATRIX) MATERIALS
Natural

- Collagen
  – Gelatin and fibrillar sponge
  – Non-cross-linked and cross-linked
- Collagen-GAG copolymer
- Albumin
- Fibrin
- Hyaluronic acid
- Cellulose
  – Most abundant natural polymer
  – Mechanism of absorbability *in vivo*?

SCAFFOLD (MATRIX) MATERIALS
Natural (Continued)

- **Chitosan**
  - –Derived from chitin, 2nd most abundant natural polymer
  - –Mechanism of absorbability *in vivo*?
- **Polyhydroxalkanoates**
  - –Naturally occurring polyesters produced by fermentation
- **Alginate (polysaccharide extracted from seaweed)**
- **Agarose**
- **Polyamino acids**