PRESSURE DEPENDENCE OF OXIDATIVE REMOVAL OF TOKAMAK CODEPOSITS

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- To study the pressure and temperature dependence of the D removal rate and film erosion rate of tokamak codeposits obtained from DIII-D and JET divertor tiles

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Background

(a) Codeposition

- Codeposition entails the formation of hydrogenated carbon layers via the redeposition of eroded C in combination with the fuel H.

- Such layers can exceed **tens of μm** (e.g., TFTR tile gaps and JET flakes).

  - Much thicker than the ion-implant zone, which is ~ **tens of nm**

  - The codeposited layer has no limit to its thickness

  - The H/C ratio in the codeposited layers is similar to that seen in the implantation zone, viz, ~0.4 at ~300K; it is lower at higher temperatures

- Based on experience with current tokamaks (e.g.,Federici et al, NF Review/2001) and predictions for ITER (Brooks et al/1998), most of the T in ITER is expected to be trapped in codeposits

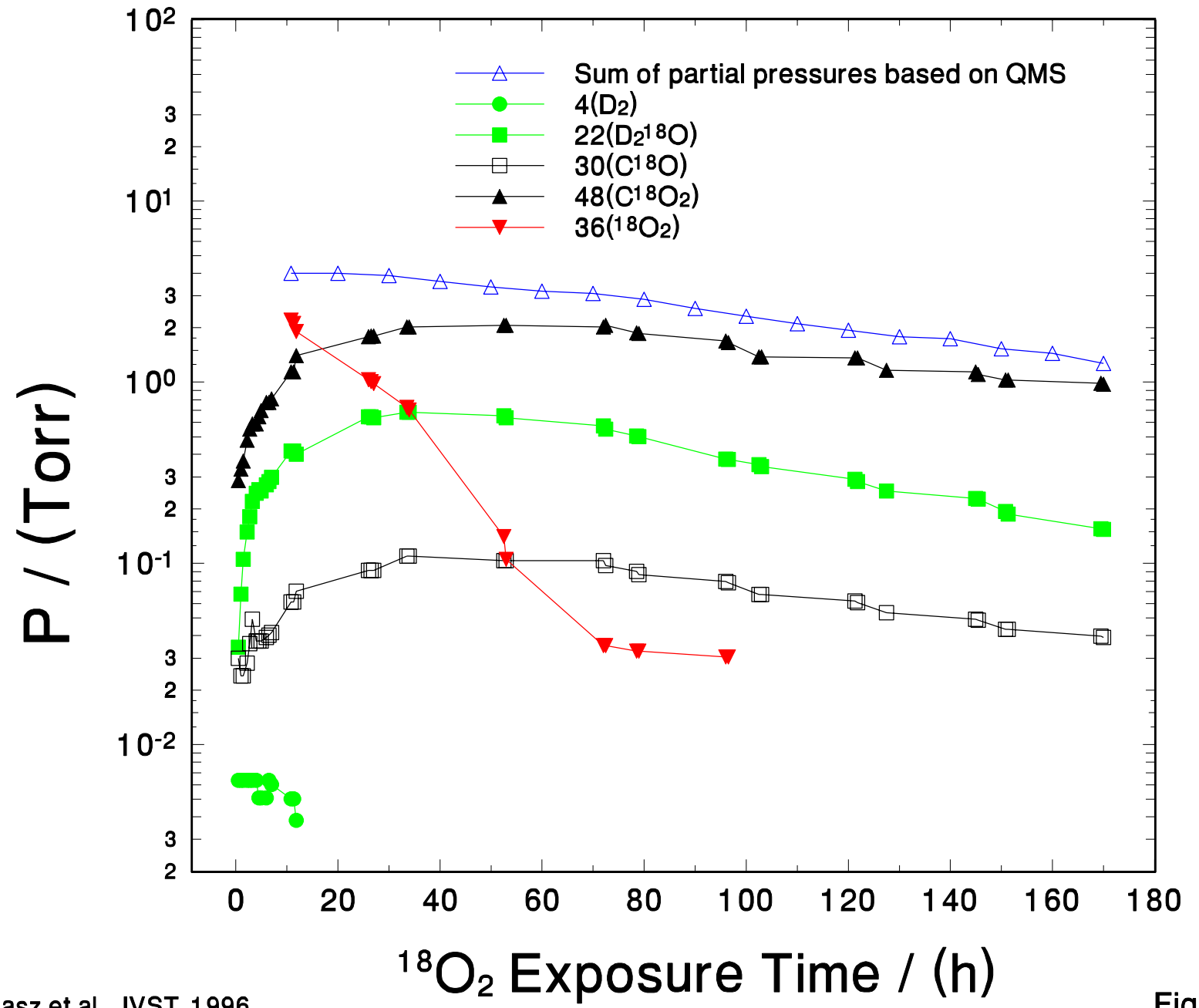
(b) Codeposit Removal via Thermo-Oxidation

- Laboratory measurements of H and D removal from lab-produced films and tokamak codeposits lead to three **key conclusions**:
  - Release of D occurs in conjunction with C erosion (Haasz et al/1996/1998, Wang et al/1997, Alberici et al/1998)
  - D removal and C erosion rates depend on film **structure**
  - D release rate during oxidation is a function of **temperature**

(c) Reaction Product Analysis during Oxidation

- Results of Haasz et al/1996 and Alberici et al/1998 show that:
  - Essentially all of the D is removed via D_2O formation
  - C is removed by the formation of CO and CO_2
  - No D_2 and no methane are formed

Figure 1 (Haasz et al/JVST/1996)



Haasz et al., JVST, 1996

Figure 1

(d) Comparison: Lab Films and Tokamak Codeposits

- C-erosion rates of lab films are of the order of a **few to tens of nm/h** at temperatures < 700 K

- C-erosion rates for tokamak codeposits (TFTR, DIII-D, JET) are 2-3 orders of magnitude higher under similar conditions

  - For tokamak codeposits C-erosion rates in O_2 (P_{O2}=2.1 kPa):

    ~ 0.1-1 μm/h at 523K (250°C)
    ~ 1-10 μm/h at 623K (350°C)

  - Similar erosion rates in air for equivalent O_2 partial pressure

- Addition of ozone to air/oxygen increases the erosion rate:
  ~ 1-2 μm/h at ~ 460 K (Moormann et al/2002)

Objective of Present Study

To study the pressure and temperature dependence of

- The D removal rate and
- The film erosion rate

of tokamak codeposits obtained from DIII-D and JET divertor tiles

Codeposits from DIII-D and JET

Previous characterization of DIII-D and JET codeposits:

DIII-D:

- Thickness: ~ 2μm (from SEM photos)
- few % metal contamination (X-PIXE, Walsh et al/JVST/1992)
- D/C ~ 0.185 (based on assumed film density of 1.3 g/cm^3)

JET:

- Thickness: ~ 2μm (from SEM photos)
- up to 10% Be content in some regions; in shadowed regions of the tiles (a substantial fraction) there was no Be deposition (Ion beam analysis, Coad et al/JNM/1997)
- D/C ~ 0.25 (based on an assumed film density of 1.8 g/cm^3)

Specimens Used in Present Study

Tile locations:

DIII-D: lower divertor **(Figure 2a)**

JET: Mark I divertor **(Figure 2b)**

XPS surface analysis:

shows the presence of Ni on the surface

DIII-D: Ni fraction < 1% prior to oxidation
(~ 9% after oxidation)

JET: Ni fraction < 1% after oxidation
(no data available for specimens prior to oxidation)

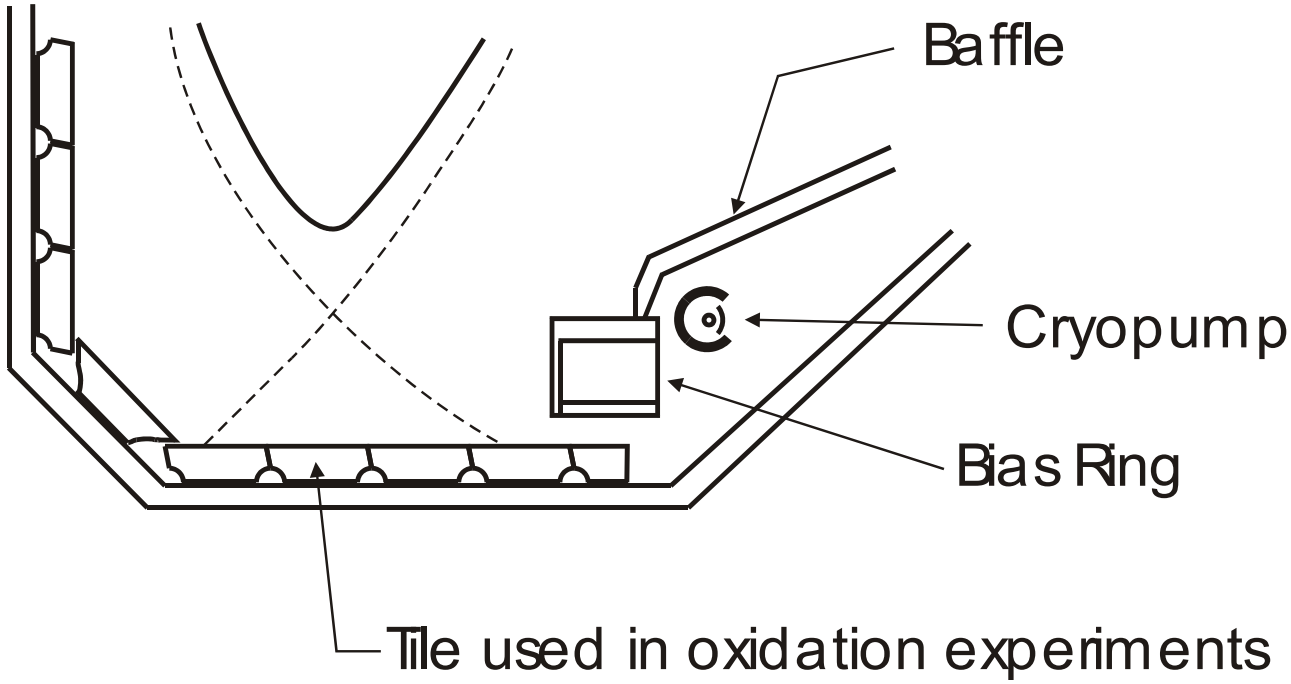


Figure 2a) Location of DIII-D Tile in the lower divertor

J.P. Coad et al. / Journal of Nuclear Materials 241–243 (1997) 408–413

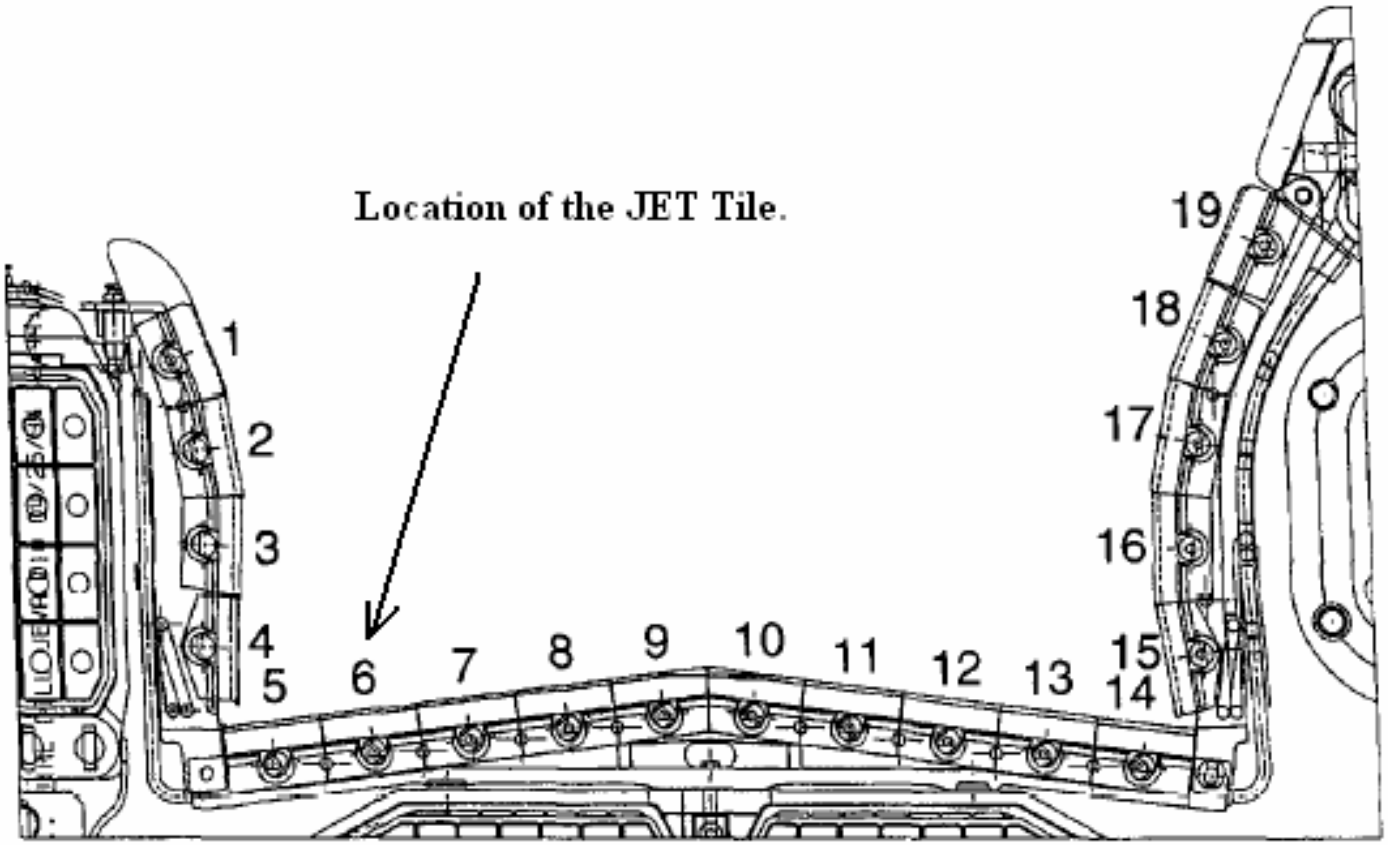


Figure 2b): Location of JET Tile (6A)

Experiment

Experimental apparatus **(See Figure 3)**

- Baking to 620 K (350°C)
- O_2 pressure to 1 atm

Procedure

- The oxidation chamber, with the specimen, is baked to the desired test temperature
- After the desired oxidation time, the remaining D content in the specimen is measured using laser-induced TDS
- RGA detection of desorption products (D_2, H_2 and HD)
- Absolute calibration of RGA using a D_2 leak bottle

University of Toronto Oxidation Facility

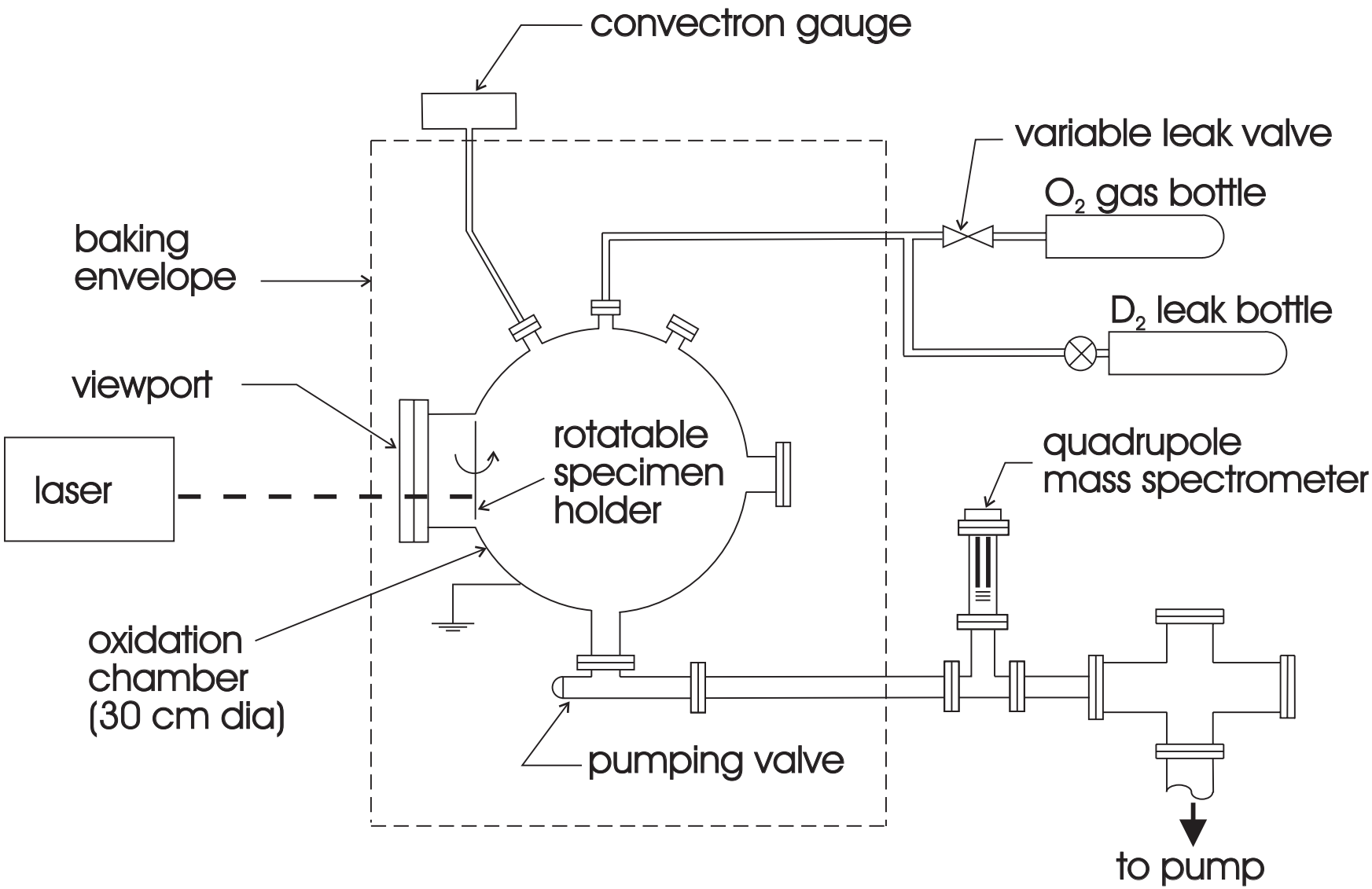


Figure 3

Results

(a) D removal and erosion rates

As function of O_2 exposure time for a fixed pressure of

2.1 kPa (16 Torr) and 3 temperatures

- DIII-D: (**Figure 4a**)
- JET: (**Figure 4b**)

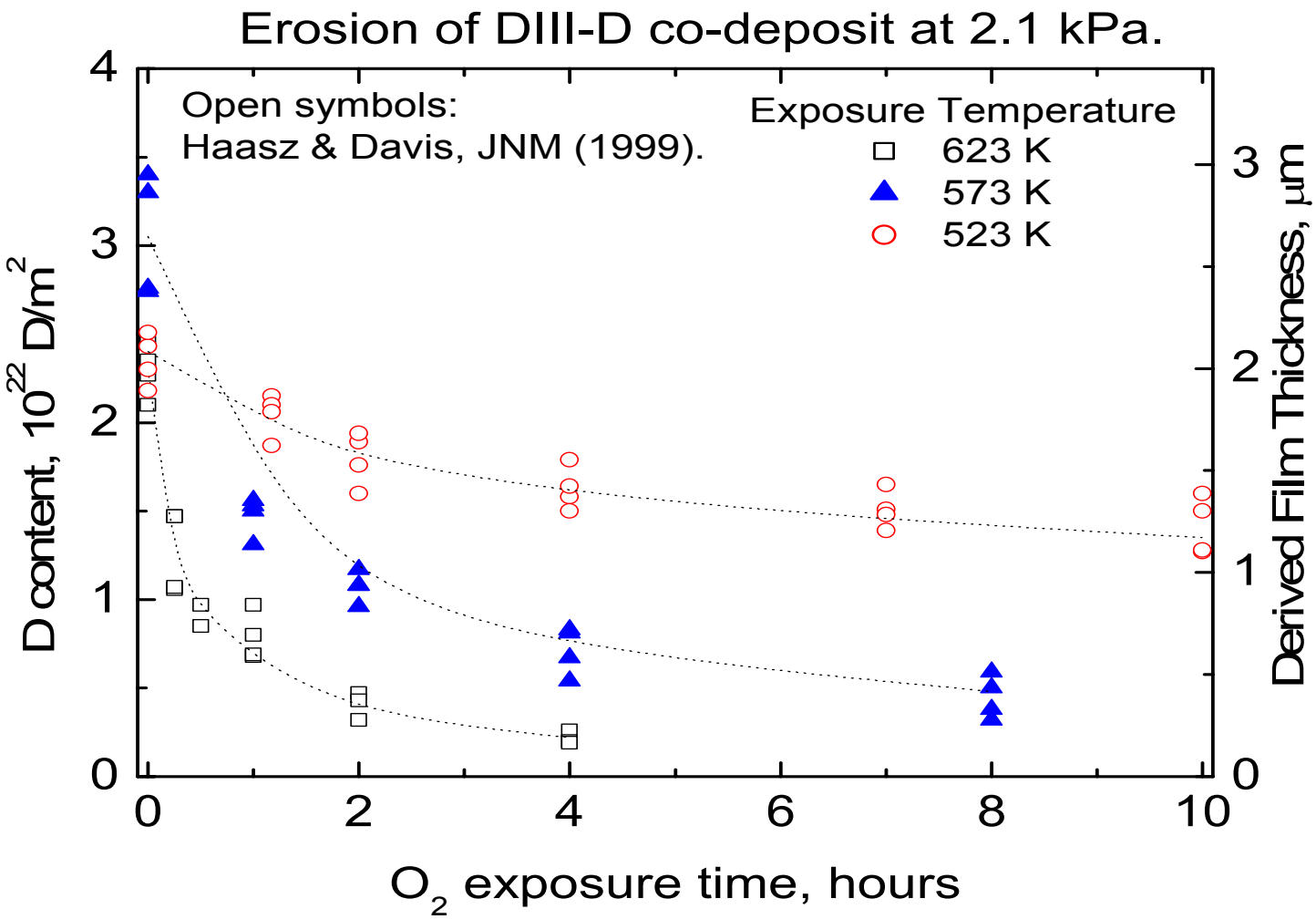

Erosion of DIII-D co-deposit at 2.1 kPa.
Open symbols:
Haasz & Davis, JNM (1999).
Exposure Temperature
623 K
573 K
523 K
D content, 10^{22} D/m^2
Derived Film Thickness, µm
O_2 exposure time, hours
0
1
2
3
4
0
2
4
6
8
10

Figure 4a)

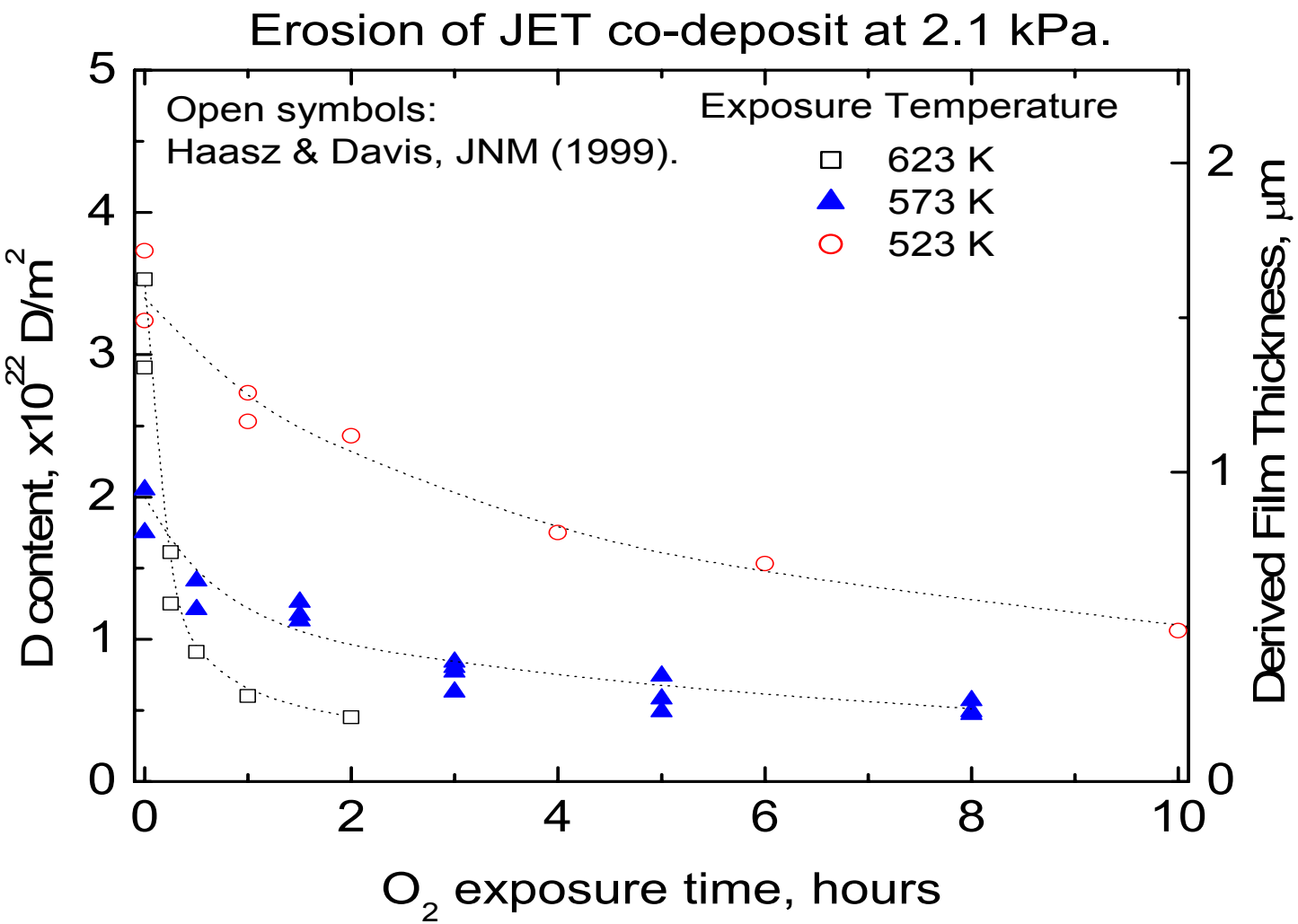

Erosion of JET co-deposit at 2.1 kPa.
Open symbols:
Haasz & Davis, JNM (1999).
Exposure Temperature
623 K
573 K
523 K
D content, x10^22 D/m^2
Derived Film Thickness, µm
O2 exposure time, hours
0
1
2
3
4
5
0
2
4
6
8
10

Figure 4b)

(a) D removal and erosion rates (cont'd)

As function of O_2 exposure time for a fixed temperature of 623 K and 3 pressures

- DIII-D: (**Figure 5a**)
- JET: (**Figure 5b**)

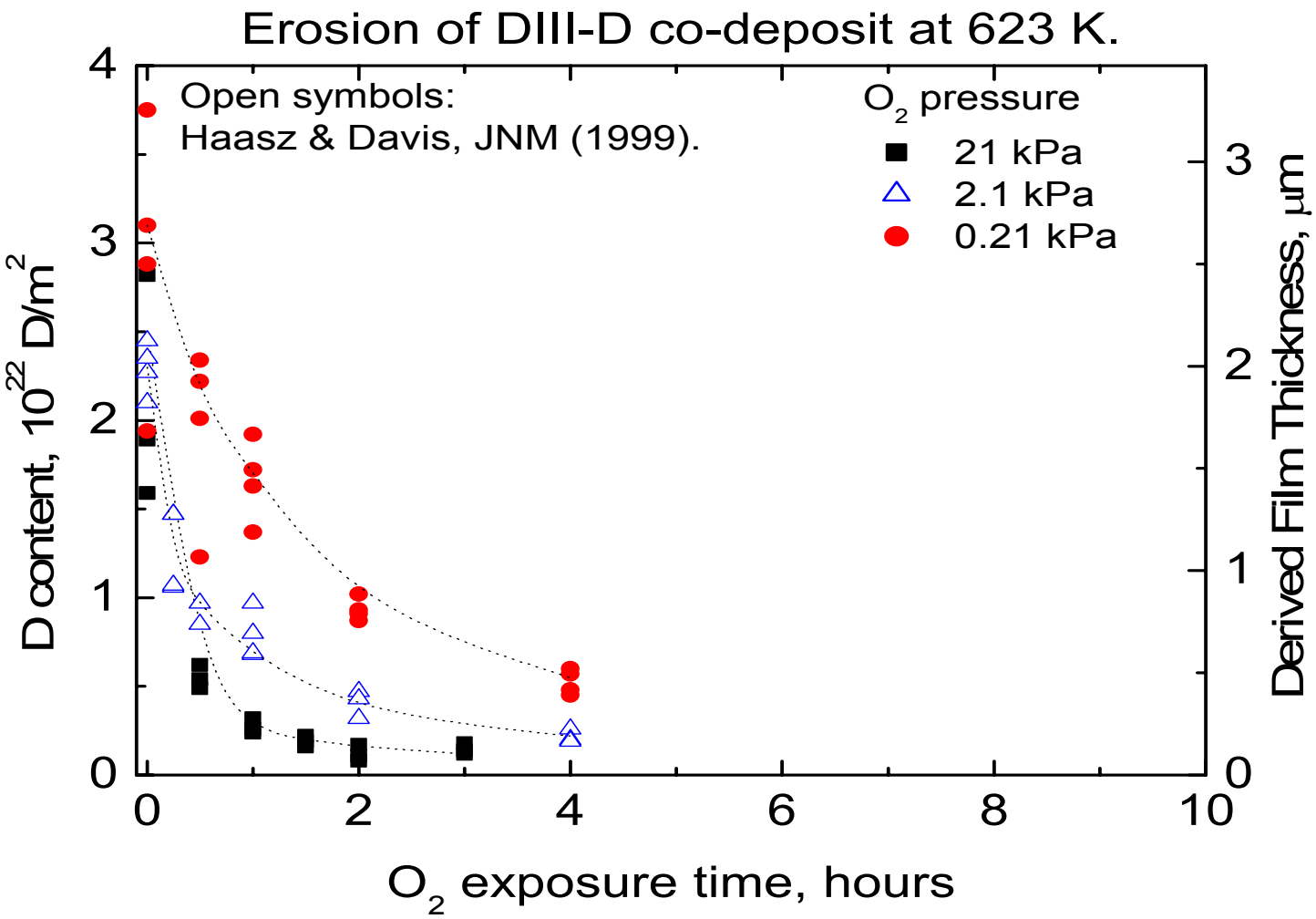

Erosion of DIII-D co-deposit at 623 K.
Open symbols:
Haasz & Davis, JNM (1999).
O2 pressure
21 kPa
2.1 kPa
0.21 kPa
D content, 10^22 D/m^2
Derived Film Thickness, µm
O2 exposure time, hours
0
1
2
3
4
0
2
4
6
8
10

Figure 5a)

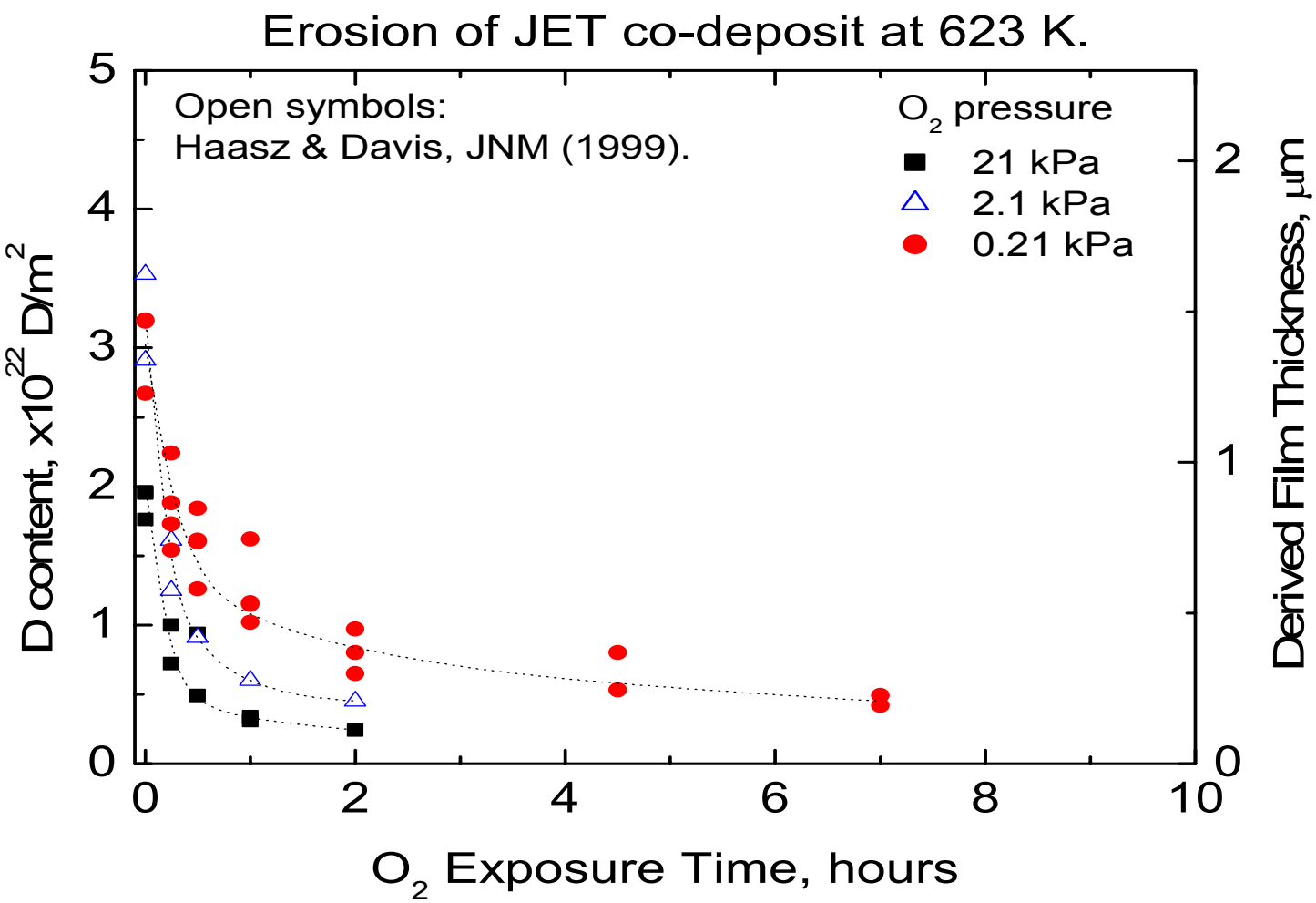

Erosion of JET co-deposit at 623 K.
Open symbols:
Haasz & Davis, JNM (1999).
O2 pressure
21 kPa
2.1 kPa
0.21 kPa
D content, x10^22 D/m^2
Derived Film Thickness, µm
O2 Exposure Time, hours
0
1
2
3
4
5
0
2
4
6
8
10

Figure 5b)

(b) Initial D removal and erosion rates

As function of O_2 pressure at 3 temperatures:

- DIII-D: **(Figure 6a)**
- JET: **(Figure 6b)**

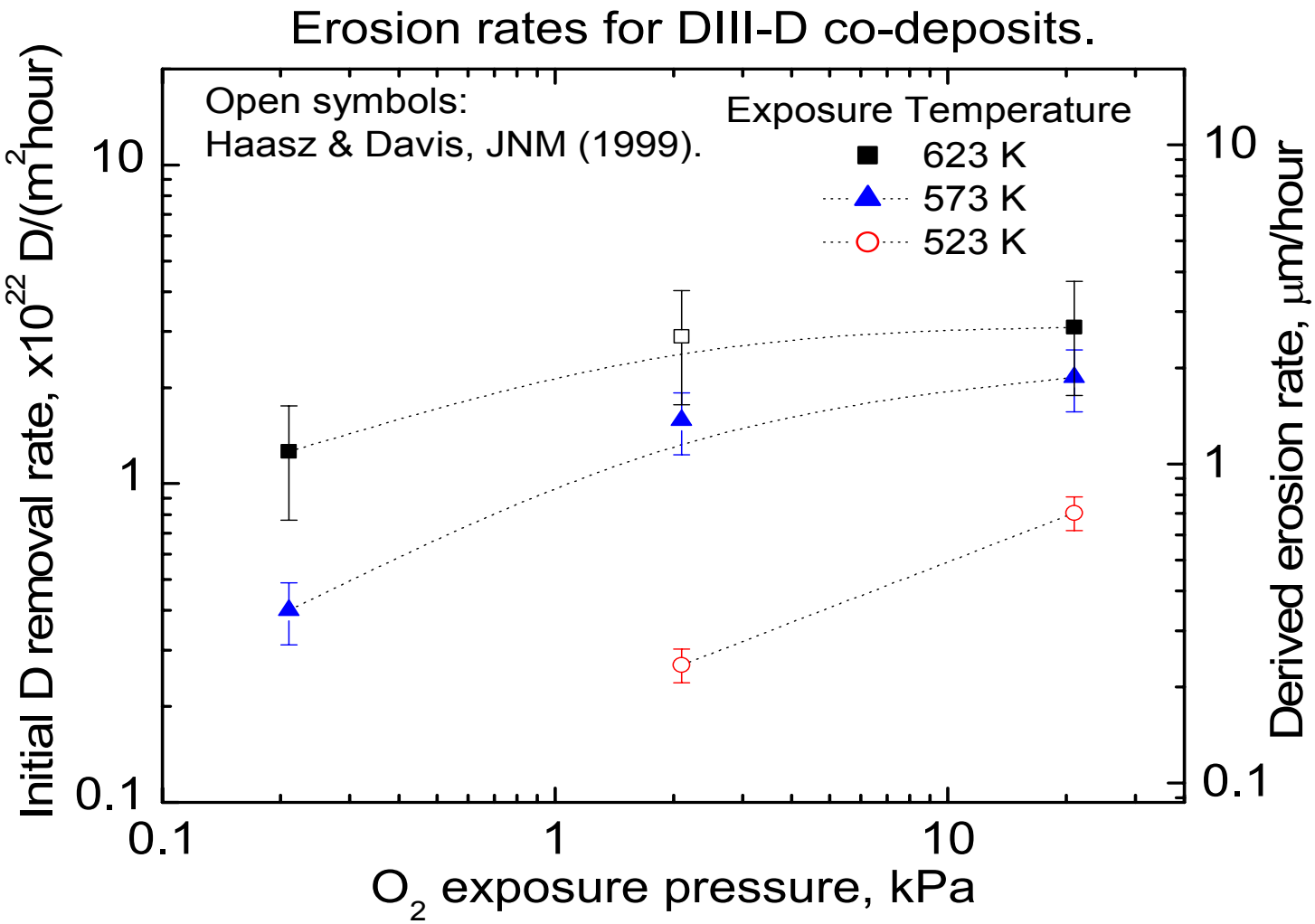

Erosion rates for DIII-D co-deposits.
Open symbols:
Haasz & Davis, JNM (1999).
Exposure Temperature
623 K
573 K
523 K
Initial D removal rate, x10^22 D/(m^2 hour)
Derived erosion rate, μm/hour
O2 exposure pressure, kPa
0.1
1
10

Figure 6a)

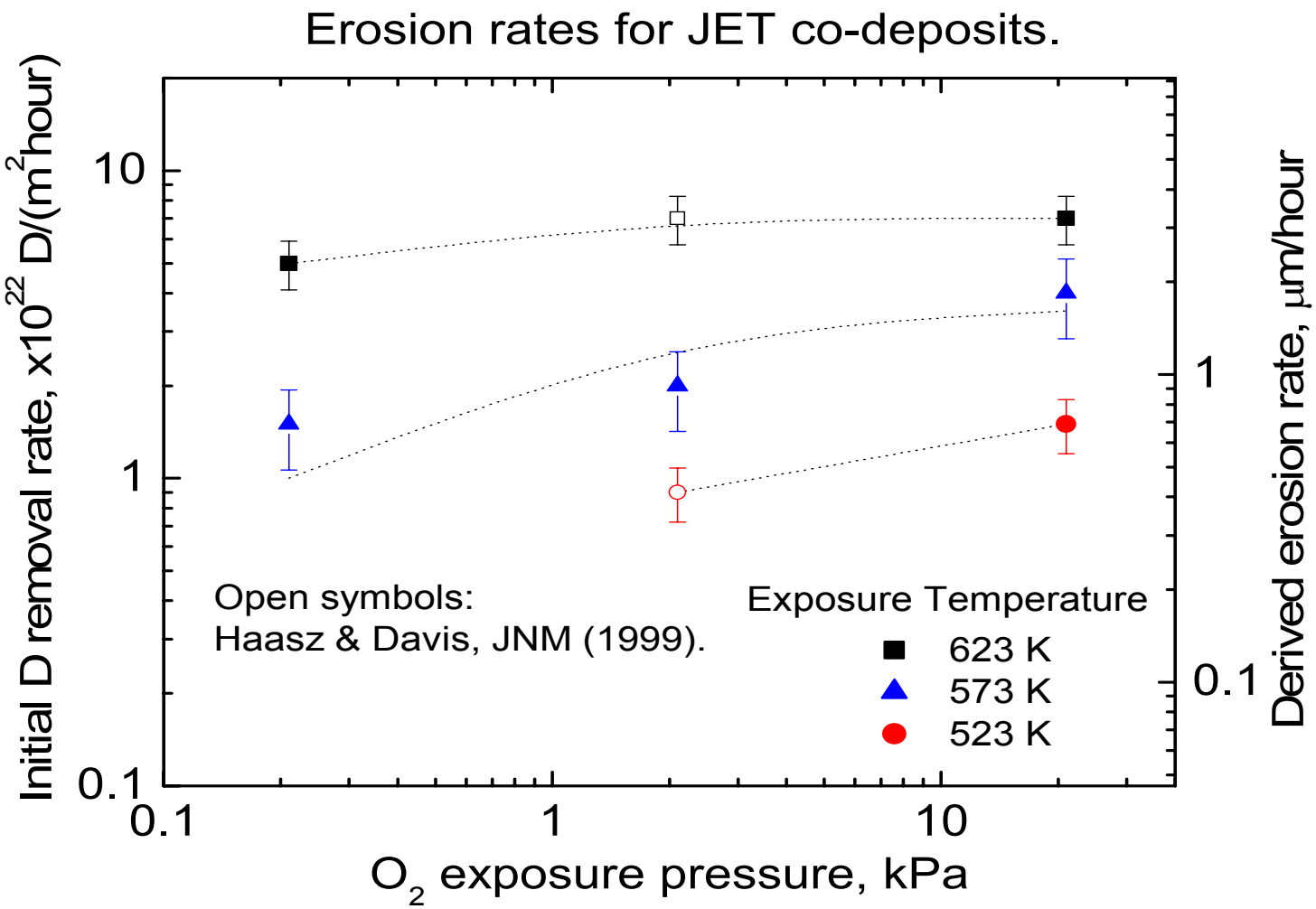

Erosion rates for JET co-deposits.
Initial D removal rate, x10^22 D/(m^2 hour)
Derived erosion rate, μm/hour
O2 exposure pressure, kPa
0.1
1
10
Open symbols:
Haasz & Davis, JNM (1999).
Exposure Temperature
623 K
573 K
523 K

Figure 6b)

(c) Final D content after oxidation

As function of O_2 pressure at 3 temperatures:

- DIII-D: **(Figure 7a)**
- JET: **(Figure 7b)**

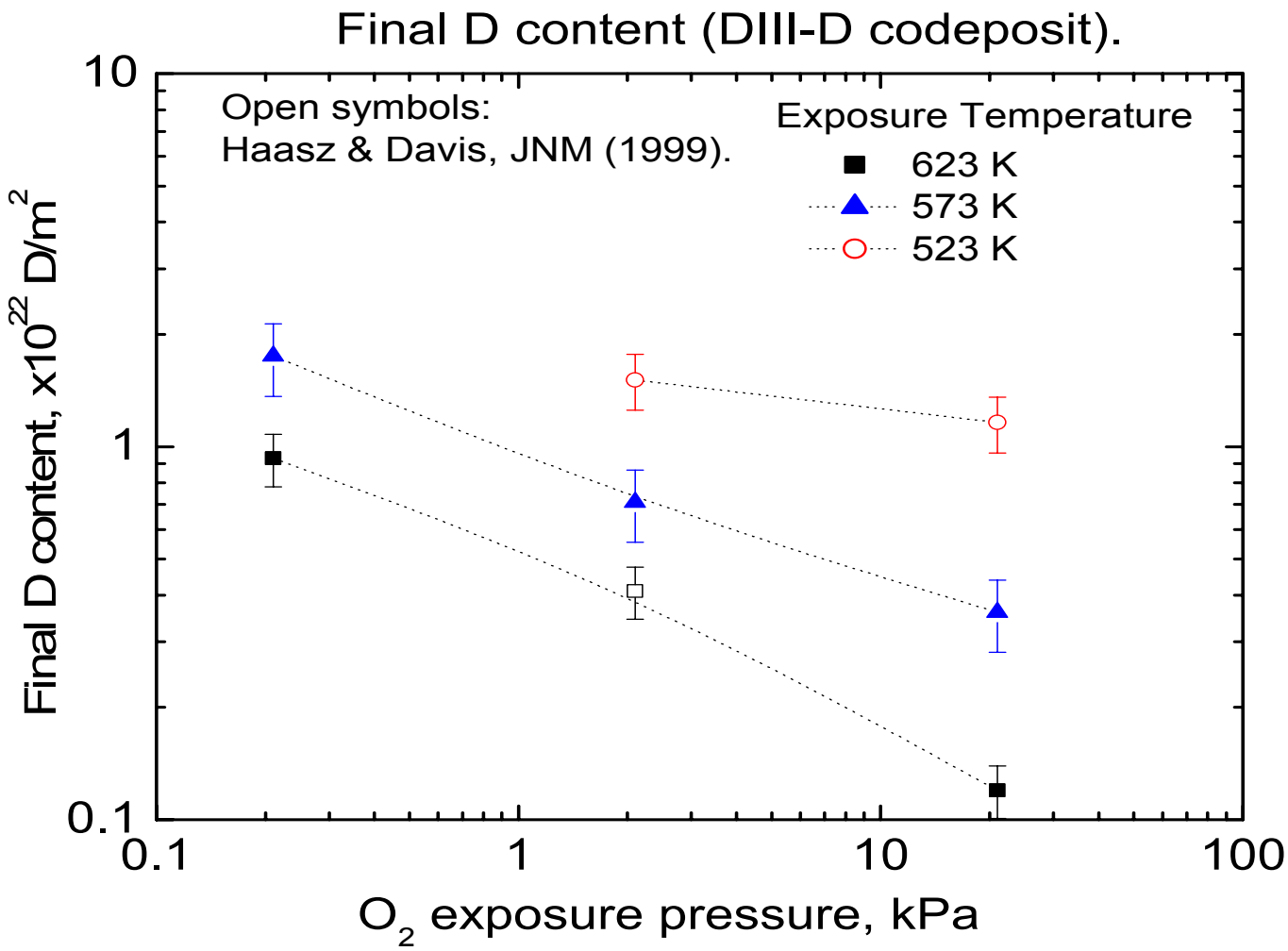

Final D content (DIII-D codeposit).
Open symbols:
Haasz & Davis, JNM (1999).
Exposure Temperature
623 K
573 K
523 K
Final D content, x10^22 D/m^2
10
1
0.1
0.1
1
10
100
O2 exposure pressure, kPa

Figure 7a)

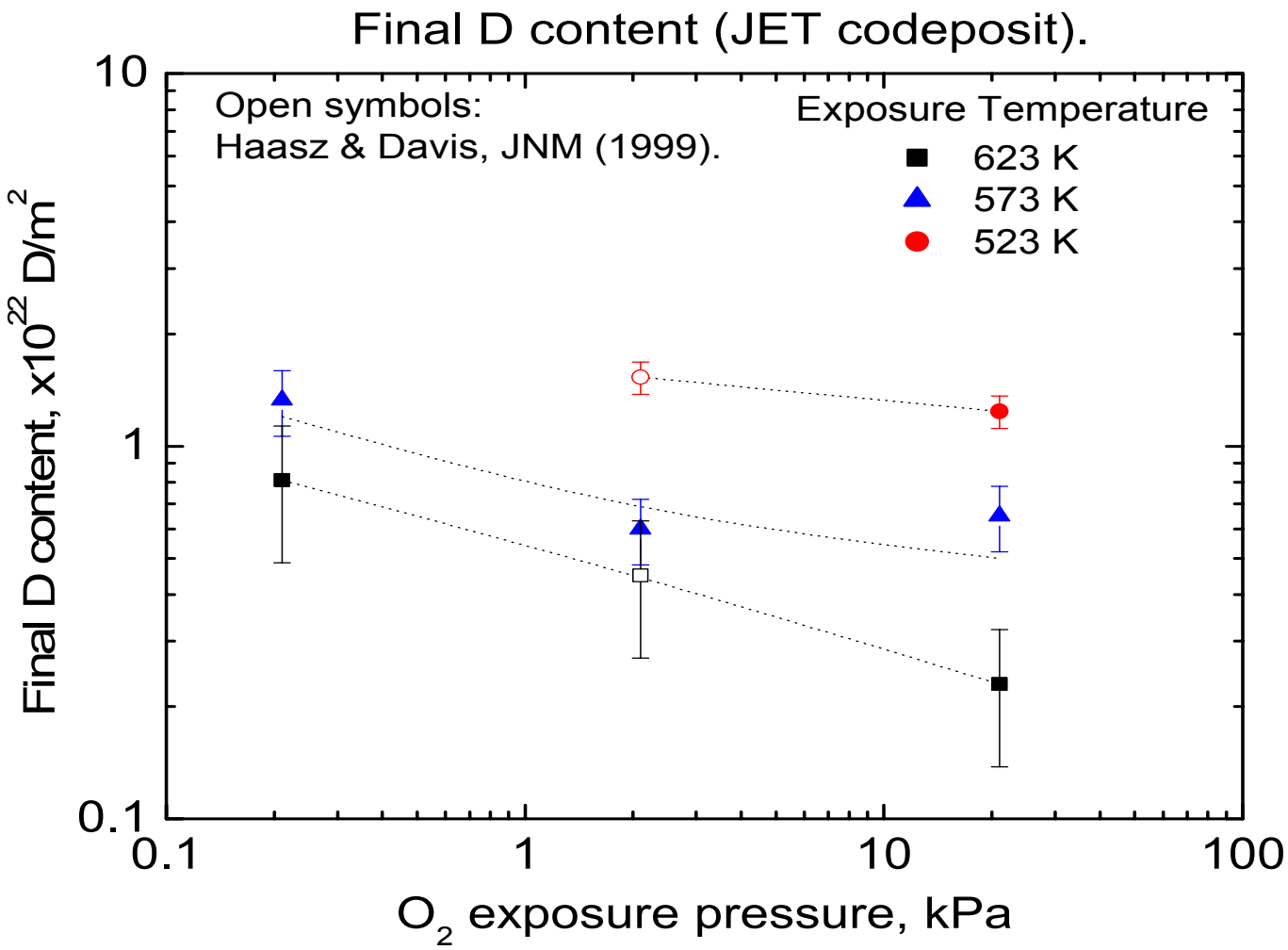

Final D content (JET codeposit).
Open symbols:
Haasz & Davis, JNM (1999).
Exposure Temperature
623 K
573 K
523 K
Final D content, x10^22 D/m^2
O2 exposure pressure, kPa
10
1
0.1
0.1
1
10
100

Figure 7b)

(d) Effect of surface impurities on D removal

- Surface analysis (XPS) of Specimens used in the present study shows the presence of Ni on the surface

  DIII-D: Ni < 1% prior to oxidation and ~ 9% after oxidation
  JET: Ni < 1% after oxidation (no prior-oxidation data)

  Not enough information to assess effect of Ni content on the final D content after oxidation **(Figures 7a and 7b)**

- Previous study with W impurity on lab film (Davis et al/JNM/2002)

  Controlled deposition of sputtered W on lab-produced film

  W inhibits oxidation **(Figure 8)**

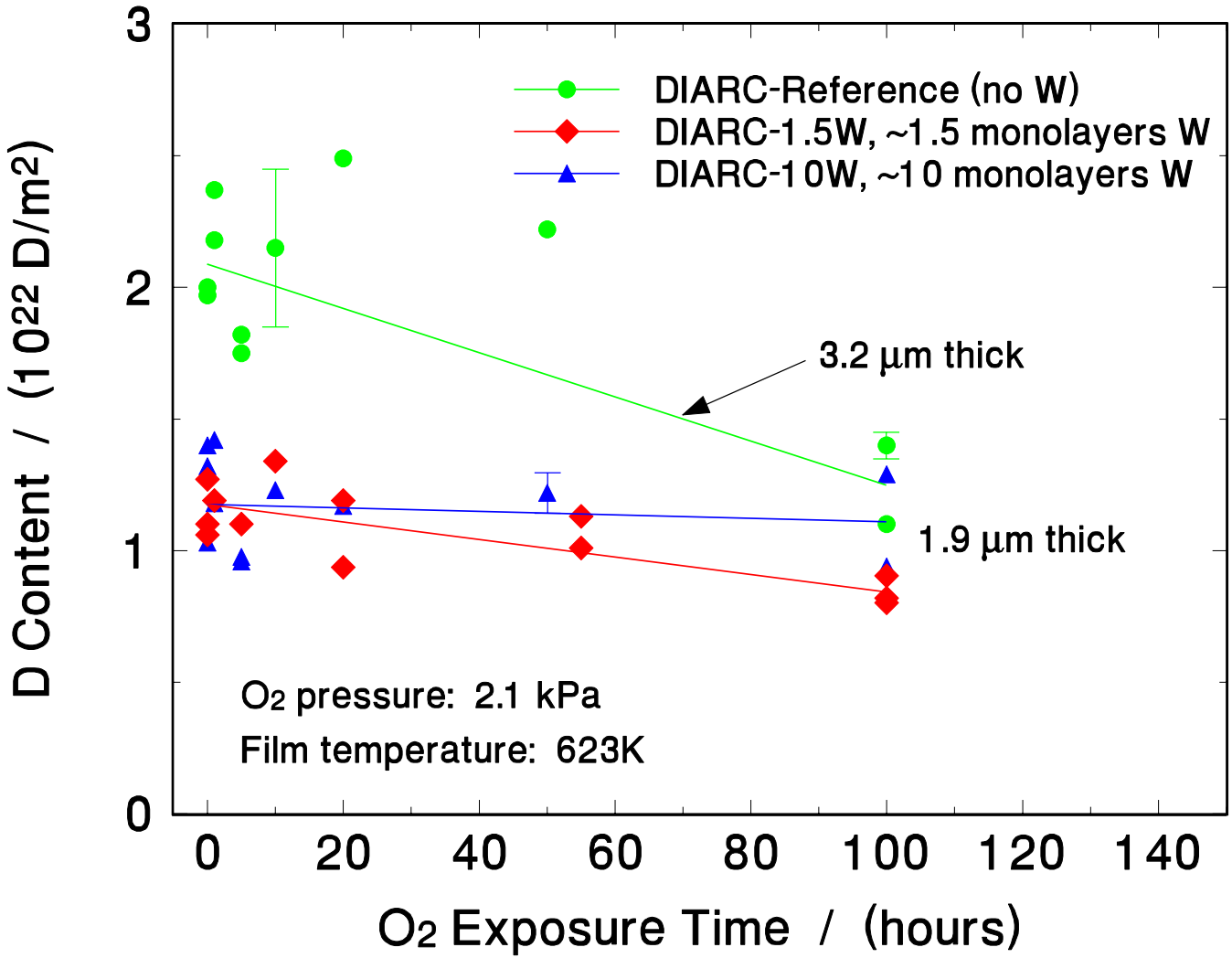


Figure 8

Davis et al, JNM 2002

Conclusion

The initial D removal rate during oxidation:

- Strongly depends on temperature – rate increases with increasing temperature
- Has a weak dependence on oxygen pressure – especially at 623 K (not much difference between 2.1 Pa and 21 Pa)

The final D content after oxidation:

- Strongly depends on temperature – D content decreases with increasing temperature
- Also has a strong dependence on oxygen pressure – especially at 623 K (a factor of 4-10 decrease as the pressure goes from 0.21 Pa to 21 Pa)

Implication for ITER

Based on the C erosion rates measured in lab experiments for tokamak codeposits, if a reactor could be **heated to approximately 620 K (350°C) during oxidation**, then T-containing codeposits of ~ 30 μm thickness could be eroded within ten hours.

Outstanding Issues for Lab Studies

- Systematic characterization of co-deposits (structure, composition) before and after oxidation
- Reaction product detection during oxidation (correlation of D and C in the reaction products and the codeposits)
- Study of temperature and O_2 pressure dependence of codeposit erosion from several locations in tokamaks
- Study of the observed levelling-off of D removal from codeposits during lab oxidation at fixed O_2 pressures
- Effect of impurities within codeposits on oxidation rates
- Collateral damage of in-vessel reactor materials