Plasma Facing Material Alternatives to Tungsten

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25th IAEA Fusion Energy Conference, Oct. 13-18, 2014, St. Petersburg, Russia

High-Z plasma facing material alternatives to tungsten

Motivation: We are very dependent on tungsten working for ITER, DEMO etc., plasma facing components (PFCs). (One issue is D-T and He induced "tendril" surface formation). We need alternatives, i.e. an "insurance policy".

Goal: Identify and evaluate alternative high-Z materials, from three standpoints:

A) Activation, waste disposal, recycling (ARIES-ACT-1 divertor; PARTISN transport code [6] and ALARA activation code analysis, with FENDL cross-section libraries. The entire divertor was modeled in poloidal, cylindrical geometry, with a typical average neutron wall loading of 1 MW/m2.

B) Sputter erosion/redeposition (REDEP/WBC code package analysis of simulated DEMO divertor. C-MOD geometry, w/ simulated DEMO plasma parameters)

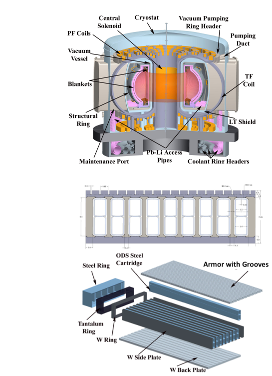
C) Plasma transient response (HEIGHTS code package analysis of ELM's, disruptions, VDE's, runaway electrons; with tungsten and alternative materials)

- ***Focus is on comparisons to tungsten***

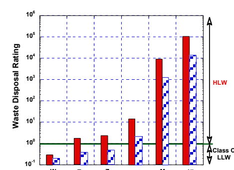
Plasma-facing high-Z materials we are examining

Class	Element	At. No.	Melting pt. Deg. C	Atomic density, 10^{28} atoms/m^3
Z~42	Zr	40	1855	4.25
	Nb	41	2477	5.40
	Mo	42	2623	6.36
Z~74	Hf	72	2233	4.39
	Ta	73	3107	5.48
	W	74	3422	6.28

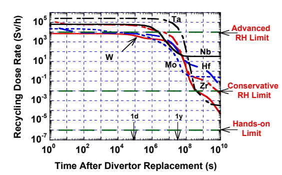
ARIES-ACT-1 Design and Divertor



Activation Analysis

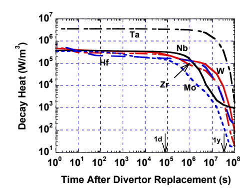


Waste disposal rating of fully compacted ARIES-ACT-1 components after 3.8 MWy/m^2 of divertor neutron irradiation. Solid bars for armor only. Hatched bars for combined armor and divertor.



Time variation of recycling dose rate to the remote handling (RH) equipment for candidate surface materials after divertor replacement (5 mm armor, after 5 year exposure).

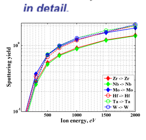
- **All candidate armors could potentially be recycled with advanced remote handling equipment, Eliminating need for waste disposal.**



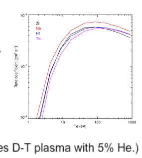
- Tantalum generates highest decay heat that remains unchanged for 10 days, while molybdenum decay heat falls off relatively rapidly after one day.
- Even for a few mm thick Ta coating, the impact on the temperature response during loss of cooling accident is minimal.

Erosion/redeposition analysis

- Analysis performed for a simulated DEMO-type tokamak divertor subject to high power loading. REDEP/WBC-ITMC modeling. (C-MOD outer divertor with actual plasma conditions, w/ X10 density)
- ***Pure metals*** analyzed,*~1-5 mm thick structure/coating.* (*There may be significant differences for mixed-material, D-T containing, and evolving material surfaces)*
- Zr and Nb sputtering and transport parameters (sputter yields, ionization rate coefficients, etc.) found to be reasonably similar to Mo; likewise Hf and Ta similar to W—***therefore compare Mo to W in detail.***



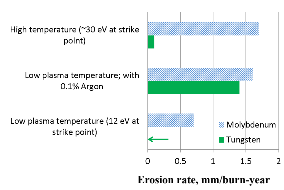
Self-sputtering yields, ITMC-DYN calculations, @ 25° incidence



Electron impact ionization rate coefficients. ADAS

- Three plasma edge cases examined: (All cases D-T plasma with 5% He.)
  1. "low temperature", 12 eV at strike point
  2. low temperature with 0.1% Argon radiating impurity
  3. "high temperature", 30 eV at strike point

W and Mo comparison; simulated DEMO tokamak conditions.
Divertor peak net sputtering erosion. *REDEP/WBC code package analysis.*

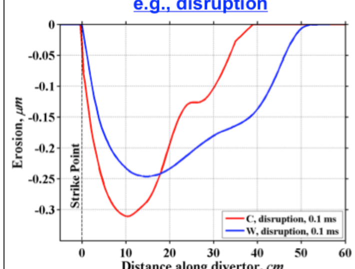


- **W generally superior to Mo, but both are acceptable. 5 mm coating would last ≥ 5 operating years, from sputtering standpoint.**
- **Mo-class, and W-class materials should be respectively similar.**

Transient response analysis

- **Transient response analysis** for the alternative materials shows similar trends during the intense transient-plasma power deposition, with some differences in the magnitude of melt layer thickness and erosion rates due to differences in thermophysical properties among these materials.
- For example, erosion of tantalum is predicted to be higher than tungsten. Ta has similar boiling characteristics as W but much lower thermal conductivity. A higher evaporation rate is also expected for hafnium plasma facing material. Compared to W, Hf has a lower boiling point, heat of vaporization, and thermal conductivity.
- Molybdenum has comparable thermal conductivity to tungsten, and a higher heat of vaporization, and is expected to have slightly less evaporation but more melting. Therefore, erosion of Mo from melt-layer splashing can be higher than W since a thicker melt layer could be developed.
- Other materials, such as niobium and zirconium, should more or less, behave similarly to molybdenum.
- **To summarize the key point, plasma facing material response to plasma transients is a serious issue for tungsten, but acceptable plasma operational windows (e.g. for ELM duration/energy) appear to exist. Based on our initial analysis, there will be differences in the degree of response, and operating windows, for the alternative plasma facing materials, but there does not appear to be fundamental differences.**
- However, issues such as degree of melt splashing, and radiation exposure to secondary nearby components, could differ significantly among various higher Z materials. Major modelling work and supporting experiments on transient response is clearly needed for fusion progress, for any of these materials.

Transient Response Analysis – e.g., disruption



Divertor surface erosion profile after the impact of a disruption; W and C surfaces; ITER divertor. HEIGHTS code package analysis. Erosion due to vaporization is serious but not strongly material-dependent. The W-alternative materials will not have fundamentally different transient responses.

Conclusions

- This identification and initial analysis of alternative high-Z plasma facing materials is encouraging showing:
  - -- Environmentally attractive activation, and minimal or no waste disposal, for a commercial power plant divertor surface, using advanced recycling equipment.
  - -- Acceptable sputtering erosion/redeposition performance, similar to a tungsten divertor. (Initial *first-wall surface* material analysis has similar conclusions)
  - -- Concerns about the transient response of the alternative materials but not fundamentally different than concerns for tungsten.
- This potentially expands the list of candidate solid high-Z facing materials from basically one (tungsten) to six, and could therefore provide a major design margin for future fusion reactors, against failure of any one material.
- This study is a start; considerable work is needed to advance the qualification of these alternative materials (and generally for tungsten as well) for divertor and first wall surfaces. Required work includes modeling, design, and supporting experiments for: a) PFC sputtering and transient response for irradiated/evolving redeposited mixed material; b) surface temperature operating windows; c) possible helium effects, d) bonding and related thermo/mechanical issues, e) dust issues, and f) plasma edge solution variation effects on overall performance.
- We encourage fusion community interest in further studying these candidate materials.