UNIVERSIDADE DE LISBOA
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Stronzada con metallo liquido

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ABSTRACT

The characterisation of the interactions

Keywords: Plasma-surface interactions, Liquid-metals, Tin, Deuterium retention, Spectroscopy

RESUMO

A caracterização das interações entre plasmas magneticamente

Palavras-chave: Plasma, metais liquidos, estanho, retenção de deutério, espectroscopia

SOMMARIO

Il soggetto del presente lavoro di tesi è la caratterizzazione dell'interazione tra la superficie di metallo liquido

Parole chiave:Interazione plasma-parete, Metalli liquidi, Stagno, Ritenzione del Deuterio, Spettroscopia

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LIST OF ABBREVIATIONS

@TODO: Review variable lists as writing the thesis

- AC - Alternating Current
- ADC - Analog to Digital Converter
- DAC - Digital to Analog Converter
- DC - Direct Current
- GUI - Graphical User Interface
- HV - High Voltage
- IO - Input Output
- IST - Instituto Superior TÃl'cnico

LIST OF VARIABLES

@TODO: Review variable lists as writing the thesis

VARIABLES:

- k - Boltzmann constant
- V_b - breakdown voltage
- j_{sat}^{+} - current density
- n - density of the plasma
- $E_{breakdown}$ - electrical breakdown field
- E - electrical field
- e - electron charge
- V_f - floating potential
- γ - flow constant
- d - gap distance
- i_{sat}^{+} - ion saturation current
- c_s - ion sound speed
- m - mass
- Γ - particle flux density
- ϵ_0 permittivity of vacuum
- V_p - plasma potential
- p - pressure
- V_s - probe voltage
- v_{se} - speed at the sheath edge
- A_s - surface of the probe
- T - temperature
- α - Townsend parameter

INDEXES:

- e - electron
- i - ion
- l - left
- lw - left wall
- r - right
- rw - right wall
- se - sheath edge
- sf - sheath floating

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INTRODUCTION

1.1 CONTEXTUALIZATION

The development of humanity has been closely related to energy and to the manners of harnessing it in its many forms. @TODO: possibly include graph with energy growth predictions

1.1.1 *Fusion Energy*

Not all the reactions of nuclear fusion are of interest to energy production. The mass of a nucleus is not the sum of the masses of the protons and neutrons that constitute it, i.e. $m \neq Zm_p + (A - Z)m_n$. Where Z is the atomic number, A is the mass number, m_p and m_n are respectively the free masses of proton and neutron. The difference corresponds to a binding energy E_B, which is the energy that should be supplied to a nucleus to decompose it in its nucleons. $E_B = (m - Zm_p + (A - Z)m_n)c^2$. To produce energy, the reactions of particular interest are those whose rest energy of the resulting nucleus is lower than the rest energy of the reacting nuclei. In such cases, a quantity of energy is released resulting from the difference in binding energy between the final and initial states. Image 1.1 shows the normalisation of the binding energy of the nucleon mass as a function of the mass numbers of elements. The steep increase for the light elements motivates the choice of reagents where nuclear fusion is favourable.

Figure 1.1.: Average binding energy (in MeV) per nucleon as function of the atomic mass number (A) for most common isotopes. The sudden increase of binding energy in the low atomic mass side manifests itself as a release of energy in the balance of a fusion reaction.

Table 1.1.: Comparison of the energy density from different power sources

Energy Density [MJ/kg]	
Fusion	335000
Fission	87600
Coal	27.8
Hydroelectric	4.9×10^{-4}

Upon deciding the underlying mechanism by energy will be produced the following subject to address if the choice of fusion reaction. There are a plethora of energy-producing fusion reactions between the low atomic mass nuclei, and some of most relevant are detailed below, on table 1.2:

Table 1.2.: Relevant nuclear reactions

Designation	Reaction	Released energy (MeV)
Deuterium - Deuterium	${}^2_1H + {}^2_1H \rightarrow {}^3_2He + {}^1_0n$	3.27
	${}^2_1H + {}^2_1H \rightarrow {}^3_1H + {}^1_1H$	4.04
Deuterium - Tritium	${}^2_1H + {}^3_1H \rightarrow {}^4_2He + {}^1_0n$	17.59
Deuterium - Helium-3	${}^2_1H + {}^3_2H \rightarrow {}^4_2He + {}^1_1H$	11.33
Tritium - Tritium	${}^3_1H + {}^3_1H \rightarrow {}^4_2He + 2\,{}^1_0n$	18.35

Since there are several possibilities with different advantages however not all of them have the same probability of occurrence. Each of these reactions will have a reaction rate or cross-section which is dependent on the conditions of the reagents, particularly their energy. Figure 1.2 show the cross-section of several fusion reactions. It becomes clear from that figure that for a large energy interval the fusion reaction that holds most potential is the Deuterium-Tritium fusion, or D-T.

Figure 1.2.: Cross-section of several fusion reactions as function of temperature. This figure illustrates how, from several reactions, the most promising for using on a fusion reactor is the deuterium with tritium. The cross-section has a peak at ≈100 keV. @TODO: from âĂŸThe physics of inertial fusionâĂŹ by Atzeni and Meyer-ter-Vehn, Oxford Science Publications

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LIQUID METALS AS PLASMA FACING COMPONENTS

2.1 INTRO

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OVERVIEW OF SPECTROSCOPY

In its pure form it has the following definition:

$$G(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \tag{3.1}$$

where μ is the expected value, the central wavelength, and σ is the standard deviation. The FWHM can be expressed explicitly in terms of the curve's standard deviation:

$$FWHM = 2\sqrt{2\ln(2)}\sigma \tag{3.2}$$

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TIN, LITHIUM AND LITHIUM-TIN ALLOYS

@TODO: cfac results should come in a different chapter. these should be in the same order as the contextualisation chapter!!!!!

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LIQUID METAL SAMPLES EXPOSURE UNDER ISTTOK PLASMAS

5.1 BLA BLA

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FTU

6.1 Collaboration in the experimental campaigns of Cooled Lithium Limiter (CLL) and Tin Liquid Limiter (TLL) held in FTU

BIBLIOGRAPHY

[1] J.P.S. Loureiro, H. Fernandes, F.L. TabarÃl's, G. Mazzitelli, C. Silva, R. Gomes, E. Alves, R. Mateus, T. Pereira, H. Figueiredo, and H. Alves. Deuterium retention in tin (sn) and lithiumâĂŞtin (liâĂŞsn) samples exposed to ISTTOK plasmas. *Nuc. Mat. E.*, 2016.

[2] J.P.S. Loureiro, F.L. TabarÃl's, H. Fernandes, C. Silva, R. Gomes, E. Alves, R. Mateus, T. Pereira, H. Alves, and H. Figueiredo. Behavior of liquid li-sn alloy as plasma facing material on ISTTOK. *Fus. Eng. Des.*, 2017.

[3] F. Romanelli. Fusion electricity - a roadmap to the realisation of fusion energy. Technical report, European Fusion Development Agreement, 2013.

[4] R.B. Gomes, H. Fernandes, C. Silva, A. Sarakovskis, T. Pereira, J. Figueiredo, B. Carvalho, A. Soares, C. Varandas, O. Lielausis, A. Klyukin, E. Platacis, and I. Tale. Interaction of a liquid gallium jet with the tokamak ISTTOK edge plasma. *Fus. Eng. Des.*, 83(1):102 – 111, 2008.

[5] R.B. Gomes, R. Mateus, E. Alves, H. Fernandes, C. Silva, and P. Duarte. Hydrogen retention in gallium samples exposed to ISTTOK plasmas. *Fus. Eng. Des.*, 86(9âĂŞ11):2458 – 2461, 2011. Proceedings of the 26th Symposium of Fusion Technology (SOFT-26).

[6] N. P. Barradas, C. Jeynes, and R. P. Webb. Simulated annealing analysis of rutherford backscattering data. *Appl. Phys. Lett.*, 71(2):291–293, 1997.

[7] J.P. Allain, D.N. Ruzic, and M.R. Hendricks. D, He and Li sputtering of liquid eutectic SnâĂŞLi. *J. Nuc. Mat.*, 290âĂŞ293:33 – 37, 2001. 14th Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices.

[8] `https://www-nds.iaea.org/exfor/exfor.html`. Accessed: 2016-05-10.

[9] Periodic table linked to tori data of known isotopes for each element. `http://nucleardata.nuclear.lu.se/toi/perchart.htm`. Accessed: 2017-11-10.

[10] F. L. Tabarés. Present status of liquid metal research for a fusion reactor. *Plasma Physics and Controlled Fusion*, 58(1):014014, 2016.

[11] E. Oyarzabal, A.B. Martin-Rojo, and F.L. Tabarés. Laboratory experiments of uptake and release of hydrogen isotopes in liquid lithium. *J. Nuc. Mat.*, 463:1173 – 1176, 2015. Proceedings of the 21st International Conference on Plasma-Surface Interactions in Controlled Fusion Devices Kanazawa, Japan May 26-30, 2014.

[12] A.B. MartÃn-Rojo, E. Oyarzabal, and F.L. Tabarés. Laboratory studies of h retention and lih formation in liquid lithium. *Fus. Eng. Des.*, 89(12):2915 – 2918, 2014.

[13] G. Mazzitelli, M.L. Apicella, G. Apruzzese, F. Crescenzi, F. Iannone, G. Maddaluno, V. Pericoli-Ridolfini, S. Roccella, M. Reale, B. Viola, I. Lyublinski, and A. Vertkov. Experiments on FTU with an actively water cooled liquid lithium limiter. *J. Nuc. Mat.*, 463:1152 – 1155, 2015. Proceedings of the 21st International Conference on Plasma-Surface Interactions in Controlled Fusion Devices Kanazawa, Japan May 26-30, 2014.

[14] R. Majeski, R. Kaita, M. Boaz, P. Efthimion, T. Gray, B. Jones, D. Hoffman, H. Kugel, J. Menard, T. Munsat, A. Post-Zwicker, J. Spaleta, G. Taylor, J. Timberlake, R. Woolley, L. Zakharov, M. Finkenthal, D. Stutman, G. Antar, R. Doerner, S. Luckhardt, R. Seraydarian, R. Maingi, M. Maiorano, S. Smith, D. Rodgers, and V. Soukhanovskii. Testing of liquid lithium limiters in CDX-U. *Fus. Eng. Des.*, 72(1âĂŞ3):121 – 132, 2004. Special Issue on Innovative High-Power Density Concepts for Fusion Plasma Chambers.

[15] C. A. F. Varandas, J. A. C. Cabral, J. T. MendonÃğa, M. P. Alonso, P. Amorim, B. B. Carvalho, C. Correia, L. Cupido, M. L. Carvalho, J. M. Dias, H. Fernandes, C. J. Freitas, S. MagalhÄĄes, A. Malaquias, M. E. Manso, A. Praxedes, J. Santana, F. Serra, A. Silva, A. Soares, J. Sousa, W. van Toledo, P. Vaessen, P. Varela, S. Vergamota, and B. de Groot. Engineering aspects of the tokamak ISTTOK. *Fusion Science and Technology*, 29(1):105–115, 1996.

[16] H Fernandes, C.A.F Varandas, J.A.C Cabral, H Figueiredo, and R Galvão. Engineering aspects of the ISTTOK operation in a multicycle alternating flat-top plasma current regime. *Fus. Eng. Des.*, 43(1):101 – 113, 1998.

[17] Ivo S. Carvalho, Paulo Duarte, HorÃącio Fernandes, Daniel F. ValcÃąrcel, Pedro J. Carvalho, Carlos Silva, AndrÃl' S. Duarte, AndrÃl' Neto, Jorge Sousa, AntÃşnio J.N. Batista, Tiago Hekkert, Bernardo B. Carvalho, and Rui B. Gomes. Real-time control for long ohmic alternate current discharges. *Fus. Eng. Des.*, 89(5):576 – 581, 2014. Proceedings of the 9th IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research.

[18] Ivo S. Carvalho, Paulo Duarte, HorÃącio Fernandes, Daniel F. ValcÃąrcel, Pedro J. Carvalho, Carlos Silva, AndrÃl' S. Duarte, AndrÃl' Neto, Jorge Sousa, AntÃşnio J.N. Batista, Tiago Hekkert, and Bernardo B. Carvalho. ISTTOK real-time architecture. *Fus. Eng. Des.*, 89(3):195 – 203, 2014. Design and implementation of real-time systems for magnetic confined fusion devices.

[19] J.P.S. Loureiro, F.L. TabarÃl's, H. Fernandes, C. Silva, R. Gomes, E. Alves, R. Mateus, T. Pereira, H. Alves, and H. Figueiredo. Behaviour of liquid Li-Sn alloy as plasma facing material on ISTTOK. *Fus. Eng. Des.*, 2017.

[20] Richard Schumacher and Alarich Weiss. Hydrogen solubility in the liquid alloys lithium-indium, lithium-lead, and lithium-tin. *Ber. Bunsenges Phys. Chem.*, 94(6):684–691, 1990.

[21] `http://www.mateck.com/`. Accessed: 2016-05-10.

[22] `http://www.srim.org/`. Accessed: 2016-05-10.

[23] T Tanabe. Review of hydrogen retention in tungsten. *Phys. Scr*, 2014(T159):014044, 2014.

[24] A.A. Haasz and J.W. Davis. Deuterium retention in doped graphites. *J. Nuc. Mat.*, 232(2):219 – 225, 1996.

[25] O.V. Ogorodnikova, J. Roth, and M. Mayer. Pre-implantation and pre-annealing effects on deuterium retention in tungsten. *J. Nuc. Mat.*, 373(1âĂŞ3):254 – 258, 2008.

[26] Rion A Causey. Hydrogen isotope retention and recycling in fusion reactor plasma-facing components. *J. Nuc. Mat.*, 300(2âĂŞ3):91 – 117, 2002.

[27] G. G. van Eden, T. W. Morgan, D. U. B. Aussems, M. A. van den Berg, K. Bystrov, and M. C. M. van de Sanden. Self-regulated plasma heat flux mitigation due to liquid sn vapor shielding. *Phys. Rev. Lett.*, 116:135002, Apr 2016.

[28] J.R. Weeks. Lead, bismuth, tin and their alloys as nuclear coolants. *Nuc. Eng. Des.*, 15:363 – 372, 1971.

[29] S. Fukada, M. Kinoshita, K. Kuroki, and T. Muroga. Hydrogen diffusion in liquid lithium from 500°C to 650°C. *J. Nuc. Mat.*, 346(2âĂŞ3):293 – 297, 2005.

[30] H. Moriyama, K. Iwasaki, and Y. Ito. Transport of tritium in liquid lithium. *J. Nuc. Mat.*, 191:190 – 193, 1992.

[31] H. Bi, Y. Hirooka, and J. Yagi. A study on hydrogen transport in liquid metals under steady state plasma bombardment. *Plasma Fus. Res.*, 11(2405026), 2016.

[32] M.J Baldwin, R.P Doerner, R Causey, S.C Luckhardt, and R.W Conn. Recombination of deuterium atoms on the surface of molten liâĂŞlid. *J. Nuc. Mat.*, 306(1):15 – 20, 2002.

[33] E. M. Sacris and N. A. D. Parlee. The diffusion of hydrogen in liquid ni, cu, ag, and sn. *Met. Trans.*, 1(12):3377–3382, 1970.

[34] C. M. Brown, S. G. Tilford, and Marshall L. Ginter. Absorption spectrum of sn i between 1580 and 2040 å. *J. Opt. Soc. Am.*, 67(5):607–621, May 1977.

[35] K Haris, A Kramida, and A Tauheed. Extended and revised analysis of singly ionized tin: Sn ii. *Phys. Scr*, 89(11):115403, 2014.

[36] K Haris and A Tauheed. Revised and extended analysis of doubly ionized tin: Sn iii. *Phys. Scr*, 85(5):055301, 2012.

[37] C E Moore. Atomic energy levels as derived from the analysis of optical spectra âĂŞ molybdenum through lanthanum and hafnium through actinium. *Nat. Stand. Ref. Data Ser.*, III(35):245, 1971.

[38] S S Churilov, Y N Joshi, and A N Ryabtsev. The 4d 10 1 s 0 -4d 9 (np+n′f) transitions in the pd i isoelectronic sequence from cd iii to cs x. *Journal of Physics B: Atomic, Molecular and Optical Physics*, 27(22):5485, 1994.

[39] B. A. Bushaw, W. Nörtershäuser, G. W. F. Drake, and H.-J. Kluge. Ionization energy of ^{6,7}Li determined by triple-resonance laser spectroscopy. *Phys. Rev. A*, 75:052503, May 2007.

[40] G. W. Drake. Theoretical energies for the nâĂĆ=âĂĆ1 and 2 states of the helium isoelectronic sequence up to zâĂĆ=âĂĆ100. *Can. J.Phys.*, 66(7):586–611, 1988.

[41] Glen W. Erickson. Energy levels of oneâĂŘelectron atoms. *J. Phys. Chem. Ref. Data*, 6(3):831–870, 1977.

[42] Keh-Ning Huang. Energy-level scheme and transition probabilities of si-like ions. *Atomic Data and Nuclear Data Tables*, 32(3):503 – 566, 1985.

[43] E Charro, I MartÃ■n, and M A Serna. Systematic trends for quartet transitions in the phosphorus sequence. *Journal of Physics B: Atomic, Molecular and Optical Physics*, 33(9):1753, 2000.

[44] Hsiang shun Chou, Jieh-Yi Chang, Yun-Hsiung Chang, and Keh-Ning Huang. Energy-level scheme and transition probabilities of s-like ions. *Atomic Data and Nuclear Data Tables*, 62(1):77 – 145, 1996.

[45] K.-N. Huang, Y.-K. Kim, K.T. Cheng, and J.P. Desclaux. Energy-level scheme and transition probabilities of cl-like ions. *Atomic Data and Nuclear Data Tables*, 28(2):355 – 377, 1983.

[46] Dong L. Lin, W. Fielder, and Lloyd Armstrong. Relativistic oscillator strengths for $e1$ transitions in the argon isoelectronic sequence. *Phys. Rev. A*, 16:589–599, Aug 1977.

[47] D.E. Post, R.V. Jensen, C.B. Tarter, W.H. Grasberger, and W.A. Lokke. Steady-state radiative cooling rates for low-density, high-temperature plasmas. *Atomic Data and Nuclear Data Tables*, 20(5):397 – 439, 1977.

[48] Chen Ming-Lun and Yu Xiao-Guang. Spectra and oscillator strengths of 3p 6 3d 9 âĂŞ3p 5 3d 10 and 3p 6 3d 9 âĂŞ3p 6 3d 8 4p transitions for cobalt-like sn 23 + ion. *Chinese Physics B*, 18(1):157, 2009.

[49] Y.Q. Liang and J.Y. Zhong. Electron impact collision strengths in sn xxiii. *Atomic Data and Nuclear Data Tables*, 94(6):807 – 902, 2008.

[50] E. Biemont. Energy levels, wavelengths, and weighted oscillator strengths for n = 3âĂŞ4 and 4-4 transitions in cu-like ions (sr x to nd xxxii). *Atomic Data and Nuclear Data Tables*, 39(1):157 – 181, 1988.

[51] U I Safronova and M S Safronova. Relativistic many-body calculations of the oscillator strengths, transition rates and polarizabilities in zn-like ions. *Journal of Physics B: Atomic, Molecular and Optical Physics*, 43(7):074025, 2010.

[52] O. Nagy and Fatma El-Sayed. Energies, wavelengths, and transition probabilities for ge-like kr, mo, sn, and xe ions. *Atomic Data and Nuclear Data Tables*, 98(3):373 – 390, 2012.

[53] R D'Arcy, H Ohashi, S Suda, H Tanuma, S Fujioka, H Nishimura, K Nishihara, C Suzuki, T Kato, F Koike, A O'Connor, and G O'Sullivan. Identification of 4dâĂŞ5p transitions in the spectra of sn xvâĂŞsn xix recorded from collisions between sn ions and he. *Journal of Physics B: Atomic, Molecular and Optical Physics*, 42(16):165207, 2009.

[54] Charro, E. and Martín, I. Relativistic calculations on e1 transitions in as-like ions. *Astron. Astrophys. Suppl. Ser.*, 131(3):523–529, 1998.

[55] Kanti M. Aggarwal and Francis P. Keenan. Radiative rates for e1, e2, m1, and m2 transitions in br-like ions with 43âĽd'zâĽd'50. *Atomic Data and Nuclear Data Tables*, 107:221 – 366, 2016.

[56] N R Badnell, A Foster, D C Griffin, D Kilbane, M O'Mullane, and H P Summers. Dielectronic recombination of heavy species: the tin 4p 6 4d q âĹŠ 4p 6 4d (q âĹŠ 1) 4f + 4p 5 4d (q + 1) transition arrays for q = 1âĂŞ10. *Journal of Physics B: Atomic, Molecular and Optical Physics*, 44(13):135201, 2011.

[57] E.P. Ivanova. Transition probabilities for 5sâĂŞ5p, 5pâĂŞ5d, 4fâĂŞ5d, and 5dâĂŞ5f transitions in ag-like ions with z=50âĂŞ86. *Atomic Data and Nuclear Data Tables*, 97(1):1 – 22, 2011.

[58] C ColÃşn and A Alonso-Medina. Calculation of oscillator strengths, transition probabilities and radiative lifetimes of levels in sn iii. *Journal of Physics B: Atomic, Molecular and Optical Physics*, 43(16):165001, 2010.

[59] P Oliver and A Hibbert. Accurate configuration-interaction calculation of transitions in sn ii. *Journal of Physics B: Atomic, Molecular and Optical Physics*, 43(7):074013, 2010.

[60] M F Gu. The flexible atomic code. *Canadian Journal of Physics*, 86(5):675–689, 2008.

[61] *Lithium Safety and Handling*, 2015. , in the procedings to 4th International Symposium on Lithium Applications Conference, Granada, Sept. 2015.

[62] *Peer Review of Lithium Safety at the Princeton Plasma Physics Laboratory and Implications for Present and Future Lithium Research*, 2015. , in the procedings to 4th International Symposium on Lithium Applications Conference, Granada, Sept. 2015.

[63] M. L. Apicella, G. Mazzitelli, V. Pericoli Ridolfini, V. Lazarev, a. Alekseyev, a. Vertkov, and R. Zagórski. First experiments with lithium limiter on FTU. *J. Nuc. Mat.*, 363-365(1-3):1346–1351, jun 2007.

[64] M. L. Apicella, V. Lazarev, I. Lyublinski, G. Mazzitelli, S. Mirnov, and a. Vertkov. Lithium capillary porous system behavior as PFM in FTU tokamak experiments. *J. Nuc. Mat.*, 386-388(C):821–823, apr 2009.

[65] G. Mazzitelli, M. L. Apicella, and a. Alexeyev. Heat loads on FTU liquid lithium limiter. *Fus. Eng. Des.*, 86(6-8):580–583, oct 2011.

[66] G. Mazzitelli, M. L. Apicella, V. Pericoli Ridolfini, G. Apruzzese, R. De Angelis, D. Frigione, E. Giovannozzi, L. Gabellieri, G. Granucci, C. Mazzotta, M. Marinucci, a. Romano, O. Tudisco, a. Alekseyev, I. Ljublinski, and a. Vertkov. Review of FTU results with the liquid lithium limiter. *Fus. Eng. Des.*, 85(6):896–901, nov 2010.

[67] V. A. Evtikhin, I. E. Lyublinski, A. V. Vertkov, S. V. Mirnov, V. B. Lazarev, N. P. Petrova, S. M. Sotnikov, A. P. Chernobai, B. I. Khripunov, V. B. Petrov, D. Yu Prokhorov, and V. M. Korzhavin. Lithium divertor concept and results of supporting experiments. *Plasma Phys. Control. Fus.*, 44(6):955–977, 2002.

[68] *Comparison between liquid lithium and liquid tin limiters in FTU*, 2017. , in the procedings to 5th International Symposium on Lithium Applications Conference, Moscow, Sept. 2017.

[69] P. Rindt, N.J. Lopes Cardozo, J.A.W. van Dommelen, R. Kaita, and M.A. Jaworski. Conceptual design of a pre-loaded liquid lithium divertor target for nstx-u. *Fus. Eng. Des.*, 112:204 – 212, 2016.

[70] A. S. Eddington. The internal constitution of the stars. *The Scientific Monthly*, 11(4):297–303, 1920.

[71] B. B. Alchagirov, L. Kh. Afaunova, F. F. Dyshekova, A. G. Mozgovoi, T. M. Taova, and R. Kh. Arkhestov. The density and surface tension of liquid lithium at melting temperature. *High Temperature*, 47(2):287–291, Apr 2009.

[72] J. Sangster and C.W. Bale. The li-sn (lithium-tin) system. *Journal of Phase Equilibria and Diffusion*, 19(1):70–75, Jan 1998.

[73] C.John Wen and Robert A. Huggins. Chemical diffusion in intermediate phases in the lithium-tin system. *Journal of Solid State Chemistry*, 35(3):376 – 384, 1980.

[74] P. Franke and D. Neuschütz. Li-sn (lithium - tin): Datasheet from landolt-börnstein - group iv physical chemistry · volume 19b5: "binary systems. part 5: Binary systems supplement 1" in springermaterials (https://dx.doi.org/10.1007/978-3-540-45280-5_87). accessed 2018-09-30.

[75] B.C.Allen. *Transactions of the Metallurgical Society of AIME*, 239:1026 – 1029, 1967.

[76] T. B. MASSALSKI. *Binary Alloy Phase Diagrams*. ASM International, Materials Park, Ohio, 1990.

[77] T. W. Morgan, D. C M Van Den Bekerom, and G. De Temmerman. Interaction of a tin-based capillary porous structure with ITER/DEMO relevant plasma conditions. *Journal of Nuclear Materials*, 463:1256–1259, 2015.

[78] R. P. Doerner, M. J. Baldwin, R. W. Conn, A. A. Grossman, S. C. Luckhardt, R. Seraydarian, G. R. Tynan, and D. G. Whyte. Measurements of erosion mechanisms from solid and liquid materials in PISCES-B. *Journal of Nuclear Materials*, 290-293:166–172, 2001.

[79] V. P. Krasin and S. I. Soyustova. Quantitative evaluation of thermodynamic parameters of Li-Sn alloys related to their use in fusion reactor. *Journal of Nuclear Materials*, 505:193–199, 2018.

[80] Richard Schumacher and Alarich Weiss. Hydrogen solubility in the liquid alloys lithium-indium, lithium-lead, and lithium-tin. *Berichte der Bunsengesellschaft/Physical Chemistry Chemical Physics*, 94(6):684–691, 1990.

[81] R. F. Mattas, J. P. Allain, R. Bastasz, J. N. Brooks, T. Evans, A. Hassanein, S. Luckhardt, K. McCarthy, P. Mioduszewski, R. Maingi, E. Mogahed, R. Moir, S. Molokov, N. Morely, R. Nygren, T. Rognlien, C. Reed, D. Ruzic, I. Sviatoslavsky, D. Sze, M. Tillack, M. Ulrickson, P. M. Wade, R. Wooley, and C. Wong. ALPS - advanced limiter-divertor plasma-facing systems. *Fusion Engineering and Design*, 49-50:127–134, 2000.

[82] R. Majeski. Liquid Metal Walls, Lithium, And Low Recycling Boundary Conditions In Tokamaks. Technical report, Princeton Plasma Physics Laboratory, 2010.

[83] Rui Barrocas Gomes. *Interaction of a liquid gallium jet with the tokamak ISTTOK edge plasma*. PhD thesis, Universidade Técnica de Lisboa, Institúto Superior Técnico, 2009.

[84] R. Kaita, R. Majeski, M. Boaz, P. Efthimion, G. Gettelfinger, T. Gray, D. Hoffman, S. Jardin, H. Kugel, P. Marfuta, T. Munsat, C. Neumeyer, S. Raftopoulos, V. Soukhanovskii, J. Spaleta, G. Taylor, J. Timberlake, R. Woolley, L. Zakharov, M. Finkenthal, D. Stutman, L. Delgado-Aparicio, R. P. Seraydarian, G. Antar, R. Doerner, S. Luckhardt, M. Baldwin, R. W. Conn, R. Maingi, M. Menon, R. Causey, D. Buchenauer, M. Ulrickson, B. Jones, and D. Rodgers. Effects of large area liquid lithium limiters on spherical torus plasmas. *Journal of Nuclear Materials*, 337-339(1-3 SPEC. ISS.):872–876, 2005.

[85] R. E. Nygren and F. L. Tabaés. Liquid surfaces for fusion plasma facing componentsâĂŤA critical review. Part I: Physics and PSI. *Nuclear Materials and Energy*, 9:6–21, 2016.

[86] V. O. Vodyanyuk. *Sov. J.Plasma Phys*, 14(370):759–764, 1988.

[87] N. C. Christofilos. Design for a high power-density astron reactor. *Journal of Fusion Energy*, 8(1):97–105, Jun 1989.

[88] B. Badger, M. A. Abdou, R. W. Boom, R. G. Brown, E. T. Cheng, R. W. Conn, and J. M. Donhowe. UWMAK-I, a wisconsin toroidal fusion reactor design - report UWFDM-68. Technical report, Fusion technology institue, University of Wisconsin, 1973.

[89] B. Badger, M. A. Abdou, R. W. Boom, E. T. Cheng, R. W. Conn, and J. M. Donhowe. UWMAK-II, A Conceptual D-T Fueled, Helium Cooled Tokamak Fusion Power Reactor - report UWFDM-112. Technical report, Fusion technology institue, University of Wisconsin, 1975.

[90] H.-K. Chung, M.H. Chen, W.L. Morgan, Y. Ralchenko, and R.W. Lee. Flychk: Generalized population kinetics and spectral model for rapid spectroscopic analysis for all elements. *H. E. Dens. Phys.*, 1(1):3 – 12, 2005.

[91] A. Kramida, Yu. Ralchenko, J. Reader, and and NIST ASD Team. NIST Atomic Spectra Database (ver. 5.5.6), [Online]. Available: https://physics.nist.gov/asd [2018, July 17]. National Institute of Standards and Technology, Gaithersburg, MD., 2018.

[92] J. H. Lienhard. Heat transfer. *J. Heat Trans.*, 2010.

[93] M. L. G. Oldfield, T. V. Jones, and D. L. Schultz. On-line computer for transient turbine cascade instrumentation. *Trans. Aero. Elec. Sys.*, AES-14(5):738–749, Sept 1978.

[94] W. J. Cook and E. J. Felderman. Reduction of data from thin-film heat-transfer gages: A concise numerical technique. *Am. Inst. Aeronaut. Astronaut. J."*, 4(3):561–562, 1966.

[95] M. Iafrati, G. Mazzitelli, M. L. Apicella, G. M. Apruzzese, J. P. S. Loureiro, I. Lyublinski, A. Vertkov, A. Berlov, G. Maddaluno, F. Crescenzi, A. Mancini, and FTU team. Comparison between liquid lithium and liquid tin limiters in FTU. 2017. , O5.132 in the procedings from 44th EPS Conference on Plasma Physics in Belfast June 2017 (to appear in Plasma Phys. and Controlled Fus.).

[96] M. D. Coventry, J. P. Allain, and D. N. Ruzic. Temperature dependence of liquid Sn sputtering by low-energy He + and D + bombardment. *J. Nuc. Mat.*, 335(1):115–120, 2004.

[97] M. D. Coventry, J. P. Allain, and D. N. Ruzic. D+, He+ and H+ sputtering of solid and liquid phase tin. *J. Nuc. Mat.*, 313-316(SUPPL.):636–640, 2003.

[98] J. Sáanchez, M. Acedo, A. Alonso, J. Alonso, P. Alvarez, E. Ascasíbar, A. Baciero, R. Balbín, L. Barrera, E. Blanco, J. Botija, A. De Bustos, E. De La Cal, I. Calvo, A. Cappa, J. M. Carmona, D. Carralero, R. Carrasco, B. A. Carreras, F. Castejón, R. Castro, G. Cataln, A. A. Chmyga, M. Chamorro, L. Eliseev, L. Esteban, T. Estrada, A. Fernndez, R. Fernndez-Gaviln, J. A. Ferreira, J. M. Fontdecaba, C. Fuentes, L. García, I. García-Cortés, R. García-Gómez, J. M. García-Regãa, J. Guasp, L. Guimarais, T. Happel, J. Hernanz, J. Herranz, C. Hidalgo, J. A. Jiménez, A. Jiménez-Denche, R. Jiménez-Gómez, D. Jiménez-Rey, I. Kirpitchev, A. D. Komarov, A. S. Kozachok, L. Krupnik, F. Lapayese, M. Liniers, D. López-Bruna, A. López-Fraguas, J. López-Rzola, A. López-Snchez, S. Lysenko, G. Marcon, F. Martín, V. Maurin, K. J. McCarthy, F. Medina, M. Medrano, A. V. Melnikov, P. Méndez, B. Van Milligen, E. Mirones, I. S. Nedzelskiy, M. Ochando, J. Olivares, J. L. De Pablos, L. Pacios, I. Pastor, M. A. Pedrosa, A. De La Pážja, A. Pereira, G. Pérez, D. Pérez-Risco, A. Petrov, S. Petrov, A. Portas, D. Pretty, D. Rapisarda, G. Ratt, J. M. Reynolds, E. Rincón, L. Ríos,

C. Rodríguez, J. A. Romero, A. Ros, A. Salas, M. Snchez, E. Snchez, E. Snchez-Sarabia, K. Sarksian, J. A. Sebastin, C. Silva, S. Schchepetov, N. Skvortsova, E. R. Solano, A. Soleto, F. Tabarés, D. Tafalla, A. Tarancón, Yu Taschev, J. Tera, A. Tolkachev, V. Tribaldos, V. I. Vargas, J. Vega, G. Velasco, J. L. Velasco, M. Weber, G. Wolfers, and B. Zurro. Confinement transitions in TJ-II under Li-coated wall conditions. *Nuclear Fusion*, 49(10), 2009.

[99] F. L. Tabarés, M. Ochando, D. Tafalla, F. Medina, K. McCarthy, J. M. Fontdecaba, M. Liniers, J. Guasp, E. Ascasíbar, T. Estrada, and I. Pastor. Energy and particle balance studies under full boron and lithium-coated walls in TJ-II. *Contributions to Plasma Physics*, 50(6-7):610–615, 2010.

[100] E. Ascasíbar, T. Estrada, M. Liniers, M. A. Ochando, F. L. Tabarés, D. Tafalla, J. Guasp, R. Jiménez-Gómez, F. Castejón, D. López-Bruna, A. López-Fraguas, I. Pastor, A. Cappa, C. Fuentes, and J. M. Fontdecaba. Global energy confinement studies in TJ-II NBI plasmas. *Contributions to Plasma Physics*, 50(6-7):594–599, 2010.

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DEMONSTRATIONS