Self-passivating smart tungsten alloys
as an intrinsic safety for the future fusion power plant

A. Litnovsky, T. Wegener, F. Klein, Ch. Linsmeier,
M. Rasinski and J.W. Coenen
**Motivation**

Conceptual study of the fusion power plant

- Accidental loss of coolant:
  - peak temperatures of first wall up to 1200 °C due to nuclear decay heat
- Additional air ingress: formation of highly volatile WO$_3$ (Re, Os)
  - >1000°C in a reactor
  - 1000 m$^2$ surface
  - Evaporation rate: 10 - 100 kg/h

Radioactive WO$_3$ may leave hot vessel

Mobilization of radioactive elements must be prevented

---

Intrinsic safety

In case of major accident:

- No immediate access to water and/or coolant
- No electricity
- Difficult logistics
- Lack of manpower

Intrinsic safety is the most reliable measure
Smart tungsten alloys

Adjust their properties to the environment conditions

**Normal operation** (730°C->550°C²):
Formation of tungsten surface by depletion of alloying element(s)
due to preferential sputtering by plasma

**Accidental conditions:**
(air ingress, up to 1200°C)
Formation of protective barrier layer

---

1F. Koch and H. Bolt, Phys. Scr. 128(2007)100
Choice of alloying elements

Choice of alloying elements

Low neutron activation

Cr, Ti, Mn, Y

Low volume increase by oxidation

Good adhesion of the oxide to the alloy

High melting point of alloys and oxides

Requirements

Choice of alloying elements

Low neutron activation

Cr, Ti, Mn, Y

Low volume increase by oxidation

Good adhesion of the oxide to the alloy

High melting point of alloys and oxides

Requirements

Choice of alloying elements

Low neutron activation

Cr, Ti, Mn, Y

Low volume increase by oxidation

Good adhesion of the oxide to the alloy

High melting point of alloys and oxides

Requirements

Choice of alloying elements

Low neutron activation

Cr, Ti, Mn, Y

Low volume increase by oxidation

Good adhesion of the oxide to the alloy

High melting point of alloys and oxides

Requirements

Choice of alloying elements

Low neutron activation

Cr, Ti, Mn, Y

Low volume increase by oxidation

Good adhesion of the oxide to the alloy

High melting point of alloys and oxides

Requirements

Choice of alloying elements

Low neutron activation

Cr, Ti, Mn, Y

Low volume increase by oxidation

Good adhesion of the oxide to the alloy

High melting point of alloys and oxides

Requirements

Choice of alloying elements

Low neutron activation

Cr, Ti, Mn, Y

Low volume increase by oxidation

Good adhesion of the oxide to the alloy

High melting point of alloys and oxides

Requirements

Choice of alloying elements

Low neutron activation

Cr, Ti, Mn, Y

Low volume increase by oxidation

Good adhesion of the oxide to the alloy

High melting point of alloys and oxides

Requirements

Choice of alloying elements

Low neutron activation

Cr, Ti, Mn, Y

Low volume increase by oxidation

Good adhesion of the oxide to the alloy

High melting point of alloys and oxides

Requirements

Choice of alloying elements

Low neutron activation

Cr, Ti, Mn, Y

Low volume increase by oxidation

Good adhesion of the oxide to the alloy

High melting point of alloys and oxides

Requirements

Choice of alloying elements

Low neutron activation

Cr, Ti, Mn, Y

Low volume increase by oxidation

Good adhesion of the oxide to the alloy

High melting point of alloys and oxides

Requirements
Yttrium as an active element

Y at the grain boundaries

- Smaller grains
- Thinner oxide layer

Y at the oxide-alloy interface

- Oxidation pegs, good adhesion
- Oxidation inwards to the surface
- Less pores

Reactivity towards impurities

- More stable oxide

High temperature oxidation: tungsten vs. smart alloys

- **W:** Oxidation and evaporation
- **W-Cr:**
  - Reduced oxidation rate
  - Delamination after 15´
- **W-Cr-Y:**
  - Even lower oxidation rate
  - No delamination/evaporation

**Oxidation constants:**
- **W:** 0.52
- **W-Cr-Y:** $3 \times 10^{-6}$

Best passivation behavior of W-Cr-Y alloy
Structure of protective layer

80 vol.% Ar + 20 vol.% O₂  1 bar  1000°C  15’

W-Cr

- Cr₂WO₆
- Cr₂O₃
- Pores

Internal oxidation

Smooth thin oxide layer in W-Cr-Y

Suppressed internal oxidation

W-Cr-Y

- No W-containing oxides
- Suppressed internal oxidation

No visible pores
High temperature oxidation of smart alloys: first results

Mass change, $\text{mg}^{2}\text{cm}^{-4}$

- W-Cr
- W-Cr-Y@1200°C
- W-Cr-Y@1000°C

Oxidation time, minutes

1. W-Cr fails
2. W-Cr-Y oxidizes faster at 1200°C
3. Still parabolic behavior of W-Cr-Y after 15 minutes@1200°C
Oxidation in steam and humid air

Steam: Ar + 70% humidity @ 40°C

Humid air: 80 vol.% Ar + 20% vol.% O₂ + 70% humidity @ 40°C

Exposure at 1000°C, 1 bar

Mass change, mg/cm²

- W in humid air
- W with steam
- Smart alloy in humid air
- Smart alloy with steam

Exposure time, min.

W oxidizes immediately

No pure tungsten in DEMO?

W remains rather inert in humid argon

No water cooling in DEMO?

Smart alloy reacts with water
Smart alloys: future challenges

* A. Litnovsky et al., "Smart alloys for a future fusion power plant: first studies under stationary plasma load and in accidental conditions“, 22nd PSI, Rome, Italy, May 30 - June 3, 2016
Safety interfaces: examples

**Power plant integrity**

![Diagram of tokamak hall, primary coolant vault, and associated components]

**Reliability of structural elements**

Corrosion of coolant pipes

**Stability of PFCs**

This presentation

Possible hazards

- Tritium in VV and in coolant
- W-dust
- Activated corrosion products
- Volatile radioactive rests of PFCs

Joint effort required

References:

Summary

- New advanced materials are required for future power plant

- Safety aspect is of prime importance

- Tungsten-based smart alloys: a promising combination of intrinsic safety and plasma performance

- First results are encouraging:
  - Suppressed oxidation of tungsten
  - Stability of smart alloy system

- Further qualification is underway
Outlook

- Manufacture of bulk samples
- Tests of plasma performance
- Mechanical properties: optimization
- Implementation of advanced technologies: $W_{f/W}$
- Working on safety interfaces
Thank you